Tillage effects on soil organic carbon and nutrient availability in a long-term field experiment in Austria

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Auswirkungen unterschiedlicher Bodenbearbeitung auf organische Substanz und verfügbare Nährstoffe im Boden in einem Langzeitversuch in Österreich

1 Introduction

Due to economic pressure surfaces under conservation tillage systems are increasing compared to those still under conventional ploughing methods. A number of ploughless tillage systems have been developed in the last decades with less tillage intensity and/or a reduced depth of tillage. They result in an accumulation of crop residue at the surface and to a reduced fertiliser distribution in the soil. As a consequence an alteration of soil conditions occurs. Most important is an increase in soil organic carbon (SOC) in the top soil and effects on the stratification of nutrients (Salinas-Garcia et al. 2002, Zibilske et al. 2002). Soil organic carbon is regarded as an eminent indicator of soil quality

Zusammenfassung

In einem Langzeitversuch auf einem sandigen Tschernosem wurden die Auswirkungen von drei unterschiedlichen Bodenbearbeitungssystemen auf ausgewählte Bodenparameter wie Organische Substanz (SOC), Gesamt-N (N_t), potentielle N-Mineralisation, CAL-löslicher Phosphor und Kalium und den pH ($CaCl_2$)-Wert als Indikatoren für die Bodenfruchtbarkeit untersucht. In diesem 1988 angelegten Feldversuch wurden eine Variante der Minimalbodenbearbeitung mit Frässaat (MT), eine reduzierte Bodenbearbeitungsvariante mit Grubber (RT) und eine konventionelle Bearbeitung mit Pflug (CT) verglichen. Die Bodenanalysen, die zwischen 1998 und 2007 durchgeführt wurden, zeigten eine Akkumulation von SOC, N_t, potentiell mineralisierbarem N und pflanzenverfügbarem P und K in 0–10 cm Bodentiefe in den MT- Parzellen verglichen mit den CT-Parzellen. Die Gehalte der RT-Variante nahmen eine Mittelstellung ein. Die Gehalte an organischem Kohlenstoff zeigten in den Parzellen der Minimalbodenbearbeitung im Versuchszeitraum eine zunehmende Tendenz, während sie in der RT- und der CT-Variante leicht abnahmen. Gesamt-N zeigte ein ähnliches Muster wie SOC. Die potentielle N-Mineralisation nahm in der Reihenfolge MT>RT>CT ab. Neunzehn Jahre nach Beginn des Feldversuches war CAL löslicher Phosphor von der Gehaltsklasse mit ausreichender Versorgung (97 mg kg^{-1}) durch Minimalbodenbearbeitung in die Gehaltsklasse mit sehr hoher Versorgung (179 mg kg^{-1}) und in der RT-Variante (auf 119 mg kg^{-1}) in die Gehaltsklasse mit hoher Versorgung angehoben worden (gemäß den Österreichischen Richtlinien). Parallel dazu stieg der Gehalt an CAL löslichem K von ursprünglich 178 mg kg^{-1} (ausreichende Versorgung) in der MT-Variante auf 405 mg kg^{-1} (sehr hohe Versorgung) und in der RT-Variante auf 285 mg kg^{-1} (hohe Versorgung). Mit der konventionellen Pflugvariante blieben die P-Gehalte mit 100 mg kg^{-1} und die K-Gehalte mit 134 mg kg^{-1} in der ursprünglichen Gehaltsklasse (ausreichende Versorgung). In der Untersuchungsperiode waren die pH ($CaCl_2$)-Werte in 0–10 cm in der MT-Variante am niedrigsten, allerdings betrug die maximale Differenz zwischen den Varianten nur bis zu 0.1 pH-Einheiten. In Bodentiefen zwischen 10 cm und 60 cm konnten bei den untersuchten Parametern kaum statistisch signifikante Unterschiede zwischen den Bodenbearbeitungsverfahren nachgewiesen werden. Aus der Anreicherung der untersuchten Nährstoffe N, P und K in der obersten Bodenschicht bei Minimalbodenbearbeitung (MT) kann bei Weiterführung der Versuchsanlage eine auf die einzelnen Kulturen abgestimmte Reduzierung der Düngeraufwandmengen abgeleitet werden.

Schlagworte: Bodenbearbeitung, C_{org}- and N-Dynamik, Phosphat, Kalium.

