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The Assessment of Soil Quality in Contrasting Land-Use and Tillage Systems on Farm Fields with Stagnic Luvisol Soil in Estonia

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Abstract: Soil quality indicates the soil's ability to provide ecosystem services. Reducing the tillage intensity has been suggested as an alternative to conventional tillage for sustaining soil quality. This study aimed to evaluate the effect of soil tillage systems on individual soil quality indicators in comparison to those on grassland with Stagnic Luvisol soil in Estonia. Four soil management systems were compared: no-tillage (NT), minimum tillage (MT), conventional tillage (CT) and grassland (G) as a reference. Soil quality indicators included physical (bulk density, water-stable aggregates, porosity, air-filled pores, moisture content, water-holding capacity, penetration resistance and water permeability), chemical (total N, total soil organic C, permanganate oxidisable C, pH, P, K, Ca and Mg) and biological (earthworm abundance) parameters. CT soils had a significantly lower aggregate stability compared to MT and G soils. The higher penetration resistance of CT under an arable layer suggested the presence of a plough pan. NT improved the soil's physical quality at 5–10 cm, which was indicated by higher moisture content, water-holding capacity and porosity and a lower bulk density, whereas penetration resistance exceeded 2 MPa in the lower part of the topsoil. NT also had significantly lower total soil organic C and total N compared to MT and G. The absence of tillage in the NT and G systems may have improved the soil's resistance to moisture loss under dry conditions, which, in turn, improved the soil habitability for earthworms a despite higher density. In general, NT or MT stabilised or increased the soil quality compared to CT.

Keywords: earthworms; minimum tillage; no-tillage; soil physical properties; water-stable aggregates (WSA)

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1. Introduction

The impact of the intensive use of soils in Europe and the consequences of climate change are causing soil quality degradation; thus, finding management practices that improve soil quality is of crucial importance to maintain sustainable agriculture [1,2]. Soil quality assessments can be used to evaluate the sustainability of soil management practices [3]. Soil quality can be defined as, "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" [3]. It is measured by integrating and assessing different physical, chemical and biological indicators related to soil processes and functioning. The provision of certain ecosystem services or soil functioning is assessed indirectly by measuring associated parameters. For instance, water-stable aggregates (WSA), water-holding capacity (WHC) and density can be used as indicators for soil structure formation and water-retention capacity [4]. Total organic C (TOC), nitrogen content (N_{tot}), available nutrient contents and soil pH can be used as the indicators for C sequestration and nutrient-cycling functions [5]. The favourability of soil for biota is most often assessed through the abundance and diversity of earthworms [6]. The vast majority of recent soil quality research has focused on soil quality parameters that are sensitive toward management practices but that are also easy to measure and that are directly related to soil functioning or certain processes [7].

Soil is an extremely complex and dynamic environment, where disturbances to one function might have consequences for others. For example, poor habitability might influence the provision of ecosystem services by soil organisms, such as water regulation and purification, nutrient cycling, and C regulation [8]. Such connections make the assessment of soil quality rather complicated and emphasise the need for a sensitive set of indicators that are easy to measure but that are also directly connected to specific functions that soils support.

Labile C fractions, such as permanganate oxidisable C (POXC), have been considered as a comprehensive indicator in recent soil quality research due to their sensitivity to tillage [9]. POXC is a labile, active form of total soil organic C that is assumed to reflect the processed fraction of soil C and is closely related to smaller and heavier particulate organic C fractions, which makes it a valuable indicator to detect early changes in soil C content [10]. Measuring POXC is rather inexpensive, and it correlates well with other measures of soil microbial activity such as microbial biomass C, substrate-induced respiration, soluble carbohydrate C and total soil organic C [11].

Studies of the impact of land management and tillage intensity on soil properties have found that reducing tillage intensity positively impacts the physical [12,13] and biological properties [14] of soil and also the overall soil quality [15]. Cereal yields can be higher in conventional tillage systems compared to no-tillage systems, but not in years with low precipitation and drought during the growing season [16]. Reducing the tillage intensity improves the soil water-holding capacity, which can be especially beneficial in years with low precipitation or during drought periods [17].

Grasslands keep the soil under permanent plant cover, which has been considered as the optimal condition for soil quality as it prevents the disturbance of the soil structure, causing less C mineralisation and more diverse plant residue input to feed soil biota. Conventional systems use intensive tilling and soil inversion for plant protection and to incorporate plant residues into the soil, which leads to changing the physicochemical soil conditions and, in some cases, reducing the soil biodiversity or changing the community composition [18]. Conservation tillage systems such as no or minimum tillage are characterised by no or minimal soil disturbance, where plant residues accumulate either on the surface of the soil or are incorporated into the top 12 cm. The stratification of soil properties under no-tillage, especially for soil organic C is explained by the accumulation of plant residues on the soil surface, which can result in increased wet aggregate stability and available water capacity and reduced compactibility at that depth [12]. For minimum and conventional tillage, soil conditions are rather homogenous in the humus horizon due to soil mixing or inversion.

Results of land management and tillage-induced effects on soil properties have been contradictory across different studies, and the effects can be soil specific and influenced by the local pedoclimatic conditions [13]. Although the effect of tillage has been widely studied in northern European conditions [13,19–21], most of the available information on soil properties in different tillage and land-use systems is collected from small research plots with controlled conditions and uniform soils, which can differ from conditions on farm fields. Studies on the farm field level that account for the variability across the landscape are scarce, although they can be valuable to characterise soil functioning under different management systems at the agroecosystem level. Although previous research exists on the impact of tillage systems in Estonia, it has been mostly focused on comparing no-tillage and conventional tillage [22–25] or focused only on soil fungal diversity [26]. There is a particular lack of studies comparing MT with either NT or CT. Due to the limited understanding of the impact of tillage intensity, a complex soil quality assessment at the farm field level using a diverse set of soil attributes is required.

The objectives of this study were to: (a) assess the effects of different agricultural management systems with a range in intensity (grassland vs. no-tillage vs. minimum tillage vs. conventional tillage) on individual soil quality indicators in Stagnic Luvisol soil; (b) evaluate the effect of the sampling layer (5–10 cm vs. 25–30 cm) on soil quality indicators to detect the stratification of soil properties within the management practice; (c) evaluate the impact of the interactions between the management treatment, layer and year to see whether the changes differ depending on the year and depth; and (d) assess the relationships between soil properties to evaluate the suitability of soil properties as soil quality indicators. The impact of the year was assessed by using the physical soil properties and earthworms.

