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Effects of tillage on winter wheat productivity and soil fertility: Results from 13 years of no-till in western Switzerland

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ABSTRACT

Understanding how different tillage practices affect crop productivity and soil fertility is essential for developing sustainable agriculture systems. Here we investigated how no-till affected winter wheat yield and soil fertility after 13 years since its introduction in a clay and a loam soil compared to conventional ploughing, shallow tillage and minimum tillage. During the study period 2007–2020 the annual yield of winter wheat did not differ significantly among the four tillage treatments. However, the no-till showed the lowest relative annual yield and the largest yield variability. The quality of winter wheat grains was affected primarily by the soil texture than by the tillage treatment. A significant effect of tillage on the stocks of soil organic carbon, total nitrogen and exchangeable potassium and magnesium was observed only in the topmost 10-cm, where larger values were found for the three non-inversion tillage treatments. However, when the entire 50-cm deep soil profiles were evaluated, only non-significant differences in nutrient stocks were detected between tillage treatments. We observed a clear stratification of microbial biomass carbon along the soil profile with larger values in the topmost soil layers in the no-till and the non-inversion minimum tillage. Overall, our data indicate that even if the no-till may still be in a transition phase in terms of crop yield, its positive effects on soil organic carbon and microbial biomass are observable after 13 years. In addition, we underline as the minimum tillage appears, at least under the local conditions, as a very suitable practice providing multiple agronomic and environmental advantages.

1. Introduction

In agriculture, soil tillage is a traditional component of most field cropping systems due to the multiple advantages that it can provide such as, for example, the mineralization of soil organic matter, the creation of optimal soil conditions for planting or for seed germination, the incorporation of amendments and/or crop residues into the soil, and the mechanical control of weeds (Thapa and Dura, 2024). However, intensive soil tillage, such as the conventional ploughing (also called "inversion tillage"), can be associated to severe environmental and agronomical problems, for example to a loss of soil organic matter and soil biodiversity as well as an increase of soil erosion (Fontana et al., 2015; Lal et al., 2007; Rickson et al., 2015; Sanaullah et al., 2020). In order to overcome some of these problems, alternative soil tillage practices have been proposed under the name of "conservation tillage", i.e., a set of different tillage practices, often in association with a permanent soil cover, ranging from no-till to non-inversion tillage down to depths that are commonly used for the conventional ploughing (Morris et al., 2010; Prairie et al., 2023; Reicosky, 2015). No-till, as the name indicates, is based on the direct-seeding of crops without ploughing, a technique that was initially adopted to effectively reduce soil erosion (Lee et al., 2021; Prashun, 2012). Since no-till leaves the soil structure intact, it is believed to provide better physical protection for soil organic carbon (SOC) from mineralization. Consequently, no-till has been promoted as a way to mitigate green-house gas emissions (Paustian et al., 1997). However, the effectiveness of no-till for increasing SOC stock in

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soil has been debated (Bregaglio et al., 2022; Brown et al., 2021; Mondal et al., 2023; Ogle et al., 2019). An alternative soil tillage practice with intermediate soil disturbance is the non-inversion tillage that refers to the possibility to loosen the soil to different depths without any inversion, a technique frequently referred to as shallow or minimum tillage (Morris et al., 2010). Non-inversion tillage can potentially promote SOC accumulation as much as the no-till due to the lesser soil disturbance and higher crop yield (Haddaway et al., 2017; Krauss et al., 2022).

The adoption rate of conservation tillage by farmers in Europe depends on the recognized advantages, e.g., less labour and fuel needed, or recognized constraints, e.g., more weed pressure (Bijttebier et al., 2018). For crop productivity, conservation tillage, in particular no-till, is often associated with a decrease of crop yield compared to conventional ploughing (Pittelkow et al., 2015) due, for example, to poor stand establishment (ten Damme et al., 2025). However, the yield from the different conservation tillage practices is highly dependent on crop species, soil tillage depth, soil type, climatic conditions (Achankeng and Cornelis, 2023) as well as the time period since the conversion from conventional tillage to conservation tillage (Cusser et al., 2020; Krauss et al., 2020). This variability underscores the importance of controlled experiments that account for these variables when comparing yields across tillage methods.

The development of a sustainable agriculture requires a better understanding of which tillage practice is more suited to the local agriculture, in particular in relation to climatic conditions, soil type and crop rotation (Pittelkow et al., 2015). The impact of individual soil tillage practices should be appraised not only based on crop productivity, but also on properties related to other soil functions like, for example, carbon and nutrient stocks, microbial abundance as well as soil aeration and water holding capacities. To properly assess the agricultural and environmental outcomes of a cropping system, it is then essential to consider a suitable temporal perspective. This approach involves observing the responses of a newly implemented system over a sufficiently long period, enabling the capture of any emerging beneficial effects of the adopted system (Cusser et al., 2020).

With the goal to assess the effect of soil tillage on soil functions and crop productivity, a long-term trial was set up at Agroscope in Nyon (Switzerland). This trial compares four different tillage practices including both inversion and non-inversion tillage as well as no-till across two soil types differing in their texture (Büchi et al., 2017). The main objective of the present study is to investigate the impact of 13 years of no-till management on a set of agronomic and environmental parameters in comparison to conventional ploughing and two other non-inversion tillage practices. More specifically, here we focused on: 1) crop yield and grain quality of winter wheat; 2) organic carbon and macronutrient stocks along the 50-cm deep soil profile; 3) soil microbial abundance; and 4) soil structural quality.

2. Materials and methods

2.1. Study area, experimental design, and agronomic practices

The field trial is located in Switzerland at Agroscope-Nyon (46°24′ N, 06°14′ E; altitude 430 m asl) and it was established in 1969 (Fig. S1). The study area is characterized by an average total annual precipitation of 942 mm and a mean annual temperature of 11.2 °C (data based on the 2000–2020 annual averages). The soil of the trial can be described as a Cambisol and the experimental area comprises two different and well separated soil textures, i.e., a clay soil (48 % clay, 37 % silt, and 15 % sand) and a loam soil (25 % clay, 45 % silt, and 30 % sand).

The experiment has a randomized block design with four main treatments of soil tillage for both the clay soil and the loam soil (Fig. S1): (1) a deep inversion tillage up to 20–25 cm hereafter named "conventional ploughing" (PL), (2) a shallow non-inversion tillage up to 12–15 cm hereafter named "shallow tillage" (ST), (3) a minimum non-inversion tillage up to 5–8 cm hereafter named "minimum tillage" (MT), and (4) a no-till treatment (= direct seeding, NT). The no-till treatment was established in 2007 resulting from the conversion of a deep (20 cm) non-inversion tillage (the last non-inversion tillage took place in autumn 2006), whereas the other three tillage treatments are in place since 1969. Each treatment is replicated three times on the clay soil and four times on the loam soil over plots with a surface of 304 m^2 each (38 m x 8 m).

During the study period, a complete crop rotation was composed by winter wheat (*Triticum aestivum*), winter rapeseed (*Brassica napus*), winter wheat, and grain maize (*Zea mays*) (Table S1). However, during the period 2014–2016, the standard rotation was interrupted to allow the setup of an additional sub-treatment where winter wheat was grown four years in a row (see Büchi et al., 2018). Because winter wheat was cultivated eight times since the start of the no-till, whereas maize three times (2008, 2012, and 2017) and rapeseed two times (2010 and 2019), we decided to focus on annual yield of winter wheat only (Table S1). The crop variety, the sowing date, the fertilization (according to the Swiss fertilization guidelines), as well as the crop protection products (herbicides and fungicides applications) were identical for all treatments (Table S1). The same variety of winter wheat, Arina, was used over the entire study period, whereas the varieties LG 31.211, Ricardinio, and LG 22.22 were used for maize and the varieties Trezzor and Visby were used for the rapeseed (Table S1). Until 2007, wheat straw used to be exported from all the treatments, while maize and rapeseed residues were chopped and left on the field. Since 2007, the residues of all crops were left on the field after harvesting in all the treatments. Cover crops were sown in all the treatments before grain maize in 2000 (white mustard, *Sinapsis alba* L., sowing density 20 kg ha^{-1}), 2008 (Indian mustard, *Brassica juncea* (L.) Czern, sowing density 8 kg ha^{-1}), 2011 (clover-mustard mixture with a sowing density of 60 kg ha^{-1}), and in 2017 (a mixture of leguminous species with a sowing density of 180 kg ha^{-1}). Currently, the main tillage implements used for the different treatments are a mouldboard plough for conventional ploughing, a rigid tine cultivator (chisel plough) machine for shallow tillage, a rototiller for minimum tillage, and a direct seeder for no-till.

2.2. Plant and soil sampling and laboratory analyses

We measured the annual crop yield in each treatment by machine harvesting along a 38-m long and 2.25-m wide strip located at the center of each plot, except during the period 2014–2016 when machine harvesting was done on a surface of 3-m x 8-m. Grain humidity is measured at harvest so to calculate the oven dry (105 °C) grain yield in t ha^{-1}. Winter wheat grains harvested in 2020 were analyzed for their macro- and micro-nutrient content. To this goal, a subsample of air-dried biomass was ground using a Retsch rotor mill (Retsch, GmbH, Haan, West Germany). Total N was measured by flash combustion (Thermo, Flash 2000) (NF ISO 13878), whereas total P, K, Ca, Mg, Fe, Mn, Cu and Zn were measured using a radial inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Varian Vista RL Simultaneous or Varian 725 ES Simultaneous) after being calcinated (550 °C for 5 h) and solubilized in hydrofluoric acid. All concentrations are referred to oven dry weight (105 °C for 24 hours). We calculated the bioaccumulation factor (enrichment factor, EF) as the ratio of the element concentration in the grain to that in the soil (Bhatti et al., 2018). The EF factor was used to determine the degree of accumulation of the element from the soil into the winter wheat grains.

In July 2020, immediately after the winter wheat harvesting and about nine months after the last tillage, we performed a campaign of soil sampling in all the four tillage treatments. In each plot, five soil cores were collected along the central axis of each plot down to a depth of 50 cm using a 3-cm diameter gauge. Each soil core was immediately separated into the following depth intervals: 0–5 cm, 5–10 cm, 10–20 cm, and 20–50 cm. Then, we mixed all soil samples from the same depth interval creating one composite soil sample per plot. Soil samples were kept in closed plastic bags to maintain the water content. Once in the laboratory, a small amount of fresh soil samples was immediately retrieved to be stored at 4 °C for subsequent microbial biomass carbon (MBC) analysis, whereas the residual amount was sieved at 2 mm and then air-dried for subsequent chemical analyses.

The soil bulk density used for the calculation of SOC and major nutrient stocks was determined by collecting samples using a Humax® impact coring system (5-cm diameter) down to a depth of 50 cm (GreenGround AG, Burgdorf, Switzerland). This method enables the extraction of consecutive soil cores of know volume at fixed depth intervals (0–10 cm, 10–20 cm and 20–50 cm) from the same hole (Guillaume et al., 2022). The samples were sieved at 2 mm and soil moisture was determined (24 h at 105° C) before calculating SOC and major nutrient stocks.

Soil organic carbon was measured with the sulfochromic oxidation method (NF ISO 14235), while total soil nitrogen (Ntot) was determined using an elemental analyzer (Thermo Scientific, FLASH 2000, USA) by dry combustion (NF ISO 13878). Exchangeable K and Mg concentrations were analyzed after ammonium acetate extraction (AAE) (NFX 31–108) combined with a Thermo Radial ICAP 6000 Series ICP-OES (Thermo Fisher Scientific, Freemont, CA, USA). Sodium bicarbonate ($NaHCO_3$) extraction was used to determine the soil available P (Olsen-P) (Olsen, 1954) according to Murphy and Riley (1962) (NF ISO 11263). Soil microbial biomass carbon (Cmic) was estimated through the chloroform fumigation extraction. Total C of fumigated and non-fumigated samples was determined using a TOC/TN auto analyzer (Shimadzu analyzer TOC-V CPH + TNM-1) after (1:10) 0.5 M K_2SO_4 extraction. Values of Cmic were corrected with the coefficient factor Kc = 0.45 so to account for the MBC extractable by fumigation (Joergensen, 1996). The microbial quotient (MicQ) was expressed as the ratio of microbial biomass C (C_{mic}) to SOC and it was used as an index of carbon availability to soil microorganisms (Anderson and Domsch, 1989) as well as a parameter to monitor organic matter dynamics and quality (McGonigle and Turner, 2017; Sparling, 1992). The soil SOC:clay ratio is here used as indicator of the structure vulnerability (Fell et al., 2018; Johannes et al., 2017).

