Soil & Tillage Research 244 (2024) 106196

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of reduced tillage and prolonged cover cropping in maize on soil quality and yield

Joost Sleiderink [a], Joachim G.C. Deru [a,*], Rommie van der Weide [b], Nick van Eekeren [a]

[a] *Louis Bolk Institute, Bunnik, the Netherlands*
[b] *Wageningen Plant Research, Open Teelten, Lelystad, the Netherlands*

ARTICLE INFO

Keywords:
Reduced tillage
Cover cropping
Earthworms
SOM
Penetration resistance
Maize productivity

ABSTRACT

Maize (*Zea mays L.*) is the most common arable crop on sandy soils in the Netherlands, and it is often grown for several consecutive years after temporary grassland. For the maize-growing years, reduced tillage intensity and prolonged growing period of cover crops could limit declines in soil organic matter (SOM) and soil biota while maintaining soil structure and maize yield. We measured soil parameters and maize yield in an eight-years field experiment on sandy Gleyic Podzol. Treatments included four cropping systems differing in tillage intensity but with conventional sowing dates (conventional inversion tillage (CT), non-inversion tillage (NIT), strip tillage (ST) and no-till (NT)), and two cropping systems (CT-prolonged and ST-prolonged) with prolonged growing period of a winter rye-winter pea cover crop combined with a late sown short-season maize (18 weeks growth). After eight years, we found no evidence for differences in SOM or total carbon content between the treatments. However, in the reduced-tillage treatments, SOM content was higher in the top (0–15 cm) than in the bottom (15–30 cm) of the plough layer, while in CT and CT-prolonged, this stratification was inverted. We observed differences in earthworm abundance, biomass and functional group distribution. In comparison to CT (100 %), the earthworm abundance was 153 % in NIT, 235 % in ST and 206 % in NT whereas earthworm biomass was 269 % in NIT, 325 % in ST and 475 % in NT. Epigeic earthworms were more affected by tillage than endogeic earthworms. Compared to CT, earthworm biomass was higher in CT-prolonged. The initially low earthworm population recovered during the course of the experiment independent of tillage intensity.

Higher soil penetration resistance was observed in the reduced tillage systems compared to CT, independent of prolonging the cover crop. Despite the increased penetration resistance, the maize yields in NIT and ST were similar to CT. The maize yields were lower in NT, CT-prolonged and ST-prolonged compared to CT, but no differences were observed between CT-prolonged and ST-prolonged. The biomass of the harvested prolonged cover crop closed the yield gap in relation to CT in four out of six years in which cover crop biomass in CT-prolonged and ST-prolonged was quantified. Based on our results, we recommend strip tillage for continuous maize-cropping systems on Dutch sandy soils. In the case of severe compacting of compaction prone soils, we recommend conventional tillage with a prolonged cover crop and short-season maize variety.

1. Introduction

Soil tillage and the lack of year-long soil coverage in annual cropping systems can lead to soil degradation (Lal, 2004; Van Eekeren et al., 2008; Poeplau et al., 2011). For this reason, regenerating practices have been put forward, such as reduced tillage and cover cropping (e.g., Lal and Kimble, 1997; Dabney et al., 2001; Hobbs et al., 2008; Schreefel et al., 2020). There is evidence that such practices may have a positive influence on soil properties.

Ploughing decreases both soil aggregation and the protection of soil organic matter (SOM) (Six et al., 2000; Sheehy et al., 2015), leading to increased SOM mineralization and carbon dioxide emissions (Paustian et al., 2000; Reicosky, 2003). Multiple meta-reviews have attributed a decrease in soil organic carbon (SOC) losses and even an increase of carbon (C) sequestration to no-till agriculture (e.g., West and Post, 2002; Freibauer et al., 2004). However, other authors have critiqued these studies as they limit soil sampling to surface soil layers where no-till shows relative increases in SOC compared to inversion tillage. When

---

Abbreviations: CT, conventional tillage; NIT, non-inversion tillage; ST, strip tillage; NT, no-till.

[*] Correspondence to: Louis Bolk Instituut, Kosterijland 3-5, Bunnik 3981 AJ, the Netherlands.

E-mail address: j.deru@louisbolk.nl (J.G.C. Deru).

https://doi.org/10.1016/j.still.2024.106196
Received 18 September 2023; Received in revised form 3 June 2024; Accepted 5 June 2024

soil sampling includes the whole plough layer or more, no-till fails to show consistent SOC accrual, as inversion tillage effectively redistributes surface SOC to deeper layers where SOC concentrations are then higher than in no-till (VandenBygaart et al., 2003; Baker et al., 2007; Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2008).

Cover cropping is another management practice which can sequester carbon. The input of organic residues of annual crops is often not enough to counteract SOM decomposition from tillage, leading to a gradual decrease in SOM (Blanco-Canqui and Lal, 2009; Poeplau and Don, 2015). Cover cropping could limit this decrease (Ruis and Blanco-Canqui, 2017).

Both tillage and cover crop residue management have a profound impact on the abundance, diversity and vertical distribution of soil organisms (House and Parmelee, 1985; Kladivko, 2001; Van Eekeren et al., 2008; Roger-Estrade et al., 2010). Earthworms are regarded as indicator species of soil health that greatly impact the physical, chemical and biological quality of the soil (Pulleman et al., 2012; Blouin et al., 2013; Bertrand et al., 2015). Earthworms can play a crucial role in maintaining and improving soil properties in the absence of tillage (Joschko et al., 1992; Chan, 2001; Yvan et al., 2012). Many authors have demonstrated that reduced tillage or no-till practices lead to higher earthworm abundance, biomass, species richness (Chan, 2001; Van Capelle et al., 2012; D'Hose et al., 2018) and functional diversity (Capowiez et al., 2009; Pelosi et al., 2014). Tillage systems also have a distinct impact on weed abundance and diversity and influence the possibilities of weed control, which in turn impact soil biodiversity too (Melander et al., 2013). However, effects on soil biodiversity may vary between histories of land-use (short- and long-term), soil and environmental conditions, types of tillage, and earthworm functional groups (Chan, 2001; Briones and Schmidt, 2017).

The effect of reduced tillage compared to conventional tillage on the physical and structural soil properties also depend on soil type, environmental conditions, crop species, crop rotation and time after adoption (Lipiec et al., 2006; Strudley et al., 2008; Vogeler et al., 2009; Soane et al., 2012). Sandy soils do not shrink and swell like soils containing clay, and thus lack the ability to maintain or restore soil structure without tillage, which may limit the success of no-till on these soils (Ehlers and Claupein, 1994; Van Ouwerkerk and Perdok, 1994 in Soane et al., 2012; Munkholm et al., 2003)

Silage maize is the most grown arable crop in the Netherlands and is dominant in regions with sandy soils (CBS, 2021). However, data are lacking on the impacts of reduced tillage or no-till in continuous maize-cropping systems in the Netherlands (see lack of Dutch studies in Cannel et al., 1985; Van den Putte et al., 2010; Rusinamhodzi et al., 2011; Soane et al., 2012; Pittelkow et al., 2015; Huang et al., 2018) and European data are scarce (Rietra et al., 2022). Additionally, no-till management may reduce maize productivity, especially under wetter and/or colder conditions (Van den Putte et al., 2010; Rusinamhodzi et al., 2011; Ogle et al., 2012; Pittelkow et al., 2015; Rietra et al., 2022). The subsequent decrease in underground C inputs from root turnover and exudation may limit the gains in SOM attributed to no-till (Ogle et al., 2012; Sheehy et al., 2015).

Based on the above, research on soil tillage in silage maize on sandy soils should focus not only on the effect of the absence of tillage – such as no-till – on soil quality and yields, but also on the effects of methods with an intermediate intensity of soil tillage. For example, non-inversion tillage disturbs the whole soil surface but leaves the soil stratification intact, and this is thought to support soil structure, water infiltration and epigeic and anecic earthworms (Morris et al., 2010; Crittenden et al., 2014; Bertrand et al., 2015). Strip tillage leaves more than 75 % of the soil surface undisturbed and only cultivates small strips in which the usual restraints on seedling emergence and crop growth are alleviated while the soil between strips is conserved (Licht and Al-Kaisi, 2005; Fernández et al., 2015; Ren et al., 2019), thus potentially leading to better maize yields on sandy soils than with no-till (Vyn and Raimbault, 1992).

Cover cropping may mitigate the detrimental effects of soil tillage on SOM and earthworms as well as the aforementioned adverse effects of reduced tillage on soil structure (Lal, 2015; Dabney et al., 2001; Blanco-Canqui et al., 2015). Winter rye (*Secale cereale* L.) is a commonly used cover crop whose residue is usually incorporated into the soil in early spring. However, new maize varieties with a very short growing season that can be sown later and reach the required dry matter content for silage within 18 weeks (Groten and Meesters, 2023) enable maximizing the growth period of the cover crop. This provides the possibility to sow a grain-legume mixture as cover crop, for example winter rye-winter pea (*Pisum sativum* L.), which can be harvested as feed.

