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Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile

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ABSTRACT

This is the first in a series of papers describing the impact of two decades of no-till in the Oberacker long-term field experiment in Switzerland. The experiment was established in 1994 on a sandy loam and compares two tillage systems, conventional tillage with mouldboard ploughing (MP) and no-till (NT). Crops are grown in a six-year rotation, namely peas (*Pisum sativum* L.) – winter wheat (*Triticum aestivum* L.) – field beans (*Phaseolus vulgaris* L.) – winter barley (*Hordeum vulgare* L.) – sugar beet (*Beta vulgaris* L.) – silage maize (*Zea mays* L.). This study investigated the impact of the two tillage systems on (i) nutrient distribution and storage in the soil profile, (ii) the depth distribution of soil organic carbon and (iii) crop productivity. Soil samples were collected layer-by-layer following cultivation layers and natural soil horizons in a metal frame (0.5 m × 0.5 m cross-sectional area) down to 0.5 m depth. The layer boundaries were approximately 0.02, 0.05, 0.15, 0.25, 0.30, 0.40, and 0.50 m for NT, and 0.15, 0.25, 0.30, 0.40, and 0.50 m for MP. Soil organic carbon (SOC), total nitrogen (TotN), phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg), pH, and bulk density were measured for each layer. The nutrient distribution was rather uniform within the plough layer in MP. In NT, there was strong stratification, with higher nutrient concentrations in the upper layers for TotN, K and Mg. This was associated with crop residue retention on the surface and reduced plant uptake due to low pH. In contrast, the distribution of P and Ca in NT was rather uniform in the 0–30 cm layer, with a trend towards maximum concentrations at around 20 cm depth. Total storage of nutrients per ha in the whole soil profile was similar in NT and MP for all nutrients. SOC stocks did not differ between NT and MP, although the depth distribution of SOC concentration was significantly different. The long-term average crop yield was slightly higher in NT than in MP, but the difference was not significant. Crop yield was significantly higher in NT for winter cereals (winter wheat, winter barley) and legumes (field beans and peas), but lower for root and tuber crops (sugar beet, potatoes). It can be assumed that the high crop yields in NT in the Oberacker long-term field experiment are due to the well-balanced crop rotation.

1. Introduction

No-till (also referred to as no tillage, zero tillage and direct drilling) is practised for a number of ecological, agronomic and economic reasons (Soane et al., 2012). Several studies have shown that no-till significantly reduces runoff, especially under high rainfall intensity (Sun et al., 2015); reduces soil erosion, due to the undisturbed soil surface and the presence of crop residues on the soil surface (Merten et al., 2015; Vogel et al., 2016); and may reduce subsoil compaction compared with conventional tillage, which induces high soil stresses on the subsoil during in-furrow ploughing (Chamen et al., 2003). No-till may be an advantage under dry conditions, as it has been shown to improve

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Table 1
Textural composition of soil at the Oberacker site. Clay <0.002 mm; silt 0.002–0.05 mm; sand 0.05–0.2 mm.

Soil characteristics	0.1 m depth	0.4 m depth
Clay (% by weight)	18.6	15.8
Silt (% by weight)	22.7	20.8
Sand (% by weight)	58.7	63.4
Particle density ($Mg\,m^{-3}$)	2.60	2.64
Textural class	Sandy loam	Sandy loam

conservation of soil water compared with conventional tillage (De Gryze et al., 2008; Jin et al., 2009; Martínez et al., 2012). Furthermore, some studies suggest that no-till improves fertiliser use efficiency (Dang et al., 2015). Rusu (2014) reported higher energy efficiency in no-till than in conventional tillage due to the smaller number of field operations (i.e. machinery passes) and the reduced tillage depth, and thus reduced energy consumption. However, crop productivity may be lower under no-till than in conventional tillage systems (Soane et al., 2012; Karlen et al., 2013; Pittelkow et al., 2014). Nevertheless, when no-till is combined with other conservation agriculture management practices, such as permanent soil cover by crop residues and crop rotation, this negative impact is largely mitigated (Fuentes et al., 2009; Pittelkow et al., 2014). In semi-arid areas, yields are higher and costs are lower under no-till, while in humid temperate regions farmers tolerate modest reductions in yield when production costs are lower, giving higher profitability than with conventional tillage (Soane et al., 2012; Karlen et al., 2013).

The absence of mechanical disturbance and crop residues on the soil surface in no-till systems influences soil chemical and physical properties. The lack of soil loosening and inversion by tillage leads to a more stable but rather heterogeneous topsoil compared with conventional tillage, where the topsoil is loosened and homogenised (Kautz et al., 2013). One of the main problems under conventional tillage occurs during the tillage operations that make the soil vulnerable to loss of organic matter and nutrients, potentially leading to a loss in soil fertility (Kautz et al., 2013). No-till results in a different depth distribution of nutrients in the soil profile compared with conventional tillage, as the distribution of nutrients in the tilled layer of conventionally tilled soils is typically rather homogeneous, while nutrients accumulate near the soil surface in no-till. Results from a long-term field experiment reported by Houx et al. (2011) showed significant phosphorus (P) and potassium (K) stratification under no-till, while the depth distribution of calcium (Ca) and magnesium (Mg) was not affected by tillage. Similarly, Deubel et al. (2011) and Noack et al. (2014) found P and K accumulation near the soil surface under no-till.

Tillage and residue management also have strong impacts on soil organic carbon (SOC) and nitrogen (N) dynamics. Omitting mechanical incorporation of crop residues into the topsoil results in a changed distribution of SOC with depth, with higher concentrations in layers close to the soil surface in no-till compared with conventional tillage (e.g. de Moraes Sá and Lal, 2009; de Oliveira Ferreira et al., 2013; Dikgwatlhe et al., 2014). However, the literature is not conclusive as to whether SOC stocks in the whole soil profile increase under no-till. Some authors report increased SOC stocks under no-till (e.g. Paustian et al., 1997; Follett, 2001; Lal, 2004; de Moraes Sá and Lal, 2009; He et al., 2009), while other studies have found no difference in SOC stocks between no-till and conventional tillage (e.g. Hermle et al., 2008; Dikgwatlhe et al., 2014). Some of these differences may be attributable to methodological differences such as the soil depth considered. Other factors that play a role are soil type and climate and the initial SOC level at the onset of no-till. The depth distribution of total nitrogen (TotN) concentration is usually similar to that of SOC concentration (He et al., 2009; Dikgwatlhe et al., 2014; Xue et al., 2015).

No-till is not widely practised in Europe (around 1.1% of total arable area) compared with other parts of the world like Australia, North and South America (around 11%, 28% and 47% of total arable area, respectively) (Basch et al., 2008; Prasuhn, 2012; Soane et al., 2012). According to Soane et al. (2012), the low uptake of no-till in Europe is partly due to the fact that much information on no-till in Europe is based on (i) short-term or (ii) monocultural field experiments, which may produce misleading results. Long-term studies (>10 yrs) are required because following transition from a conventional system to a no-till system, it takes some years for the soil to reach a new equilibrium (e.g. Alvarez and Steinbach, 2009; de Moraes Sá and Lal, 2009). A well-balanced crop rotation is particularly important in no-till systems in order to control weeds and pests (Soane et al., 2012). Hence, there is a need for data from long-term crop rotation no-till experiments on different soils and under various climate conditions in Europe (Soane et al., 2012). Furthermore, in their review on no-till in Europe, Soane et al. (2012) identified a need for better knowledge on the distribution of major nutrients in the soil profile in no-till systems, which is important information for refining fertilisation recommendations.