In addition, in July 2020, two undisturbed 150 cm^3 soil samples were collected for soil physical characterization at, respectively, 2–6 cm and 8–12 cm depths at the center of each of the 28 plots. These undisturbed samples were collected with a custom-made sampler, allowing retrieval of the soil cores for matric potential equilibration (sandbox). Before analysis, the samples were kept at 4°C. After discarding the samples showing defects such as large coarse fraction or damaged structure due to the presence of earthworms, 50 samples (from a total of 56) were left for water retention measurements. These 50 undisturbed soil samples were initially put on a sandbox at −10 hPa matric potential until they had equilibrated. Then, the samples were drained at −60 hPa matric potential in another sandbox before determining their weight. Thereafter, we measured their bulk volume V_{60} (cm^3) using the plastic bag method (Boivin et al., 1990). Finally, the samples were oven-dried at 105 °C for one day and weighed and sieved to 2 mm to determine the dry mass of the < 2 mm fraction m_s (g). The weight and volume of the coarse fraction (> 2 mm) were measured and subtracted from the soil sample volume V_{60} and weight m_s to obtain bulk soil volume V_{60} and dry mass m_s of the fine soil fraction. The bulk density ρ_b (g cm^{-3}) was yielded from ms/V60.

We calculated the air capacity θ_{AC} (cm^3 cm^{-3}) of the fine soil using $\theta_{AC} = 1 - \theta_{FC}\rho_b/\rho_s$ where ρ_s (g cm^{-3}) is the density of the soil solid phase, estimated to be 2.65 g cm^{-3} and θ_{FC} is the gravimetric field capacity calculated as $\theta_{FC} = m_{FC} / (\rho_w \times V_{60})$ with m_{FC} (g) being the mass of water in the soil at field capacity, here defined at a matrix potential of -60 hPa. Following Jurin-Laplace's law, θ_{AC} corresponds approximately to the fraction of pores with a radius > 25 µm, while θ_{FC} expresses the fraction of pores with radius < 25 µm. Therefore, we also refer to θ_{AC} as the macroporosity in the following. The field capacity θ_{FC} is the fraction of the sum of meso and micropores. The permanent wilting point θ_{PWP} (cm^3 cm^{-3}) expresses the fraction micropores, i.e., pores with radii of less than approximately 0.1 µm. It is known that it is predominantly determined by soil texture, with only minor influences of soil organic carbon. We therefore estimated θ_{PWP} from the average clay, silt and organic carbon concentrations for all treatments using the pedotransfer function published in Tóth et al. (2015). We found θ_{PWP} of 0.25 and 0.17 cm^3 cm^{-3} for the clay and loam soil, respectively. We then derived the estimated plant available water content θ_{PAW} (cm^3 cm^{-3}) from the difference of θ_{FC} and θ_{PWP} (see also the Supplementary material).

2.3. Data treatment

The relative winter wheat yield during the period 2007–2020 was calculated as relative percentage difference of the mean annual yield of the no-till (NT), minimum tillage (MT) and shallow tillage (ST) treatments to the correspondent mean annual yield of the ploughed treatment (PL). Each relative percentage difference corresponds to the mean of three replicates for the clay soil and or four replicates for the loam soil. The effect of tillage treatment on crop yield and grain quality was tested separately for each soil texture by an analysis of variance. Only for the overall effect of soil texture on grain macro- and micro-nutrient concentrations we pooled together all the tillage treatments and we used soil texture as factor in an analysis of variance. For each soil texture separately, a principal component analysis (PCA) was performed using the enrichment factor values for macro- and micro-nutrients in relation to the tillage treatment (factor). The stocks of SOC, Ntot, P-Olsen, as well as the exchangeable K and Mg along the entire 50-cm long soil profile were calculated on equivalent soil mass basis using the average bulk density measured across all treatments for the respective depth and soil texture because treatments had no effect on bulk density (see Result section). As element concentrations were determined for the depth intervals 0–5 cm and 5–10 cm, SOC and nutrient stocks for the 0–10 cm layer were calculated using the arithmetic mean of the two concentrations. The effect of tillage treatment on SOC concentration, SOC and nutrient stocks, as well as on microbial biomass was tested separately for each soil texture based on an analysis of variance. These analyses were performed using the software TIBCO Statistica (version 13.5) and R (version 4.3.2) (R Core Team, 2022).

The differences in soil physical properties between the different tillage treatments and depths were tested separately for each soil texture (clay and loam) with the non-parametrical Kruskall-Wallis test and a non-parametrical pair-wise comparison with the "dunn.test" function of the "dunn.test" package (version 1.3.6) in the R software.

3. Results

3.1. Winter wheat yield

During the period 2007–2020, the mean annual yield of winter wheat under conventional ploughing (PL) was 3.9 and 3.5 t ha^{-1} for the clay and the loam soil, respectively. For the shallow tillage (ST), it was 3.9 and 3.2 t ha^{-1}, for the minimum tillage (MT) 4.2 and 3.4 ha^{-1}, and for the no-till (NT) 3.1 and 2.5 ha^{-1} (Fig. S2). The one-way ANOVA did not detect any significant difference in the mean annual yields between the tillage treatments in neither of the two soil textures ($p > 0.35$). Similarly, no significant differences in mean annual yield were detected ($p > 0.18$) between the two soil textures for the same tillage treatment. However, the coefficient of variability (CV) of annual yields was larger in the no-till (CV = 46.4 and 49.0 for clay and the loam soil, respectively), and smaller in the minimum tillage (CV = 31.0 and 34.3 for the clay and the loam soil, respectively).

Comparing the mean annual yield under shallow tillage, minimum tillage and no-till to that under conventional ploughing, we observed that no-till was overall characterized by smaller relative annual yields along the entire study period, the only exception being the year 2014 for the loam soil (Fig. 1). It is interesting to note that the strongest decline (up to −80 %) of the relative yield in the no-till treatment took place in 2015 and, in particular, in 2016 after four consecutive years of winter

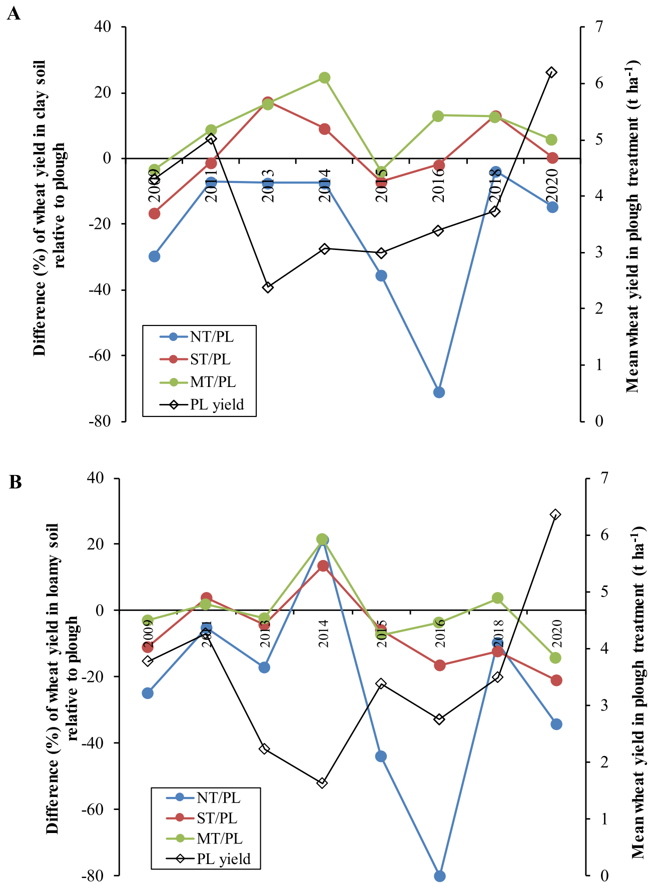

Fig. 1. Temporal trend of the relative difference (%) of the mean winter wheat yield in the no-till (NT), shallow tillage (ST), and minimum tillage (MT) treatment to the mean yield in the conventional ploughing (PL) for the clay (panel A) and the loam (panel B) texture. As reference, the mean yield (t ha^{-1}) in the ploughed treatment is also reported for both soil textures (PL yield).

wheat (Fig. 1). In general, for both soil textures, the mean annual yield in the no-till was c. 23 % smaller than in the conventionally ploughed treatment, but it was approximately 12 % smaller if the yields of the years 2015 and 2016 were not included. In contrast, the relative yields under shallow tillage and the minimum tillage were, respectively, + 2 % and + 9 % in the clay soil, and −6 % and −0.5 % in the loam soil compared to the conventional ploughing (Fig. 1).

3.2. Grain quality

Higher concentrations of P, K, Mg, Fe and Zn were observed in wheat grains from the loam soil compared to the clay soil, the latter being characterized by grains with slightly larger, albeit not significant, Mn concentration (Table S2). In the clay soil, the grains from the minimum tillage were characterized by larger concentration of N and smaller concentration of Zn if compared to the no-till as well as by smaller Mn concentration if compared to the other tillage treatments (Table 1). In contrast, in the loam soil, the effect of tillage treatment on grain nutrient concentrations was overall less evident than for the clay soil, with the exception of the shallow tillage and the minimum tillage where wheat grains had smaller Mn concentration compared to the no-till and the ploughed treatment (Table 1).

The values of the enrichment factor (EF) in response to the tillage treatments for the macro- and micro-nutrients were rather similar for the two soil textures, with the ploughed treatment being overall more effective in increasing the EF, particularly for N, P and Cu in the clay soil and for N, P, and Zn in the loam soil compared to the other three tillage treatments (Fig. 2).

3.3. SOC concentrations and nutrient stocks

By considering the entire 50-cm deep soil profile, the mean concentration of SOC depth was, overall, significantly larger ($p < 0.001$) in the clay soil (2.75 % ± 8.17) than in the loam soil (1.39 % ± 4.63). In both soil textures, a decreasing trend of SOC concentration with soil depth was detected in all the tillage treatments ($r^2 > 0.35$, $p < 0.015$) with the only exception of the ploughed treatment in the clay soil ($r^2 = 0.11$, $p = 0.29$). The most significant SOC differences between tillage treatments can be observed in the first 10 cm for the clay soil and in the first 5 cm for the loam soil (Fig. 3). Indeed, in the clay soil the minimum tillage and the no-till treatments were both characterized by similar SOC concentrations which were also significantly larger compared to the shallow tillage and the ploughed treatment (Fig. 3). A similar trend can be observed for the loam soil where the minimum tillage and the no-till showed larger SOC values compared to shallow tillage and, in particular, to conventional ploughing in the upper 5 cm (Fig. 3).

In each of the two soil texture types, the soil bulk density (BD) was affected by depth ($p < 0.001$) but not by tillage treatment ($p > 0.63$) (Table S3). Because of the absence of a significant tillage effect on BD and the large variability between plots, SOC and nutrient stocks were

Table 1
Mean (± standard error) concentration of macro- and micro-nutrients in winter wheat grains from the 2020 harvest in the different soil tillage treatments in the clay ($n = 3$) and the loam soil ($n = 4$). Within each soil texture, significant differences between tillage treatments for the same nutrient are indicated by different superscripts based on post-hoc Fisher-LSD test ($p < 0.05$). Concentrations refer to oven-dry weight.