In silage maize production systems, the effects of reduced tillage and prolonged cover cropping on an integral set of soil and yield parameters have not been studied before. The objective of this research was therefore to investigate the long-term effects of reduced tillage and cover cropping on soil properties and maize yield. An eight-year long experiment was carried out on a sandy soil in the Netherlands, which included four tillage techniques (differing in tillage intensity, tillage depth and soil inversion), and two cover crop strategies (conventional and prolonged). We hypothesized that in a period of eight years of maize cropping after grassland conversion, decreasing the intensity of tillage and prolonging the cover cropping period will (1) limit SOM and C_{total} declines and (2) improve the abundance, biomass and diversity of earthworms, compared to conventional tillage without prolonged cover cropping. Furthermore, we hypothesized that (3 a) reduced tillage will increase soil physical constraints to crop growth, but that (3 b) prolonged cover cropping can mitigate this. Lastly, we hypothesized that (4) reduced tillage and a shorter growing season for maize will reduce yield compared to respectively conventional tillage and a longer growing season.

2. Materials and methods

2.1. Study site

The field experiment was established in April 2012 in De Moer, in the south of the Netherlands (5.013E – 51.629 N) on a sandy Gleyic Podzol with an A-horizon of 40 cm. The previous crop was a five-year-old conventionally managed grassland with a mixture of perennial winter ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). The grassland was only mown (no grazing) and was fertilized yearly with 55 m^3 ha^{-1} cattle slurry manure (4.4 g N, 1.4 g P_2O_5 and 5.3 g K_2O per kg fresh slurry) and inorganic fertilizer (180 kg N ha^{-1} calcium ammonium nitrate). Mean annual precipitation and temperature at the site during the experimental period were 786 mm and 11.0 °C, respectively (KNMI weather station Gilze-Rijen, 2021).

2.2. Experimental setup

The experiment consisted of six treatments in a randomized block design with four replicates (blocks) and lasted for eight years (2012 – 2019). Four treatments were tillage-intensity treatments in a conventional maize-cropping system with a winter rye cover crop that was chemically killed in April, before maize sowing in early May (treatments 1–4). Below, treatments 2, 3 and 4 are referred to as reduced-tillage treatments. Two treatments (5 and 6) were an alternative maize-cropping system combining a short-season maize and a prolonged winter rye–winter pea cover crop that was harvested in the second half of May before the sowing of maize at the end of May.

1) CT: conventional inversion tillage (25 cm deep ploughing + cultivator for shallow seedbed preparation) with glyphosate-killed winter rye cover crop
2) NIT: non-inversion tillage, full-field (Kverneland CLI (30 cm deep subsoiler, 4 tines per 3 m) + power harrow (3 m)) with glyphosate-killed winter rye cover crop

3) ST: rotary strip tillage (Kuipers-Pol Strip Rotavator: tilled strips 15 cm wide and deep, with 60 cm untilled between strips) with glyphosate-killed winter rye cover crop
4) NT: no-till (direct drilling without seedbed preparation; Evers Agro Hunter) with glyphosate-killed winter rye cover crop
5) CT-prolonged: conventional inversion tillage (ploughing) with delayed cover crop termination by harvesting in generative stage and late sowing of an ultra-short season maize variety (18 weeks from sowing to harvest at > 34 % whole plant dry matter content)
6) ST-prolonged: rotary strip tillage with delayed cover crop termination by harvesting at the generative stage and late sowing of an ultra-short season maize variety (18 weeks from sowing to harvest at > 34 % whole plant dry matter content)

The plot size was 18 ×6 m, including eight maize rows at a row width of 75 cm. Manuring, sowing, weed control, harvesting and cover crop sowing were carried out in line with normal practice for silage maize in this part of the Netherlands (details in Supplementary Table A1). In April 2012, the five-year-old grassland was killed using glyphosate (Round-Up, Monsanto, 5 L/ha) before soil tillage. In treatments 1–4, after the maize harvest in September/October, a winter rye cover crop was sown which was terminated with glyphosate in April of the following years (2013–2019). In treatments 5 and 6, the winter rye-winter pea cover crop was harvested at the end of May at the generative stage; no glyphosate was used. Prior to the grassland conversion in 2012, 25 m^3 of cattle slurry was applied and no further manure was applied in 2012 after grassland conversion. In each of the following years, all treatments received 40 m^3 ha^{-1} of cattle slurry by shallow injection. This slurry manure was applied after cover crop termination in CT, NIT, ST and NT. In CT-prolonged and ST-prolonged, this slurry manure was split, with 25 m^3 given to the cover crop in early spring and 15 m^3 given prior to maize sowing, except in 2018 and 2019 when all 40 m^3 was applied before maize sowing. In the ST and ST-prolonged treatments, the slurry was injected in the maize row from 2012 to 2015 and injected full-field from 2016 to 2019; the other treatments received slurry manure by full-field injection throughout the experiment. Together with maize sowing, inorganic N fertilizer was applied in the maize row at a rate of 30 kg N ha^{-1}. Potassium sulphate (K_2SO_4) was applied full-field at the start of the growing season at a rate of 400 kg ha^{-1} (years 2012, 2013, 2014) and 300 kg ha^{-1} (year 2016). Dolokal (47 % CaO and 5 % MgO) was applied in 2017 at a rate of 300 kg ha^{-1}. In all treatments, weeds were controlled using a herbicide application in June following normal practice. No irrigation was used, except for the extremely dry year 2018.

2.3. Measurements

2.3.1. Soil chemical properties

The soil properties (0–30 cm) in April 2012, before establishment of the experiment, were pH_{KCl} 5.4, SOM 4.5 % by weight, P_{AL} 75 mg P_2O_5 100 g^{-1} soil, and P_{CaCl2} 7.6 mg P kg^{-1} soil. In October 2019, per plot 40 randomly distributed 0–30 cm soil cores were taken at random in and in between the two central maize rows (auger diameter 1.2 cm; Eijkelkamp, Giesbeek, the Netherlands) and at a minimal distance of 2 m from the plot borders and directly divided into two samples, one from the 0–15 cm soil layer and one from the 15–30 cm soil layer. After collection, the samples were passed through a sieve (mesh size 1 cm) to remove plant material and debris, homogenized and oven-dried at 40°C. From this sample, a sub-sample was taken to determine SOM, C_{total}, N_{total}, P_{total}, hot water extractable carbon (HWC), pH_{KCl} and soil moisture content. SOM was determined by loss-on-ignition. C_{total} was measured by incineration of dry material at 1150 °C, after which the produced CO_2 was determined by an infrared detector (LECO Corporation, St. Joseph, MI, USA). N_{total} was determined by digestion with H_2SO_4/H_2O_2/Se and subsequent SFA-analysis. P_{total} was measured using Fleishmann acid (Houba et al., 1997), and HWC was determined according to the method of Ghani et al. (2003). Soil acidity was measured in 1 M KCl (pH_{KCl}). Soil as dried at 105 °C for 24 h to determine soil moisture content.

2.3.2. Soil physical properties

Water infiltration was measured in October 2019 *in situ*, using a single ring method in which PVC pipes of 15 cm height and 15 cm diameter were inserted 10 cm into the soil. Each ring received 500 mL of tap water, and the time needed for complete infiltration in the soil was recorded. The average infiltration time of the three rings per plot was calculated and expressed in mm min^{-1}. Penetration resistance was measured in October 2019 in each experimental plot using an electronic penetrologger (Eijkelkamp, Giesbeek, the Netherlands) with a cone surface of 1.0 cm^2 and a 60° apex angle. Cone resistance was recorded per cm of soil depth and expressed as an average of 10 randomly distributed penetrations per layer (0–10, 10–20, 20–30, 30–40 and 40–50 cm), in MPa. Bulk density was measured in October 2019 using 100 cm^3 rings in the soil layer 5–15 cm depth in blocks 1, 2 and 3 for the CT and ST treatments, by drying and weighing the collected soil at 105 °C for 48 h. Soil structure was determined in October 2019 *in situ* between two rows of maize in two soil blocks (20 × 20 cm) per experimental plot: one collected at 0–25 cm and one at 25–45 cm depth. In each block, the percentage of crumbs, sub-angular blocky elements and angular blocky elements was estimated visually as described by Peerlkamp (1959) and Shepherd (2000). In the same blocks, rooting intensity and macroporosity were assessed as described by De Boer et al. (2018), by scoring the root density (score 0–10; 0 for no roots and 10 for above average) and abundance of macropores (score 0–10; 0 for no macropores and 10 for above average), respectively.

2.3.3. Earthworms

Earthworms were sampled in September, in 2012, 2013 (excluding CT-prolonged and ST-prolonged treatments), 2015 and 2019, by digging two soil cubes of 20 ×20×20 cm per plot per sampling year. Soil cubes were hand-sorted to extract all earthworms. The earthworms were carefully rinsed with water, dried with a paper tissue, weighed and stored in 70 % ethanol prior to identification. Each earthworm was examined to determine life stage (adult versus juvenile), species (Sims and Gerard, 1985; Stöp-Bowitz, 1969) and functional group (epigeic or endogeic; Bouché, 1977). Numbers and biomass were expressed per m^2, and mean individual biomass was calculated at plot level.

