Soil chemical properties as affected by tillage and crop rotation in a long-term field experiment

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ABSTRACT

Long-term field experiments are important for explaining tillage and rotation effects on soil fertility and to develop sustainable nutrient management strategies. An experiment was established in 1996 in Raasdorf (Austria) on chernozem with four tillage treatments (mouldboard ploughing (MP); no-till; deep conservation tillage and shallow conservation tillage) and two crop rotations. Soil samples were taken in November 2003 from 10 cm soil layers down to 40 cm to assess the effects on pH, carbonate content ($CaCO_3$), soil organic carbon (SOC), total nitrogen (N_t), potentially mineralizable N (PMN) and plant-available phosphorus (P) and potassium (K). Soil pH and $CaCO_3$ were not affected by soil tillage. SOC, N_t, PMN, P and K increased in the uppermost soil layer with reduced tillage intensity. SOC, N_t, P and K were more evenly distributed in MP whereas a generally higher decline downwards the soil profile was observed with lower tillage intensity. Lower tillage intensity resulted in a decrease of P and K in 30–40 cm. Rotation affected pH and K distribution in the soil whereas the other parameters were not affected.

Keywords: pH; carbonate; soil organic carbon; nitrogen; phosphorus; potassium

Long-term field experiments are important for explaining tillage and rotation effects on soil fertility and to develop nutrient management strategies. Tillage systems can be generally categorized in plow tillage, reduced tillage using chisel plow, disc plow, harrow disc or cultivators and no-till systems using direct drilling in untilled soil. There is worldwide an increasing interest in conservation agriculture systems due to their economic and environmental benefits for farmers, environment and society. Economic benefits may arise from lower drought susceptibility due to higher plant-available soil water content resulting in higher yield stability, the saving of labor and fuel and higher economic returns. Ecological benefits include the increase of soil organic carbon (SOC), biotic activity, soil porosity, agro-ecological diversity and less soil erosion and carbon emissions (due to less fuel consumption) (Derpsch et al. 2010). Soil tillage is influencing soil chemical characteristics, carbon sequestration and nutrient distribution (West and Post 2002, López-Fando and Pardo 2009, Houx et al. 2011). On a short-term scale, tillage operations mainly affect nutrient dynamics through altering of physical properties of the soil and by incorporating crop residues and mineral or organic fertilizers. On a long-term scale, the short-term effects accumulate; thereby an additional system effect builds up (Pekrun et al. 2003).

The aim of this study was to assess the influence of four different soil tillage systems and two crop rotations on soil chemical parameters and the nutrient stratification in the soil layers seven years after establishing a field trial on a chernozem in eastern Austria.

MATERIAL AND METHODS

Experimental site. The long-term experiment was carried out in Raasdorf (48°14'N, 16°33'E; altitude: 153 m a.s.l.) in eastern Austria on the experimental farm of the BOKU University. Raasdorf is located close to the east of Vienna, Austria, on the edge of the Marchfeld plain, an important crop production region in the north-western part of the Pannonian Basin. The silty loam soil is classified as chernozem of alluvial origin and is rich in calcareous sediments. The mean annual temperature is 10.6°C and the mean annual precipitation is 538 mm (1980–2009).

Experimental design. The split-plot design involves two factors: tillage system is assigned to the main plots (24 × 40 m) and crop rotation to the subplots (12 × 40 m). Performed fertilization is crop-specific according to good agricultural practice. The experiment was established in August 1996 with four replications.

The tillage treatments include: (1) Mouldboard ploughing (MP) after harvest to a soil depth of 25–30 cm. The crumbled and loosened soil is turned over and thereby residues are fully incorporated into the soil. (2) No-till (NT): Direct drilling in un-tilled soil with a disc drill without previous removal of residues. A total herbicide is sprayed before sowing for weed control. (3) Deep conservation tillage (CTd) to a soil depth of 20–25 cm using a wing share cultivator. A part of the plant residues remains on the soil surface. (4) Shallow conservation tillage (CTs) to a soil depth of 8–10 cm using a wing share cultivator. A high share of the plant residues remains on the soil surface.