Clay soil	**N (%)**	**P (%)**	**K (%)**	**Ca (%)**	**Mg (%)**	**Cu (ppm)**	**Fe (ppm)**	**Mn (ppm)**	**Zn (ppm)**
Ploughing (PL)	2.08^{ab}	0.43^{b}	0.47^{a}	0.054^{a}	0.13^{b}	5.1^{a}	35.0^{b}	49.8^{a}	31.5^{ab}
	(0.09)	(0.012)	(0.011)	(0.002)	(0.005)	(0.19)	(2.9)	(2.4)	(1.8)
No-till (NT)	1.98^{b}	0.43^{b}	0.46^{a}	0.051^{b}	0.13^{ab}	5.4^{a}	33.1^{b}	46.1^{a}	37.2^{a}
	(0.12)	(0.005)	(0.007)	(0.001)	(0.003)	(0.25)	(1.9)	(2.1)	(5.3)
Shallow tillage (ST)	2.06^{ab}	0.45^{a}	0.47^{a}	0.051^{ab}	0.14^{a}	5.2^{a}	46.2^{a}	46.0^{a}	35.1^{ab}
	(0.04)	(0.005)	(0.013)	(0.002)	(0.002)	(0.53)	(6.1)	(2.2)	(6.0)
Minimum tillage (MT)	2.14^{a}	0.43^{b}	0.46^{a}	0.053^{ab}	0.13^{b}	4.9^{a}	32.1^{b}	41.7^{b}	29.6^{b}
	(0.04)	(0.003)	(0.002)	(0.001)	(0.003)	(0.30)	(2.7)	(2.2)	(1.1)
Loam soil	**N (%)**	**P (%)**	**K (%)**	**Ca (%)**	**Mg (%)**	**Cu (ppm)**	**Fe (ppm)**	**Mn (ppm)**	**Zn (ppm)**
Ploughing (PL)	2.0^{a}	0.44^{a}	0.48^{a}	0.053^{a}	0.13^{a}	5.0^{a}	39.6^{a}	48.8^{a}	39.6^{a}
	(0.07)	(0.024)	(0.011)	(0.001)	(0.011)	(1.3)	(8.3)	(3.0)	(1.9)
No-till (NT)	2.1^{a}	0.44^{a}	0.47^{b}	0.055^{a}	0.14^{a}	5.4^{a}	45.7^{a}	47.2^{a}	35.5^{b}
	(0.05)	(0.009)	(0.002)	(0.004)	(0.005)	(0.11)	(1.8)	(1.8)	(1.9)
Shallow tillage (ST)	2.0^{a}	0.44^{a}	0.47^{ab}	0.052^{a}	0.14^{a}	5.3^{a}	46.4^{a}	36.8^{b}	34.2^{b}
	(0.09)	(0.005)	(0.007)	(0.001)	(0.004)	(0.44)	(7.1)	(5.3)	(2.9)
Minimum tillage (MT)	2.1^{a}	0.45^{a}	0.48^{ab}	0.053^{a}	0.14^{a}	5.8^{a}	45.6^{a}	38.2^{b}	37.5^{ab}
	(0.17)	(0.011)	(0.005)	(0.002)	(0.004)	(0.69)	(3.0)	(4.4)	(2.7)

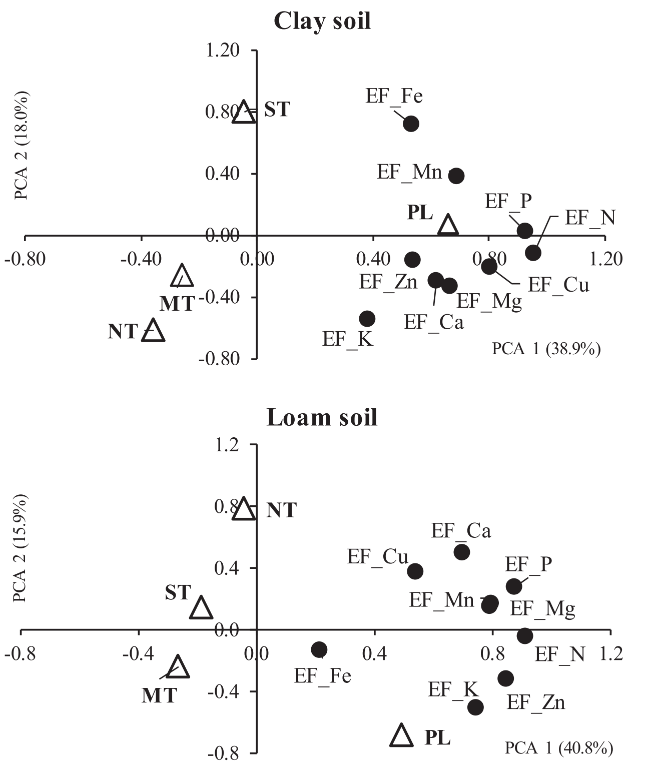

Fig. 2. PCA ordination of the enrichment factors (EF) for macro- and micro-nutrients in winter wheat grains for the clay and the loam soil in relation to the tillage treatments. PL: ploughing (20–25 cm); ST: shallow tillage (12–15 cm); MT: minimum tillage (5–8 cm); and NT: no-till.

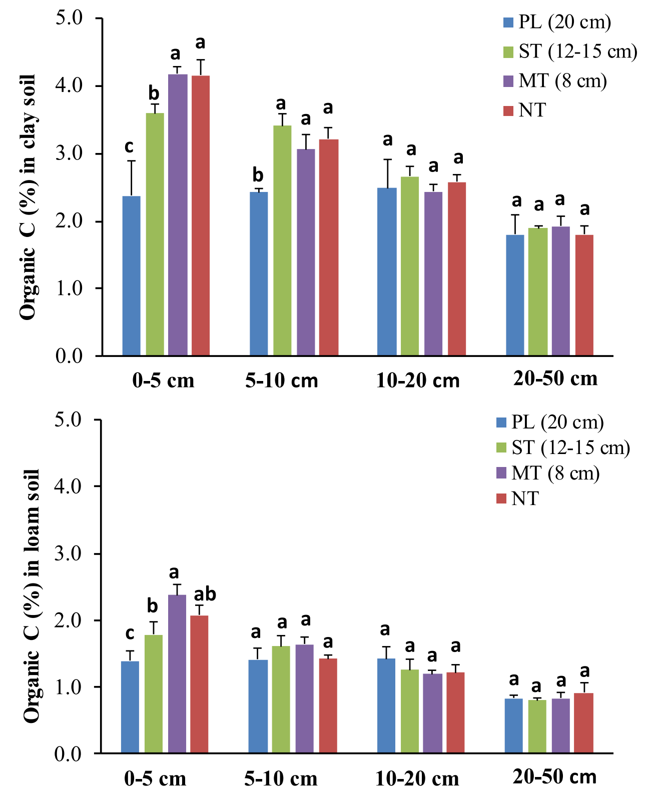

Fig. 3. Mean values (± standard error) of soil organic carbon (SOC) concentration in the clay ($n = 3$) and in the loam ($n = 4$) soil in response to the four tillage treatments along the soil profile. Within each soil depth interval, significant differences among tillage treatments are identified by different superscript letters ($p < 0.05$, Fisher LSD post-hoc test). PL: ploughing (20–25 cm); ST: shallow tillage (12–15 cm); MT: minimum tillage (5–8 cm); and NT: no-till.

calculated using a BD that was averaged for each depth and for each soil type across all the four tillage treatments (Table S3).

In both soil textures, a strong effect of tillage treatment on SOC stocks was observed primarily in the topmost 10 cm ($p < 0.001$) where, in line with SOC concentration trends (Fig. 3), significantly larger C stocks were found for the three non-inversion tillage treatments as compared to the ploughed treatment (Table 2). When the SOC stocks of the 10–20 cm soil layer were included in the comparisons, significant differences between tillage treatments disappeared (Table 2). Although the SOC stock under ploughing treatment was 10–12 % smaller than under non-inversion tillage treatments in the clay soil, and 1–8 % smaller in the loam soil, no significant differences in SOC stocks were detected among tillage treatments across the entire 50-cm soil profile.

The soil N stocks followed the same pattern of the SOC stocks, so that significant differences between the ploughed treatment and the other non-inversion treatments can be observed only in the upper 10-cm of the soil (Table 2). Along the entire 50-cm soil profile, no significant differences in N stocks were detected among tillage treatments, although in the clay soil the N stock in the ploughed treatment was between 4 % and 15 % smaller than the non-inversion tillage treatments whereas, in the loam soil, the N stock was between 2 % and 9 % smaller (Table 2).

The soil texture had an effect on the stocks of exchangeable K ($p < 0.05$) and Mg ($p < 0.001$) down to a depth of 50 cm, but not for the Olsen-P stock ($p = 0.43$). Tillage type had an effect on exchangeable K ($p < 0.05$) and Mg ($p < 0.01$) in the topmost 10 cm with smaller exchangeable cations in the ploughed treatment compared to the other three non-inversion tillage treatments. In both soil textures, the stock of exchangeable K was significantly larger in the ploughed treatment, whereas the exchangeable Mg stock did not differ between tillage teatments (Table 2). Nonetheless, differences in the stock of exchangable K and Mg disappered when stocks were summed up down to 50 cm depth (Table 2). The stock of Olsen-P in the top 20 cm layers was not affected by soil texture ($p = 0.88$), although tillage treatment had a significant effect for each soil depth (Table 2). In the top 10 cm layer, the Olsen-P stocks were the smallest in the ploughed treatment and the largest under minimum tillage ($p < 0.001$). In contrast, in the 10–20 cm layer, the ploughed treatment showed the largest Olsen-P stock, whereas minimum tillage had the smallest ($p < 0.05$). Summing Olsen-P stocks down to 50 cm depth revealed larger values in the ploughed treatment, particularly in the clay soil (Table 2).

3.4. Soil microbial biomass carbon

A positive correlation (Pearson's $R^2 > 0.54$, $p < 0.001$) was found between the amount of SOC and the correspondent amount of microbial biomass C for each soil type (Fig. 4). On average, we observed larger microbial biomass C in the clay soil (c. 139 mgC kg^{-1}) than in the loam soil (average c. 80 mgC kg^{-1}) with a clear stratification along the soil profile (Fig. 5). Larger values of microbial biomass C were found in the upper 5 cm of soil depth (c. 223 mgC kg^{-1} for the clay soil and 132 mgC kg^{-1} for the loam soil) compared to the 20–50 cm depth (c. 45 mgC kg^{-1} for the clay soil and 57 mgC kg^{-1} for the loam soil). Within each soil texture, the tillage treatment had different effects on microbial biomass C (Fig. 5). In the clay soil, the minimum tillage treatment was characterized by the largest microbial biomass C in the topmost 0–5 cm, whereas the ploughed treatment showed the smallest microbial biomass C in the upper 0–5 cm layer. Between 5 cm to 20 cm depth, microbial biomass C did not differ significantly among the four tillage treatments, but at 20–50 cm depth, the minimum tillage showed again the largest amount of microbial biomass C (Fig. 5). In the loam soil, the minimum tillage exhibited the largest microbial biomass C across most the soil

Table 2
Mean (± s.d.) stock (Mg ha^{-1}) of organic carbon (Corg), total nitrogen (Ntot), bicarbonate extractable phosphorus (Olsen-P), and exchangeable potassium (AAE-K) and magnesium (AAE-Mg) at different depths (0–10 cm and 10–20 cm) as well as along the entire soil profile (0–50 cm) in response to the four tillage treatments in the clay ($n = 3$) and the loam soil ($n = 4$). For each nutrient, significant differences between treatments for the same soil depth are indicated by different superscripts based on post-hoc Fisher-LSD test ($p < 0.05$).