2. Materials and Methods

2.1. Selected Field Sites and Management

Eight farm fields in southern Estonia were chosen, representing a range of land use and tillage intensity. The fields had been under a specific management system for at least 8 years before the collection of the first samples. Since these were agricultural fields, there were differences in crop sequence and farm operations, but all the fields had a cereal-based crop rotation. Synthetic fertilisers were used in all fields (except on grasslands) according to normal practices in the area and were applied in equal quantities. The objective was to differentiate the fields based on their main land management treatment, which included: (1) grassland, i.e., permanent plant cover (G); (2) no-tillage (NT); (3) minimum tillage at a 0–12 cm depth (ploughless, MT); and (4) conventional tillage, ploughing at a 20–23 cm depth (CT). The plant species in the grasslands included Phleum pratense, Festuca Pratensis, Trifolium pratense, Trifolium repens, Lolium perenne, Poa pratensis and Lolium multiflorum. The soil type of all the fields was Stagnic Luvisol (WRB soil classification system), which was chosen due to its large share (around 15%) of use in agricultural fields in Estonia. According to the FAO classification [27], the textural classes were between sandy loam and loam (Table 1). The texture was measured by using the pipette method [28]. All the laboratory measurements were performed at the Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences.

Table 1. Characteristics of the selected fields used in present study.

Field No.	Management Type	Clay, % (<0.002)	Silt, % (0.002–0.063)	Sand, % (>0.063)	Soil Texture (FAO)
1	Grassland	15.3	26.3	58.4	Sandy loam
2	Grassland	11.2	30.0	58.8	Sandy loam
3	No-tillage, cereals	9.6	43.8	46.6	Loam
4	No-tillage, cereals	7.2	37.2	55.6	Sandy loam-loam
5	Minimum tillage, cereals	11.4	32.6	56.0	Sandy loam
6	Minimum tillage, cereals	11.2	23.4	65.4	Sandy loam
7	Conventional tillage, cereals	9.1	37.5	53.4	Sandy loam-loam
8	Conventional tillage, cereals	8.5	42.6	48.9	Sandy loam

Estonia is in a transitional zone between maritime and continental climate. According to data extracted from the Estonian Environment Agency weather station (Tartu-Tõravere) closest to the studied sites, the annual sum of precipitation in 2016 was 790.4 mm and in 2018 it was 551.7 mm (Figure 1) [29,30]. The average air temperature was 6.5 °C in 2016 and 7.0 °C in 2018. The mean air temperature from April to August in 2016 was 14.2 °C and in 2018 it was 15.3 °C. The sum of precipitation during that period was about twice as high in 2016 (468.8 mm) than in 2018 (221.5 mm), indicating drought conditions during the summer of 2018.

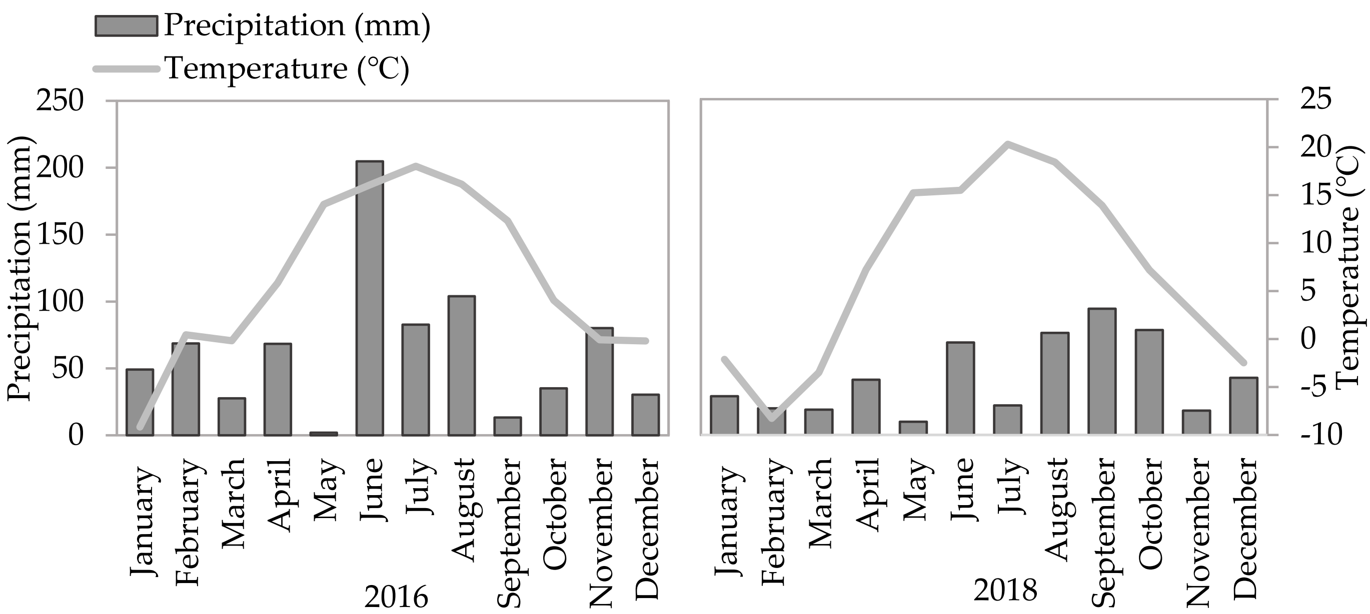

Figure 1. Mean monthly sum of precipitation and temperature in 2016 and 2018 [29,30].

2.2. Soil Sample Collection and Analysis

Soil samples were collected in 2016 and 2018 after the crop harvest and before any tillage operations. A representative area was selected for each field and, the soil physical, chemical and biological indicators were measured at three fixed points. The distance between the sampling spots was approximately 100 m to account for the heterogeneity of the field. Soil samples were collected at depths of 5–10 cm, to characterise the root zone and at 25–30 cm, which is slightly lower than the depth of ploughing, in order to detect the differences in the humus horizon within a specific management practice. At each plot and depth, four 100 cm^3 sampling cylinders were used to measure the bulk density (BD), moisture content (MC), maximum water-holding capacity (WHC), porosity and the percentage of air-filled porosity (AFP). The parameters were calculated following the same procedure as used in [31]. Water permeability (*k*) was determined from core samples using the Hauben permeameter (Eijkelkamp, Giesbeek, The Netherlands). An Eijkelkamp penetrologger with a 60 degree, 1 cm^2 cone was used to measure the penetration resistance down to 60 cm. Penetration resistance was determined in 10 replications, forming a circle around each sampling spot.

The percentage of water-stable aggregates (WSAs) was by using the Eijkelkamp Wet Sieving Apparatus, following the method described by Kemper et al. [32]. Prior to analysis, the samples were air-dried and 4 g of soil from the <2 mm soil fraction was placed on sieves with a mesh size of 0.25 mm. The soil on the sieves was shaken into cans with distilled water for 3 min. Subsequently, the cans were replaced with cans containing 0.4% of NaOH solution. Subsequently, the contents of the cans were dried in a water bath at 94 °C, and then in an oven at 105 °C for 2 h. The percentage of WSAs was calculated as follows:

$$\text{WSA } (\%) = \frac{C_{NaOH}}{C_w + C_{NaOH}} \times 100, \tag{1}$$

where C_{NaOH} is the can with the NaOH solution and C_w is the can with the distilled water. Prior to the calculation, the mass of the NaOH (0.4 g) was subtracted from the mass of the soil in the NaOH -containing cans. Due to the high content of the soil organic matter in analysed soils, the procedure was modified by using twice as high of a concentration of NaOH solution, which was needed to reduce the time required to perform the analysis.