Two crop rotations are performed. Winter wheat was included three times in each rotation, catch crops twice. Sugar beat was included twice in rotation A and oilseed rape twice in rotation B (Table 1).

Soil sampling and sample preparation. Soil sampling was performed with soil probes (Purckhauer type, core diameter: 30 mm) in depths of 0–10, 10–20, 20–30 and 30–40 cm on November 5th, 2003. A mixed sample was composed per plot for each sampled layer consisting of 20 equally sized, discrete sub-samples randomly collected from across the individual plots. Samples were air-dried, homogenized and sieved (2-mm). Crops grown before sampling were harvested on October 20th, 2003 (maize) and on June 23rd, 2003 (oilseed rape).

Soil analysis. Soil pH was measured in a 1:2.5 (w/v) soil to 0.01 mol/L $CaCl_2$ suspension after 12 h with a glass electrode. Stirring was performed after filling and before determination (ÖNORM L 1083). Calcium carbonate ($CaCO_3$) was measured through volumetrically released CO_2 of dry soil samples treated with 10% HCl (ÖNORM L 1084).

Soil organic carbon (SOC) and total-N (N_t) were analysed by dry combustion using an elemental analyser (CNS-2000, LECO Corp., St. Joseph, USA) at temperatures of 650°C (SOC) (ÖNORM L 1080) and 1250°C (N_t) (ÖNORM L 1095). The potentially mineralizable N (PMN) was measured by anaerobic incubation of the dry soil for 7 days at 40°C (Kandeler 1993). Determination of plant-available phosphorus (K) and potassium (P) was performed after extraction with calcium-acetate-lactate (ÖNORM L 1087); K was determined by flame photometry (Model 410, Sherwood Scientific Ltd, Cambridge, UK) and P was determined by the molybdenum-blue method (Murphy and Riley 1962) using a spectrophotometer (Skalar San Plus autoanalyser, Skalar, Breda, Netherlands).

Table 1. Crops grown in the tillage trial in Raasdorf from 1996–2003

	Crop rotation	
	A	B
1996		(phacelia)
1997	sugar beet	maize
1998	winter wheat (mustard)	winter wheat
1999	sunflower	oilseed rape
2000	winter wheat (phacelia + oilseed radish)	winter wheat (phacelia + oilseed radish)
2001	sugar beet	soybean
2002	winter wheat	winter wheat
2003	maize	oilseed rape

Crops in brackets are catch crops

Statistical analysis. Statistical analyses were performed using software SAS version 9.2 (Cary, USA). Analysis of variance (PROC MIXED) was performed and means were separated by least significant differences (*LSD*), when the *F*-test indicated factorial effects on the significance level of $P < 0.05$.

RESULTS AND DISCUSSION

Soil pH increased with soil depth. Different tillage systems for seven years had no effect on pH (Table 2). Our findings are consistent with those reported by Aase and Pikul (1995) for a sandy loam soil after 12 year of different tillage. Anyhow, López-Fando and Pardo (2009) reported in the uppermost soil layer a lower pH for NT than for MP after 5 years attributing this to acidifying processes as mineralization of organic matter, nitrification of surface-applied N fertilizer and root exudation; for 20–30 cm depth, they reported a higher pH for NT than for MP.

The soil pH in of 0–10 cm and 10–20 cm depth in rotation B showed slightly but statistically significant lower values than in rotation A. Crop rotation may affect pH through rhizosphere processes and

Table 2. Soil pH, calcium carbonate ($CaCO_3$) content and plant-available phosphorus (P) and potassium (K) for mouldboard ploughing (MP), no-till (NT), deep (CTd) and shallow conservation tillage (CTs)