The objective of this study was to investigate the impact of two contrasting tillage systems, no-till (NT) and conventional tillage with mouldboard ploughing (MP), in a long-term field experiment on the Swiss plateau (slightly humic sandy loam, temperate climate) with respect to (i) crop productivity, (ii) nutrient distribution and storage in the soil profile and (iii) total stocks and depth distribution of soil organic carbon in the soil profile.

2. Materials and methods

2.1. Site description, experimental design and soil management

The Oberacker long-term field experiment was established in 1994 as a demonstration site at INFORAMA Ruetti in Zollikofen near Berne, Switzerland (47.0°N, 7.5°E; 557 m a.s.l.). The soil has a sandy loam texture (USDA classification) and is classified as a Eutric Cambisol (WRB, 2006) (Table 1). The climate is temperate (*Cfb* according to the Köppen climate classification), with mean annual air temperature of 9.3 °C and mean annual precipitation of 1109 mm (Table 2).

The Oberacker experiment has a split-plot design, with six plots and two subplots per plot (Fig. 1). Different crops are grown in the different plots, but all plots have the same crop rotation. Two tillage systems are compared: No-till (NT) is used on every second subplot (size: 9 m × 80 m), and mouldboard ploughing (MP) on every other subplot. Crop residues are left in the field in both systems. Conventional in-furrow ploughing to about 0.25 m depth was used in MP until 2002. In order to minimise tillage intensity and adapt best soil management practices in MP, on-land ploughing to approximately 0.15 m depth has been used since 2003. A true no-till system is used in NT, i.e. crops are sown without

Table 2
Average monthly precipitation and air temperature at the Oberacker site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total/Mean
Precipitation (mm)	64	51	87	86	103	107	126	135	93	97	69	91	1109
Temperature (°C)	0.3	0.5	4.6	9.6	13.2	17.0	18.6	17.6	14.5	10.1	4.5	0.5	9.3

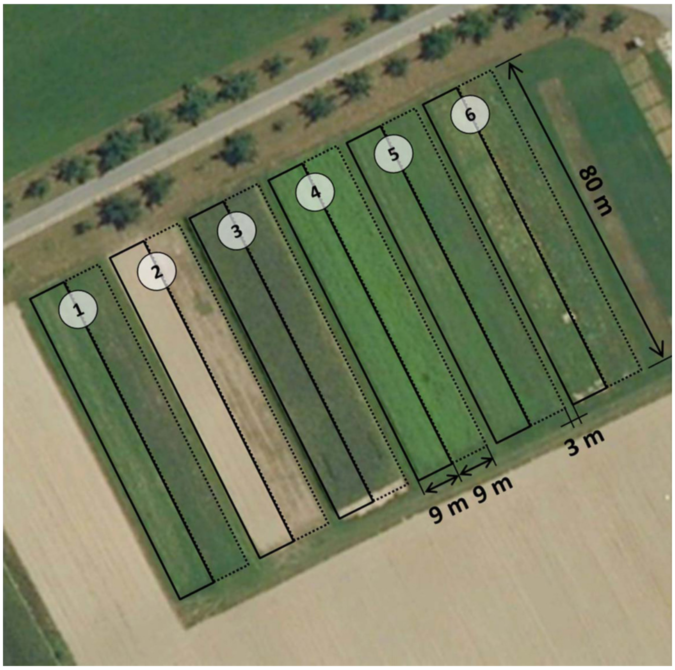

Fig. 1. Aerial view of the Oberacker long-term field experiment, with six plots and two subplots per plot (rectangles with solid lines: mouldboard ploughing (MP); rectangles with dotted lines: no-till (NT)). There are 3 m wide permanent grass (PG) strips between plots. Photo: Gabriela Brändle (Agroscope, Zurich, Switzerland).

any prior loosening of the soil and the only mechanical soil disturbance arises from the disc openers of the drill. However, some soil disturbance is unavoidable during sugar beet harvest. Sowing dates are the same in both treatments and all crop seeds are sown with direct drill machines (since 2001). Different direct drills have been used throughout the years, but with a few exceptions they all have disc coulters. Seedbed preparation in MP was performed using a rotovator until 2006. Since 2007, conventional seedbed preparation is not performed any longer in MP, in order to minimise the tillage intensity. Instead, a combination of a front packer and a no-till drill is used to place seeds directly in the ploughed soil.

2.1.1. Crop rotation

The Oberacker long-term field experiment is run with a six-year crop rotation, but the rotations started with a different crop in each of the six plots. The crop rotation has slightly changed during the years and has been modified based on crop performance and the need for crop protection, with the aim of optimising soil quality while maximising overall yield of a whole crop rotation and minimising pesticide use. Ley, which is typically included in crop rotations in Switzerland, was originally included in the crop rotation but was stopped after two years. Potatoes (*Solanum tuberosum* L.) were included in the crop rotation until 1999, using direct mulch planting in NT. However, this cropping system was unsatisfactory and the tubers were of poor quality, and therefore potatoes were replaced with peas in 2000. Soybean (*Glycine max* L.) was grown in 2002 but has not been grown again due to late crop maturation and the high cost of drying. Winter rye (*Secale cereal* L.) was grown between 2001 and 2006. Field beans (*Phaseolus vulgaris* L.) were included in the crop rotation in 2007. Spring wheat (*Triticum aestivum* L.) had to be grown instead of winter wheat in 2012 due to frost damage. The current crop rotation (since 2006) is: peas (*Pisum sativum* L.) – winter wheat – field beans – winter barley (*Hordeum vulgare* L.) – sugar beet (*Beta vulgaris* L.) – silage maize (*Zea mays* L.). Crops are harvested with conventional commercial harvesters. Crop yield is determined over the whole subplot except for maize and sugar beet (partial surface area measurements). Cover crops (field mustard (*Brassica rapa* L.), fodder radish (*Raphanus sativus* L.) and common vetch (*Vicia sativa* L.)) are grown in both tillage treatments after cereals and peas. Since 2008, a mixture of nine non-frost resistant species has been used in order to lower glyphosate use.

2.1.2. Fertilisation and crop protection

Fertilisation is performed according to the Swiss fertilisation recommendations (GRUDAF) (Flisch et al., 2009). The fertiliser rates from 2008 to date are summarised in Table 3. Fertilisation is similar in both tillage treatments in terms of N, P, Mg, sulphur (S) and boron (B). Based on soil chemical analyses, NT received approximately 50% less K_2O than MP during the past four years. MP was limed with $CaCO_3$ in 2010–2011 and 2011–2012, while only a low rate was applied in NT in 2011–2012. No P has been applied in either of the tillage treatments since 2010.

Crop protection (weed and disease control) is carried out according to the principles of integrated pest management (IPM), which aims to suppress pest populations below the economic injury level and largely relies on pesticides in both NT and MP. MP also includes mechanical weed control. Thermal methods were applied in NT after potato and sugar beet harvest in the first years of the experiment. A broad-spectrum herbicide (typically glyphosate) was used in NT to regulate cover crops until 2006. Since 2007, glyphosate application has been gradually reduced. In MP, cover crops are incorporated into the soil by ploughing.