Since management-induced changes in soil texture and soil organic C content are slow and might take up to a decade [33], we measured the chemical properties only in 2016.

The soil organic C content (SOC) was measured according to the Tjurin method [34] and permanganate oxidisable C (POXC) was determined using a spectrophotometer following the procedure of Weil et al. [11]:

$$\text{POXC}\left(\text{mg g}^{-1}\right) = \left[0.02\ \text{mol L}^{-1} - (\text{a} + \text{b} \times \text{absorbance})\right] \times \left(9000\ \text{mg C mol}^{-1}\right) \times \left(0.02\ \text{L solution}/\text{Wt}^{-1}\right) \quad (2)$$

where 0.02 mol L^{-1} is the concentration of $KMnO_4$ solution, a is the intercept, b is the slope of the calibration curve, 9000 mg is the amount of C oxidised by 1 mol of MnO_4 changing from Mn^{+7} to Mn^{+4}, 0.02 L is the volume of the $KMnO_4$ solution reacting with the samples and Wt is the mass of soil in g used for the reaction, which was approximately 5 g.

Total nitrogen (N_{tot}) content was measured after Kjeldahl digestion [35]. Soil pH was determined from a water solution of 1:2.5 using a glass-electrode pH meter. Plant-available phosphorus, potassium, calcium and magnesium contents were measured following the Mehlich 3 method [36]. The number of earthworms was determined by hand sorting a $20 \times 20 \times 20\ cm^3$ soil monolith. TOC, POXC, N_{tot}, C/N, pH and plant-available phosphorus, potassium, calcium and magnesium contents were measured in 2016. WSAs, BD, MC, WHC, TP, AFP, k, penetration resistance and earthworm abundance were studied in 2016 and 2018.

2.3. Statistical Analysis

Linear mixed-effects models were used to test the effect of fixed factors and their interactions with soil quality parameters. The fixed factors in the model were land management treatment, sampling depth and, if applicable, the year. Plots on each field were set as a random factor to generalise the heterogeneity of soil properties at the field scale and across different sites of the same management types. The normality of the variances was tested visually and with the Shapiro–Wilk test. All soil variables (except pH, water content, bulk density and water-stable aggregates) were log transformed or square-root transformed before analysis to meet the ANOVA assumptions.

In the case of significant influences, a post hoc Tukey test was used to perform pairwise comparisons between variable categories. A *t*-test was used to assess significant differences between the variables of each year within the management systems. The Pearson correlation coefficient was calculated to investigate the relationships between soil properties. The correlation analysis of the soil physical and chemical properties was performed using only the data obtained in 2016. The significance threshold value was set at $p < 0.05$ for all analyses. Statistical analyses were carried out using R version R i386 4.1.1 and RStudio version 1.4.1717, using the additional packages nlme [37], emmeans [38] and car [39].

3. Results

3.1. Soil Physical Properties

Management treatments (grassland (G) vs. no-tillage (NT) vs. minimum tillage (MT) vs. conventional tillage (CT)) affected soil properties differently at each depth and in each year (Tables 2–4). Soil physical properties were sensitive to the tillage intensity; however, the sampling layer and year had a higher impact on soil physical properties, indicating stratification of properties between layers and differences in years across the investigated management treatments. The interaction effects of management, sampling depth and year on soil properties show that the direction of the impact can differ between the studied management types and can depend on the sampling depth and conditions of a specific year. The years 2016 and 2018 were rather contrasting in terms of precipitation in Estonia, which was also reflected in the results, where the year seemed to have the highest impact on all the physical soil properties, but especially on soil moisture content ($F = 709.25$, $p = 0.0000$). Comparing the average values of soil physical properties in 2016 and 2018, a significant general decrease in soil BD, WSAs and MC and an increase in TP, AFP and WHC were observed in all the management systems.

Table 2. Effects of management type (G, NT, MT and CT), sampling layer (5–10 cm vs. 25–30 cm) and year (2016 and 2018) on soil physical properties as analysed with linear mixed-effects models (n = 96, except for aggregate stability where n = 48 per each management type and year), where the F-statistics and p-values (values $\leq$ 0.05 are in bold) for the factors and their interactions are reported.

Factors		WSA %	BD g cm^{-3}	MC %	WHC %	TP %	AFP %	k cm d^{-1}
Management type (T)	F	8.83	1.74	10.64	4.88	3.8	1.58	3.44
	p	**0.0000**	0.1589	**0.0000**	**0.0024**	**0.0112**	0.1949	**0.0172**
Layer (L)	F	21.65	53.73	147.65	105.33	41.42	7.40	3.57
	p	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0068**	0.0595
Year (Y)	F	63.28	497.21	709.25	401.68	470.11	192.33	16.25
	p	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0001**
T × L	F	2.97	12.05	19.26	20.66	10.51	0.18	0.22
	p	**0.0335**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.9114	0.8849
T × Y	F	2.56	5.64	52.73	7.67	5.65	3.49	4.20
	p	0.0566	**0.0009**	**0.0000**	**0.0001**	**0.0009**	**0.0159**	**0.0062**
L × Y	F	0.54	11.29	62.39	19.93	7.58	1.46	11.47
	p	0.4642	**0.0009**	**0.0000**	**0.0000**	**0.0062**	0.2277	**0.0008**
T × L × Y	F	6.35	3.00	6.27	4.15	3.05	2.26	1.00
	p	**0.0004**	**0.0306**	**0.0004**	**0.0065**	**0.0288**	0.0813	0.3945

G—grassland; NT—no-tillage; MT—minimum tillage; CT—conventional tillage; WSAs—water stable aggregates; BD—bulk density, MC—moisture content; WHC—water-holding capacity; TP—total porosity; AFP—air-filled pores; k—water permeability.

Table 3. Mean values and standard deviations of soil physical properties between different management types. Different capital letters following mean values within each layer indicate significant differences between the years within the same system (t-test, p < 0.05). Different small letters following means indicate significant differences between management types (p < 0.05) according to Tukey post hoc tests, and have to be read per year and soil layer (n = 96, except for aggregate stability where n = 48 for each management type and year).