2.3.4. Crop yields

Per plot, 12 m of the two central maize rows were harvested at silage maturity using a two-row Haldrup maize harvester (J. Haldrup a/s, Løgstør, Denmark), and the yield was subsequently weighed. From a representative subsample of approximately 1000 g, the dry matter (DM) content of the harvested biomass was obtained after drying at 70 °C for 24 hours, and was then used to calculate maize DM yield (t ha^{-1}). The maize N and starch contents in the DM were determined by NIRS by Eurofins (Wageningen, the Netherlands). The N (kg ha^{-1}) and starch yields (t ha^{-1}) were calculated by multiplying the N and starch contents with the DM yield. In 2015, the N and starch contents could not be determined as all designated samples were lost after their DM content had been determined. The DM yield of the winter rye-winter pea cover crop in the CT-prolonged and ST-prolonged treatments, which was intended to be harvested as silage feed, was determined from 2014 to 2019 a few days before maize sowing by harvesting and weighing three strips of 3 ×0.83 m crop per plot. DM content was determined in a subsample and was used to calculate DM yield. For the CT-prolonged and ST-prolonged treatments, the winter rye-winter pea yield was added to the maize yield to provide a combined DM yield of the cropping system.

2.4. Statistical analyses

All statistical analyses were performed in R, version 4.0.3 (R Core

Team, 2023). The Shapiro-Wilk test of normality (Royston, 1982) was carried out for all parameters, using the residuals of block and treatment (for the parameters measured in 2019 only), and of block, treatment, year and treatment × year for maize yield and earthworm data as they were measured over a number of years. Parameters that did not meet the assumption of normality were square root-transformed. ANOVA (randomized block design) was carried out on the parameters to test for treatment effects (for the parameters measured in 2019 only) and for treatment × year effects for maize yield and earthworm data. In case of significant ($P \leq 0.05$) treatment effects or interactions, the least significant difference (l.s.d.; $\alpha = 5$ %) was used to assess differences between treatments.

3. Results

3.1. Soil chemical properties

There was no treatment effect on SOM in the 0–30 cm soil layer after the eight years of the experiment (Table 1). However, significant differences were found in the sub-layers 0–15 cm and 15–30 cm. The CT and CT-prolonged treatments had lower SOM contents in the top 0–15 cm layer and higher SOM content in the 15–30 cm layer, as compared to the reduced-tillage treatments (NIT, ST, NT and ST-prolonged). No significant differences between the four reduced-tillage treatments were found in either soil layer. C_{total} showed similar treatment effects as observed for SOM, but with lower significance levels. The effects on HWC were identical to those on SOM. For N_{total}, a trend in the 0–15 cm layer indicated an increase with decreasing tillage intensity. The C:N ratio was not affected by the treatments in any soil layer.

3.2. Soil physical properties

Soil macro-structure and bulk density were not significantly affected by treatments after the eight years of the experiment (Table 2). CT-prolonged showed the highest macroporosity in the subsoil (25–45 cm depth) followed by NT (Table 5). The root intensity in the 25–45 cm soil layer tended to be lower in ST and ST-prolonged, similar between CT and NT, and highest in CT-prolonged and NIT. Water infiltration rate was not influenced by treatment. The penetration resistance showed treatment effects in the 0–30 cm layer, where CT and CT-prolonged generally had the lowest values and NT, ST and ST-prolonged the highest (Fig. 1 and Table 2). Soil moisture was lowest in CT, NIT and ST the 15–30 cm layer.

3.3. Earthworms

Significant treatment effects were found for the total earthworm abundance, total biomass, epigeic earthworm abundance and adult earthworm abundance (Table 3). All earthworm parameters showed significant year effects but no significant treatment × year interactions.

Throughout the experiment, ST-prolonged had the highest total earthworm abundance and biomass, and ST had the highest epigeic earthworm abundance (Table 4); for these parameters, however, the differences between ST-prolonged, ST and NT were not significant. CT had the lowest total earthworm abundance and total earthworm biomass. CT-prolonged had a higher total earthworm biomass, but no higher total earthworm abundance compared to CT. CT-prolonged and CT had the lowest epigeic earthworm abundance. NIT had a total earthworm abundance and biomass that were similar to CT. On average, NIT had more epigeic earthworms than CT-prolonged, but the difference with CT was not significant.

Earthworm abundances and biomass changed during the course of the experiment, as indicated by the significant year effects (Table 3). In general, the earthworm parameters showed a decline between 2012 and 2013 and a recovery beyond the 2012 level from 2013 to 2019.

At the end of the experiment (October 2019), the total earthworm abundance and adult earthworm abundance tended to increase with decreasing tillage intensity (Table 5). The number of species tended to be lowest in CT, CT-prolonged and ST-prolonged, and they tended to be higher in increasing order in ST, NT and NIT. The epigeic earthworm abundance and total earthworm biomass showed significant treatment effects (Table 5). The epigeic earthworm abundance increased with reduced tillage intensity, both in the conventional maize-cropping system (CT, NIT, ST and NT) and in the prolonged cover crop systems (CT-prolonged and ST-prolonged), in particular for the epigeic species *L. rubellus* (Table A3). Although the endogeic earthworm abundance was not affected by treatment, the adults of the dominant species *A. caliginosa* were most abundant in CT-prolonged (Table A3). The earthworm biomass increased with reduced tillage intensity in the conventional cropping system, but not in the prolonged cover cropping

Table 1

Soil chemical properties in October 2019 after eight years of the experiment (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop).

Parameter	Unit	Layer (cm)	Treatment						P-value
			CT	NIT	ST	NT	CT-prolonged	ST-prolonged	
SOM	%	0–30	4.1	4.15	4.1	4.15	4.1	4.15	0.951
		0–15	4.1b	4.6 a	4.5 a	4.6 a	4.0 b	4.5 a	0.003
		15–30	4.1 a	3.8 b	3.8 b	3.7 b	4.2 a	3.8 b	<0.001
C_{total}	g C kg^{-1} soil	0–30	21.8	22	22.4	21.8	21.7	21.4	0.618
		0–15	22.1 bc	23.8 a	24.2 a	23.7 ab	21.2 c	22.6 abc	0.015
		15–30	21.6	20.3	20.7	19.9	22.2	20.1	0.069
HWC	mg C kg^{-1} soil	0–30	794	774	837	835	774	819	0.575
		0–15	766 b	930 a	1025 a	994 a	734 b	942 a	0.002
		15–30	822 a	618 b	649 b	676 b	814 a	696 b	<0.001
N_{total}	g N kg^{-1} soil	0–30	1.45	1.43	1.48	1.48	1.45	1.49	0.823
		0–15	1.5	1.58	1.65	1.68	1.45	1.6	0.062
		15–30	1.4	1.28	1.3	1.28	1.45	1.38	0.145
C:N ratio		0–15	14.9	15.4	14.7	14.2	14.7	14.2	0.372
		15–30	15.5	16.2	16.2	15.7	15.3	14.9	0.452
		0–30	15.2	15.7	15.3	14.8	15.0	14.5	0.307
P_{total}	mg P kg^{-1} soil	0–30	735.5	727.5	729	731.6	725.2	715.4	0.937
		0–15	741	724.2	727.5	740.2	725.5	688.5	0.380
		15–30	730	730.8	730.5	723	725	742.2	0.958
pH_{KCl}		0–30	4.85	4.95	4.86	4.90	4.74	4.80	0.674
		0–15	4.81	5.01	4.90	4.97	4.70	4.86	0.191
		15–30	4.89	4.88	4.83	4.83	4.78	4.74	0.929

Values followed by the same letter (a-c) within a row are not statistically different at the 5 % error level.

Table 2
Soil physical properties in October 2019 after eight years of the experiment (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop).

Parameter		Layer (cm)	Unit	Treatment						P-value
				CT	NIT	ST	NT	CT-prolonged	ST-prolonged	
Soil macro-structure	Crumb	0–25	%	6	0	9	3	8	4	0.502
		25–45		0	0	0	0	0	0	
	Blocky	0–25		48	86	59	78	54	55	0.430
		25–45		83	87	91	81	82	89	0.381
	Sub- angular blocky	0–25		46	14	33	20	39	41	0.440
		25–45		18	13	9	19	18	11	0.381
Macroporosity		0–25	Visual score	4.5	4.3	7.0	6.4	4.0	4.8	0.209
		25–45	(0−10)	3.0 b	3.0 b	2.3 b	3.8 ab	6.1 a	2.0 b	0.033
Rooting intensity		0–25	Visual score (1−10)	6.9	5.5	5.4	6.3	5.4	5.4	0.578
		25–45		5.8	6.3	4.1	5.6	6.9	4.1	0.052
Water infiltration		n/a	mm min^{-1}	2.6	2.7	3.2	2.8	1.9	2.3	0.529
Penetration resistance		0–10	MPa	0.39c	0.60 bc	0.92 a	0.90 a	0.41c	0.71 ab	<0.001
		10–20		0.85c	1.34 b	1.75 a	1.60 ab	0.77c	1.50 ab	<0.001
		20–30		1.82 bc	2.27 a	2.45 a	2.21 ab	1.60c	2.27 a	0.002
		30–40		3.20	3.18	3.15	3.12	3.07	3.06	0.977
		40–50		3.44	3.35	3.33	3.32	3.29	3.18	0.896
Bulk density[a]		5–15	g cm^{-3}	1.40		1.30				0.897
Soil moisture		0–30	%	13.5 cd	13.2 d	13.8 bcd	14.6 ab	15.0 a	14.2 abc	0.010
		0–15		15.6	15.5	16.0	16.6	16.0	16.4	0.280
		15–30		11.5c	11.0c	11.5c	12.6 ab	14.1 a	12.1 bc	<0.001

Values followed by the same letter (a-d) within a row are not statistically different at the 5 % error level.
[a] Only measured for CT and ST in blocks 1, 2 and 3.