2.2. Measurement procedure for soil organic carbon and nutrient profiles

Four randomly selected plots per treatment were sampled in summer 2014 (i.e. after 20 years of no-till and mouldboard ploughing). Soil samples were collected layer-by-layer following cultivation layers and natural soil horizons using a metal frame ($0.5\,m \times 0.5\,m$ cross-sectional area) down to 0.5 m depth. The

Table 3
Fertiliser rates applied ($kg\,ha^{-1}$) from 2008 to 2014 in the no-till (NT) and mouldboard ploughing (MP) treatments.

Year[a]	N		P_2O_5		K_2O		$CaCO_3$		Mg		S		B	
	NT	MP	NT	MP	NT	MP	NT	MP	NT	MP	NT	MP	NT	MP
2008–2009	65	65	83	83	221	221	0	0	14	14	79	79	0	0
2009–2010	66	66	81	81	210	210	0	0	0	0	60	60	0	0
2010–2011	65	65	0	0	68	108	0	139	35	35	57	57	0	0
2011–2012	71	71	0	0	0	112	19	145	0	38	88	68	5	0
2012–2013	70	70	0	0	64	97	0	0	19	19	65	66	0	0
2013–2014	71	71	0	0	92	138	0	0	23	23	74	74	2	2
Mean	68	68	27	27	109	148	3	47	15	22	71	67	1	0.3

[a] From sowing to harvest.

layers were approximately 0-0.02, 0.02-0.04, 0.04-0.08, 0.08-0.15, 0.15-0.30, 0.30-0.40, 0.40-0.50 m for NT and 0-0.15, 0.15-0.25, 0.25-0.30, 0.30-0.40, 0.40-0.50 m for MP. The level of the surface of each boundary was measured with a digital laser meter (PLR 50, Bosch) by taking eight measurements along two perpendicular transects across the frame (four per transect). The average thickness of each layer was then calculated as the difference between the mean level of the top and bottom boundary surface. The soil from each layer was weighed in the field (accuracy 0.1 kg, corresponding to 0.1-1% for layer weights of 10–100 kg). The soil from each layer was then thoroughly mixed and a sample of approximately 1 kg was sealed in plastic boxes in the field and kept frozen until chemical analysis. Another sample was used for determination of the soil gravimetric water content by the oven-drying method (drying at 105 °C for at least 24 h). Hence, it was assumed that the bulk density and nutrient concentrations were constant within layers, a commonly used approach (Nunes et al., 2015). The dry bulk density of each layer was then calculated from the weight of the soil, the gravimetric water content and the layer thickness. Nutrient and SOC stocks were calculated from layer thickness, bulk density and nutrient and SOC concentrations (see Section 2.3).

2.3. Soil chemical analyses

The following analyses were performed for each layer: The soil pH was measured in $CaCl_2$. Soil organic carbon (SOC) was determined in soil samples (<2 mm sieved) by the wet combustion technique, which determines total SOC content by digesting SOC with potassium dichromate and sulphuric acid, and titrating the residual potassium dichromate with ammonia ferrous sulphate (ISO 10694). For total nitrogen (TotN), the Dumas combustion method was used with an element analyser (varioMAX CN-Analyser, Elementar Analysensysteme GmbH, Hanau, Germany) (ISO 13878). Mineral nitrogen (MinN), ammonium-N (N-$NH^{+}{}_4$) and nitrate-N (N-$NO^{-}{}_3$) were measured after Kjeldahl digestion according to Swiss standard protocols using a flow injection analyser (Skalar Analytical B.V., The Netherlands). Soil phosphorus reserves were measured using 0.6 M HCl as extractant. The concentrations of exchangeable bases, i.e. Ca, K, Mg and P, were measured by the ammonium acetate method at pH 4.65. These analyses were carried out according to Swiss standard protocols (Swiss Federal Research Stations, 1996).

2.4. Soil penetration resistance

Penetration resistance was measured in spring 2012 at a water content close to field capacity with a hand-pushed Eijkelkamp cone penetrometer (cone base area 1 cm^2, cone apex angle 60°) to a depth of 0.80 m. Ten insertions were made in each plot and averaged for further analysis.

2.5. Statistical analysis

Crop productivity was analysed using a linear mixed model with log yield as response variable. The model included fixed effects of years, crops and tillage treatments (i.e. MP and NT), and random effects of plots and subplots. The model also included fixed effects of year-by-tillage and crop-by-tillage interactions, and random effects of year-by-plot and year-by-subplot interactions. The year-by-crop interaction and the three-way interaction of years, crops and tillage treatments could not be included in the model, since these interactions would be confounded with the year-by-plot and year-by-subplot interactions, respectively. Observations from the same subplot were assumed to be temporally correlated. A banded covariance structure, i.e. toep(2), was chosen based on the Akaike information criterion. The model was fitted using SAS 9.2, procedure Mixed (Littell et al., 2006).

Table 4
Average crop yields (1995–2014) in the Oberacker long-term field experiment. All crop yields are given in dt ha^{-1} (cereals: 14% moisture content; legumes: 15% moisture content; maize: dry matter; potatoes: fresh weight) except for sugar beet yield, which is in Mg sugar ha^{-1}. *N*: number of experimental years; NT: no-till; MP: mouldboard ploughing. Values followed by different letters are significantly different ($p < 0.05$).

Crop	*N*	Yield NT	Yield MP	$100\frac{Yield_{NT}}{Yield_{MP}}$
Winter barley	20	65.9 *a*	62.2 *b*	105.9
Sugar beet	20	11.5	11.9	96.6
Silage maize	20	199.9	198.7	100.6
Winter wheat	19	55.0 *a*	51.9 *b*	105.9
Spring peas	8	42.5 *a*	37.3 *b*	113.7
Spring field beans	6	30.9 *a*	26.3 *b*	117.3
Winter rye	6	59.5	58.6	101.5
Winter peas	5	32.1 *a*	26.6 *b*	120.9
Potatoes	5	341.1 *b*	399.5 *a*	85.4
Ley	2	n/a	n/a	n/a
Soybean	2	26.3	29.4	89.7
Winter field beans	1	23.6	29.0	81.2
Spring wheat	1	60.5	49.7	121.5
Average all crops				102.6

The depth distributions of SOC and nutrients were analysed using the InfoStat statistical analysis software (Di Rienzo et al., 2009). Because the layer boundaries were not identical in all plots, the soil profile was divided into 1-cm intervals. SOC and nutrients were analysed using a split-plot linear mixed model with fixed effects of tillage treatment, depth and tillage treatment-by-depth interaction, and with random effects of plots. Pairs of means were tested using the Tukey method at significance level $p < 0.05$. Nutrient storage in the topsoil and subsoil of four replicate samples was tested by Tukey's least significant difference (LSD, $p < 0.05$) derived from analysis of variance (ANOVA).