Depth (cm)	0–10	10–20	20–30	30–40	Mean	0–10	10–20	20–30	30–40	Mean
	pH ($CaCl_2$)					$CaCO_3$ (%)				
Tillage										
MP	7.56	7.58	7.59	7.60	7.58	13.8	13.5	13.7	14.8	14.0
NT	7.54	7.58	7.60	7.61	7.58	13.4	13.0	13.8	15.3	13.9
CTd	7.54	7.59	7.59	7.61	7.58	14.2	14.2	14.1	15.4	14.5
CTs	7.56	7.56	7.59	7.61	7.58	14.2	14.3	14.4	17.4	15.1
Mean	7.55	7.58	7.59	7.61		13.9	13.7	14.1	15.9	
Rotation										
A	7.57	7.59	7.60	7.62	7.60	13.9	13.9	14.2	16.0	14.6
B	7.53	7.56	7.58	7.60	7.57	13.8	13.6	13.8	15.4	14.2
Effect		Pr > F	*LSD*				Pr > F	*LSD*		
Tillage										
Rotation		**	0.02							
Depth		***	0.02				***	0.7		
	P (mg/kg)					K (mg/kg)				
Tillage										
MP	69	69	70	53	66	151	172	167	108	150
NT	86	79	75	41	70	438	237	132	75	220
CTd	83	77	76	57	73	368	277	179	96	230
CTs	82	68	69	38	63	390	194	121	76	195
Mean	79	74	72	47		336	220	150	89	
Rotation										
A	80	73	73	47	68	345	209	139	83	193
B	82	74	72	47	69	329	231	161	94	204
Effect		Pr > F	*LSD*				Pr > F	*LSD*		
Tillage (T)							***	23		
Rotation (R)										
Depth (D)		***	3				***	15		
T × D		**	10				***	32		
R × D							**	21		

**$P < 0.01$; ***$P < 0.001$. Blank values indicate no significant effect ($P > 0.05$). Omitted interactions are not significant crop residues. Root-mediated pH changes in the rhizosphere depend on initial pH, plant species and nutritional constraints to which plants can respond (Hinsinger et al. 2003). Kotková et al. (2008) reported a pronounced acidification in the rhizosphere of oilseed rape grown in a Cambisol whereas pH increased in the rhizosphere of winter wheat. A decrease of pH is among the short-term chances of soil properties which can result during decomposition of crop residues due to production of organic acids and microbial respiration (Hulugalle and Weaver 2005). Consequently, the lower pH in rotation B could result from oilseed rape root exudates and on-going decomposition of oilseed rape residues whereas this process might be negligible in rotation A where sampling was performed shortly after maize harvest.

Calcium carbonate increased with depth with the highest values in 30–40 cm depth (Table 2). No tillage effect on $CaCO_3$ was also reported by Fernández-Ugalde et al. (2009) whereas Moreno et al. (2006) observed that the loss of $CaCO_3$ was notably reduced by conversation tillage due to greater retention of water in the soil profile.

Plant-available phosphorus was affected by tillage (T) × depth (D) interaction and plant-available potassium (K) was affected by the interactions of T × D and rotation (R) × D (Table 2). Both elements were more uniformly distributed in the soil profile in MP due to the more thorough mixing of the soil by ploughing.

NT, CTd and CTs resulted in higher P in the uppermost soil layer (0–10 cm) compared to MP whereas NT and CTs had lower P than MP and CTd in of 30–40 cm depth. According to the Austrian fertilization guidelines (BMLFUW 2006), P was sufficiently available except for NT and CTs in 30–40 cm depth where plant-available P was low.

K was available in 0–10 cm depth as follows: NT > CTs, CTd > MP with CTs showing slightly higher values than CTd; in a depth of 30–40 cm, MP had higher K contents than the other treatments with CTd showing slightly higher values than CTs and NT. Thus, K was sufficient in 0–10 cm depth for MP and very high for NT, CTd and CTs; in 10–20 cm depth K was sufficient for MP and CTs and high for NT and CTd; in 20–30 cm K was sufficient and in 30–40 cm K was low for all treatments (BMLFUW 2006).

Results indicate that an accumulation of P and K with reduced tillage (NT and CTs) occurs in the upper soil layers and depletion in the deepest sampled soil layer over time. NT resulted in 0–10 cm depth in a 1.25-fold increase of P and in a 2.90-fold the increase of K compared to MP; in 10–20 cm depth, increase was 1.14-fold for P and 1.38-fold for K. Contrary to that, P and K levels were 23% and 31%, respectively, lower in NT than in MP in 30–40 cm depth. Similar observations are reported by Houx et al. (2011) for the upper soil layer in an 18-year old tillage experiment on a silt loam; but contrary to our findings, no differences between MP and NT below plough depth were reported.