	Corg			Ntot			Olsen-P			(AAE)-K			(AAE)-Mg		
	0–10 cm	10–20 cm	0–50 cm	0–10 cm	10–20 cm	0–50 cm	0–10 cm	10–20 cm	0–50 cm	0–10 cm	10–20 cm	0–50 cm	0–10 cm	10–20 cm	0–50 cm
Clay soil															
Ploughing	31^{b} (9)	30^{a} (7)	152^{a} (36)	3.6^{b} (1)	3.4^{a} (0.8)	17.4^{a} (3.7)	0.020^{c} (0.002)	0.020^{a} (0.004)	0.104^{a} (0.014)	0.23^{b} (0.04)	0.23^{a} (0.02)	1.09^{a} (0.15)	0.33^{b} (0.11)	0.32^{a} (0.09)	1.79^{a} (0.58)
Shallow tillage	45^{a} (3)	32^{a} (2)	172^{a} (6)	4.8^{a} (0.3)	3.8^{a} (0.2)	18.9^{a} (0.2)	0.029^{cb} (0.002)	0.012^{bc} (0.002)	0.084^{b} (0.004)	0.32^{a} (0.06)	0.18^{b} (0.02)	1.05^{a} (0.12)	0.47^{a} (0.05)	0.40^{a} (0.05)	2.21^{a} (0.28)
Minimum tillage	47^{a} (3)	30^{a} (2)	173^{a} (16)	4.8^{a} (0.2)	3.6^{a} (0.1)	20.0^{a} (1.9)	0.041^{a} (0.008)	0.010^{c} (0.004)	0.089^{ab} (0.019)	0.37^{a} (0.08)	0.17^{b} (0.02)	1.13^{a} (0.21)	0.45^{a} (0.00)	0.39^{a} (0.04)	2.15^{a} (0.27)
No-till	48^{a} (3)	31^{a} (2)	169^{a} (11)	4.8^{a} (0.1)	3.8^{a} (0.1)	18.2^{a} (0.7)	0.031^{ab} (0.003)	0.015^{b} (0.002)	0.088^{ab} (0.019)	0.35^{a} (0.03)	0.20^{b} (0.02)	1.11^{a} (0.10)	0.53^{a} (0.03)	0.41^{a} (0.04)	2.32^{a} (0.34)
Loam soil															
Ploughing	23^{b} (4)	19^{a} (4)	85^{a} (10)	2.4^{a} (0.3)	2.0^{a} (0.3)	9.1^{a} (0.6)	0.031^{c} (0.004)	0.026^{a} (0.005)	0.103^{a} (0.014)	0.25^{b} (0.03)	0.23^{a} (0.03)	1.02^{a} (0.10)	0.18^{b} (0.03)	0.14^{a} (0.01)	0.84^{a} (0.15)
Shallow tillage	28^{a} (3)	17^{b} (3)	86^{a} (5)	3.0^{b} (0.3)	1.9^{a} (0.2)	9.3^{a} (0.6)	0.034^{bc} (0.008)	0.015^{bc} (0.003)	0.082^{b} (0.028)	0.31^{a} (0.03)	0.15^{b} (0.02)	0.89^{a} (0.07)	0.22^{a} (0.04)	0.14^{a} (0.02)	0.82^{a} (0.09)
Minimum tillage	33^{a} (2)	16^{b} (1)	91^{a} (6)	3.5^{b} (0.3)	1.8^{a} (0.1)	10.0^{a} (0.8)	0.043^{a} (0.004)	0.008^{c} (0.004)	0.084^{ab} (0.008)	0.37^{a} (0.02)	0.14^{b} (0.00)	0.98^{a} (0.03)	0.22^{a} (0.03)	0.16^{a} (0.02)	0.84^{a} (0.13)
No-till	29^{a} (2)	17^{b} (2)	92^{a} (12)	3.0^{b} (0.2)	1.8^{a} (0.1)	9.5^{a} (1.0)	0.043^{ab} (0.004)	0.017^{b} (0.001)	0.108^{ab} (0.009)	0.39^{a} (0.04)	0.17^{b} (0.02)	1.05^{a} (0.15)	0.24^{a} (0.04)	0.15^{a} (0.02)	0.90^{a} (0.09)

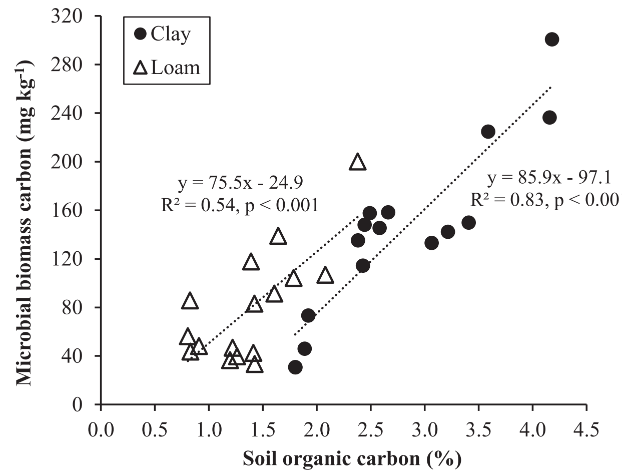

Fig. 4. Linear regression and Pearson's correlation coefficient between the concentration of soil organic carbon (%) and the corresponding amount of microbial biomass carbon (mgC kg^{-1} of dry soil) across the four soil tillage treatments at each of the four soil depths. Each value is the mean of three replicates for the clay soil and four replicates for the loam soil.

depth intervals, except at 10–20 cm. In contrast, microbial biomass C in the no-tillage did not differ either from the conventional ploughing or the shallow-tillage along most of the soil depth profile (Fig. 5).

The microbial quotient (MicQ), i.e., the ratio between the microbial biomass carbon (MBC) and the concentration of SOC, was significantly affected, in both soil textures, by tillage treatment ($p < 0.001$) and by soil depth ($p < 0.001$) with a significant interaction between tillage type and depth ($p < 0.001$) only in the loam soil. The microbial quotient in the minimum tillage was generally larger at the surface and at the bottom of the soil profile in the clay soil compared to the other three tillage treatments (Fig. 6). Similarly, in the loam soil, the microbial quotient was significantly larger at the surface in the ploughed and the minimum tillage treatments, whereas at the bottom of the soil profile it was significantly larger for the minimum tillage (Fig. 6). Overall, the no-till did not show any significant spatial pattern but it was, particularly in the upper soil layers, generally lower if compared to the other two non-inverison tillage treatments (Fig. 6).

3.5. Soil structure vulnerability and soil porosity

On the basis of the ratio of SOC to clay content, it is possible to distinguish two major clusters of plots corresponding to the loam and the clay soil (Fig. 7). By using a SOC:clay ratio of 1:10 as a threshold for an acceptable soil structure vulnerability, we can observe as all the plots from the clay soil were below this threshold, whereas only few plots from the loam soil were close or above the threshold (Fig. 7). Among the tillage treatments, the no-till (NT) and the minimum tillage (MT) were characterized by the largest SOC:clay ratios, particularly for the upper soil depth of 0–5 cm (Fig. 7).

The mean values of soil physical properties for all the treatments and soil types at 2–6 cm and 8–12 cm are reported in Table S4. Overall, we can observe that bulk density was higher in the loam soil (Fig. 9a) than in the clay soil (Fig. 8a) at both sampled depths with a range from 1.29 to 1.62 g cm^{-3} and from 1.09 to 1.41 g cm^{-3}, respectively. In the plough and the shallow tillage treatment, the bulk density at the two depths showed similar values in both soils (Figs. 8a, 9a). Differently, in the minimum tillage and the no-till treatments, there was an increase of bulk density with increasing depth in both soils (Figs. 8a, 9a). In the clay soil, the highest bulk density is found in the ploughing for both depths and in the 8–12 cm depth of both the no-till and the minimum tillage, whereas the lowest values are found in the shallow tillage treatment and in the

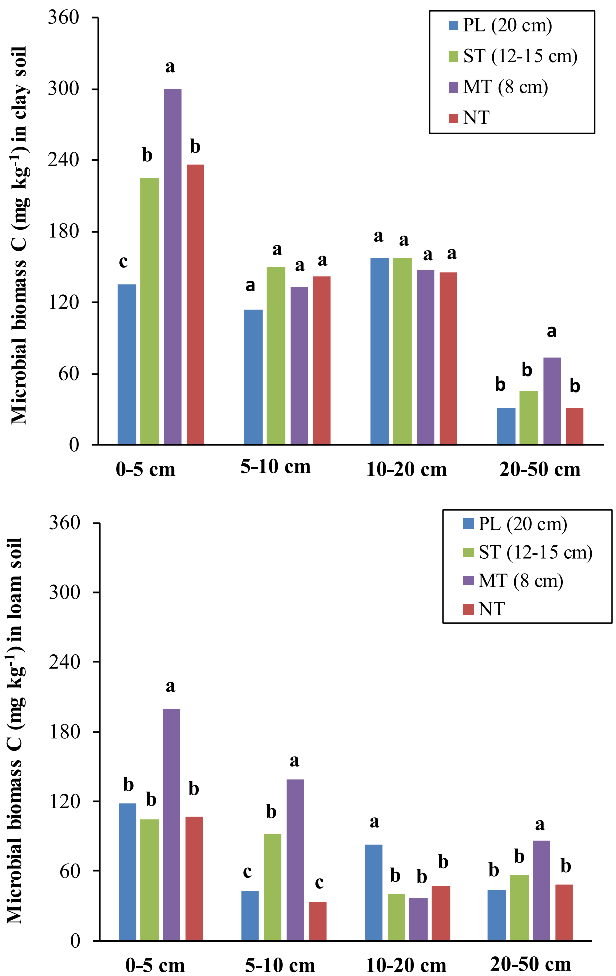

Fig. 5. Mean values of microbial biomass carbon (C) in the clay ($n = 3$) and in the loam ($n = 4$) soil in response to the four tillage treatments along the soil profile. Within each soil depth interval, significant differences among tillage treatments are identified by different superscript letters ($p < 0.05$, Fisher LSD post-hoc test). PL: ploughing (20–25 cm); ST: shallow tillage (12–15 cm); MT: minimum tillage (5–8 cm); and NT: no-till.

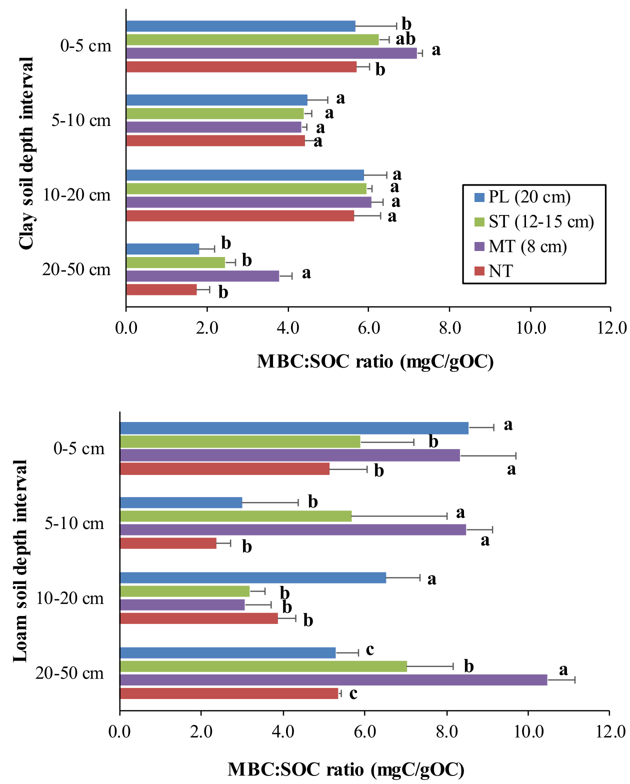

Fig. 6. Mean values (± standard error) of microbial quotient (MicQ), i.e., the ratio between the microbial biomass carbon (MBC) and the soil organic carbon (OC), in the clay ($n = 3$) and in the loam ($n = 4$) soil in response to the four tillage treatments along the soil profile. Within each soil depth interval, significant differences among tillage treatments are identified by different superscript letters ($p < 0.05$, Fisher LSD post-hoc test). PL: ploughing (20–25 cm); ST: shallow tillage (12–15 cm); MT: minimum tillage (5–8 cm); and NT: no-till.

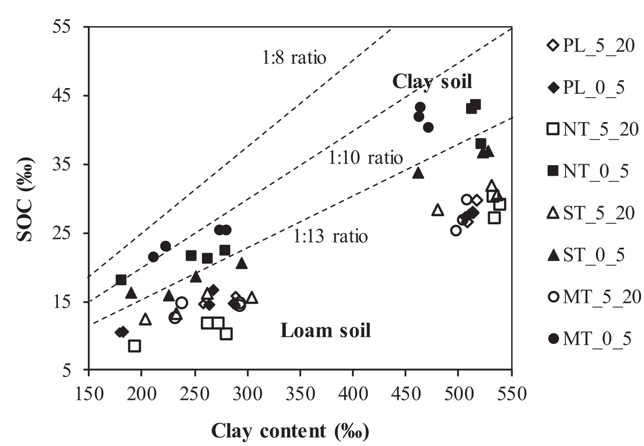

Fig. 7. Clay content and soil organic carbon (SOC) concentration of all the experimental plots ($n = 3$ for the clay soil and $n = 4$ for the loam soil) for the four soil tillage treatments (PL = ploughing, NT = no-till, ST = shallow tillage, MT = minimum tillage) and for two soil depth intervals, i.e., the 0–5 cm and 5–20 cm. The values of the 5–20 cm depth interval are the mean of the 5–10 cm and 10–20 cm depth intervals.