	2016				2018			
	G	**NT**	**MT**	**CT**	**G**	**NT**	**MT**	**CT**
Layer 5–10 cm								
WSA %	54.6a ± 7.4	48.1Aab ± 4.9	53.10Aa ± 10.4	45.2Ab ± 5.9	51.2a ± 13.6	42.4Bab ± 5.1	36.7Bb ± 7.3	39.4Bb ± 5.5
BD g cm^{-3}	1.44Aab ± 0.10	1.41Aa ± 0.10	1.48Ab ± 0.13	1.48Ab ± 0.06	1.09Ba ± 0.14	1.18Bb ± 0.10	1.16Bab ± 0.17	1.14Bab ± 0.09
MC %	26.5Aa ± 3.3	33.2Ac ± 3.1	28.8Aab ± 3.3	29.5Ab ± 2.5	31.2Ba ± 10.3	21.2Bb ± 5.0	16.4Bc ± 7.0	13.3Bc ± 4.4
WHC %	45.6Aa ± 2.9	48.5Ab ± 4.5	42.5Ac ± 4.6	42.9Aac ± 3.2	59.1Ba ± 7.2	55.7Bab ± 3.3	54.5Bb ± 5.0	53.6Bb ± 2.6
TP %	44.2Aab ± 3.5	46.1Aa ± 3.5	42.9Ab ± 4.3	43.4Ab ± 2.4	57.8B ± 5.5	54.6B ± 4.0	55.2B ± 6.5	55.9B ± 3.5
AFP %	22.3A ± 3.9	24.5A ± 3.9	23.1A ± 3.8	22.9A ± 2.7	35.7B ± 7.6	34.5B ± 6.1	36.6B ± 8.9	38.4B ± 5.1
k cm d^{-1}	674.6A ± 1004.4	1718.9 ± 6686.4	1562.9 ± 3902.2	1460.7 ± 3685.7	1157.8A ± 1335.5	1492.6 ± 1112.7	1818.6 ± 980.7	1085.9 ± 731.0
Layer 25–30 cm								
WSA %	53.9Aa ± 6.1	40.2b ± 7.0	45.8ab ± 13.0	41.3Ab ± 6.2	33.5B ± 10.5	36.3 ± 6.1	40.5 ± 6.4	34.8B ± 6.0
BD g cm^{-3}	1.55Aa ± 0.07	1.47Ab ± 0.09	1.50Aab ± 0.15	1.48Aab ± 0.06	1.39Ba ± 0.21	1.30Bab ± 0.10	1.18Bb ± 0.12	1.23Bbc ± 0.09
MC%	22.9Aa ± 4.1	28.8Ab ± 3.0	28.7Ab ± 5.1	29.5Ab ± 2.5	13.0Ba ± 5.2	10.5Bab ± 3.2	11.3Bab ± 3.2	9.1Bb ± 3.2
WHC %	41.1Aa ± 2.6	43.9Ab ± 2.8	42.3Aab ± 4.6	42.9Aab ± 3.2	44.7Ba ± 6.3	48.7Bb ± 2.7	53.2Bc ± 4.6	49.4Bb ± 4.5
TP %	40.7Aa ± 2.7	44.2Ab ± 3.4	42.13Aab ± 5.4	43.4Aab ± 2.3	46.9Ba ± 8.1	50.7Bab ± 3.9	55.0Bc ± 4.4	52.8Bbc ± 3.6
AFP %	22.2A ± 3.6	24.4A ± 4.3	22.5A ± 6.5	22.9A ± 2.7	29.5Ba ± 9.0	30.7Ba ± 5.9	36.3Bb ± 4.8	33.9Bab ± 5.4
k cm d^{-1}	615.8 ± 721.3	1346.5 ± 3265.0	477.7A ± 704.3	1460.7 ± 3685.7	539.9a ± 803.4	395.0a ± 514.1	1518.9Bb ± 1194.0	512.9a ± 465.1

G—grassland; NT—no-tillage; MT—minimum tillage; CT—conventional tillage; WSA—water stable aggregates; BD—bulk density, MC—moisture content; WHC—water-holding capacity; TP—total porosity; AFP—air-filled pores; k—water permeability.

According to the F-statistics, WSAs and MC were the most sensitive indicators for the management treatment among the physical soil quality indicators (F = 8.83 and p < 0.000 and F = 10.64 and p < 0.000, respectively). Additionally, WSAs and MC were the most influenced by the interaction between the management type, layer and the year (F = 6.35 and p = 0.0004 and F = 6.27 and p = 0.0004, respectively). The content of WSAs was 17.48 and 20.8% higher in MT and G fields compared to CT at 5–10 cm in 2016. For the 25–30 depth, WSAs were 30.51 and 34.08% higher in G fields compared to NT and CT, respectively. However, in 2018, the WSAs were 29.35 and 39.51% higher in G fields compared to CT and MT.

Table 4. Mean soil penetration resistance and standard deviation presented at 5 cm depth interval across different management types (n = 60), where different capital letters following mean values within each depth indicate significant differences between the years within the same system (*t*-test, $p < 0.05$). Different small letters indicate statistical differences ($p < 0.05$) between management types at each depth and year according to Tukey post hoc test.

Depth, cm	Penetration Resistance, MPa							
	2016				2018			
	G	NT	MT	CT	G	NT	MT	CT
5	1.89Aa ± 0.69	1.21b ± 0.49	1.09Ab ± 0.47	1.05Ab ± 0.58	0.92Bab ± 0.83	1.19b ± 0.54	0.15Bc ± 0.14	0.70Ba ± 0.75
10	2.4Aa ± 0.71	1.50Ab ± 0.49	1.37Ab ± 0.49	1.25Ab ± 0.65	1.35Ba ± 0.92	1.72Ba ± 0.57	0.30Bb ± 0.35	1.07Bc ± 1.01
15	2.47Aa ± 0.65	1.99b ± 0.60	1.79Abc ± 0.67	1.53Ac ± 0.72	1.86Ba ± 0.79	1.87a ± 0.56	0.63Bb ± 0.71	1.28Bc ± 1.04
20	2.53Aa ± 0.65	2.19b ± 0.68	2.05Abc ± 0.62	1.74Ac ± 0.74	2.08Ba ± 0.7	2.23a ± 0.64	1.03Bb ± 0.77	1.59Bc ± 1.05
25	2.65Aa ± 0.63	2.31bc ± 0.83	2.47Aab ± 0.83	2.12Ac ± 0.77	2.25Ba ± 0.59	2.47a ± 0.72	1.53Bb ± 0.82	1.74Bb ± 1.1
30	2.81a ± 0.64	2.60ab ± 0.79	2.77Aab ± 0.77	2.42Ab ± 0.86	2.58a ± 0.70	2.63a ± 0.66	1.89Bb ± 0.79	2.35Ba ± 1.25
35	2.87 ± 0.69	2.84 ± 0.95	3.11A ± 1.03	2.84A ± 0.86	2.73a ± 0.77	2.64a ± 0.66	2.19Bb ± 0.74	2.88Ba ± 1.15
40	2.99 ± 0.83	2.98A ± 0.84	3.27A ± 1.13	3.23A ± 1.08	2.85a ± 0.76	2.64Ba ± 0.74	2.47Ba ± 0.89	3.38Bb ± 1.28
45	2.83a ± 0.73	3.10Aab ± 1.09	3.22ab ± 1.09	3.37Ab ± 1.13	3.03a ± 0.91	2.69Ba ± 0.84	2.57a ± 0.91	3.60Bb ± 1.24
50	2.86Aa ± 0.87	2.99Aa ± 1.24	3.28ab ± 1.06	3.57Ab ± 1.22	3.23Bab ± 1.01	2.87a ± 0.92	2.80Ba ± 0.83	3.69Bb ± 1.30
55	2.85Aa ± 0.52	3.02a ± 1.18	3.27ab ± 1.06	3.71b ± 1.30	3.37Bab ± 1.01	3.20a ± 1.24	2.94a ± 0.81	3.84b ± 1.67
60	2.80Aa ± 0.71	2.94Aa ± 1.05	3.05a ± 0.72	3.90b ± 1.28	3.64Ba ± 1.14	3.47Bab ± 1.30	2.96b ± 0.89	4.35c ± 1.85

G—grassland; NT—no-tillage; MT—minimum tillage; CT—conventional tillage.