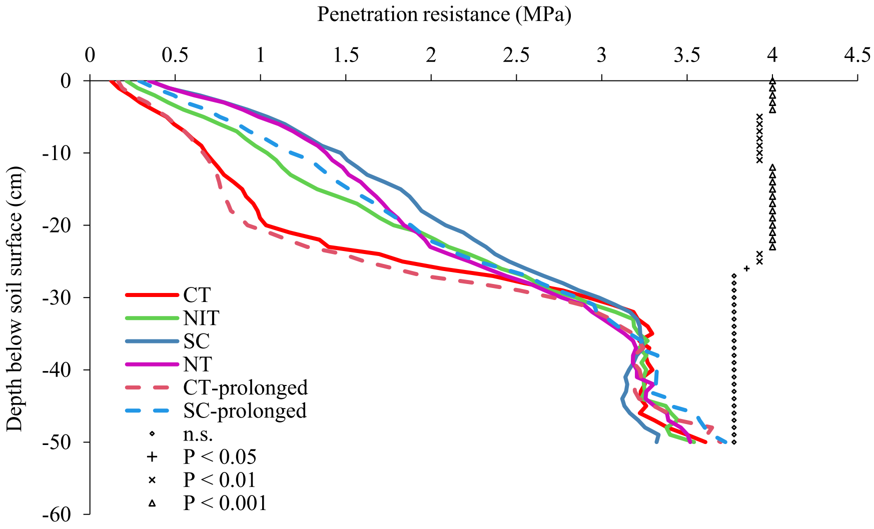

Fig. 1. Penetration resistance (MPa) from 0 to 50 cm depth in October 2019 after eight years of the experiment (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop). Grey symbols (see legend) indicate significance of the treatment effect per cm soil depth.

Table 3
P-values of fixed effects (6 treatments and 4 years): of earthworm parameters.

Effect	Total abundance	Adult abundance	Juvenile abundance[a]	Epigeic abundance[a]	Endogeic abundance[a]	Total biomass	Individual biomass	Number of species
Treatment (T)	0.003	0.011	0.118	<0.001	0.126	0.002	0.267	0.593
Year (Y)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.008	<0.001
Y × T	0.393	0.419	0.694	0.722	0.808	0.435	0.567	0.372

[a] Parameters were square-root-transformed prior to ANOVA

system.

3.4. Crop yields

The average maize yield over all treatments and years was 14.5 t DM ha^{-1}. For all tested yield properties, significant year × treatment interactions were found (Table 6). Fig. 2 presents the mean values for each year × treatment combination. Maize DM yield of NT was significantly lower than CT in all years except 2015. In 2013–2019, ST had similar maize DM yields compared to CT, and in 2012 it had a higher yield than

Table 4

Treatment effects on earthworm parameters over the course of the experiment (measured in September in 2012, 2013, 2015 and 2019). In 2013, earthworm data were not collected for the CT-prolonged and ST-prolonged treatments (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop). Year effects are shown in Supplementary Material Table A4.

Parameter	Unit	Treatment					
		CT	NIT	ST	NT	CT-prolonged	ST-prolonged
Total abundance	n m^{-2}	49 d	75 cd	115 ab	101 abc	76 bcd	126 a
Adult abundance	n m^{-2}	20c	36 bc	43 ab	41 ab	31 bc	57 a
Juvenile abundance[a]	n m^{-2}	14(27)	18(35)	38(66)	34(53)	25(39)	42(63)
Epigeic abundance[a]	n m^{-2}	3(8) cd	12(21) bc	33(52) a	19(37) ab	2(7) d	29(49) ab
Endogeic abundance[a]	n m^{-2}	30(41)	37(54)	44(63)	48(61)	60(68)	71(76)
Total biomass	g m^{-2}	19c	28 bc	41 ab	43 ab	36 b	55 a
Individual biomass	g worm^{-1}	0.37	0.48	0.37	0.54	0.56	0.50
Number of species	n	1.3	1.6	1.6	1.5	1.4	1.8

Means followed by the same letter (a-d) within a row are not statistically different at the 5 % error level, if no letters appear in a row these results are not statistically different.

[a] Parameters were square-root-transformed prior to ANOVA due to non-normality. Numbers in brackets represent original means, numbers outside brackets represent back-transformed means.

Table 5

Earthworm numbers and biomass in October 2019 after eight years of the experiment (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop).

Parameter	Unit	Treatment						P-value
		CT	NIT	ST	NT	CT-prolonged	ST-prolonged	
Total abundance	n m^{-2}	63	151	209	200	109	152	0.075
Adult abundance	n m^{-2}	13	59	53	66	56	56	0.058
Juvenile abundance	n m^{-2}	47	84	153	122	47	91	0.142
Epigeic abundance	n m^{-2}	22 b	47 ab	106 a	106 a	19 b	94 a	0.024
Endogeic abundance	n m^{-2}	38	97	100	81	84	53	0.460
Total biomass	g m^{-2}	16c	43 bc	52 ab	76 a	51 ab	56 ab	0.022
Individual biomass	g worm^{-1}	0.31	0.31	0.24	0.36	0.52	0.43	0.162
Number of species	n	1.8	2.8	2.3	2.5	1.5	1.8	0.085

Means followed by the same letter (a-c) within a row are not statistically different at the 5 % error level.

Table 6

P-values of fixed effects of yield parameters[a].

Effect	Maize DM yield	Combined DM yield	N yield[c]	Starch yield[c]
Treatment (T)	<0.001	<0.001	<0.001	<0.001
Year (Y)	<0.001	<0.001	<0.001	<0.001
Y × T	<0.001	0.006	<0.001	<0.001

[b] Analysis of combined DM yield excluded the years 2012 and 2012 as the DM yield of winter rye-winter pea cover crop was not measured in those years, which meant no combined DM yield could be calculated for these years.

[a] Data of block 1 from 2018 were excluded from all ANOVA tests of yield parameters. Irrigation was unsuccessful in reaching this block, causing outlying yields.

[c] N and starch yields missing from 2015.

CT. Furthermore, ST had a significantly higher maize DM yield than NT in 2012, 2014, 2018 and 2019. In all years, NIT did not differ significantly from either CT or ST, but it had higher maize DM yields than NT in 2012, 2014 and 2017–2019.

CT-prolonged and ST-prolonged maize DM yields were statistically similar in all eight years. These treatments had lower maize DM yields than CT, NIT and ST throughout the experiment, except in 2012, when ST-prolonged had a maize DM yield which was not lower than CT and NIT. Throughout the experiment, ST-prolonged had lower DM yields than ST. Similarly, CT-prolonged had a consistently lower maize DM yield than CT. However, compared to NT, CT-prolonged had similar maize DM yields in 2012, 2014, 2018 and 2019, and in 2012 and 2019 maize DM yields were similar between ST-prolonged and NT. In the other years (2013, 2015, 2016 and 2017), CT-prolonged and ST-prolonged had lower maize DM yields than NT. Nitrogen and starch yields of maize followed similar trends to the maize DM yield (Table A5 and Figure A1).

From 2014 onwards, combining the DM yield of maize and winter rye-winter pea cover crop in CT-prolonged and ST-prolonged changed the trend described above (Table A5). This combined DM yield did not differ between the two prolonged treatments in most years, except for in 2012, when the combined DM yield was significantly lower for ST-prolonged. Furthermore, CT had higher combined DM yields compared to the combined DM yields of both CT-prolonged and ST-prolonged only in 2016 and 2017. In addition, in 2014 CT-prolonged had a higher combined DM yield than ST.

4. Discussion

4.1. *Effects of tillage system*

4.1.1. *Soil organic matter and C*

After eight growing seasons, the SOM and C_{total} content in 0–30 cm were not affected by tillage treatment. Consequently, we reject our first hypothesis that in a continuous maize-cropping system, reduced tillage can limit the decline in SOM and C_{total} that is found in inversion tillage in the medium- to long-term following grassland conversion.