2–6 cm depth of the minimum tillage. A similar trend is observed in the loam soil, except that the ploughing here was less dense than the 8–12 cm depth of both the no-till and the minimum tillage treatment. The plant available water was in a similar range for both soils with no differences among treatments (Figs. 8b, 9b), with the only exception of the loam soil where the plant available water at 2–6 cm depth of the minimum tillage was significantly higher (Table S5). Both soils followed similar trends across the treatments for the air content values, with minimum tillage at 8–12 cm depth in the clay soil being characterized by the lower air content (Fig. 8c, Table S5) and with the shallow tillage in the loam soil displaying significantly higher air content at both depths (Fig. 9c, Table S5). For what concerns the water content, it was overall higher in the clay soil than the loam soil with a pattern of variation that was similar between treatments in both soils (Figs. 8d, 9d) with the only exception of the high value observed in minimum tillage at 2–6 cm depth in the loam soil.

4. Discussion

4.1. Winter wheat yield

During the study period 2007–2020, the annual yield of winter wheat did not differ significantly among the four tillage systems. However, the no-till showed the lowest relative annual yield and the highest yield variability if compared to the relative annual yield of the minimum tillage and the shallow tillage. Such a result is in accordance with

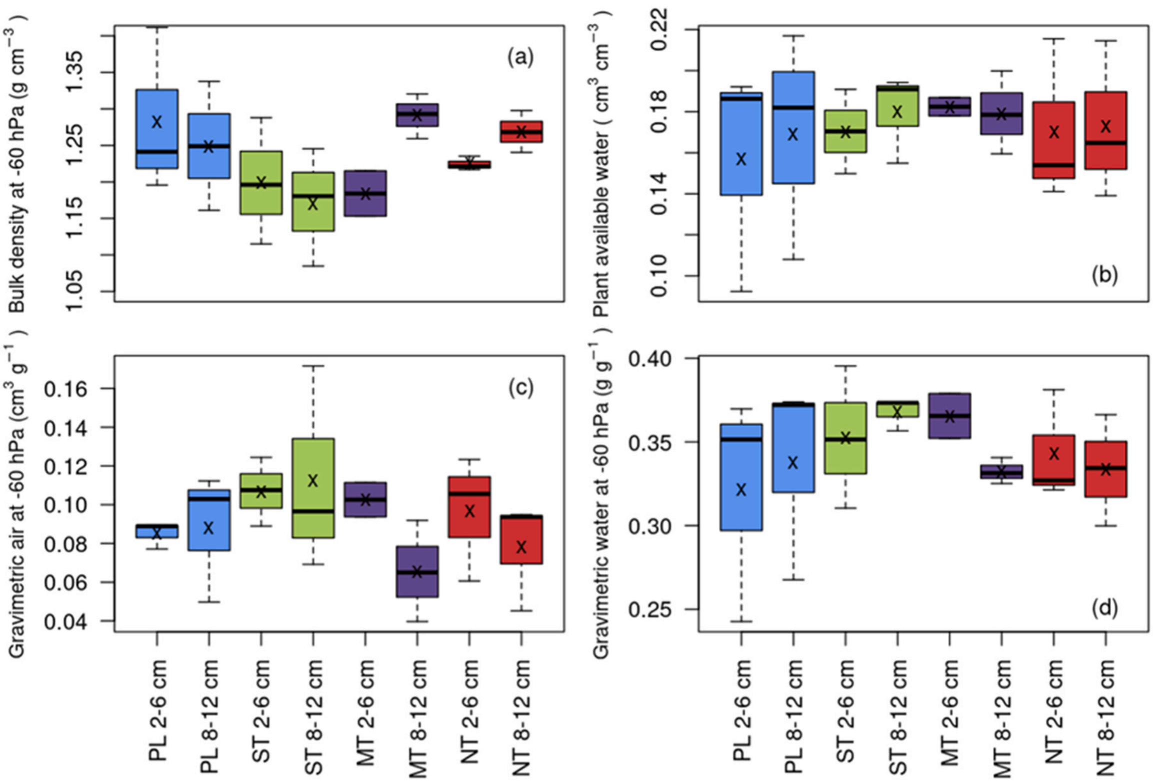

Fig. 8. Boxplots of bulk density (a), plant available water (b), gravimetric air content (c), and gravimetric water content at −60 hPa in the clay soil for the four tillage treatments (PL: ploughing, ST: shallow tillage, MT: minimum tillage, NT: no-till) at two soil depths (2–6 cm and 8–12 cm). Boxplots show mean values (cross), median values (solid horizontal line), 50th percentile values (box outline), minimum and maximum values (whiskers).

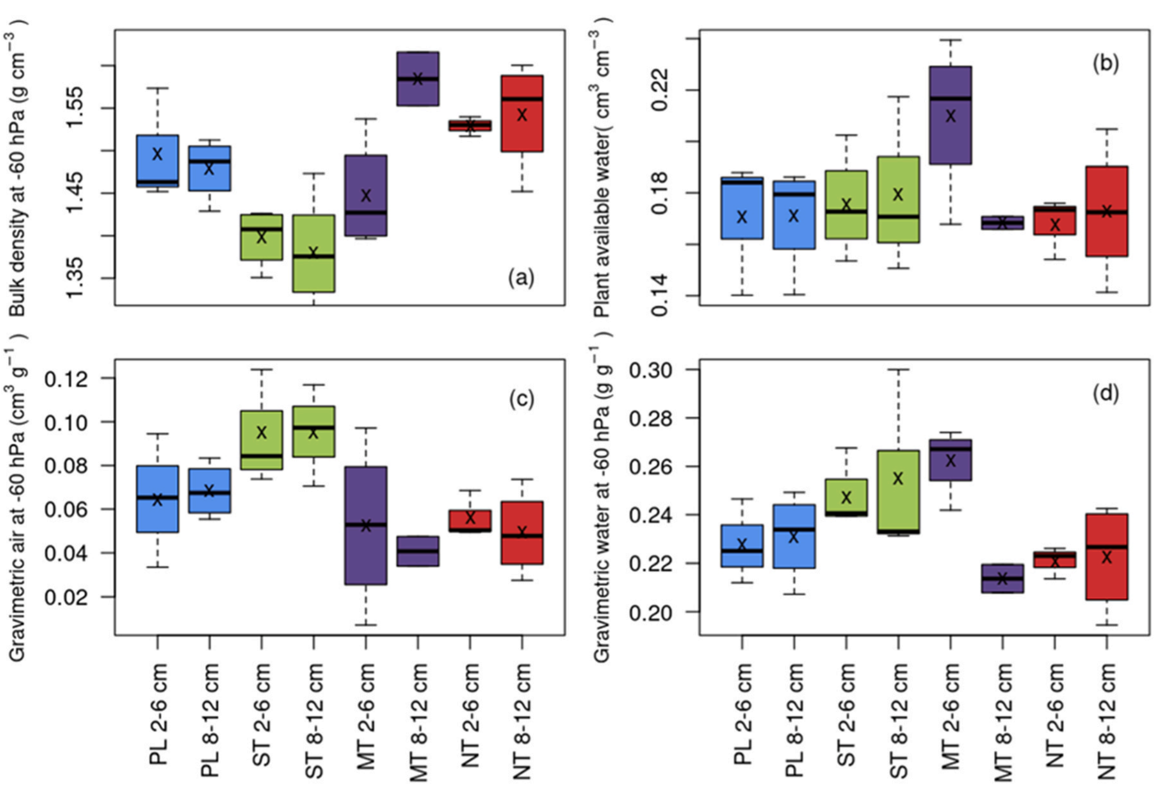

Fig. 9. Boxplots of bulk density (a), plant available water (b), gravimetric air ccontent (c), and gravimetric water content at −60 hPa in the loam soil for the four tillage treatments (PL: ploughing, ST: shallow tillage, MT: minimum tillage, NT: no-till) at two soil depths (2–6 cm and 8–12 cm). Boxplots show mean values (cross), median values (solid horizontal line), 50th percentile values (box outline), minimum and maximum values (whiskers).

previous studies reporting lower yields in the no-till compared to other tillage systems, particular for cereals (Achankeng and Cornelis, 2023; Cui et al., 2022; Pittelkow et al., 2015; Van den Putte et al., 2010). The average decrease of winter wheat yield of about 12 % compared to the ploughed treatment in our no-till treatment is in line with previous findings from other long-term trials in Switzerland (Rieger et al., 2008; Spiess et al., 2020). On the other hand, the observed + 9 % increase of mean yield in the minimum tillage compared to the ploughed treatment, particularly for the clay soil, is also in accordance with a recent meta-analysis of Achankeng and Cornelis (2023). Higher yield from the (non-inversion) minimum tillage may be explained by the more favourable conditions for seed emergence, particularly if compared to the no-till as suggested by other studies (e.g., Arvidsson et al., 2014; Cárceles Rodríguez et al., 2022; Licht and Al-Kaisi, 2005; Soane et al., 2012; ten Damme et al., 2025). It is challenging to determine whether the observed lower yield in the no-till is due to the fact that this treatment is still in a transition phase (see Cusser et al., 2020), considering that this treatment is in place for 13 years compared to the ploughing, the shallow tillage and the minimum tillage which are established since 1969. Additionally, agricultural advisors (pers. comm.) are more insisting that good initial soil conditions, especially the SOC level, may be important for the success of the transition to no-till, so that soils already rich in SOC are likely to show more immediate benefits. Considering the very low SOC:clay values at the beginning of our trial (Büchi et al., 2017), the optimal conditions for transitioning to no-till may not have been met.

The strong reduction of winter wheat yield in the no-till treatment during four consecutive years of monoculture, i.e., up to −80 % compared to the conventional plough during 2013–2016, confirms as the yield of a cereal monoculture is particularly sensitive in a no-till system, probably due to increased incidence of pests and weeds (Van den Putte et al., 2010; Woźniak and Soroka, 2014). This finding emphasizes that most of the benefits in no-till systems can be obtained only with a diversified rotation (Büchi et al., 2018; Shahzad et al., 2016; Woźniak, 2020). We argue that the low frequency of cover crops within our rotation may have exacerbated the negative effect of no-till practice on crop yield, for example through compaction or delayed seed emergence, considering the multiple positive effects that cover crops have on soil quality particularly in no-till systems (Büchi et al., 2018; Dai et al., 2024; Lieskamp et al., 2024).

4.2. *Winter wheat grain quality in response to tillage treatment*

Throughout the scientific literature, the relationships between soil tillage intensity and crop grain quality are not consistent. Indeed, a primary role in controlling grain quality seem to play climate variability, rotation diversity (including cover crops), crop variety and soil type, i.e., a pool of factors creating complex interactions with soil tillage intensity (e.g., Gaweda and Haliniarz, 2021; Kwiatkowski et al., 2022; Manzeke-Kangara et al., 2023; Minhas et al., 2023; Mitura et al., 2023; Shiwakoti et al., 2019; Yousefian et al., 2021; Zargar et al., 2018). In our study, we used the winter wheat plants of the year 2020 as a phytometer (see Dietrich et al., 2013) to assess the relative effects of tillage treatments on grain quality in each soil texture. Overall, we observed that in 2020 the quality of winter wheat grains was more affected by soil texture than by tillage treatment. It is interesting to underline that in the clay soil the grain N concentration from the no-till was significantly lower than the grain N concentration from the minimum tillage, a response already observed in other studies (e.g., Amato et al., 2013; Kwiatkowski et al., 2022; Waibel et al., 2025). This may be related to a reduction in plant-available soil N under no-till (López-Bellido et al., 1998). The observed positive role of ploughing in increasing the enrichment factor (EF) of macro- and micro-nutrients in winter wheat grains is in accordance with previous findings (Dolijanovic et al., 2022) and can be explained by the increase of nutrient availability and accessibility due to enhanced mineralization (Awale et al., 2022; Ishaq et al., 2001; Yousefian et al., 2021; Waibel et al., 2025).