In 2016, BD was significantly lower, and MC, WHC and porosity were higher for NT compared to MT and CT in the 5–10 cm layer, whereas at 25–30 cm these properties were not significantly different between these management types. MC and WHC were also significantly higher for NT compared to G fields at both depths. Additionally, BD was lower and TP was higher for NT compared to G fields. However, in 2018, MC was 1.5–2.4 times higher in G fields compared to the other cropland management types and 29.27 and 59.4% higher for NT compared to MT and CT at 5–10 cm, respectively. WHC was also significantly higher in G fields compared to MT and CT, whereas at 25–30 cm, the WHC was the lowest in G fields and the highest for MT compared to the other management types. MC was 42.86% higher in G fields compared to CT at 25–30 cm. BD was significantly higher under G fields compared to MT and CT at the lower depth. TP and AFP were higher for MT compared to G and NT systems. Water permeability was the highest for MT compared to other management types at 25–30 cm.

The management type (F = 59.6 and $p = 0.0000$), year (F = 104.69 and $p = 0.0000$) and depth (F = 368.2 and $p = 0.0000$) had a significant effect on soil penetration resistance (from 5–60 cm at a 5 cm interval). Comparing the average penetration resistance in 2016 and 2018, there was a significant decrease almost throughout the profile under MT (Table 4). Penetration resistance decreased under G and CT management up to 30 cm, whereas for the latter, there was an increase from 35 to 50 cm. There was an increase at 10 cm and a decrease at 40 to 50 cm under NT. In 2016, the soil penetration resistance was significantly higher in G fields at 5–20 cm compared to other management types, but was also higher at 25 cm compared to NT and CT, whereas CT had a significantly lower penetration resistance at 10–20 cm compared to NT. However, at 45 cm and deeper, the penetration resistance was higher for CT. Similar tendencies were apparent in 2018, where the soil penetration resistance was significantly lower for MT and CT in the humus horizon and below the ploughing depth was higher for CT, indicating subsoil compaction. For G and NT systems, the penetration resistance exceeded the limit of 2 MPa which is considered limiting for the root growth of many plant species. For MT, the soil penetration resistance tended to be lower throughout the soil profile in 2018.

3.2. Soil Chemical and Biological Properties

The management treatment influenced most of the chemical soil properties, whereas the interaction effect of the management and layer was not significant, indicating that there was no significant stratification of properties between the layers induced by management practices (Table 5). The management types did not significantly affect soil phosphorus and potassium contents. POXC, when expressed as the percentage of TOC, and N_{tot}, were the most influenced by management types among these parameters (F = 8.33 and p = 0.0002 and F = 7.08 and p = 0.0007, respectively).

Table 5. Mean (± standard deviation) values of soil chemical properties in 2016 are presented. Letters indicate statistical differences in soil properties between management treatments according to Tukey post hoc test, which have to be read per column and per layer. Effects of management treatment (G, NT, MT and CT) and sampling layer (5–10 cm vs. 25–30 cm) on soil chemical properties as analysed with linear mixed-effects models (n = 12 per management treatment), where the F-statistics and p-values (values ≤ 0.05 are in bold) for the factors and their interactions are reported in the lower part of the table.

		TOC %	POXC mg g^{-1}	POXC % of TOC	N_{tot} %	C/N	pH
Layer 5–10							
G		1.92a ± 0.40	0.604a ± 0.098	3.3a ± 1	0.223a ± 0.04	8.6a ± 0.57	6.3ab ± 0.7
NT		1.20b ± 0.21	0.689b ± 0.006	5.9c ± 1.08	0.142b ± 0.04	8.6a ± 1.02	6.2a ± 0.4
MT		1.72a ± 0.44	0.661ab ± 0.03	4.0ab ± 0.80	0.205ab ± 0.09	8.7a ± 1.04	6.9b ± 0.32
CT		1.47ab ± 0.14	0.692b ± 0.009	4.8bc ± 0.40	0.136b ± 0.03	11.1b ± 2.01	6.6ab ± 0.2
Layer 25–30							
G		1.18 ± 0.39	0.616 ± 0.083	5.9ab ± 2.76	0.14ab ± 0.03	8.1 ± 1.14	6.4 ± 0.7
NT		0.81 ± 0.19	0.676 ± 0.003	8.8a ± 2.32	0.09a ± 0.01	8.5 ± 1.23	6.6 ± 0.3
MT		1.45 ± 0.81	0.653 ± 0.033	5.3b ± 1.80	0.16b ± 0.08	9.2 ± 0.28	7.0 ± 0.2
CT		1.12 ± 0.22	0.680 ± 0.008	6.2ab ± 1.08	0.11ab ± 0.01	10.2 ± 2.32	6.7 ± 0.2
Management treatment (T)	F	6.54	6.46	8.33	7.08	6.70	5.10
	p	0.0011	0.0011	0.0002	0.0007	0.0009	0.0044
Layer (L)	F	21.57	0.15	18.08	14.45	0.33	2.24
	p	0.0000	0.7014	0.0001	0.0005	0.5707	0.1426
T × L	F	0.70	0.18	0.77	0.73	0.73	0.29
	p	0.5572	0.9072	0.5194	0.5406	0.539	0.8325

G—grassland; NT—no-tillage; MT—minimum tillage; CT—conventional tillage; TOC—total organic C; POXC—permanganate oxidisable C; N_{tot}—total nitrogen.

TOC was 43.33 and 60% higher for MT and G fields compared to NT at 5–10 cm, whereas no significant differences were found at 25–30 cm. However, POXC was the lowest and N_{tot} was the highest for G fields (significant differences with NT and CT). POXC, when expressed as the percentage of TOC, was significantly higher for NT and CT fields compared to G at 5–10 cm. The percentage of POXC of TOC was also higher for NT compared to MT at both depths. N_{tot} was significantly lower for NT compared to MT. Soil C/N was significantly higher and nearest to optimal for CT compared to other management treatments. The soil pH was slightly acidic to neutral between the management types. At the first depth, the soil pH was significantly higher for MT compared to NT.

Earthworm abundance was significantly influenced by the management type (F = 4.89 and p = 0.0055), year (F = 73.06 and p = 0.0000) and their interaction (F = 6.42 and p = 0.0012). Comparing the average earthworm abundance values of 2016 and 2018, a general decrease was observed under all the management systems (significant differences between investigated years under G, NT and CT management systems; Figure 2). In 2016, the earthworm abundance was significantly lower for MT compared to that in G and CT fields, whereas in 2018, the earthworms were absent under CT (significant differences with G and NT fields).