Inversion tillage led to an alteration in the vertical distribution of SOM through a translocation of surface SOM and crop residues (0–15 cm) to deeper soil layers (15–30 cm) and a subsequent ploughing up of this deeper layer which was lower in SOM. Surface SOM may be responsible for the greatest benefits both to the functioning of ecosystem components and to the delivery of ecosystem services (Chan, 2001; Franzluebbers, 2002; Holland, 2004); nevertheless, this process of burial by inversion tillage can apparently maintain SOM or C_{total} content in the

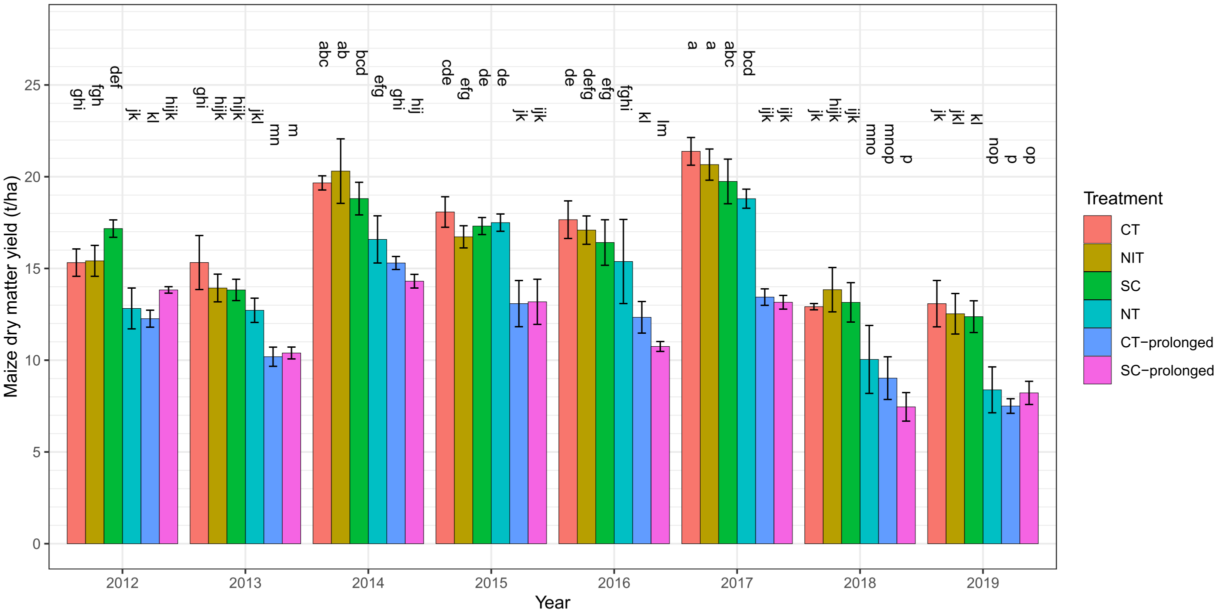

Fig. 2. Maize DM yield for all year-treatment combinations; (CT: conventional tillage, NIT: non-inversion tillage, ST: strip tillage, NT: no-till, CT-prolonged, conventional tillage with prolonged period of cover crop and ST-prolonged: strip tillage with prolonged period of cover crop). Bars with overlap in letters overhead are not statistically different at the 5 % error level.

plough layer that is similar to reduced or no-till methods. This is confirmed by several meta-analyses of studies that included sampling to a depth beyond just the topsoil (0–15 cm; VandenBygaart et al., 2003; Baker et al., 2007; Blanco-Canqui and Lal, 2008). Similarly, using a sampling depth of 40 cm, another meta-analysis found the same decrease in SOM after conversion of grassland to arable cropping, irrespective of whether conventional tillage or no-till methods were used (Luo et al., 2010). This underlines the importance of sampling depth when determining SOM build-up and carbon sequestration in a tillage experiment (VandenBygaart and Angers, 2006; Baker et al., 2007; Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2008). However, these studies lacked geographic and soil conditions that are comparable to the present study. Krauss et al. (2022), analysing a cohort of long-term reduced tillage experiments from France, Germany, the Netherlands, and Switzerland found an average increase in SOC with reduced tillage compared to conventional inversion tillage of 20.8 % in the layer 0–10/15 cm of soils, and a decrease in the layers 10–20 and 15–20/30 of 1.7 % and 6.6 %, respectively. Digging deeper they also observed differences in SOC stratification in the soil layers below the plough layer up to a depth om 1 m. Cumulative carbon sequestration in the soil profile (0–100 cm) was 0.27–0.28 Mg ha^{-1} y^{-1} higher with reduced tillage relative to conventional inversion tillage, independent of bulk density correction. The experiments included in Krauss et al. (2022) were however all managed organically, with organic fertilization and without chemical weed control and were all in a diverse crop rotation. They were also performed on soil types with a minimum clay content of 10 % and thus not represent conditions similar to our present study. Moreover, De Los Rios et al. (2022) found that in north-west Germany, on a sandy loam, no-till limited SOC declines by 28 % in the soil layer 0–30 cm in comparison to conventional tillage during 7 years following grassland conversion to silage maize, while subsoil (30–90 cm) SOC was unaffected by tillage treatment. The benefits of reduced tillage or no-till to SOC storage thus seem to be highly dependent on soil texture. Our results show no net effect on SOM of reduced tillage in a sandy soil under north-western European conditions, and indicate a translocation of surface SOM to a deeper layer rather than (only) a decrease in SOM due to higher mineralization when inversion tillage is applied. Furthermore, reduced maize yield with NT and – by correlation – reduced belowground biomass could have limited SOM inputs with NT.

4.1.2. *Soil structure*

No difference in soil macrostructure, bulk density (measured in CT and ST) or water infiltration rate was observed after the final harvest of this eight-year study. However, differences occurred in penetration resistance that do not correspond to the differences found in soil moisture (Table 2), but more clearly reflect differences in soil tillage. The rooting intensity score in the subsoil showed a trend which seemed to correspond to the treatment effect on penetration resistance in the 20–30 cm layer, as CT had a lower penetration resistance and a higher rooting score than ST and CT-prolonged had a lower penetration resistance and higher rooting intensity score than ST-prolonged. NT also showed a higher penetration resistance than CT but a similar penetration resistance to ST. NIT had a higher penetration resistance than CT in the layers 10–20 cm and 20–30 cm, but it had a slightly higher root intensity in the subsoil. These results partially confirm our hypothesis (3 a) that reduced tillage leads to increased soil physical constraints to crop growth.

Munkholm et al. (2003) also found increases in penetration resistance in a Danish sandy loam soil in which no-till was compared to ploughing. On sandy soils in the Netherlands, no-till led to soil compaction and increased penetration resistance in the 5–30 cm layer (Van Ouwerkerk and Perdok, 1994 in Soane et al., 2012). Ehlers and Claupein (1994) explained that sandy soils in Germany may not be able to maintain structural stability with no-till as they are incapable of restoring soil structure by “endogenous forces”, due to the physio-chemical nature of sand.

On the other hand, loamy and clayey soils can stabilize or recover after an initial increase in bulk density or penetration resistance in the topsoil from no-till due to shrinking/swelling nature of clay-containing soils (Munkholm et al., 2003; Vogeler et al., 2009). Jabro et al. (2011) concluded that on a sandy soil strip tillage in comparison to conventional tillage reduced in-row soil compaction, as it increased porosity and decreased bulk density, which consequently increased the water infiltration rate. Our study does not support this finding and ST could also not limit soil compaction in relation to NT. However, we measured neither penetration resistance nor bulk density separately in the in-row and between-row positions. NIT had similar penetration resistance to NT and higher penetration resistance than CT in the 10–30 cm layer, meaning that although NIT loosened up the 0–10 cm topsoil, it could not limit soil compaction relative to NT in the 10–30 cm layer. Furthermore, NT may increase penetration resistance in the topsoil, but may have no adverse effect on penetration resistance in the subsoil (Yang et al., 2022). The score of root intensity in the subsoil tended to be lowest in ST and ST-prolonged, similar between CT and NT, and highest in CT-prolonged and NIT. Low root intensity scores in ST and ST-prolonged could be explained by restricted root proliferation to the rotavated strips (Ren et al., 2019) and the fact that root intensity was determined between the rotavated strips in this study.

Macropore (earthworm burrows, root channels) connectivity is usually found to increase with no-till management on soil types other than sandy, which generally translates to higher water infiltration rates (Strudley et al., 2008). However, opposite effects of no-till have also been reported (Lipiec et al., 2006). Divergent responses of several soil hydraulic functions can also occur when no-till and conventional tillage are compared; in a loamy soil, Vogeler et al. (2009) found higher water infiltration rates that increased with time after adoption of no-till due to an increase in vertically-oriented macroporosity (biopores), but they did not find increased water retention due to a similar overall macroporosity. Studies on sandy soils are lacking, and our study suggests these benefits of no-till to water infiltration do not appear in these soils.

4.1.3. Earthworms

The total earthworm abundance, epigeic earthworm abundance and total earthworm biomass increased with decreased tillage intensity, which confirms our hypothesis (2). In a meta-analysis, Briones and Schmidt (2017) found that no-till practices could increase earthworm biomass by 196 %, compared to conventional ploughing. In our experiment, differences were even more pronounced. In 2019, total earthworm biomass increased by 225 % in ST and 375 % in NT, compared to CT. This is more in line with Van Capelle et al. (2012) and D'Hose et al. (2018), who found, in their respective German and European meta-analyses, that no-till increased earthworm biomass by 350 % and 416 %, respectively. D'Hose et al. (2018) also found an increase of 125 % in earthworm abundance with no-till and no interaction with soil texture. However, Van Capelle et al. (2012) found an interaction of tillage effects with soil texture on earthworm abundance, showing increases with reduced or no-till on silt and loam soils but not on sandy soils. They state that this interaction is strong for soil biota that rely on sufficient pore space. Moreover, macropore disruption by tillage is a greater problem for earthworms on clay soils, in which it is more difficult for earthworms to rebuild burrows.

Our finding that treatment effects were more pronounced for earthworm biomass than for abundance resonates with the findings from D'Hose et al. (2018). The greater influence of no-till on earthworm biomass may be caused by the vulnerability of larger earthworms to soil disturbance (Briones and Schmidt, 2017). No-till can favour earthworm proliferation through reduced injuries, exposure to predation, micro-climate changes such as aeration or soil moisture, and increased food availability at the soil surface, as it leaves SOM stratification intact (Capowiez et al., 2009; Roger-Estrade et al., 2010). Our finding that earthworm biomass was not significantly higher in NIT than in CT is reflected in comparisons of deep (>15 cm) non-inversion tillage with ploughing in both Briones and Schmidt (2017) and D'Hose et al. (2018). Deep non-inversion tillage may still alter soil properties too much or directly injure too many earthworms.