4.3. *SOC concentration and nutrient stocks*

For each soil texture, the differences in SOC concentrations between the four tillage treatments in the upper layers clearly highlight the role of tillage intensity in affecting the amount of organic matter in agricultural soils (Bohoussou et al., 2022; Lv et al., 2023). If we compare the SOC concentration measured within the topmost 20 cm depth in 2013 in the no-till treatment (see Büchi et al., 2017), i.e., six years after the start of the treatment, and the SOC concentration measured in 2020, i.e., after 13 years of no-till, we can then observe a relative increase of SOC of about 24 % in the clay soil (from 2.52 % to 3.13 %, respectively) and about 22 % in the loam soil (from 1.28 % to 1.49 %, respectively). Similarly, under minimum tillage the SOC concentration increased, from 2013 to 2020, of about 20 % and 13 % in the clay and loam soil, respectively, whereas for the ploughed treatment the corresponding SOC increase was of about 9 % and 14 %. Overall, we can hypothesize that the systematic wheat straw return since 2007 in all the treatments has indeed a positive effect in increasing SOC concentration in the upper layers, particularly in the no-till (Wang et al., 2021; Yang et al., 2024). Interestingly, we can also observe that the minimum tillage has SOC concentrations comparable to the no-till along the entire soil profile. In a previous study, Büchi et al. (2017) already reported that the minimum tillage was the only treatment that did not show a significant decreasing trend of SOC concentration over time. Here we can further confirm that the minimum tillage is a practice promoting SOC concentration as effectively as the no-till (Li et al., 2020; Wuest et al., 2023). However, the additional main advantage of the minimum tillage is that, under the specific climatic conditions of the studied area, it also provides a larger and more stable crop yields compared to the no-till.

Major differences between treatments can be observed primarily in the upper 10 cm of soil depth, as previously reported by other studies (Mondal et al., 2023; Priori et al., 2024; West and Post, 2002). In the case of no-till, the SOC stratification can be explained by the absence of soil mixing and by surface residue deposition (Souza et al., 2023), but the same pattern can be observed for the minimum tillage even if the soil is disturbed only in the upper 5–8 cm.

Similar to the SOC concentration, the observed stratification patterns of the stocks of organic C, Ntot, exchangeable K and Mg in the upper 20 cm of the soil profile may be explained by the degree of tillage disturbance (Table 2). Indeed, we found approximately constant nutrient concentrations with depth in the topmost 20 cm of the ploughed treatment, whereas significantly larger nutrient stock values were measured in the topmost 10 cm in the three non-inversion tillage treatments than in the soil layer at 10–20 cm depth (Table 2). Such stratification of organic C, Ntot, exchangeable K and Mg stocks has been already reported by other studies, in particular for the SOC (Krauss et al., 2022; Luo et al., 2010; Meurer et al., 2018; Ogle et al., 2019). However, when we consider the entire 50-cm long profile, we did not detect any statistically significant difference in nutrient stocks among the different tillage treatments, even if there was a clear tendency of larger SOC, Ntot, exchangeable K and Mg stocks in the three non-inversion tillage treatments. In the case of SOC stock, for example, the range of increment in the non-inversion tillage treatments was between 10 % and 14 % in the clay soil and between 1 % and 8 % in the loam soil compared to the ploughed treatment (Table 2). From a methodological point of view, we argue that a large spatial variability of relevant parameters, such as the bulk density, can make it difficult to detect differences in stocks that are also statistically significant (Poeplau et al., 2022; Peng et al., 2024; Raffeld et al., 2024). In contrast, the Olsen-P stock along the entire 50-cm long soil profile was characterised by larger values in the ploughed treatment, a pattern that can be explained by the deeper incorporation of P as fertilizer or plant residues with ploughing so limiting its loss by surface run-off or access by crop roots (Xomphoutheb et al., 2020).

4.4. Microbial biomass carbon

In our study, larger values of soil microbial biomass C can be observed in all the three non-inversion tillage treatments, i.e., the no-till, the minimum tillage and the shallow tillage, with the largest microbial biomass C in the minimum tillage for both soil textures (Fig. 5). Such a result is in accordance with previous studies reporting an increase of microbial biomass in response to reduced tillage or in response to non-inversion tillage (Chen et al., 2020; D'Hose et al., 2018; Engell et al., 2022; Fontana et al., 2015; Li et al., 2018; Zuber and Villamil, 2016). The strongest differences in microbial biomass C between the tillage treatments are primarily observable in the topsoil, i.e., in the upper 5 cm for the clay soil and in the upper 10 cm for the loam soil (Fig. 5). Such strong stratification of microbial abundance was already observed in other studies (e.g., Chen et al., 2020; Mondal et al., 2023; Sun et al., 2021) and can be explained by the larger SOC concentration in the topsoil, thus promoting more favorable environmental conditions for microbes. Indeed, the positive correlation between microbial biomass C and SOC (Fig. 4) for both soil textures is consistent with the role of organic matter as the primary driver of microbial spatial distribution (Liu et al., 2014; Schmidt et al., 2018; Zhou et al., 2023).

The microbial quotient (MicQ), i.e., the Cmic-to-organic C (SOC) ratio, represents an index of the activity of microbial communities (Anderson and Domsch, 1978) that has been reported to respond positively to reduced soil tillage (Li et al., 2018). In our study, there are generally larger MicQ values in the upper layer of both the minimum tillage and the shallow tillage, whereas smaller MicQ values can be observed in the no-till (Fig. 6). Such a result may indicate a reduction of microbial activity in the no-till compared to the other treatments, probably due to the accumulation of more recalcitrant organic matter (McGonigle and Turner, 2017) or to a reduction of the microbial metabolic efficiency (Hao et al., 2019; Mbuthia et al., 2015). Another possibility is that that the organic matter is less accessible in the no-till due to a reduction of aggregate porosity, i.e., due to an increase of micro-aggregates (Cooper et al., 2021). This hypothesis seems to be supported by the generally lower MicQ in the clay soil compared to the loam soil (Fig. 6) and to the relatively high proportion of water filled porosity (< 25 μm radius) in the no-till (Table S4).

4.5. Soil structure vulnerability and soil porosity

A soil SOC:clay ratio of 1:10 has been proposed as a threshold of structure vulnerability (Fell et al., 2018) and so as a target for soil quality management evaluation (Johannes et al., 2017) in soils with a soil clay content up to c. 50 % (Johannes et al., 2023; Prout et al., 2022). Some major outcomes based on the observed SOC:clay ratios of our trial can be highlighted. Firstly, in the clay soil all the tillage treatments were characterized by a threshold smaller than 0.1, indicating a deficiency in organic matter and a strong structural vulnerability. This result suggests the necessity to adopt agronomic practices promoting organic matter accumulation, for example by increasing the frequency of cover crops in the rotation (Büchi et al., 2018). In a structurally vulnerable situation, the soil system relies mainly on mechanical loosening to avoid a compacted state, whereas a no-till system necessarily must rely on biological loosening for creating a functional porosity, but this can be possible only when a sufficient amount of organic matter is already available. This would mean that for a successful implementation of a no-till system the soil may require, before changing from inversion tillage to no-till, a sufficiently high SOC:clay ratio. Secondly, the no-till and the minimum tillage appears as the two more effective practices in promoting a higher SOC:clay ratio (Gubler et al., 2019), even if only in the uppermost soil layer (0–5 cm deep). Albeit the SOC:clay ratio has been criticized due to the effect of clay, particularly at large clay contents (Rabot et al., 2024), we can observe that, for the same amount of clay, the type of tillage practice can actually promote a larger ratio so suggesting that there is still the possibility to increase this ratio also in high clay content soil by adopting a set of suitable agronomic practices.

In general, the soil structure within this trial was rather poor, especially in the loam soil, but it exhibited patterns that were specific to the tillage type for both investigated soil types (Figs. 8 and 9). Bulk density was especially high in the loam soil reaching up to 1.53 g cm^{-3} for the plough treatment. Overall, shallow tillage and the upper layer of the minimum tillage had the lowest density. This can be explained by the mechanical loosening through shallow tillage increasing the coarse porosity and therefore the air content. The effect is clearer in the loam soil. For the upper layer of minimum tillage, the smaller bulk density is mainly explained by a larger microporosity filled with water. The increase in SOC may explain these results because SOC binds aggregates (e.g., Six et al., 2000; Tisdall and Oades, 1982) and could therefore stabilize a loosened structure created by minimum or shallow tillage. SOC also plays a role in creating microporosity and therefore might explain the increased water content (Rawls et al., 2003) in the minimum tillage treatment. This would also explain that in the plough treatment, characterized by the lowest SOC amount, the loosened structure due to the tillage may have not been stabilized through SOC, thus reducing the porosity and therefore promoting higher densities. Larger bulk densities in the no-till and at 8–12 cm depth in the minimum tillage treatments can be explained by the absence of the loosening effect of tillage and the concomitant compacting effect of trafficking, leading to "shallow" plow pans (Schlüter et al., 2018).

Different threshold values for soil air capacity have been reported in the literature, under which plant growth is thought to be restricted. These values vary between 0.05 and 0.1 cm^3 cm^{-3} (Johannes et al., 2019). In the clay soil, most volumetric air capacities were larger than 0.1 cm^3 cm^{-3}. The gravimetric air content at field capacity was larger than 0.068 cm^3 g^{-1}, a threshold proposed by Johannes et al. (2017) to classify the soil structure as "degraded". In the clay soil, the only potentially insufficient values were found for the minimum tillage treatment at 8–12 cm depth. In the loam soil, only the gravimetric air content at field capacity for the shallow tillage was predominantly larger than 0.068 cm^3 g^{-1} while mean gravimetric air content at field capacity for minimum tillage and no-till were lowest with 0.041 and 0.049 cm^3 g^{-1}. Again, the smaller values under minimum tillage and no-till are most likely related to machine trafficking and the lack of soil loosening during tillage. The air gravimetric air content at field capacity in these treatments was small enough to classify the respective soil structure as 'degraded'. A deficit in soil aeration did obviously not hinder crop growth under minimum tillage. However, it nevertheless may have contributed to the decreased crop yields under no-till, because not only the macropore volume alone secures oxygen supply in the soil, but also the macropore connectivity and distribution within the soil (ten Damme et al., 2025). It is known that tilled soil exhibits artificially created inter-aggregate pore networks that pervade the soil volume at regular distances. In contrast, no-till soil contains larger soil volumes that are by-passed by connected macropores, which are more susceptible for temporary anaerobic conditions (Schlüter et al., 2020). Therefore, we expect that oxygen supply to the wheat seedlings' roots was better under minimum tillage than under no-till.

The potentially plant available water content was comparable for both soils, despite the clay soil having much larger overall water contents because in clay soils a large portion of this water is in micropores, where the capillary pressures are too large for plant water uptake. Most values were comparable among the different tillage treatments and depths, with the exception of minimum tillage in the loam soil at 2–6 cm depth, which harbored potentially plant available water contents that were larger than in the rest (Fig. 8b). However, the yields from the ploughed and shallow tillage treatments are very similar to the ones under minimum tillage and the larger observed potentially plant available water appeared to be rather non-decisive for crop yield.

5. Conclusions

Our data showed that, after 13 years since its introduction, the no-till treatment was characterized by SOC concentrations in the upper layers that were comparable to those under minimum tillage and higher than the ones under shallow tillage and conventional ploughing, being the last three tillage treatments on place for about 50 years. In terms of nutrient stocks, the study clearly shows that the three non-inversion tillage practices, including no-till, promoted a significant increase of C, N, and K stock in the upper 10-cm deep soil layers. The no-till treatment was also characterized, similarly to the minimum tillage treatment, by larger microbial biomass C in the topmost soil layers. However, the no-till treatment exhibited a smaller, although statistically non-significant, winter wheat yield of about 12 % compared to the ploughed and the other two non-inversion tillage treatments. By comparing the three non-inversion tillage treatments, the non-inversion minimum tillage appears, at least for the studied parameters and under the local pedological and climatic conditions, a suitable tillage practices providing environmental and agronomical advantages similar or higher than the no-till treatment.