3. Results

3.1. Crop yields

The average yields of the various crops in the entire experimental period (1995–2014, i.e. 20 experimental years) are presented in Table 4. Considering all crops, the average yield in NT was 102.6% of that in MP, but this difference was not statistically significant ($p = 0.28$). The yield in NT relative to that in MP for the

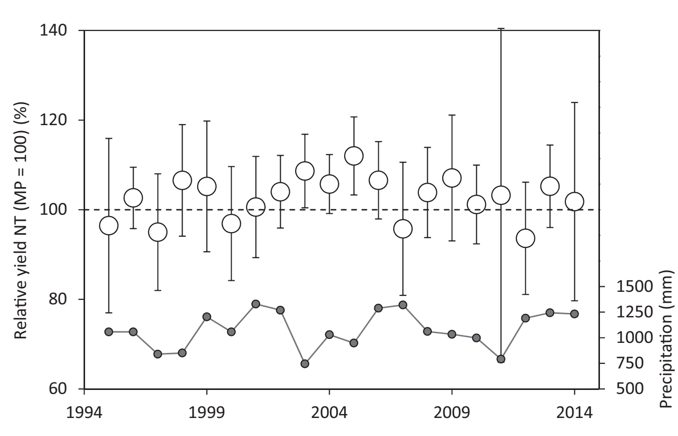

Fig. 2. Relative crop yield (in %) for no-till, (NT, open circles), where yield in mouldboard ploughing (MP, dashed line) is set at 100%, for the period 1995–2014. Each data point represents the average of six replicate plots. Error bars indicate standard deviation. Annual precipitation 1995–2014 is indicated by grey circles.

different years is plotted together with annual precipitation in Fig. 2. No temporal trend (for higher or lower yield in NT as a function of the duration of NT) was observed, and no relationship with precipitation could be found. Crop yield was significantly higher ($p < 0.05$) in NT for winter cereals (winter wheat, winter barley), winter peas, spring field beans and peas, and significantly lower ($p < 0.05$) for potatoes (Table 4). Lower yield in NT was also obtained for sugar beet, but the difference was not statistically significant ($p = 0.20$). The yield of winter barley (Fig. 3a) was higher in NT in all but three years (1996, 2000 and 2012), resulting in 5.9% higher average yield in NT (Table 4). There was rather high variability in winter barley yield, with low yields in both tillage systems in 1995, 2000, 2006 and 2012 (Fig. 3a). There was no obvious reason for the low yields except in 2012, when weed pressure (mainly couchgrass, *Elymus repens* L.) was high. The sugar yield (from sugar beet) in NT and MP is presented in Fig. 3b. Although the 20-year average yield was 3.4% lower in NT (Table 4), the sugar yield was higher in NT than in MP in nine out of the 20 experimental years (Fig. 3b). As regards average crop yield over the 20-year period (Table 4), the lower average winter barley yield in MP (62.2 decitons (dt) ha^{-1}) compared with NT (65.9 dt ha^{-1}) corresponds to an accumulated yield loss of more than one average harvest for winter barley in 20 years (20 × (65.9 dt ha^{-1}–62.2 dt ha^{-1}) = 74 dt). Similarly, the accumulated yield loss for peas was almost two average pea harvests in 13 experimental years ([8 × (42.5 dt ha^{-1}–37.3 dt ha^{-1})] + [5 × (32.1 dt ha^{-1}–26.6 dt ha^{-1})] = 69.1 dt). The lower sugar beet yield in NT represented an accumulated sugar yield loss in NT of about two-thirds of an annual yield in 20 experimental years (20 × (11.9 Mg ha^{-1}–11.5 Mg ha^{-1}) = 8 Mg). The difference in maize yield between NT and MP was marginal (Table 4).

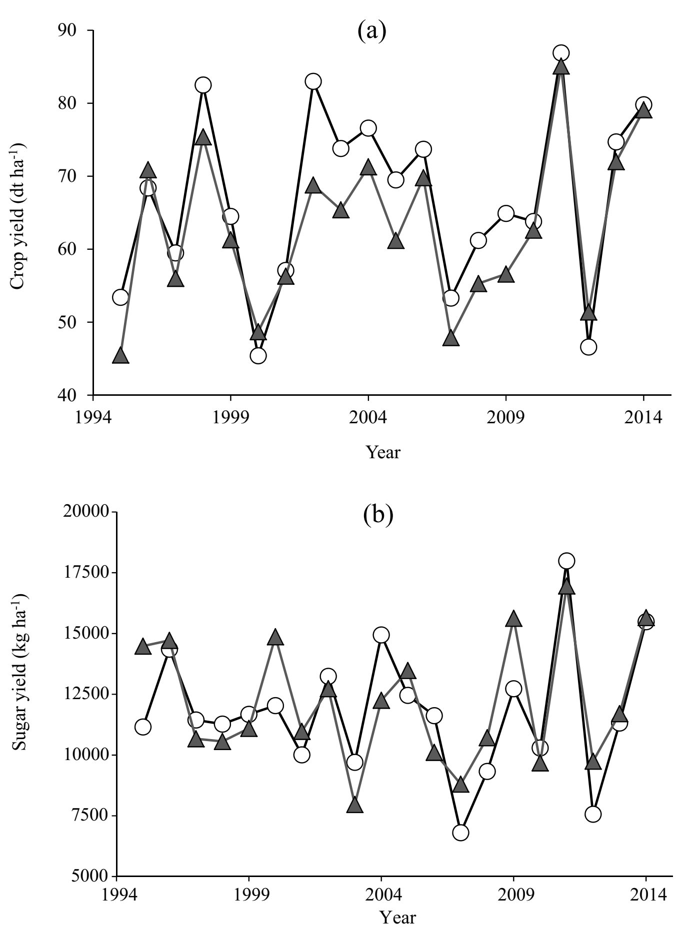

Fig. 3. (a) Winter barley yield (14% moisture content) and (b) sugar yield in no-till (open circles) and mouldboard ploughing (grey triangles).

3.2. Bulk density and penetration resistance profile

The depth distributions of bulk density and penetration resistance are shown in Figs. 4a and 4b. The new ploughing depth at ~0.15 m (cf. Section 2.1) was clearly visible from the bulk density measurements (Fig. 4a). The depth distribution of penetration resistance (Fig. 4b) closely followed the depth distribution of bulk density at depths >0.1 m (Fig. 4a). NT plots generally displayed higher bulk density and higher penetration resistance than MP in the topsoil, with the exception of the uppermost centimetres, an effect that may relate to the higher SOC concentration (see below). Note also that the depth resolution in topsoil was poorer in MP than in NT (cf. Section 2.2). In the subsoil, the relationship was reversed and NT had lower bulk density and lower penetration resistance than MP (Fig. 4).

3.3. Soil pH

Soil pH generally increased with soil depth (Fig. 5), showing slight acidification in the subsoil, with no differences between NT and MP. However, significant differences were found in the topsoil (Fig. 5): after 20 years of NT, the soil pH was around 5.3 (slightly acid) in the 0–5 cm layer and approximately 5.0 (moderately acid) in the 5–10 cm layer, while the pH in MP was about 5.4 in both these layers.