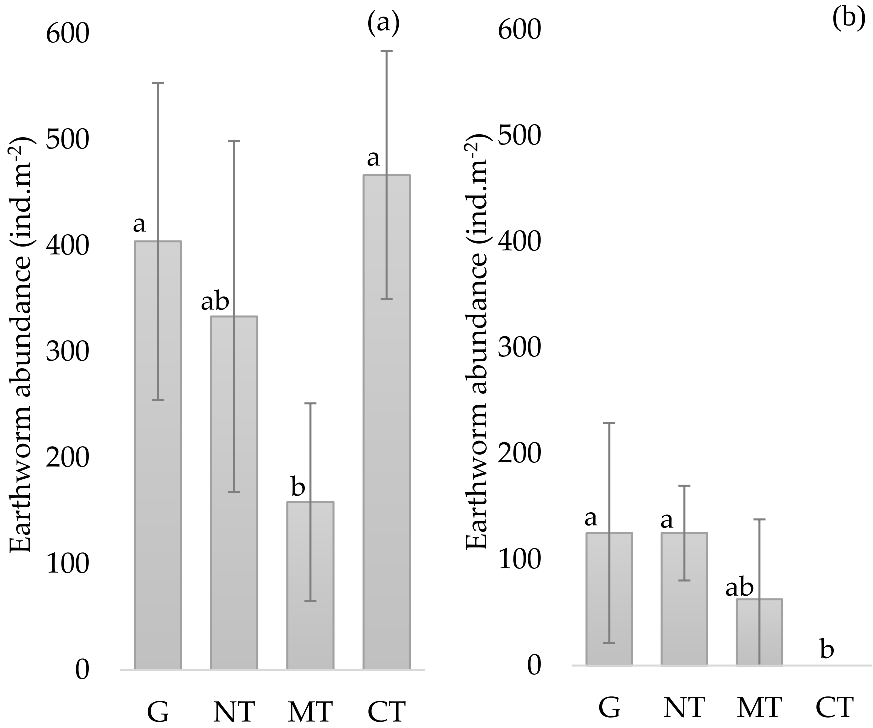

Figure 2. Earthworm abundance of studied management treatments in (**a**) 2016 and (**b**) 2018 (n = 6 per each year and management treatment). Letters indicate statistical differences between management types according to Tukey post hoc test ($p < 0.05$) within each year. Codes for land management types: G—grassland; NT—no-tillage; MT—minimum tillage; CT—conventional tillage.

3.3. Relationships between Soil Quality Parameters

Most of the physical properties correlated strongly with each other; however, no correlations were found between WSAs or water permeability and the other physical indicators in 2016 (Table 6). In 2018, soils with higher water permeability had higher WHC and TP and lower BD. However, water permeability did not correlate with any of the chemical indicators, and the POXC, C/N, pH and phosphorus content did not correlate to any of the physical properties. Soils with a lower bulk density had a higher water content, water-holding capacity, porosity and air-filled pores. The content of WSAs was more related to the soil chemical properties and clay content, with a positive low-to-high correlation with TOC, N_{tot}, Ca and Mg contents (Table 7). Soils with higher WSAs, WHC and TP and lower BD had higher TOC and N_{tot} contents. POXC, when expressed as a percentage of TOC, decreased with an increase in WSAs, WHC and TOC ($r = -0.58$ and $p < 0.000$; $r = -0.31$ and $p = 0.031$; $r = -0.87$ and $p < 0.000$) and increased with a higher BD ($r = 0.37$ and $p = 0.009$). POXC was in a negative relationship with pH ($r = -3.7$ and $p = 0.0095$), p ($r = -0.59$ and $p = 0.000$), K ($r = -0.32$ and $p = 0.0291$), Ca ($r = -0.64$ and $p = 0.000$), Mg ($r = -0.70$ and $p = 0.000$), clay ($r = -0.61$ and $p = 0.000$) and sand ($r = -0.29$ and $p = 0.042$) contents, and positively correlated with soil silt fraction ($r = 0.49$ and $p = 0.0004$). Contradictorily, POXC was not significantly correlated with TOC and N_{tot}.

Based on the data of the physical properties measured in 2018, the WSAs were in a moderate negative relationship with BD ($r = -0.55$ and $p < 0.0001$) and correlated positively to WHC ($r = 0.64$ and $p < 0.0001$), TP ($r = 0.53$ and $p < 0.0001$) and AFP ($r = 0.35$ and $p = 0.0156$). A higher soil porosity resulted in higher WHC, AFP and water permeability. We did not find any significant correlations between earthworm abundance and other soil properties in 2016. However, in 2018, earthworm abundance was in a moderate positive relationship with soil MC ($r = 0.50$ and $p = 0.0124$).

Table 6. Pearson's correlation coefficients (r) between soil physical properties in 2016 and 2018; n = 48 per year.

	WSA %		BD g cm^{-3}		MC %		WHC %		TP %	
2016										
BD g cm^{-3}	−0.28	-								
MC %	0.01	-	−0.53	***						
WHC %	0.22	-	−0.82	***	0.71	***				
TP %	0.19	-	−0.99	***	0.53	***	0.81	***		
AFP %	0.13	-	−0.78	***	0.08	-	0.38	*	0.81	***
k cm d^{-1}	−0.19	-	0.06	-	0.18	-	0.12	-	−0.06	-
2018										
BD g cm^{-3}	−0.55	***								
MC %	0.23	-	−0.22	-						
WHC%	0.64	***	−0.82	***	0.53	***				
TP %	0.53	***	−0.99	***	0.19	-	0.81	***		
AFP %	0.35	*	−0.89	***	−0.09	-	0.53	***	0.90	***
k cm d^{-1}	0.23	-	−0.46	*	0.14	-	0.46	*	0.46	*

WSAs—water-stable aggregates; BD—bulk density, MC—moisture content; WHC—water-holding capacity; TP—total porosity; AFP—air-filled porosity; *k*—water permeability; * $p \leq 0.05$; *** $p \leq 0.0001$.

Table 7. Pearson's correlation coefficients (r) between soil physical and chemical properties and texture; n = 48.

Soil Properties	WSA %		BD g cm^{-3}		MC %		WHC %		TP %		AFP %	
TOC %	0.68	***	−0.47	*	0.20	-	0.37	*	0.36	*	0.16	-
POXC per TOC, %	−0.58	***	0.37	*	−0.17	-	−0.31	*	−0.27	-	−0.07	-
N_{tot} %	0.77	***	−0.51	*	0.16	-	0.40	*	0.40	*	0.23	-
k mg kg^{-1}	−0.07	-	−0.14	-	0.37	*	0.12	-	0.13	-	−0.01	-
Ca mg kg^{-1}	0.37	*	−0.09	-	0.02	-	0.14	-	0.01	-	−0.12	-
Mg mg kg^{-1}	0.33	*	−0.01	-	−0.05	-	0.13	-	−0.06	-	−0.22	-
Clay < 0.002	0.57	**	0.08	-	0.01	-	0.06	-	−0.18	-	−0.37	*
Silt 0.002–0.063	−0.23	-	−0.23	-	0.38	*	0.24	-	0.31	*	0.21	-
Sand > 0.063	0.02	-	0.23	-	−0.43	*	−0.30	*	−0.27	-	−0.09	-

WSAs—water-stable aggregates; BD—bulk density, MC—moisture content; WHC—water-holding capacity; TP—total porosity; AFP—air-filled porosity; *k*—water permeability; TOC—total organic C; POXC—permanganate oxidisable C; N_{tot}—total nitrogen; * $p \leq 0.05$; ** $p \leq 0.001$; *** $p \leq 0.0001$.