CRediT authorship contribution statement

Thomas Guillaume: Writing – review & editing, Methodology, Formal analysis. **Raphael Charles:** Writing – review & editing. **John Koestel:** Writing – review & editing, Formal analysis. **Lucie Büchi:** Writing – review & editing. **Orly Mendoza:** Writing – review & editing. **Luca Bragazza:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Mario Fontana:** Writing – review & editing, Methodology. **Alice Johannes:** Writing – review & editing, Methodology, Formal analysis.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127722.

Data availability

Data will be made available on request.

References

Achankeng, E., Cornelis, W., 2023. Conservation tillage effects on European crop yields: a meta-analysis. Field Crops Res. 298, 108967. https://doi.org/10.1016/j.fcr.2023.108967.

Amato, G., Ruisi, P., Frenda, A.S., Di Miceli, G., Saia, S., Plaia, A., Giambalvo, D., 2013. Long-term tillage and crop sequence effects on wheat grain yield and quality. Agron. J. 105, 1317–1327.

Anderson, J.P.E., Domsch, K.H., 1978. A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biol. Biochem. 10, 215–221. https://doi.org/10.1016/0038-0717(78)90099-8.

Anderson, T.H., Domsch, K.H., 1989. Ratios of microbial biomass carbon to total organic-C in arable soils. Soil Biol. Biochem. 21, 471–479.

Arvidsson, J., Etana, A., Rydberg, T., 2014. Crop yield in Swedish experiments with shallow tillage and no-tillage 1983–2012 (Part B). Eur. J. Agron. 52, 307–315. https://doi.org/10.1016/j.eja.2013.08.002.

Awale, R., Singh, S., Machado, S., 2022. Soil chemical properties and wheat yields under different tillage and nitrogen rates in eastern Oregon. Agrosyst. Geosci. Environ. 5, e20272. https://doi.org/10.1002/agg2.20272.

Bhatti, S.S., Sambyal, V., Nagpal, A.K., 2018. Analysis of genotoxicity of agricultural soils and metal (Fe, Mn and Zn) accumulation in crops. Int. J. Environ. Res. 12, 439–449.

Bijttebier, J., Ruysschaert, G., Hijbeek, R., et al., 2018. Adoption of non-inversion tillage across Europe: use of a behavioural approach in understanding decision making of farmers. Land Use Policy 78, 460–471. https://doi.org/10.1016/j.landusepol.2018.05.044.

Bohoussou, Y.N., Kou, Y.H., Yu, W.B., Lin, B., Virk, A.L., Zhao, X., Dang, Y.P., Zhang, H.L., 2022. Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: a global meta-analysis. Sci. Total Environ. 842, 156822. https://doi.org/10.1016/j.scitotenv.2022.156822.

Boivin, P., Brunet, D., Gascuel-Odoux, C., 1990. Densité apparente d'échantillon de sol: Méthode de la poche plastique. Milieux poreux et transferts hydriques. Bulletin du Groupe français d'humidimétrie neutronique et des techniques associées 28, 59–71.

Bregaglio, S., Mongiano, G., Ferrara, R.M., Ginaldi, F., Lagomarsino, A., Rana, G., 2022. Which are the most favourable conditions for reducing soil CO2 emissions with no-tillage? Results from a meta-analysis. Int. Soil Water Conserv. Res 10, 497–506. https://doi.org/10.1016/j.iswcr.2022.05.003.

Brown, J., Stobart, R., Hallett, P., et al., 2021. Variable impacts of reduced and zero tillage on soil carbon storage across 4–10 years of UK field experiments. J. Soils Sediment. 21, 890–904. https://doi.org/10.1007/s11368-020-02799-6.

Büchi, L., Wendling, M., Amossé, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term field experiment in Switzerland. Soil Tillage Res. 174, 120–129. https://doi.org/10.1016/j.still.2017.07.002.

Büchi, L., Wendling, M., Amossé, C., Necpalova, M., Charles, R., 2018. Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. Agric. Ecosyst. Environ. 256, 92–104. https://doi.org/10.1016/j.agee.2018.01.005.

Cárceles Rodríguez, B., Durán-Zuazo, V.H., Soriano Rodríguez, M., García-Tejero, I.F., Gálvez Ruiz, B., Cuadros Tavira, S., 2022. Conservation agriculture as a sustainable system for soil health: a review. Soil Syst. 6, 87. https://doi.org/10.3390/soilsystems6040087.

Chen, H., Dai, Z., Veach, A.M., Zheng, J., Xu, J., Schadt, C.W., 2020. Global meta-analyses show that conservation tillage practices promote soil fungal and bacterial biomass. Agric. Ecosyst. Environ. 293, 106841. https://doi.org/10.1016/j.agee.2020.106841.

Cooper, H.V., Sjögersten, S., Lark, R.M., et al., 2021. Long-term zero-tillage enhances the protection of soil carbon in tropical agriculture. Eur. J. Soil Sci. 72, 2477–2492. https://doi.org/10.1111/ejss.13111.

Cui, Y., Zhang, W., Zhang, Y., et al., 2022. Effects of no-till on upland crop yield and soil organic carbon: a global meta-analysis. Plant ad Soil 499, 363–377. https://doi.org/10.1007/s11104-022-05854-y.

Cusser, S., Bahlai, C., Swinton, S.M., Robertson, G.P., Haddad, N.M., 2020. Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. Glob. Change Biol. 26, 3715–3725. https://doi.org/10.1111/gcb.15080.

D'Hose, T., Molendijk, L., Van Voorena, L., et al., 2018. Responses of soil biota to non-inversion tillage and organic amendments: an analysis on European multiyear field experiments. Pedobiologia 66, 18–28. https://doi.org/10.1016/j.pedobi.2017.12.003.

Dai, W., Feng, G., Huang, Y., Adeli, A., Jenkins, J.N., 2024. Influence of cover crops on soil aggregate stability, size distribution and related factors in a no-till field. Soil Tillage Res. 244, 106197. 〈https://doi-org.agros.swissconsortium.ch/10.1016/j.still.2024.106197〉.

ten Damme, L., Goberna, M., Sánchez-Moreno, S., Pulido-Moncada, M., Philippot, L., Ros, M., Bragazza, L., Hallin, S., Feiziene, D., Munkholm, L.J., 2025. Long-term application of no-tillage-induced greater risk of poor topsoil aeration along a European pedoclimatic gradient. Eur. J. Soil Sci. 76, e70081. https://doi.org/10.1111/ejss.70081.

Dietrich, A.L., Nilsson, C., Jansson, R., 2013. Phytometers are underutilised for evaluating ecological restoration. Basic. Appl. Ecol. 14, 369–377. https://doi.org/10.1016/j.baae.2013.05.008.

Dolijanovic, Ž., Nikolic, S.R., Dragicevic, V., Mutic, J., Šeremešic, S., Jovovic, Z., Djordjevic, J.P., 2022. Mineral composition of soil and the wheat grain in intensive and conservation cropping systems. Agronomy 12, 1321. https://doi.org/10.3390/agronomy12061321.

Engell, I., Linsler, D., Sandor, M., Joergensen, R.G., Meinen, C., Potthoff, M., 2022. The effects of conservation tillage on chemical and microbial soil parameters at four sites across Europe. Plants 11, 1747. https://doi.org/10.3390/plants11131747.

Fell, V., Matter, A., Keller, T., Boivin, P., 2018. Patterns and factors of soil structure recovery as revealed from a tillage and cover-crop experiment in a compacted orchard. Front. Environ. Sci. 6, 134. https://doi.org/10.3389/fenvs.2018.00134.

Fontana, M., Berner, A., Mäder, P., Lamy, F., Boivin, P., 2015. Soil organic carbon and soil bio-physicochemical properties as co-influenced by tillage treatment. Soil Sci. Soc. Am. J. 79, 1435–1445.

Gaweda, D., Haliniarz, M., 2021. Grain yield and quality of winter wheat depending on previous crop and tillage system. Agriculture 11, 133.

Gubler, A., Wächter, D., Schwab, P., Müller, M., Keller, A., 2019. Twenty-five years of observations of soil organic carbon in Swiss croplands showing stability overall but