Different species and functional groups respond differently to ploughing (Chan, 2001; Pelosi et al., 2014; Briones and Schmidt, 2017). Pelosi et al. (2014) and Van Capelle et al. (2012) found no difference in abundance of epigeic earthworms between ploughing and no-till. Briones and Schmidt (2017) found that epigeic earthworms were more likely to benefit from reduced or no-till practices than endogeic earthworms because of decreased mechanical disturbance and increased food availability at the soil surface. We also found a significant increase in epigeic earthworm abundance with reduced tillage intensity, but no additional increase between ST and NT. The epigeic species *L. rubellus* benefitted specifically from reduced tillage intensity, which is confirmed by Crittenden et al. (2014). Different studies have found that endogeic abundance can either suffer from (De Oliveira et al., 2012), show no response to (Pelosi et al., 2014) or even benefit from (Nuutinen, 1992; Wyss and Glasstetter, 1992; Pelosi et al., 2009; Van Capelle et al., 2012) inversion tillage as the layer they live in is enriched with organic material that would otherwise largely remain in the topsoil or on top of the soil (Chan, 2001). Our study resonates with the findings of Pelosi et al. (2014), as endogeic earthworm abundance showed no response to reduced tillage in relation to CT. Since SOM was increased in the soil layer at 15–30 cm depth with CT due to SOM burial, sampling worms only to a depth of 20 cm may have underestimated the actual abundance of endogeic earthworms, as they may have migrated to a depth lower than 20 cm (Pitkänen, 1988 as cited in Nuutinen, 1992; Van Capelle et al., 2012). We observed an increase in earthworm abundance after an initial decline between 2012 and 2013 (Table A4). This regeneration shows that the earthworm population is able to adapt to tillage and cropping regimes after grassland conversion. However, the absence of an interaction between treatment and year suggests that this regeneration over time does not happen faster or more pronounced in reduced-tillage situations than in conventional inversion tillage.

4.1.4. Yield

In seven out of eight years, NT gave a significantly lower maize yield than CT. In contrast, ST gave a maize yield that was similar to CT in 2nd to 8th year and a higher yield in the first year. Furthermore, NIT did not differ in maize yield from either CT or ST in any of the years. Therefore, we accept our hypothesis (4) that no-till leads to lower maize yields, but we reject the hypothesis (4) that reduced tillage reduces yields.

Pittelkow et al. (2015) concluded in the largest meta-analysis on the topic of crop yields with no-till that maize yield is globally reduced by 7.6 % on average compared to traditional inversion tillage. Several other studies have shown that no-till tends to reduce maize yield more in colder climates or regions with high rainfall (Van den Putte et al., 2010; Toliver et al., 2012; Rusinamhodzi et al., 2011; Ogle et al., 2012; Huang et al., 2018). This may explain why our eight-year average no-till maize yield decreased by more than twice this average reduction, namely by 17.8 %. Our results are thus in line with studies which have found no-till maize yield declines of 12.8 % on average for Europe (Van den Putte et al., 2010), 13.2 % over the course of 14 years on a sandy loam soil in Switzerland (Anken et al., 2004), and 13.8 % on a loamy sandy soil in the two years after grassland conversion in Germany (Struck et al., 2019).

The possible reason for yield reduction with NT is that early development of maize is impeded by restrictive soil physical conditions, as we found that the penetration resistance in the upper 30 cm of the soil was higher in NT than in CT. No-till may, through a higher soil strength, depress fine root growth on sandy soils (Dobre, 2000; Chassot et al., 2001). An additional cause of the lower yield in NT could be that conventional inversion tillage provides a more homogenous seedbed, which results in a more uniform sowing depth and optimal soil-seed contact for germination (Pittelkow et al., 2015). Seedbed preparation may have been sufficient in the ST treatment to obtain similar yields to CT, but this may not be the case for NT. This is reflected in the lower gemination rate with NT, but not with ST compared to CT (Table A2). The lower germination rate with NT may also be caused by a sub-optimal sowing technique. Regarding strip-tillage, Ren et al. (2019) found that it could sufficiently loosen the topsoil for maize seedlings. Ren et al. (2019) also found that although root proliferation was restricted to the tilled rows, this did not negatively impact yield. Furthermore, no-till can lead to lower soil temperatures, especially on wet soils, and slower N mineralization, which can slow down early development (Anken et al., 2004). Both Anken et al. (2004) and Van den Putte et al. (2010) found no silage maize yield reduction relative to ploughing when non-inversion tillage practices were applied, which is in line with our results. Further investigations into soil-seed contact and early plant (i.e., fine root) development, soil temperature, N-mineralization and microbial activity directly following cultivation and sowing are necessary to better explain why NT gave a lower yield than CT, whereas there was no lower yield in ST and NIT. Another contributing factor to the yield deficit of NT compared to CT may have been increased weed coverage (Table A2), which is known to be an increased risk with reduced tillage (Melander et al., 2013; Krauss et al., 2022).

4.2. *Effects of prolonged cover cropping*

Similar to the effects of tillage system, SOM and C_{total} content in 0–30 cm were not affected by cover cropping strategy. Consequently, we reject the hypothesis that in a continuous maize-cropping system, prolonging the period of cover cropping can limit the decline of SOM and C_{total} that is observed in the medium- to long-term following grassland conversion. The similar SOM and C_{total} may indicate that in prolonged cover cropping, lower belowground maize C allocation, as a result of decreased maize productivity, was compensated for by higher belowground cover crop C allocation. Delaying cover crop termination can increase the yield of a winter rye cover crop by between 83 % and 200 %, according to Clark et al. (1994) and Duiker and Curran (2005). Cover crop biomass has been positively correlated with SOC (Jian et al., 2020). Greater aboveground cover crop biomass has been linked to greater root biomass and rhizo-deposition, which are all factors that contribute substantially and more effectively than aboveground biomass to SOC (Rasse et al., 2005; Kong and Six, 2012; Austin et al., 2017).

For soil structure, the hypothesis (3 b) that prolonged cover cropping can mitigate the soil physical constraints to crop growth induced by reduced tillage is partially rejected, since no notable differences between ST and ST-prolonged were observed in soil physical variables.

Earthworm biomass at the end of the eight years period was higher in the CT-prolonged treatment than in the CT treatment, which may be explained by a higher (belowground) biomass production of the cover crop in CT-prolonged, providing more food for earthworm growth as reflected in the relatively high individual earthworm biomass in CT-prolonged and ST-prolonged. However, this may not be the only explaining factor, as no similar difference was observed between ST-prolonged and ST.

Maize yields were lower in prolonged cropping systems compared to conventional systems, which can be explained by the shorter maize growing season and a higher weed coverage in CT-prolonged and ST-prolonged comparted to CT and ST, respectively. No glyphosate was used to terminate the prolonged cover crop that was harvested prior to maize sowing, which may have promoted weed growth especially in the ST-prolonged treatment. When left as mulch, the higher biomass of the prolonged cover crop would have likely led to lower weed pressure (Melander et al., 2013) and potentially increased maize yields (Yang et al., 2022). However, by harvesting the cover crop mixture as silage, the DM yield gap compared to CT was bridged in four out of six years in which cover crop biomass in CT-prolonged and ST-prolonged was measured. Feed value of the cover crop biomass would, however, have differed from that of the maize silage. To reduce the yield gap and make the system with prolonged cover cropping more profitable, breeders are currently successfully working on ultra short-season maize varieties (18 weeks growth) that currently yield 2–3 t DM more than the varieties used in this experiment (Groten, 2014; Groten and Meesters, 2023).

5. Conclusion and recommendations

No-till and reduced tillage are generally assumed to be a management strategy that by default sequester C and improves both soil-physical and biological quality. However, this may be an over-generalization which disregards differences in response to no-till and reduced tillage between crops, climatic zones and soil types. On a sandy soil in the temperate climate of the Netherlands, no-till and reduced tillage did not lead to a higher SOM and C_{total} in the plough layer (0–30 cm) compared to conventional ploughing after eight years of continuous maize cropping. From the perspective of climate change mitigation, our results do therefore not suggest a benefit of reduced tillage and prolonged cover cropping in a continuous maize-cropping system. At the same time, no-till led to a reduction in maize yield compared to conventional tillage, which may have been due to sub-optimal soil-physical circumstances and direct drilling technique.

A goal in future maize cropping can be to improve soil biodiversity without the yield penalty of no-till that has been confirmed in this study. Throughout our experiment, both strip tillage and non-inversion tillage maintained maize yields at the level of inversion tillage. In the first year after grassland conversion, strip tillage led to a higher maize yield than inversion tillage. Moreover, strip tillage had beneficial effects on the earthworm community that were similar to no-till, in contrast to the detrimental effects of inversion tillage. Therefore, strip tillage may also have beneficial effects on other biological soil properties. Non-inversion tillage did not have a favourable influence on earthworms relative to inversion tillage. Based on our results, we would therefore recommend strip tillage for grassland conversion and continued use during maize cropping on sandy soils in the Netherlands.