4. Discussion

4.1. Soil Physical Properties

We found higher aggregate stability under permanent plant cover and minimum tillage in 2016 relative to conventional tillage in the upper 5–10 cm layer. In the lower topsoil, the content of WSAs was significantly higher under permanent plant cover relative to no-tillage and conventional tillage. This is probably attributable to the slightly higher organic matter content under G and MT management, as indicated by TOC and N_{tot}. These results agree with earlier studies, which have found higher aggregate stability and soil organic matter content for grasslands and reduced tillage relative to conventional tillage [20,40–42]. Tillage reduces the portion of larger aggregates [43], making soil organic matter that is physically protected in micro-aggregates available for microbial decomposition resulting in reduced soil organic matter content. This can influence soil aggregate stability because soil organic matter contains stabilising binding agents [44]. It is possible that the lower organic C content at 25–30 (nonsignificant) could partially explain the significantly lower aggregate stability at the same depth under NT fields compared to G. Although the soil aggregate stability was not significantly higher under NT compared to CT management, the surface soil residue cover still could protect the surface aggregates from the direct destructive forces of rainfall, reducing the threats of slaking and erosion [45].

Comparing the studied years of 2016 and 2018, we found a general reduction in aggregate stability among all the management systems. This could be the result of environmental processes such as freeze–thaw and dry–wet cycles [46,47] that frequently affect northern European soils. The highest reduction in aggregate stability was under MT, which could be partially related to drought in 2018 and the low moisture content during the time of harvest, which might have made soil aggregates more prone to break down due to the weight of machinery. A higher antecedent water content can increase the resistance of aggregates and reduce particle detachment [48] because occluded air causes compression upon rapid water entry, leading to a decreased proportion of aggregates. Thus, the content of WSAs can also highly depend on soil moisture variation [49] and management practices that favour lower moisture variability, which might reduce the effect of drying and wetting on soil aggregates.

Comparing the average soil physical values from 2016 and 2018, a significant general decrease in soil bulk density and water content was observed in all the management systems. The decrease in bulk density was likely the result of annual environmental processes rather than management systems, and most probably induced an increase in general soil porosity, air-filled porosity and maximum water-holding capacity. However, a higher proportion of air-filled pores might have been the result of the decrease in moisture content as well. The soil physical environment was slightly better under NT in the 5–10 cm layer with a significantly lower BD and higher MC, WHC and TP relative to MT and CT in 2016. Although improved soil properties in the uppermost topsoil layer under NT have been previously associated mostly with a higher organic matter content [50], TOC and N_{tot} levels tended to be slightly lower for NT management in this present study. However, the improved physical quality in the upper topsoil layer under NT can also be explained by a more complex native soil structure and improved pore connectivity [51] that could have formed due to the absence of tillage and remain quite persistent. NT could also favour higher biological activity with the creation of biopores and fissures [52], which might have loosened the soil and lowered the density. Furthermore, the residue mulch layer might have protected against structure deterioration in the uppermost topsoil layer, which likely led to better physical soil quality at 5–10 cm under NT.

Similar to bulk density, penetration resistance generally decreased in 2018 across all the management systems, except under CT from 35 to 50 cm and under NT at 10 cm. Similar to previous findings [53,54], we found that the absence of tillage caused the density of the topsoil under NT to be higher compared to the tilled treatments and that it was more similar to a naturally settled soil, whereas MT and CT had a lower penetration resistance. Despite a lower bulk density at 5–10 cm, the soil penetration resistance exceeded the 2 MPa limit in the topsoil under G and NT management, which is considered to limit seedling emergence and impede crop root growth [55]. The risk of soil compaction and consolidation is higher under NT due to the absence of soil mixing and can be enhanced when field operations are performed under wet conditions. It is important to note that soil density, among other properties under reduced or no-tillage systems, can be influenced by the time under management [12]. In the long term, differences in soil density tend to be reduced relative to intensive inversion tillage, and the positive effects of reducing soil tillage or using no-tillage management could be enhanced [56]. Thus, it is possible that in this study, 8 years under NT management was not sufficient for positive changes to appear regarding topsoil density.

Despite lower topsoil hardness, penetration resistance measurements revealed a significantly higher density between 40 and 45 cm under CT relative to other treatments in both years, indicating subsoil compaction that is most probably induced by heavy machinery. A plough pan is formed by the weight of the plough and tractor tyres rolling in the open furrow [57], which can be limiting for plant growth [58] and is quite persistent [59]. Therefore, our results indicate that MT might be more optimal for sandy loam soil, due to it having a slightly lower density in the topsoil and not forming a plough pan. The results coincided with soil water permeability, where MT had significantly higher values compared to other treatments at 25–30 in 2018, implying that a lower density increased porosity and improved the transport of soil water.

4.2. Earthworms

Earthworm abundance showed a general decrease within management systems when 2016 and 2018 were compared, which was likely the result of lower soil moisture content. In 2018, after the drought period, earthworms were still absent in CT fields, whereas the abundance was at a moderate level in MT fields and high in G and NT fields. Earthworm abundance tends to be higher under G and NT systems due to the absence of tillage, which damages them directly [60] and destroys their permanent burrows. The absence of earthworms under CT was most likely caused by the low soil moisture content in 2018. One possible explanation is that a higher intensity of tillage might have extended the inactive period due to higher moisture loss. The authors of [61] also concluded that the earthworm populations were related to soil temperature and moisture, which were determined by the tillage treatment. Since earthworms do not have the ability to maintain their internal water content at a certain level, they depend on the water content of the soil [62]. However, in 2016 at near-optimal moisture conditions, CT and G systems had a significantly higher earthworm density compared to MT. An experiment conducted in southern Finland on sandy loam soil showed similar results, where the total number of earthworms under plough-based tillage was 1.5–2 times higher compared to stubble-cultivated soils [63]. In general, less intensive land use has been considered to have a positive impact on earthworm abundance [18,64]. The exception can be found when tillage is conducted during the period when earthworms are inactive, as it can then have a positive impact with lower density, better aeration and a greater food supply [65]. However, it is important to note that not all species react the same way to tillage and land management [65]; thus, assessing the effect of soil management on species community structure and diversity might be more informative than earthworm abundance alone.