3.4. Soil organic carbon and total nitrogen

Soil organic carbon and TotN increased under NT in the upper soil layers (0–10 cm depth), as a result of the residues left on the surface and probably also root concentration in this layer (Fig. 6). The C:N ratio was about 10 and did not differ between NT and MP. The SOC and TotN concentrations generally decreased with soil depth under both tillage systems. There was a tendency for higher concentrations of both SOC and TotN at around 15–25 cm depth in MP compared with NT. Although the depth distribution of SOC differed between MP and NT (Fig. 6), there was no significant difference ($p > 0.05$) in total SOC storage between MP and NT. Total C stock in the 0–50 cm profile was 70 and 73 Mg ha^{-1} in NT and MP, respectively. Total C stock based on equivalent soil mass (Powlson et al., 2011) was also calculated, but this had only marginal effects compared with the calculation based on soil depth (Section 2.2), since the total soil mass in the 0–50 cm layer was similar in NT and MP because sampling was performed to well below tillage depth.

3.5. Macronutrient distribution in the soil profile

3.5.1. Phosphorus

The distribution of P was similar in both tillage systems and was rather uniform in the 0–50 cm soil profile (Fig. 7). However, NT showed a trend for maximum P concentration at around 20 cm depth. Despite almost no P fertilisation during recent years (see P_2O_5 rates in Table 3), both systems had high P levels in the whole profile (>30 mg P kg^{-1}). There was no significant difference ($p > 0.05$) in the total amount of P between NT and MP for the topsoil, subsoil, or entire 0–50 cm profile (Fig. 8).

3.5.2. Calcium, magnesium and potassium

The distribution of Ca was rather uniform in the 0–50 cm profile in both tillage systems, but NT showed a trend for maximum concentrations at around 20 cm depth (Fig. 7). $CaCO_3$ was applied in MP during 2010/11 and 2011/12, while only a low rate was

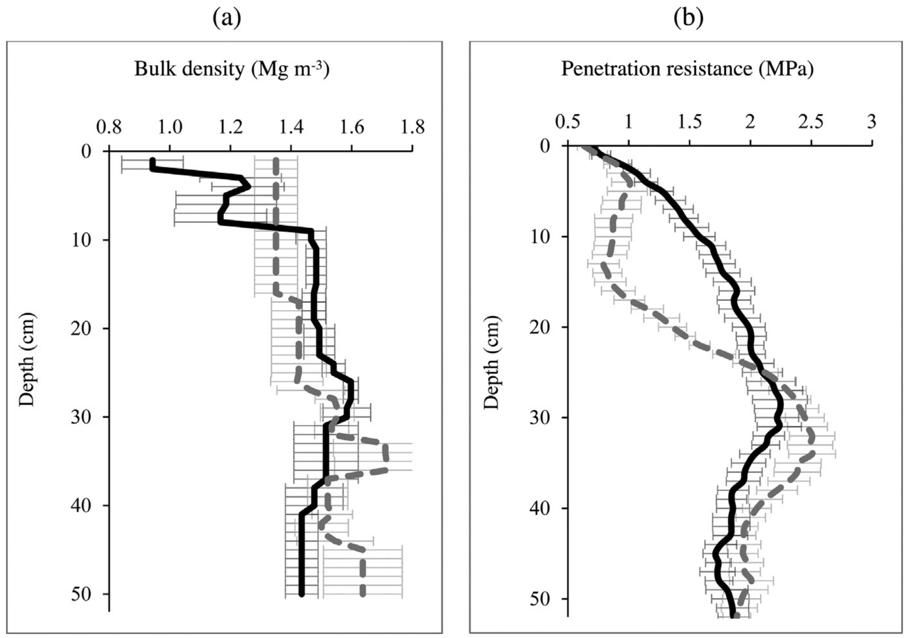

Fig. 4. Depth distribution of (a) bulk density and (b) penetration resistance at field water content in no-till (NT, black curves) and mouldboard ploughing (MP, grey dashed curves). Error bars indicate standard error.

applied in NT, in 2011/2012 (Table 3), but this did not result in higher concentrations in MP compared with NT.

Strong stratification was found in the uppermost centimetres of NT plots for both Mg and K. The K fertiliser rate was drastically reduced in both tillage systems from the 2010/2011 season onwards (Table 3). Moreover, while K fertilisation was similar in NT and MP prior to 2010/2011, the rate applied in NT is now about two-thirds of that in MP (Table 3). Rate of Mg fertiliser application is the same in both systems.

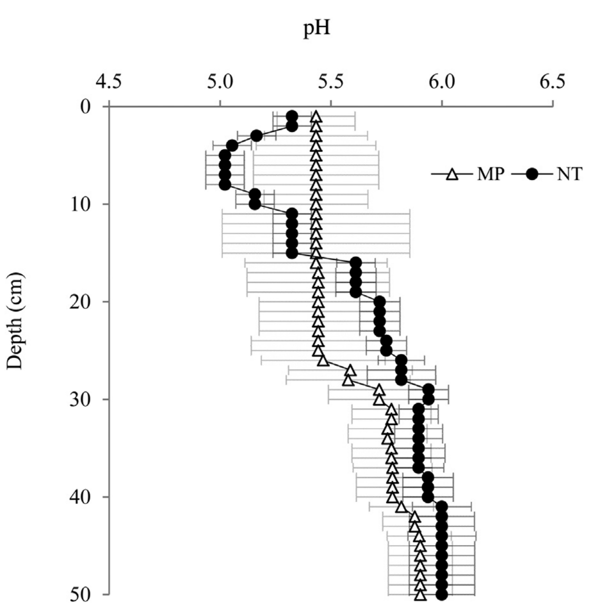

Fig. 5. Influence of tillage system on soil pH. Black circles: no-till (NT); open triangles: mouldboard ploughing (MP). Error bars indicate standard error.

4. Discussion

4.1. Soil pH

Tillage affected soil pH in the upper soil layers, being lower under NT than MP. Soil pH in NT ranged from moderately acidic in the topsoil layers to slightly acidic in the subsoil, while pH was slightly acidic in the whole profile in MP. Other studies have also reported acidification in the topsoil under conservation tillage and have attributed this to retention of residues on the soil surface (Hickman, 2002; Houx et al., 2011) and to the lack of soil homogenisation in that system (Kautz et al., 2013). Similarly, we found that soil pH was negatively correlated with SOC, with the higher SOC in the topsoil layers of NT being associated with lower pH in NT compared with MP (Figs. 5 and 6). In addition, the liming operations in MP in 2010 and 2011 (139 and 145 $CaCO_3$ kg ha^{-1}, respectively; Table 3) could have contributed to the higher soil pH in MP than NT. The pH for optimum plant growth and nutrient uptake is between 6.0 and 7.0, i.e. slightly acid to neutral (Fageria, 2009), although some crops perform well in slightly more acid conditions (e.g. pH 5.5–6.5 for field beans, 5.5–7.0 for maize; Mutiro et al., 2006). The slight acidification observed in the surface layers of NT (Figs. 5 and 7) could reduce the availability of some nutrients to crops (Fuentes et al., 2009; Soane et al., 2012).