On sandy soils a potentially effective way to optimize soil biodiversity and productivity is to prolong the cover cropping period. Indeed, in the plough layer the reduced-tillage treatments had higher penetration resistance than inversion tillage. Using a prolonged cover crop with inversion tillage for the maize combines a loose topsoil and improved earthworm abundance. Due to the prolonged period of cover cropping, the reduced length of the growing season for maize led to reduced maize yields. However, improved, high-yielding short-season maize cultivars may close the maize yield gap observed in this study and cause the prolonged cover cropping system to outperform the conventionally cover cropped systems in terms of total DM yield.

CRediT authorship contribution statement

Nick van Eekeren: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Rommie van der Weide:** Writing – review & editing, Funding acquisition, Conceptualization. **Joachim G.C. Deru:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joost Sleiderink:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis.

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.

Data Availability

Data will be made available on request.

Acknowledgements

The authors thank Paul Hazenberg for providing the experimental site, Riekje Bruinenberg, Hans Dullaert, René Groenen and Coen ter Berg for practical work and soil analyses. Marius Heinen is acknowledged for providing additional soil measurements and reading the manuscript. The experiment was designed and run with the precious advice of Udo Prins, Henk Pol, Herman van Schooten, Hilfred Huiting, Marcia Stienezen, Michel and Grietje Raaphorst, Jos Groot Koerkamp and Ad Buijs.

We thank all parties involved in the Public-Private Partnerships “Innovatieve maisteelt – op weg naar chemievrij, minder uitspoeling, biodiverser”, “KLIMAP” and “Ruwvoer, Bodem en Kringlooplandbouw” co-funded by the Dutch Ministry of Agriculture, Nature and Food Safety, via the top sector Agri & Food and Water & Maritiem (LWV 20.008, BO-60-001-002, BO-56-001-047).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2024.106196.

References

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72 (5), 1370–1374. https://doi.org/10.2136/sssaj2007.0342.

Anken, T., Weisskopf, P., Zihlmann, U., Forrer, H., Jansa, J., Perhacova, K., 2004. Long-term tillage system effects under moist cool conditions in Switzerland. Soil Tillage Res 78 (2), 171–183. https://doi.org/10.1016/j.still.2004.02.005.

Austin, E.E., Wickings, K., McDaniel, M.D., Robertson, G.P., Grandy, A.S., 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. GCB Bioenergy 9 (7), 1252–1263. https://doi.org/10.1111/gcbb.12428.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—what do we really know? Agric. Ecosyst. Environ. 118 (1-4), 1–5. https://doi.org/10.1016/j.agee.2006.05.014.

Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., Roger-Estrade, J., 2015. Earthworm services for cropping systems. A review. Agron. Sustain. Dev. 35 (2), 553–567. https://doi.org/10.1007/s13593-014-0269-7.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J. 72 (3), 693–701. https://doi.org/10.2136/sssaj2007.0233.

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. Crit. Rev. Plant Sci. 28 (3), 139–163. https://doi.org/10.1080/07352680902776507.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron. J. 107 (6), 2449–2474. https://doi.org/10.2134/agronj15.0086.

Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Brun, J.J., 2013. A review of earthworm impact on soil function and ecosystem services. Eur. J. Soil Sci. 64 (2), 161–182. https://doi.org/10.1111/ejss.12025.

Bouché, M.B., 1977. Strategies lombriciennes. Ecol. Bull. 122–132 http://www.jstor.org/stable/20112572.

Briones, M.J.I., Schmidt, O., 2017. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. Glob. Chang. Biol. 23 (10), 4396–4419. https://doi.org/10.1111/gcb.13744.

Capowiez, Y., Cadoux, S., Bouchant, P., Ruy, S., Roger-Estrade, J., Richard, G., Boizard, H., 2009. The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. Soil Tillage Res 105 (2), 209–216. https://doi.org/10.1016/j.still.2009.09.002.

CBS, 2021. Landbouw; gewassen, dieren, grondgebruik en arbeid op nationaal niveau, accessed on 04-08-2023. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81302ned/table?dl=59867.

Chan, K.Y., 2001. An overview of some tillage impacts on earthworm population abundance and diversity—implications for functioning in soils. Soil Tillage Res 57 (4), 179–191. https://doi.org/10.1016/S0167-1987(00)00173-2.

Chassot, A., Stamp, P., Richner, W., 2001. Root distribution and morphology of maize seedlings as affected by tillage and fertilizer placement. Plant Soil 231 (1), 123–135. https://doi.org/10.1023/A:1010335229111.

Clark, A.J., Decker, A.M., Meisinger, J.J., 1994. Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. Agron. J. 86 (6), 1065–1070. https://doi.org/10.2134/agronj1994.00021962008600060025x.

Crittenden, S.J., Eswaramurthy, T., De Goede, R.G.M., Brussaard, L., Pulleman, M.M., 2014. Effect of tillage on earthworms over short-and medium-term in conventional and organic farming. Appl. Soil Ecol. 83, 140–148. https://doi.org/10.1016/j.apsoil.2014.03.001.

D'Hose, T., Molendijk, L., Van Vooren, L., van den Berg, W., Hoek, H., Runia, W., Ruysschaert, G., 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.

Dabney, S.M., Delgado, J.A., Reeves, D.W., 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32 (7-8), 1221–1250. https://doi.org/10.1081/CSS-100104110.

De Boer, H.C., Deru, J.G.C., Van Eekeren, N., 2018. Sward lifting in compacted grassland: effects on soil structure, grass rooting and productivity. Soil Tillage Res 184, 317–325. https://doi.org/10.1016/j.still.2018.07.013.

De Los Rios, J., Poyda, A., Taube, F., Kluß, C., Loges, R., Reinsch, T., 2022. No-till mitigates SOC losses after grassland renovation and conversion to silage maize. Agriculture 12 (8), 1204. https://doi.org/10.3390/agriculture12081204.

De Oliveira, T., Bertrand, M., Roger-Estrade, J., 2012. Short-term effects of ploughing on the abundance and dynamics of two endogeic earthworm species in organic cropping systems in northern France. Soil Tillage Res 119, 76–84. https://doi.org/10.1016/j.still.2011.12.008.

Duiker, S.W., Curran, W.S., 2005. Rye cover crop management for corn production in the northern Mid-Atlantic region. Agron. J. 97 (5), 1413–1418. https://doi.org/10.2134/agronj2004.0317.

Ehlers, W., Claupein, W., 1994. Approaches toward conservation tillage in Germany. In Conservation tillage in temperate agroecosystems. CRC Press, Boca Raton, pp. 141–165.

Fernández, F.G., Sorensen, B.A., Villamil, M.B., 2015. A comparison of soil properties after five years of no-till and strip-till. Agron. J. 107 (4), 1339–1346. https://doi.org/10.2134/agronj14.0549.

Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res 66 (2), 197–205. https://doi.org/10.1016/S0167-1987(02)00027-2.

Freibauer, A., Rounsevell, M.D., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122 (1), 1–23. https://doi.org/10.1016/j.geoderma.2004.01.021.

Ghani, A., Dexter, M., Perrott, K.W., 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. Soil Biol. Biochem. 35, 1231–1243. https://doi.org/10.1016/S0038-0717(03)00186-X.

Groten, J., 2014. Rassenbulletin ultravroege snijmais 2015. Praktijkonderzoek Plant & Omgeving, Lelystad. https://edepot.wur.nl/369888.

Groten, J. & Meesters, K., 2023. Rassenbulletin snijmais ultra vroeg 2024 - Groeiseizoen 18 weken. Wageningen University & Research Open Teelten, Lelystad. https://www.wur.nl/nl/show/rassenbulletin-snijmais-ultra-vroeg-zeer-vroeg-2024-18-en-20-wkn.htm.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363 (1491), 543–555. https://doi.org/10.1098/rstb.2007.2169.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103 (1), 1–25. https://doi.org/10.1016/j.agee.2003.12.018.

Houba, V.J.G., van der Lee, J.J.G., Novozamsky, I., 1997. Soil and plant analysis: soil analysis procedures. Soil And Plant Analysis. Wageningen University, Wageningen.

House, G.J., Parmelee, R.W., 1985. Comparison of soil arthropods and earthworms from conventional and no-tillage agroecosystems. Soil Tillage Res 5 (4), 351–360. https://doi.org/10.1016/S0167-1987(85)80003-9.

Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J.H., Yang, X., Goff, B., 2018. Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis. Agric. Ecosyst. Environ. 268, 144–153. https://doi.org/10.1016/j.agee.2018.09.002.

Jabro, J.D., Stevens, W.B., Iversen, W.M., Evans, R.G., 2011. Bulk density, water content, and hydraulic properties of a sandy loam soil following conventional or strip tillage. Appl. Eng. Agric. 27 (5), 765–768 https://pubag.nal.usda.gov/catalog/53877.

Jian, J., Du, X., Reiter, M.S., Stewart, R.D., 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol. Biochem. 143, 107735 https://doi.org/10.1016/j.soilbio.2020.107735.

Joschko, M., Söchtig, W., Larink, O., 1992. Functional relationship between earthworm burrows and soil water movement in column experiments. Soil Biol. Biochem. 24 (12), 1545–1547. https://doi.org/10.1016/0038-0717(92)90148-Q.