Soil organic carbon was affected by T × D interaction whereas rotation had no effect (Table 3). The SOC in the upper three layers of MP were in a similar range; NT and CTs showed a distinct downwards decline of SOC whereas this decrease was less pronounced in CTd. Differences in SOC between tillage treatments were highest in the uppermost soil layer where they were ranked as follows: NT > CTs > CTd > MP. The Austrian fertilization guidelines (BMLFUW 2006) classify the humus content (SOC × 1.72) as low: < 2%, medium: 2–4.5% or high: > 4.5%. Thus, NT and CTs enhanced SOC in the upper soil layer to high level of humus categorization. The increase of SOC in reduced tillage systems may make these systems more sustainable over the long-term (Salinas-Garcia et al. 1997) as thereby CO_2 is sequestered; a global data analysis indicated that carbon sequestration rates peak in 5 to 10 years with a change from MP to NT and SOC reaching a new equilibrium in 15 to 20 years (West and Post 2002).

Total-N was significantly influenced by T × D but no rotation effect was observed (Table 3). N_t was higher in 0–10 cm than in 20–30 cm depth in NT and the CTs whereas no differences were observed in MP and CTd.

Tillage affected potentially mineralizable N (PMN) in 0–10 cm depth with NT, CTs and CTd showing higher values than MP (Table 3). The PMN is classified as low: < 35, medium 35–75 or high: > 75 mg N 1000 g/soil/7 days (BMLFUW 2006). Thus, the PMN was low for MP, in the upper range of medium for NT and CTd and high for CTs. Also Doran (1987) and Martín-Lammerding et al. (2013) reported a higher PMN in the uppermost soil layer in no-till compared to ploughed soil. Plant residues that accumulate on the soil surface in no-till and conservation tillage systems are important sources for mineralizable N (Willson et al. 2011). The PMN is positively correlated with SOC, soil organic nitrogen (Romanyà et al.

Table 3. Soil organic carbon (SOC), total nitrogen (N_t) and potentially mineralizable N (PMN) for mouldboard ploughing (MP), no-till (NT), deep (CTd) and shallow conservation tillage (CTs)

	SOC (%)					N_t (%)			PMN (mg/kg/7 days)	
Depth (cm)	0–10	10–20	20–30	30–40	mean	0–10	20–30	mean	0–10	
Tillage										
MP	2.26	2.31	2.27	2.12	2.24	0.194	0.195	0.194	24.8	
NT	2.70	2.43	2.24	2.11	2.37	0.231	0.198	0.214	72.8	
CTd	2.48	2.44	2.36	2.13	2.36	0.220	0.206	0.213	62.6	
CTs	2.63	2.38	2.23	2.02	2.30	0.231	0.192	0.211	81.4	
Mean	2.52	2.39	2.27	2.09		0.219	0.198			
Rotation										
A	2.49	2.38	2.26	2.10	2.30	0.216	0.196	0.206	60.4	
B	2.54	2.40	2.30	2.09	2.34	0.222	0.199	0.211	60.4	
Effect		Pr > F	*LSD*			Pr > F	*LSD*		Pr > F	*LSD*
Tillage (T)						**	0.011		***	19
Rotation										
Depth (D)		***	0.08			***	0.008		–	
T × D		***	0.16			**	0.016		–	

**$P < 0.01$; ***$P < 0.001$. Blank values indicate no significant effect ($P > 0.05$). Omitted interactions are not significant

2012) and microbial biomass in the soil (Doran 1987). Contrary to Martín-Lammerding et al. (2013), no rotation effect was observed on PMN. Salinas-Garcia et al. (1997) have shown that N dynamics are dependent on substrate availability from crop residues. However, differences in quality and availability of residues at the time of soil sampling did not result in differences between the two rotations.

In conclusion, crop rotation caused an alteration of plant-available P and K, SOC, N_t and PMN after seven years whereas no influence on pH and $CaCO_3$ was observed. Rotation affected pH and K distribution in the soil. Thus, a clear differentiation of tillage systems is visible already after seven years.

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