with some divergent trends. Environ. Monit. Assess. 191, 277. https://doi.org/10.1007/s10661-019-7435-y.
Guillaume, T., Makowski, D., Libohova, Z., Elfouki, S., Fontana, M., Leifeld, J., Bragazza, L., Sinaj, S., 2022. Carbon storage in agricultural topsoils and subsoils is promoted by including temporary grasslands into the crop rotation. Geoderma 422, 115937. https://doi.org/10.1016/j.geoderma.2022.115937.
Haddaway, N.R., Hedlund, K., Jackson, L.E., et al., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6, 30. https://doi.org/10.1186/s13750-017-0108-9.
Hao, M., Hu, H., Liu, Z., Dong, Q., Sun, K., Feng, Y., Li, G., Ning, T., 2019. Shifts in microbial community and carbon sequestration in farmland soil under long-term conservation tillage and straw returning. Appl. Soil Ecol. 136, 43–54. https://doi.org/10.1016/j.apsoil.2018.12.016.
Ishaq, M., Ibrahim, M., Lal, R., 2001. Tillage effect on nutrient uptake by wheat and cotton as influenced by fertilizer rate. Soil Tillage Res 62, 41–53.
Joergensen, R.G., 1996. The fumigation-extraction method to estimate soil microbial biomass: calibration of the kEC value. Soil Biol. Biochem. 28, 25–31.
Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P.C., Boivin, P., 2017. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? Geoderma 302, 14–21. https://doi.org/10.1016/j.geoderma.2017.04.021.
Johannes, A., Weisskopf, P., Schulin, R., Boivin, P., 2019. Soil structure quality indicators and their limit values. Ecol. Indic. 104, 686–694.
Johannes, A., Sauzet, O., Matter, A., Boivin, P., 2023. Soil organic carbon content and soil structure quality of clayey cropland soils: a large-scale study in the Swiss Jura region. Soil Use Manag 39, 707–716. https://doi.org/10.1111/sum.12879.
Krauss, M., Berner, A., Perrochet, F., Frei, R., Niggli, U., Mäder, P., 2020. Enhanced soil quality with reduced tillage and solid manures in organic farming–a synthesis of 15 years. Sci. Rep. 10, 4403.
Krauss, M., Wiesmeier, M., Don, A., et al., 2022. Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil Tillage Res 216, 105262. https://doi.org/10.1016/j.still.2021.105262.
Kwiatkowski, C.A., Harasim, E., Klikocka-Wiśniewska, O., 2022. Effect of catch crops and tillage systems on the content of selected nutrients in spring wheat grain. Agronomy 12, 1054. https://doi.org/10.3390/agronomy12051054.
Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res 93, 1–12. https://doi.org/10.1016/j.still.2006.11.004.
Lee, S., Chu, M.L., Guzman, G.A., Botero-Acosta, A., 2021. A comprehensive modeling framework to evaluate soil erosion by water and tillage. J. Environ. Manag 279, 111631. https://doi.org/10.1016/j.jenvman.2020.111631.
Li, Y., Chang, S.X., Tian, L., Zhang, Q., 2018. Conservation agriculture practices increase soil microbial biomass carbon and nitrogen in agricultural soils: a global meta-analysis. Soil Biol. Biochem. 121, 50–58. https://doi.org/10.1016/j.soilbio.2018.02.024.
Li, Y., Li, Z., Chang, S.X., Cui, S., Jagadamma, S., Zhang, Q., Cai, Y., 2020. Residue retention promotes soil carbon accumulation in minimum tillage systems: implications for conservation agriculture. Sci. Total Environ. 740, 140147. https://doi.org/10.1016/j.scitotenv.2020.140147.
Licht, M.A., Al-Kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res 80, 233–249. https://doi.org/10.1016/j.still.2004.03.017.
Lieskamp, D.R., Moseley, A.M., Legrain, I.M.R., Kelly, C., Haque, M.A., Ku, S., Haruna, S. I., 2024. No-till cover crop effects on the hydro-physical properties of a silt loam. Soil Sci. Soc. Am. J. 88, 764–778. https://doi.org/10.1002/saj2.20645.
Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Change Biol. 20, 1366–1381. https://doi.org/10.1111/gcb.12517.
López-Bellido, L., Fuentes, M., Castillo, J.E., López-Garrido, F.J., 1998. Effects of tillage, crop rotation and nitrogen fertilization on wheat-grain quality grown under rainfed Mediterranean conditions. Field Crops Res 57, 265–276. https://doi.org/10.1016/S0378-4290(97)00137-8.
Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224–231. https://doi.org/10.1016/j.agee.2010.08.006.
Lv, L., Gao, Z., Liao, K., Zhu, Q., Zhu, J., 2023. Impact of conservation tillage on the distribution of soil nutrients with depth. Soil Tillage Res. 225, 105527. https://doi.org/10.1016/j.still.2022.105527.
Manzeke-Kangara, M.G., Joy, E.J.M., Lark, R.M., Redfern, S., Eilander, A., Broadley, M. R., 2023. Do agronomic approaches aligned to regenerative agriculture improve the micronutrient concentrations of edible portions of crops? A scoping review of evidence. Front. Nutr. 10, 1078667. https://doi.org/10.3389/fnut.2023.1078667.
Mbuthia, L.W., Acosta-Martínez, V., DeBruyn, J., Schaeffer, S., Tyler, D., Odoi, E., Mpheshea, M., Walker, F., Eash, N., 2015. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: implications for soil quality. Soil Biol. Biochem. 89, 24–34.
McGonigle, T.P., Turner, W.G., 2017. Grasslands and croplands have different microbial biomass carbon levels per unit of soil organic carbon. Agriculture 7, 57. https://doi.org/10.3390/agriculture7070057.
Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil -A systematic review using an ESM approach. Earth-Sci. Rev. 177, 613–622. https://doi.org/10.1016/j.earscirev.2017.12.015.
Minhas, W.A., Mehboob, N., Yahya, M., Rehman, H.U., Farooq, S., Hussain, M., 2023. The influence of different crop mulches on weed infestation, soil properties and productivity of wheat under conventional and conservation production systems. Plants 12, 9. https://doi.org/10.3390/plants12010009.
Mitura, K., Cacak-Pietrzak, G., Feledyn-Szewczyk, B., Szablewski, T., Studnicki, M., 2023. Yield and Grain Quality of Common Wheat (*Triticum aestivum* L.) Depending on the Different Farming Systems (Organic vs. Integrated vs. Conventional). Plants 12, 1022. https://doi.org/10.3390/plants12051022.
Mondal, S., Chakraborty, D., Paul, R.K., Mondal, A., Jadha, J.K., 2023. No-till is more of sustaining the soil than a climate change mitigation option. Agric. Ecosyst. Environ. 352, 108498. https://doi.org/10.1016/j.agee.2023.108498.
Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment - a review. Soil Tillage Res 108, 1–15. https://doi.org/10.1016/j.still.2010.03.004.
Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36. https://doi.org/10.1016/S0003-2670(00)88444-5.
Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci. Rep. 9, 11665. https://doi.org/10.1038/s41598-019-47861-7.
Olsen, S.R., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. US Department of Agriculture.
Paustian, K.A., et al., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manag 13, 230–244. https://doi.org/10.1111/j.1475-2743.1997.tb00594.x.
Peng, Y., Chahal, I., Hooker, D.C., Van Eerd, L.L., 2024. Comparison of equivalent soil mass approaches to estimate soil organic carbon stocks under long-term tillage. Soil Tillage Res 238, 106021. https://doi.org/10.1016/j.still.2024.106021.
Pittelkow, C., Liang, X., Linquist, B., et al., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368. https://doi.org/10.1038/nature13809.
Poeplau, C., Prietz, R., Don, A., 2022. Plot-scale variability of organic carbon in temperate agricultural soils - Implications for soil monitoring. J. Plant Nutr. Soil Sci. 185, 403–416. https://doi.org/10.1002/jpln.202100393.
Prairie, A.M., King, A.E., Cotrufo, M.F., 2023. Restoring particulate and mineral-associated organic carbon through regenerative agriculture. Proc. Natl. Acad. Sci. USA 120, e2217481120. https://doi.org/10.1073/pnas.2217481120.
Prashun, V., 2012. On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. Soil Tillage Res 120, 137–146. https://doi.org/10.1016/j.still.2012.01.002.
Priori, S., Zanini, M., Falcioni, V., Casa, R., 2024. Topsoil vertical gradient in different tillage systems: an analytical review. Soil Tillage Res. 236, 105947. https://doi.org/10.1016/j.still.2023.105947.
Prout, J.M., Shepherd, K.D., McGrath, S.P., Kirk, G.J.D., Hassall, K.L., Haefele, S.M., 2022. Changes in organic carbon to clay ratios in different soils and land uses in England and Wales over time. Sci. Rep. 12, 5162. https://doi.org/10.1038/s41598-022-09101-3.
R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org.
Rabot, E., Saby, N.P.A., Martin, M.P., et al., 2024. Relevance of the organic carbon to clay ratio as a national soil health indicator. Geoderma 443, 116829. https://doi.org/10.1016/j.geoderma.2024.116829.
Raffeld, A.M., Bradford, M.A., Jackson, R.D., Rath, D., Sanford, G.R., Tautges, N., Oldfield, E.E., 2024. The importance of accounting method and sampling depth to estimate changes in soil carbon stocks. Carbon Balance Manag 19, 2. https://doi.org/10.1186/s13021-024-00249-1.
Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/S0016-7061(03)00094-6.
Reicosky, D.C., 2015. Conservation tillage is not conservation agriculture. J. Soil Water Conserv 70, 103A–108A. https://doi.org/10.2489/jswc.70.5.103.
Rickson, R.J., et al., 2015. Input constraints to food production: the impact of soil degradation. Food Sect. 7, 351–364. https://doi.org/10.1007/s12571-015-0437-x.
Rieger, S., Richner, W., Streit, B., Frossard, E., Liedgens, M., 2008. Growth, yield, and yield components of winter wheat and the effects of tillage intensity, preceding crops, and N fertilization. Eur. J. Agron. 28, 405–411. https://doi.org/10.1016/j.eja.2007.11.006.
Sanaullah, M., Usman, M., Wakeel, A., Cheema, S.A., Ashraf, I., Farooq, M., 2020. Terrestrial ecosystem functioning affected by agricultural management systems: a review. Soil Tillage Res. 196, 104464. https://doi.org/10.1016/j.still.2019.104464.
Schlüter, S., Großmann, C., Diel, J., Wu, G.M., Tischer, S., Deubel, A., Rücknagel, J., 2018. Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties. Geoderma 332, 10–19. https://doi.org/10.1016/j.geoderma.2018.07.001.
Schlüter, S., Albrecht, L., Schwärzel, K., Kreiselmeier, J., 2020. Long-term effects of conventional tillage and no-tillage on saturated and near-saturated hydraulic conductivity – Can their prediction be improved by pore metrics obtained with X-ray CT? Geoderma 361, 114082. https://doi.org/10.1016/j.geoderma.2019.114082.
Schmidt, R., Gravuer, K., Bossange, A.V., Mitchell, J., Scow, K., 2018. Long-term use of cover crops and no-till shift soil microbial community life strategies in agricultural soil. PLoS 13, e0192953. https://doi.org/10.1371/journal.pone.0192953.
Shahzad, M., Farooq, M., Jabran, K., Hussain, M., 2016. Impact of different crop rotations and tillage systems on weed infestation and productivity of bread wheat. Crop Prot. 89, 161–169. https://doi.org/10.1016/j.cropro.2016.07.019.
Shiwakoti, S., Zheljazkov, V.D., Gollany, H.T., Kleber, M., Xing, B., 2019. Effect of tillage on macronutrients in soil and wheat of a long-term dryland wheat-pea rotation. Soil Tillage Res 190, 194–201. https://doi.org/10.1016/j.still.2019.02.004.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681–689.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res 118, 66–87.

Souza, J.L.B., Antonangelo, J.A., Zhang, H., Reed, V., Finch, B., Arnall, B., 2023. Impact of long-term fertilization in no-till on the stratification of soil acidity and related parameters. Soil Tillage Res. 228, 105624. https://doi.org/10.1016/j.still.2022.105624.

Sparling, G.P., 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Aust. J. Soil Res 30, 195–207.

Spiess, E., Humphrys, C., Richner, W., Schneider, M.K., Piepho, H.-P., Chervet, A., Prasuhn, V., 2020. Does no-tillage decrease nitrate leaching compared to ploughing under a long-term crop rotation in Switzerland? Soil Tillage Res 199, 104590. https://doi.org/10.1016/j.still.2020.104590.

Sun, T., Wang, Y., Lucas-Borja, M.E., Jing, X., Feng, W., 2021. Divergent vertical distribution of microbial biomass with soil depth among groups and land uses. J. Environ. Manag 292, 112755. https://doi.org/10.1016/j.jenvman.2021.112755.

Thapa, B., Dura, R., 2024. A review on tillage system and no-till agriculture and its impact on soil health. Arch. Agric. Environ. Sci. 9, 612–617. https://doi.org/10.26832/24566632.2024.0903028.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x.

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G., Tóth, G., 2015. New generation of hydraulic pedotransfer functions for Europe. Eur. J. Soil Sci. 66, 226–238. https://doi.org/10.1111/ejss.12192.

Van den Putte, A., Govers, G., Diels, J., Gillijns, K., Demuzere, M., 2010. Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur. J. Agron. 33, 231–241. https://doi.org/10.1016/j.eja.2010.05.008.

Waibel, M., Michel, J., Antoine, M., et al., 2025. Tensions in tillage: reduction in tillage intensity associates with lower wheat growth and nutritional grain quality despite enhanced soil biological indicators. Agric. Ecosyst. Environ. 389, 109675. https://doi.org/10.1101/2024.12.09.627503.

Wang, Q., Liu, X., Li, J., Yang, X., Guo, Z., 2021. Straw application and soil organic carbon change: a meta-analysis. Soil Water Res 16, 112–120. https://doi.org/10.17221/155/2020-SWR.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946. https://doi.org/10.2136/sssaj2002.1930.

Woźniak, A., 2020. Effect of cereal monoculture and tillage systems on grain yield and weed infestation of winter durum wheat. Int. J. Plant Prod. 14, 1–8. https://doi.org/10.1007/s42106-019-00062-8.

Woźniak, A., Soroka, M., 2014. Effects of a 3-year reduced tillage on the yield and quality of grain and weed infestation of spring triticale (*Tritico secale* Wittmack). Int. J. Plant Prod. 8, 231–242.

Wuest, S.B., Schillinger, W.F., Machado, S., 2023. Variation in soil organic carbon over time in no-till versus minimum tillage dryland wheat-fallow. Soil Tillage Res 229, 105677. https://doi.org/10.1016/j.still.2023.105677.

Xomphoutheb, T., Jiao, S., Guo, X., et al., 2020. The effect of tillage systems on phosphorus distribution and forms in rhizosphere and non-rhizosphere soil under maize (*Zea mays* L.) in Northeast China. Sci. Rep. 10, 6574. https://doi.org/10.1038/s41598-020-63567-7.

Yang, C., Wang, X., Li, J., et al., 2024. Straw return increases crop production by improving soil organic carbon sequestration and soil aggregation in a long-term wheat–cotton cropping system. J. Integr. Agric. 23, 669–679. https://doi.org/10.1016/j.jia.2023.06.009.

Yousefian, M., Shahbazi, F., Hamidian, K., 2021. Crop yield and physicochemical properties of wheat grains as affected by tillage systems. Sustainability 13, 4781. https://doi.org/10.3390/su13094781.

Zargar, M., Polityko, P., Pakina, E., Bayat, M., Vandyshev, V., Kavhiza, N., Kiselev, E., 2018. Productivity, quality and economics of four spring wheat (*Triticum aestivum* L.) cultivars as affected by three cultivation technologies. Agron. Res. 16, 2254–2264.

Zhou, R., Liu, Y., Dungait, J.A.J., et al., 2023. Microbial necromass in cropland soils: a global meta-analysis of management effects. Glob. Change Biol. 29, 1998–2014. https://doi.org/10.1111/gcb.16613.

Zuber, S.M., Villamil, M.B., 2016. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities, 176e187 Soil Biol. Biochem. 97. https://doi.org/10.1016/j.soilbio.2016.03.011.