4.2. Nutrient concentrations and stocks

The distribution of P and Ca was rather uniform in the 0–50 cm layer in both tillage systems (Fig. 7). However, NT showed a trend for maximum concentration at around 20 cm depth for both P and Ca. Neither P nor Ca was applied as fertiliser in NT during the last four years (Table 3), but release of nutrients such as P from crop residues provides significant amounts to subsequent crops (Noack et al., 2014). Hence, the maximum concentrations of P and Ca at 20 cm in NT are the result of (i) plant uptake in the surface layers, (ii) downward transport, or a combination of the two. Downward transport could be facilitated through more continuous

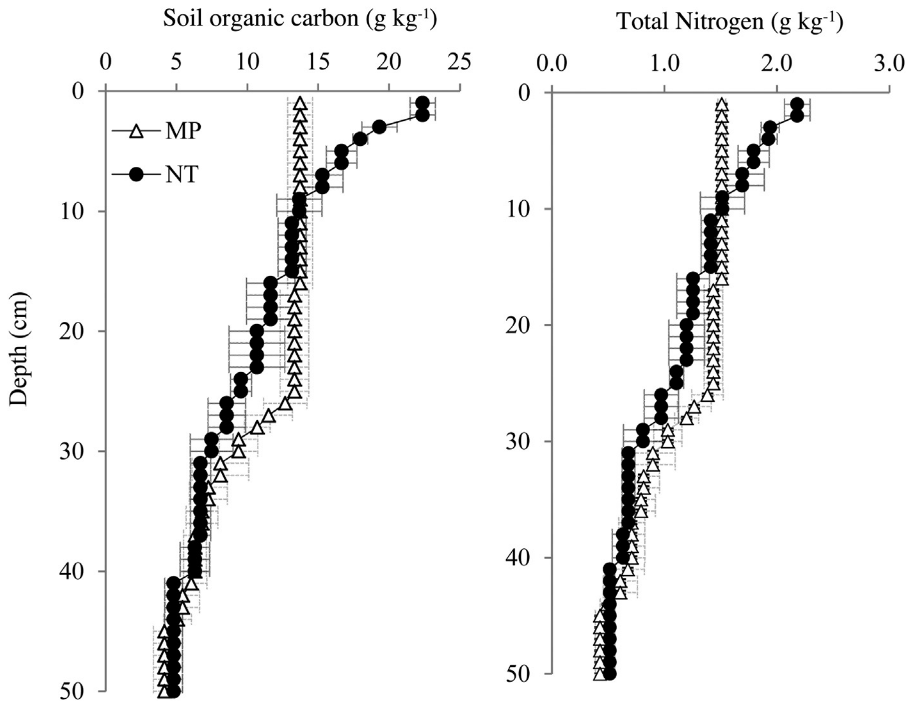

Fig. 6. Influence of tillage system on soil organic carbon (SOC) and total nitrogen (TotN). Error bars indicate standard error.

macropores in NT (see also Martínez et al., 2016). However, no difference in P or Ca concentration between NT and MP was found in the subsoil (Fig. 7). Furthermore, the peak concentration of P seemed to be rather stable with respect to depth. A similar peak was observed in the 15–20 cm layer of the Oberacker long-term field experiment by Sturny et al. (2007), who measured the nutrient concentration profiles after 10 years. In the present study, both tillage systems had high P availability, despite the fact that the last P fertiliser application occurred in 2009/2010. For Ca, both tillage systems showed medium availability, except for the 15–25 cm layer in NT, which had high availability.

Strong stratification was found in the uppermost centimetres for Mg and K. The Mg concentration in the uppermost soil layer (0–2 cm) was 50% higher than in the 10–30 cm layer in NT, while there was a rather uniform distribution in MP, despite similar fertilisation rates being used in both tillage systems (Table 3). The K concentration in NT was 75% higher in the uppermost soil layer than at 10 cm depth. Strong K stratification in NT was also observed by Deubel et al. (2011), who suggested that the main reason for K accumulation near the soil surface in NT was the presence of plant residues on the soil surface. In NT, K and Mg presented very high and medium availability, respectively, in the 0–2 cm layer and medium and low availability, respectively, in the 30–50 cm soil layer.

Two distinctly different nutrient depth distributions were found in NT. The depth distributions of P and Ca were rather uniform, with slight depletion in the uppermost centimetres and a tendency for accumulation at around 20 cm depth (Fig. 7). In contrast, the depth distributions of K and Mg were characterised by high accumulation at the soil surface and a strong decrease with depth (Fig. 7). These differences can primarily be attributed to fertilisation effects in combination with the omission of soil tillage in NT. Little P and Ca fertiliser was applied, while K and Mg were applied at normal rates (Table 3). According to the Swiss fertilisation recommendations (Flisch et al., 2009), the K and Mg fertilisation rates are relatively high compared with the P and Ca rates. Hence, K and Mg accumulate at the surface, while P and Ca are depleted due to plant uptake and no fertiliser input. Calcium was possibly also leached in NT, due to the low pH (e.g. Houx et al., 2011), which could contribute to the maximum at 20 cm. Nutrient balances could be determined in future research, to gain a better understanding of the differing nutrient distributions. The depth distribution of all nutrients was uniform within the topsoil in MP due to annual mixing caused by tillage. No significant differences ($p > 0.05$) in nutrient stocks were found for P, Ca, K and Mg between NT and MP (Fig. 8).

4.3. Soil organic carbon

The depth distribution of SOC was strongly affected by the soil tillage system, with significantly higher SOC in the uppermost centimetres in NT (Fig. 6). In contrast, SOC in the 15–30 cm layer was lower in NT than in MP (Fig. 6). This was expected and is in agreement with earlier work (for an overview, see Soane et al., 2012). The absence of soil disturbance in NT leads to higher SOC (as well as higher TotN) concentrations in the surface layers. Conversely, the lack of mechanical crop residue incorporation as a result of NT (i.e. lack of tillage operations that incorporate residues) is the primary reason for the lower SOC and TotN concentrations in NT compared with MP at the topsoil-subsoil boundary (Franzluebbers, 2002; Xue et al., 2015). No differences in SOC between tillage systems were found at depths greater than about 30 cm (Fig. 6). It has been speculated that SOC could increase in subsoil under NT as a result of colloid transport (OC-clay complexes), facilitated by continuous macropores (Kadzienè et al., 2011), but data on 20 years of NT in the Oberacker long-term field experiment did not support this hypothesis.

Total SOC storage in the 0–50 cm soil profile was approximately 70 Mg ha^{-1} in both NT and MP (Fig. 8), which is comparable to amounts reported in the literature (Hermle et al., 2008; Schjønning and Thomsen, 2013). There was no specific effect of tillage system on C stocks, i.e. NT did not increase C sequestration. This agrees with findings in other studies in central and northern Europe (Hermle et al., 2008; Schjønning and Thomsen, 2013) and China (Huang et al., 2015). However, positive effects of no-till on C sequestration have been found, especially at North American sites