4.3. Soil Organic Matter and POXC

Our results showed that G and MT management systems had significantly higher TOC levels relative to NT at 5–10 cm. The content of total nitrogen followed similar trends as TOC, with significantly higher N_{tot} under G fields relative to NT and CT, which is most probably attributable to differences in soil organic matter levels. A higher soil organic matter content under G fields can be the result of the absence of tillage, which prevents excessive soil organic C mineralisation but also provides a larger plant residue input that increases soil organic matter formation. The plant residue input on managed grasslands is usually comprised mostly of roots and can have a narrower C/N ratio due to the inclusion of leguminous crops, which enhance soil organic matter formation [66]. Poor soil and residue contact under NT management could inhibit the decomposition and the formation of soil organic matter [67], which can explain the significantly lower soil organic matter content under NT relative to MT. Previous studies have shown the stratification of soil organic matter under NT [68] with increased organic C and total nitrogen only at the first 5 cm layer [69], suggesting the limited downward movement of soil C; whereas, under shallow tillage, additional C is better stabilised and may become more recalcitrant [70] since plant residues are better connected to the soil matrix compared to NT, and are likely to have more surface organic C with a higher turnover. Another possible explanation for lower soil organic matter under NT could be related to higher soil density, which might have inhibited the deeper distribution of roots and could result in lower root-derived soil organic C [71]. A large proportion of the soil organic matter in agricultural soils originates from roots, especially when aboveground plant residues are not mixed with soil, which could explain the low TOC content at 25–30 cm under NT management.

Although surface residue cover has many benefits, it slightly decreased the soil pH under NT management (significantly lower in the upper layer under NT compared to MT) as commonly reported [56]. Slight acidification in the surface layer occurs under NT when organic anions are released during the decomposition of the plant residue layer, but it could also be attributed to the effect of nitrogenous fertilisers, which are not mixed into the soil. However, the average soil pH was not below the critical values that could compromise crop yield. The C/N ratio, an indicator of the expected decomposability of soil organic matter, was significantly lower for G, NT and MT systems relative to CT at a 5–10 cm depth, which was nearest to the optimal average values for the latter. A relatively low C/N ratio for low-intensity systems might indicate a much quicker SOM decomposition and suggest the increased utilisation of C and N by microorganisms resulting in increased soil fertility. The low C/N ratio under G fields may have been due to differences in vegetation cover with a narrower residue C/N ratio [72], and possibly the result of biological nitrogen fixation. NT and MT could favour a lower C/N ratio due to a larger proportion of root biomass rather than aboveground biomass, which favours a higher C/N ratio [69].

The POXC content in bulk soil and when expressed as a percentage of TOC tended to be higher under NT and CT relative to G and MT fields, implying a higher fraction of labile C per total organic C under NT and CT and compared to it being more stable under G and M fields. In general, labile C and total organic C tends to follow a positive relationship [9], and when soil is near C saturation, the additional C will be mostly labile [73]. One possible explanation for our contradictory results is that the method was unsuitable for comparing active C at different soil organic matter levels. This can be explained by the findings of Calderón et al. [74] who concluded as well that soils with a higher SOC content tend to have proportionally less labile C relative to soils with a lower organic C content. It is possible that the size of the fraction of oxidised SOC depends on the ratio of the MnO_{4^-} and SOC mass, which, in the case of higher SOC contents, leads to the underestimation of the active or labile pool [75]. The authors stated that when analysing per 5.0 g of soil, the results might not be reliable when the SOC contents exceed 26 g C kg^{-1}. Although our soils did not reach this threshold, the values were close. This makes the comparability of POXC outcomes for monitoring soil quality at the national level across different soil types and land uses questionable.

4.4. Soil Quality Indicators

Most of the soil physical indicators were correlated with each other in both years, except for the water permeability outcomes in 2016, which was probably due to the high variability of this parameter. The high variability could be the result of earthworm burrows and root channels, which, in some cases, might limit the accurate determination of this parameter. Soils with a lower density had a higher moisture content, water-holding capacity, porosity and air-filled porosity. We did not find any significant correlations between WSAs and other soil physical quality indicators in 2016. However, in 2018, soils with higher WSAs had a better physical quality in terms of a lower BD and higher WHC, TP and AFP. The content of WSAs was correlated with the soil chemical properties as well, which was indicated by the significant positive relationships with TOC, N_{tot}, Ca, Mg and clay content. This can be explained by the mechanisms of the maintenance and formation of a favourable soil structure. To improve aggregation and bind soil particles for aggregate formation, it is necessary to have enough soil organic matter, free cations (Ca^{2+}, Mg^{2+} and Fe^{3+}) and clay particles [76].

An increase in soil organic matter improves the soil physical properties, which is mostly due to the lower density of SOM and its ability to absorb and hold water. This agrees with various other studies, elucidating the importance of soil organic matter for improving soil physical quality and its relevance as a soil quality indicator [77].

Based on our findings the method for measuring active C as POXC that was followed by Weil et al. [11], was most likely not suitable for this study due to the differences in the soil organic C mass, which influenced the appropriate determination of the active C pool of each site. This was corroborated by the contradictory results of the correlation analysis, indicating a better physical condition and higher fertility with a lower percentage of labile C per TOC. Similar to Pulleman et al. [75], we found a very high negative relationship between relative POXC (as a percentage of TOC) and TOC (r = −0.87 and $p < 0.001$) suggesting that the method might underestimate POXC at higher soil organic matter levels.

Significant correlations among the physical, chemical and biological parameters of soil quality suggest that most of the selected indicators could detect differences across management practices. However, we found that some indicators were more sensitive than others. Based on our results, we can conclude that the content of WSAs was one of the most sensitive indicators for the management practices and were linked with multiple physical and chemical soil quality indicators, suggesting that the WSAs can be highly informative about soil quality and the effect of management on soil functions, such as structure formation and C sequestration. Although indicator selection needs to remain sufficiently diverse and include physical, chemical and biological indices that account for different soil functions, reducing the number of highly correlated parameters, which are proxies for the same soil functions, is recommended. This could be observed among some soil physical parameters such as BD, TP, AFP, WHC and MC, meaning there is no advantage in measuring all of them. Furthermore, indicators with high internal variability, such as water permeability, might require a larger number of replications, which makes measuring this attribute laborious. Although earthworm abundance was significantly correlated only to soil MC in 2018, the results showed differences across different management systems and years with contrasting climatic conditions, thus providing an indication of soil habitability and resilience to environmental conditions. Assessing soil properties at different depths gave a better overview of how soil management and tillage influence soil quality indicators, as some effects might be reduced when the data from different depths are combined. Furthermore, soil penetration resistance measurements up to 60 cm revealed a more detailed view of the extent of the effect of soil management than bulk density alone measured at the two layers.

5. Conclusions

Various management types influence soil quality differently depending on soil depth, which can affect soil functioning. Relative to other cropland fields, these findings reflected the existing knowledge about the benefits of NT on soil quality at 5–10 cm based on a lower bulk density and higher water-holding capacity and porosity. Penetration resistance measurements revealed subsoil compaction under CT, which was associated with machinery-induced consolidation, whereas NT fields had a high penetration resistance in the topsoil and were more similar to naturally settled G soils. The results indicated that the C accumulation was favoured under MT and G fields relative to NT fields. A higher SOC content improved soil aggregate stability under MT and G fields and was correlated to most of the physical properties. Despite the potential benefits of NT on earthworm abundance and soil functioning, our results indicate a slightly better soil quality under MT and G compared to under the NT and CT management systems.

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