Kladivko, E.J., 2001. Tillage systems and soil ecology. Soil Tillage Res 61 (1-2), 61–76. https://doi.org/10.1016/S0167-1987(01)00179-9.

KNMI weather station Gilze-Rijen, 2021, accessed 04-08-2023. https://cdn.knmi.nl/knmi/map/page/klimatologie/gegevens/monv_reeksen/neerslaggeg_GILZE-RIJEN_843.zip.

Kong, A.Y., Six, J., 2012. Microbial community assimilation of cover crop rhizodeposition within soil microenvironments in alternative and conventional cropping systems. Plant Soil 356 (1), 315–330. https://doi.org/10.1007/s11104-011-1120-4.

Krauss, M., Wiesmeier, M., Don, A., Cuperus, F., Gattinger, A., Gruber, S., Steffens, M., 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.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677), 1623–1627. https://doi.org/10.1126/science.1097396.

Lal, R., 2015. Soil carbon sequestration and aggregation by cover cropping. J. Soil Water Conserv. 70 (6), 329–339. https://doi.org/10.2489/jswc.70.6.329.

Lal, R., Kimble, J.M., 1997. Conservation tillage for carbon sequestration. Nutr. Cycl. Agroecosyst. 49 (1), 243–253. https://doi.org/10.1023/A:1009794514742.

Licht, M.A., Al-Kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res 80 (1-2), 233–249. https://doi.org/10.1016/j.still.2004.03.017.

Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res 89 (2), 210–220. https://doi.org/10.1016/j.still.2005.07.012.

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 (1-2), 224–231. https://doi.org/10.1016/j.agee.2010.08.006.

Melander, B., Munier-Jolain, N., Charles, R., Wirth, J., Schwarz, J., Van der Weide, R., Kudsk, P., 2013. European perspectives on the adoption of nonchemical weed management in reduced-tillage systems for arable crops. Weed Technol. 27 (1), 231–240. https://doi.org/10.1614/WT-D-12-00066.1.

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 (1-2), 1–15. https://doi.org/10.1016/j.still.2010.03.004.

Munkholm, L.J., Schjønning, P., Rasmussen, K.J., Tanderup, K., 2003. Spatial and temporal effects of direct drilling on soil structure in the seedling environment. Soil Tillage Res 71 (2), 163–173. https://doi.org/10.1016/S0167-1987(03)00062-X.

Nuutinen, V., 1992. Earthworm community response to tillage and residue management on different soil types in southern Finland. Soil Tillage Res 23 (3), 221–239. https://doi.org/10.1016/0167-1987(92)90102-H.

Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric. Ecosyst. Environ. 149, 37–49. https://doi.org/10.1016/j.agee.2011.12.010.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48 (1), 147–163. https://doi.org/10.1023/A:1006271331703.

Peerlkamp, P.K., 1959. A visual method of soil structure evaluation. Mededelingen van de Landbouwhogeschool en der opzoekingsstations van den. Staat te Gent 24, 216–221.

Pelosi, C., Bertrand, M., Roger-Estrade, J., 2009. Earthworm community in conventional, organic and direct seeding with living mulch cropping systems. Agron. Sustain. Dev. 29 (2), 287–295. https://doi.org/10.1051/agro/2008069.

Pelosi, C., Pey, B., Hedde, M., Caro, G., Capowiez, Y., Guernion, M., Cluzeau, D., 2014. Reducing tillage in cultivated fields increases earthworm functional diversity. Appl. Soil Ecol. 83, 79–87. https://doi.org/10.1016/j.apsoil.2013.10.005.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., Van Groenigen, K.J., Lee, J., Van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crops Res 183, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–a meta-analysis. Agric. Ecosyst. Environ. 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B.A.S., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone–carbon response functions as a model approach. Glob. Chang. Biol. 17 (7), 2415–2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x.

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Peres, G., Rutgers, M., 2012. Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches. Curr. Opin. Environ. Sustain. 4 (5), 529–538. https://doi.org/10.1016/j.cosust.2012.10.009.

R Core Team (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269 (1-2), 341–356. https://doi.org/10.1007/s11104-004-0907-y.

Reicosky, D.C., 2003. Tillage-induced CO2 emissions and carbon sequestration: effect of secondary tillage and compaction. In Conservation Agriculture. Springer, Dordrecht, pp. 291–300.

Ren, L., Nest, T.V., Ruysschaert, G., D'Hose, T., Cornelis, W.M., 2019. Short-term effects of cover crops and tillage methods on soil physical properties and maize growth in a sandy loam soil. Soil Tillage Res 192, 76–86. https://doi.org/10.1016/j.still.2019.04.026.

Rietra, R., Heinen, M., Oenema, O., 2022. A Review of Crop Husbandry and Soil Management Practices Using Meta-Analysis Studies: Towards Soil-Improving Cropping Systems. Land 11 (2), 255. https://doi.org/10.3390/land11020255.

Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G., 2010. Tillage and soil ecology: partners for sustainable agriculture. Soil Tillage Res 111 (1), 33–40. https://doi.org/10.1016/j.still.2010.08.010.

Royston, JP., 1982. Algorithm AS 181: The W test for normality. Journal of the Royal Statistical Society Series C (Applied Statistics) 31 (2), 176–180. https://doi.org/10.2307/2347986.

Ruis, S.J., Blanco-Canqui, H., 2017. Cover crops could offset crop residue removal effects on soil carbon and other properties: a review. Agron. J. 109 (5), 1785–1805. https://doi.org/10.2134/agronj2016.12.0735.

Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K. E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron. Sustain. Dev. 31 (4), 657. https://doi.org/10.1007/s13593-011-0040-2.

Shepherd, G., 2000. Visual soil assessment. In: Field Guide for Pastoral Grazing and Cropping on Flat to Rolling Country, Volume 1. Regional Council & Landcare Research, Palmerston North, New Zealand.

Six, J. A E T, Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32 (14), 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6.

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. https://doi.org/10.1016/j.still.2011.10.015.

Struck, I.J., Reinsch, T., Herrmann, A., Kluß, C., Loges, R., Taube, F., 2019. Yield potential and nitrogen dynamics of no-till silage maize (Zea mays L.) under maritime climate conditions. Eur. J. Agron. 107, 30–42. https://doi.org/10.1016/j.eja.2019.04.009.

Strudley, M.W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil Tillage Res. 99 (1), 4–48. https://doi.org/10.1016/j.still.2008.01.007.

Toliver, D.K., Larson, J.A., Roberts, R.K., English, B.C., De La Torre Ugarte, D.G., West, T. O., 2012. Effects of no-till on yields as influenced by crop and environmental factors. Agron. J. 104 (2), 530–541. https://doi.org/10.2134/agronj2011.0291.

Van Capelle, C., Schrader, S., Brunotte, J., 2012. Tillage-induced changes in the functional diversity of soil biota–a review with a focus on German data. Eur. J. Soil Biol. 50, 165–181. https://doi.org/10.1016/j.ejsobi.2012.02.005.

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 (3), 231–241. https://doi.org/10.1016/j.eja.2010.05.008.

Van Eekeren, N., Bommelé, L., Bloem, J., Schouten, T., Rutgers, M., de Goede, R., Brussaard, L., 2008. Soil biological quality after 36 years of ley-arable cropping, permanent grassland and permanent arable cropping. Appl. Soil Ecol. 40 (3), 432–446. https://doi.org/10.1016/j.apsoil.2008.06.010.

Van Ouwerkerk, C., & Perdok, U.D., 1994. Experiences with minimum and no-tillage practices in The Netherlands. I. 1962-1971. In Experience with the applicability of no-tillage crop production in the West-European Countries. Proc. Concerted Action EC Workshop-I, Giessen (pp. 59-68).

VandenBygaart, A.J., Angers, D.A., 2006. Towards accurate measurements of soil organic carbon stock change in agroecosystems. Can. J. Soil Sci. 86 (3), 465–471. https://doi.org/10.4141/S05-106.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can. J. Soil Sci. 83 (4), 363–380. https://doi.org/10.4141/S03-009.

Vogeler, I., Rogasik, J., Funder, U., Panten, K., Schnug, E., 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil Tillage Res 103 (1), 137–143. https://doi.org/10.1016/j.still.2008.10.004.

Vyn, T.J., Raimbault, B.A., 1992. Evaluation of strip tillage systems for corn production in Ontario. Soil Tillage Res 23 (1-2), 163–176. https://doi.org/10.1016/0167-1987(92)90012-Z.

West, T.O., Post, W.M., 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. Soil Sci. Soc. Am. J. 66 (6), 1930–1946.

Wyss, E., Glasstetter, M., 1992. Tillage treatments and earthworm distribution in a Swiss experimental corn field. Soil Biol. Biochem 24 (12), 1635–1639. https://doi.org/10.1016/0038-0717(92)90162-Q.

Yang, P., Dong, W., Heinen, M., Qin, W., Oenema, O., 2022. Soil compaction prevention, amelioration and alleviation measures are effective in mechanized and smallholder agriculture: a meta-analysis. Land 11 (5), 645. https://doi.org/10.3390/land11050645.

Yvan, C., Stéphane, S., Stéphane, C., Pierre, B., Guy, R., Hubert, B., 2012. Role of earthworms in regenerating soil structure after compaction in reduced tillage systems. Soil Biol. Biochem. 55, 93–103. https://doi.org/10.1016/j.soilbio.2012.06.013.