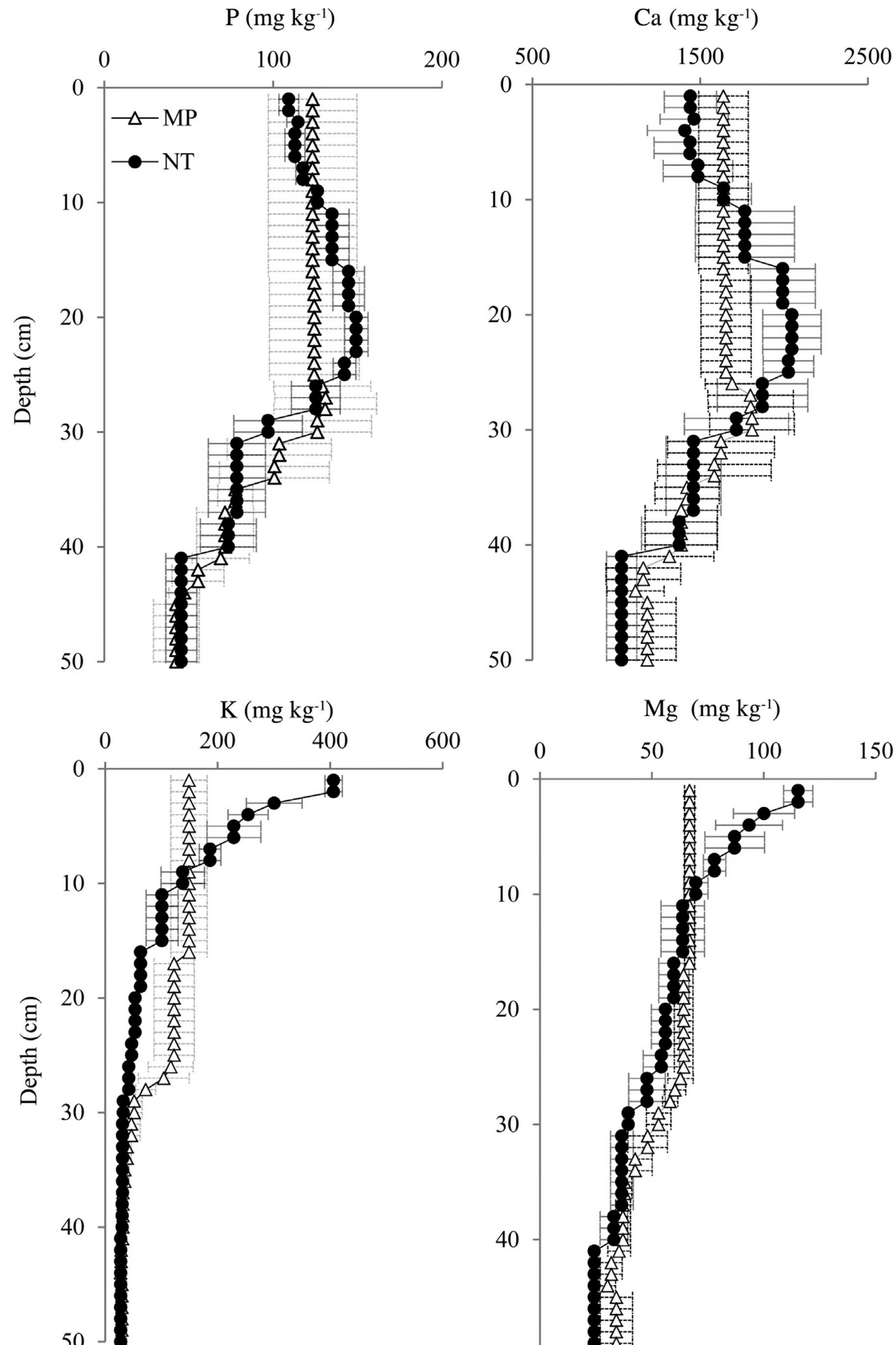

Fig. 7. Influence of tillage system on P, Ca, Mg and K concentrations in soil. Error bars indicate standard error.

(Paustian et al., 1997; Smith et al., 1998; Follett, 2001; West and Post, 2002; Lal, 2004). de Oliveira Ferreira et al. (2013) showed that C sequestration is affected by climate and soil type in tropical areas.

The potential for organic carbon storage was calculated according to Dexter et al. (2008), who assumed that organic carbon complexed with clay is more stable and suggested that organic carbon should be complexed for carbon sequestration in arable soil. We calculated the potential concentration of complexed organic carbon (CMAX) based on the clay content in the soil profile (Table 1), assuming that 1 g organic carbon is associated with 10 g clay (Dexter et al., 2008). The potential stock of complexed organic carbon in the soil is then readily obtained from CMAX and the soil bulk density. We found that the potential organic carbon storage capacity was approximately 120 Mg ha^{-1} for the 0–50 cm profile, with no significant differences between MP and NT. Considering the actual organic carbon storage of roughly 70 Mg ha^{-1} (Fig. 8), an additional 50 Mg ha^{-1} of organic carbon could potentially be stored in the 0–50 cm soil profile. In other words, the actual organic carbon storage is only about 60% of the potential capacity. About two-thirds of the additional organic carbon storage capacity was associated with the subsoil (25–50 cm depth), and this was the case for both NT and MP. The soil was C-saturated (i.e. SOC > CMAX) only in the uppermost 3 cm in NT, while SOC < CMAX for all other depths in NT and for the whole profile in MP.

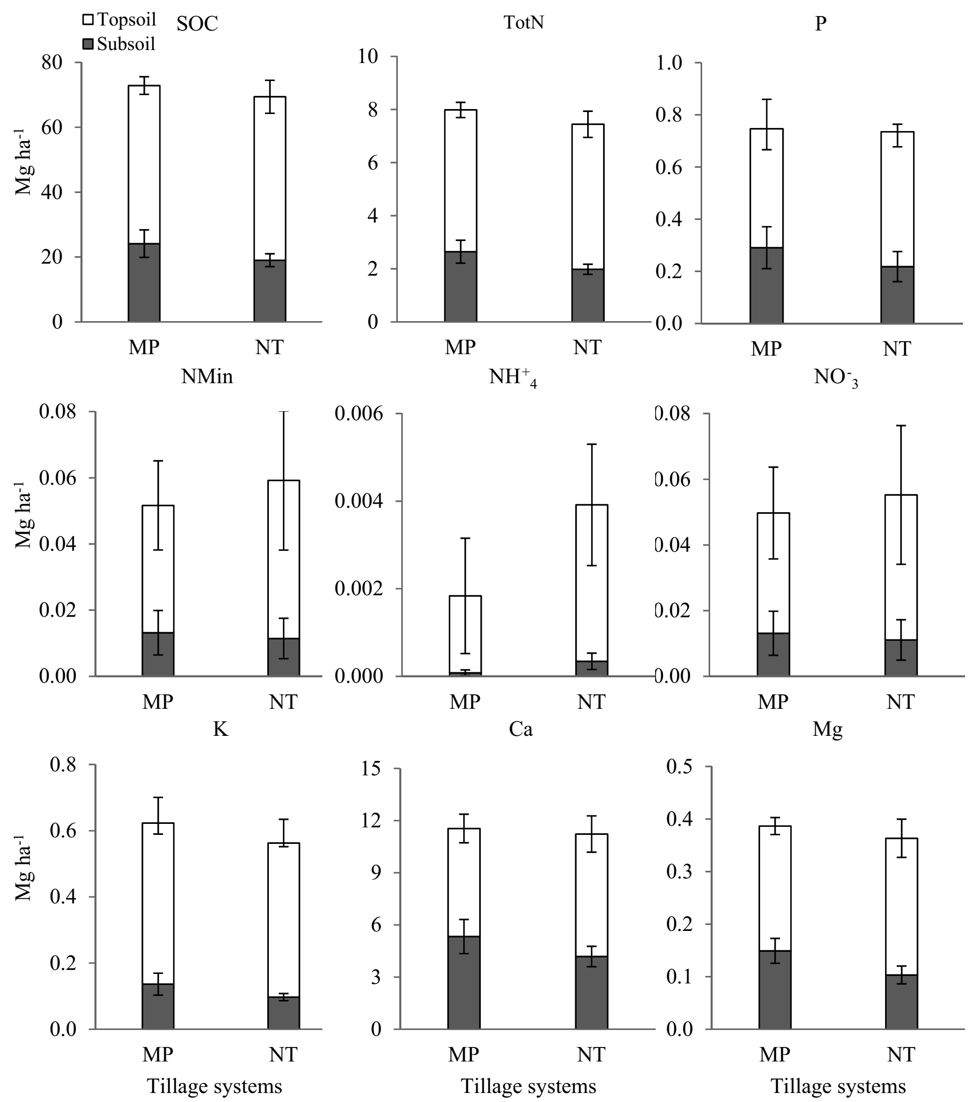

Fig. 8. Nutrient storage (in Mg ha^{-1}) in the topsoil (0–25 cm) and the subsoil (25–50 cm) after 20 years of different soil tillage treatments (NT: no till; MP: mouldboard ploughing). Error bars indicate standard error.

4.4. Crop yield

Overall average crop yield was higher in NT (102.6%) than in MP, although the difference was not statistically significant. The NT treatment in the Oberacker long-term field experiment includes residue retention and a well-planned crop rotation, two measures known to be of the utmost importance for the success of no-till (Soane et al., 2012; Derpsch et al., 2014; Pittelkow et al., 2014). Average yield was higher in NT, even though the climate at the experimental site is humid according to the classification in Pittelkow et al. (2014). A meta-analysis by Pittelkow et al. (2014) revealed negative yield responses to no-till in humid climates, irrespective of residue treatment and crop rotation. Arvidsson et al. (2014) analysed a large dataset from Swedish field experiments and reported an average yield loss of 10% in no-till. They obtained the highest no-till yields on soils with < 15% clay, although there was no clear relationship between soil texture and yield. Van den Putte et al. (2010) observed the lowest yields in no-till on sandy soils. Arvidsson et al. (2014) found that the preceding crop had a large influence on the yield of winter wheat and spring barley. It can be conjectured that one of the reasons for the high crop yields in NT in the Oberacker long-term field experiment is the well-balanced crop rotation including cover crops. In addition, the focus is not on yield maximisation of individual crops, but on yield optimisation of the whole crop rotation. This involves, for example, harvesting sugar beet relatively early to minimise the risk of soil compaction under moist soil conditions at harvest, although later harvest would increase sugar yield, especially in NT, due to compensation effects. Because there is no mechanical loosening of the soil in NT, soil compaction would be especially detrimental in that treatment.

Although the overall average yield was not significantly different between NT and MP, significant differences were found for certain crops (Table 4). The yields were lower in NT than in MP for tuber and root crops (significantly lower for potatoes, lower for sugar beet; Table 4), and this may be associated with the denser topsoil in NT (Fig. 4; see also Martínez et al., 2016). Potatoes were part of the initial crop rotation (see Section 2.1.1), but were removed because the cultivation technique in NT (direct mulch planting) proved unsatisfactory. Hence, the lower yield in NT was not only caused by the denser topsoil, but also by generally poor establishment and more tuber damage by firm soil clods at harvest. The lower sugar yield in NT is also caused by the relatively early harvest date (as mentioned above): the sugar beet crop generally starts more slowly in the early season in NT, so the sugar content may potentially increase more than in MP with a late harvest date. On the other hand, crop yields of legumes (field beans, peas) and winter cereals (winter wheat, winter barley) were significantly higher in NT than in MP (Table 4). The yields of spring field beans and spring peas were much higher (>150%) in NT than in MP in some years (spring peas: 2011, 2014; spring field beans: 2011). The differences could not be explained by weeds, diseases or rainstorms. 2011 was a dry year, while 2014 was wetter than normal (Fig. 2). However, unfavourable weather conditions at early growth stage (rainy and cold periods) may have been unfavourable for MP, but not for NT, e.g. because the crops were already further developed in MP. Nevertheless, the yield in NT was still significantly higher (relative yield in NT (MP = 100%) of 104.5% for spring peas and 109.1% for spring peas), even when excluding these years from the analyses. Legumes are thought to be sensitive to soil compaction (Håkansson, 2005). Hence, our results indicate that legume roots were able to grow well, even though the topsoil of NT is denser. This would support the claim that the critical limits of soil physical conditions may be different in no-till systems than in conventionally tilled soil (Reichert et al., 2009). Furthermore, it is possible that roots were better able to explore the subsoil in NT, which had better structural quality than the MP subsoil (Fig. 4; Martínez et al., 2016). Another reason could be that the higher nutrient concentrations in the topsoil (Figs. 6 and 7) compensated for the higher density (Fig. 4). Similar reasons could explain the higher yields of winter cereals in NT, as cereals are generally less sensitive to compaction (Håkansson, 2005).

Regression of the yields of the various crops against precipitation within selected time intervals (i.e. growing periods) did not reveal any relationships that would explain the yield differences between NT and MP (see also Fig. 2). However, Sturny et al. (2007) found that more soil water was being preserved and continually delivered to plant roots in NT than in MP in the Oberacker long-term field experiment.

5. Conclusions

This study examined the effect of 20 years of no-till and conventional tillage with mouldboard ploughing in the Oberacker long-term field experiment (slightly humic sandy loam, temperate climate) on crop yield and nutrient and soil organic carbon concentrations in the soil profile. The nutrient distributions in NT showed strong stratification, with higher concentrations in the topsoil layers for TotN, K and Mg. The considerable accumulation of nutrients at the soil surface in NT was probably due to fertilisation in combination with omission of soil tillage and retention of crop residues on the surface. In NT, P and Ca were rather uniformly distributed in the soil profile, but with a trend towards maximum concentrations at around 20 cm depth. In MP, the depth distribution of all nutrients was uniform within the topsoil, due to mixing caused by soil tillage. The total storage of nutrients in the whole soil profile was similar between NT and MP for all nutrients, despite the significantly different nutrient profiles. The SOC concentration was significantly higher in the uppermost soil layers in NT than in MP, but total C storage in the 0–50 cm profile did not differ between NT and MP. Hence, the results show that 20 years of NT have not increased soil C stocks, supporting earlier findings in similar climate conditions. The overall average crop yield was 2.6% higher in NT than in MP, although the difference was not significant. However, significantly higher yields were obtained in NT for winter cereals (winter wheat, winter barley) and legumes (field beans, peas), while potatoes yielded significantly less in NT than in MP. Lower yields in NT than in MP were also obtained for sugar beet, but the difference was not significant. These results show that NT can produce crop yields that are at a similar level or even exceed the yields under MP, if a good crop rotation is used and crop residues are left on the surface. We presume that the high crop yields in NT in the Oberacker long-term field experiment are due to the well-balanced crop rotation, the use of cover crops and the focus on yield optimisation of the whole crop rotation rather than yield maximisation of individual crops.

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