Summary

Long-term field experiments are important tools to study the effects of soil management systems on soil fertility. A long-term field experiment on a fine-sandy loamy Haplic Chernozem was conducted to investigate the influence of three different tillage treatments on selected soil parameters such as soil organic carbon (SOC), total N (N_t), potential N mineralisation, CAL-extractable P and K and pH ($CaCl_2$) as indicators for soil fertility. The experiment was established in 1988 and compares minimum tillage with a rotary driller (MT), reduced tillage with a cultivator (RT) and conventional ploughing (CT). Analyses carried out on soil samples taken between 1998 and 2007 showed accumulations of SOC, N_t, potentially mineralisable N and available P and K in the upper 10 cm of the MT plots compared to CT. Intermediate results were obtained in the RT plots. In the MT plots the SOC contents tended to increase during the experiment in contrast to RT and CT, where organic C tended to decrease. Total N showed a pattern similar to SOC. The potential N mineralisation decreased in the order MT>RT>CT. Nineteen years after the beginning of the field experiment, CAL soluble P increased from 97 mg kg^{-1} (sufficient supply according to the Austrian guidelines) to 179 mg kg^{-1} (very high supply) at MT and 119 mg kg^{-1} (high supply) at RT. CAL soluble K increased from 178 mg kg^{-1} (sufficient) to 405 mg kg^{-1} (very high) with MT and 285 mg kg^{-1} (high) with RT. With conventional ploughing the P and K levels remained within the initial sufficient supply class (P: 100 mg kg^{-1}, K: 134 mg kg^{-1}). In the period of investigation the soil pH in 0–10 cm in this soil was lowest in MT, however the greatest differences between the variants did not exceed 0.1 pH units. Few statistically significant results were observed between tillage systems at soil depths of 10–60 cm. Due to the accumulation of the nutrients N, P and K in the uppermost soil layer with MT a reduction of fertilisation – adjusted to the crop needs – can be deduced.

Key words: Soil cultivation, C_{org}- and N-dynamics, Phosphate, Potassium.

(DIAZ-ZORITA and GROVE, 2002) and influences soil chemical, physical and biological properties. It has impacts on the cation exchange capacity of soils, improves soil structure and aggregate stability, influences water content, aeration and temperature of the soils (TEBRÜGGE et al. 1997). An increase of SOC leads to enhanced enzymatic and microbial activities (KANDELER et al. 1999). Increasing SOC stocks in agricultural soils are assumed to mitigate CO_2 emissions (MRABET et al. 2001). DERSCH and BÖHM (2001) come to the conclusion that minimum tillage can result in a supplementary carbon storage. However, the storage of carbon in topsoil results only in a mid-term sequestration. If management practices in the short term are changed, these carbon amounts might be a source of additional CO_2 emissions in the future. CHAN and HULUGALLE (1999) state that the imposition of intensive tillage practices in previously untilled soils leads to a rapid breakdown of organic matter connected with a deterioration in physical quality of the soils. KÖRSCHENS et al. (2002) emphasise the threat of N-losses with elevated C_{org} contents.

Less intensive tillage with plants covering the soil almost throughout the whole year helps to decrease the danger of N-losses to the ground water (SPIEGEL et al. 2002). Several authors have reported that different tillage systems heavily affect potential nitrogen mineralization due to surface accumulation of crop residues (SALINAS-GARCIA et al., 2002, FRANZLUEBBERS et al., 1994).

However, it is important to evaluate the potential as well as the limitations of different tillage practices under site specific conditions. Changes occur with different speed. Therefore, long-term field experiments and the possibility to analyse a number of parameters as indicators for soil quality over a certain period are a helpful tool to evaluate changes due to management alteration as comprehensive as possible. Different tillage systems also influence soil biological activities as arbuscular mycorrhizae (JANSA et al., 2003) and earthworms (ANKEN et al., 2004). Several authors have investigated changes in plant nutrients and pH with different tillage measures (LIMOUSIN and TESSIER, 2007; THOMAS et al., 2007).

The objective of these investigations was to study the long term effects of two systems of conservation tillage – reduced tillage with a cultivator (RT) and minimum tillage with a rotary driller (MT) – compared with a conventional ploughing system (CT) on chemical soil parameters. We determined SOC, N_t, potential N mineralisation, CAL soluble K and P and pH as indicators for soil quality and followed their changes due to tillage within different soil depths. These parameters are analysed also in soil routine analyses and give information about soil fertility and the nutrient status to the farmers.

2 Materials and methods

2.1 Sites and treatments

In 1988 a field experiment was designed in Fuchsenbigl, Lower Austria, to study the effect of different tillage systems (conventional, reduced and minimum) on chemical, physical and microbial soil parameters and plants. The soil is classified as a fine-sandy loamy Haplic Chernosem (clay 22 % , silt 41 % , sand 37 %). On average, soils on this site had a pH of 7.6, 13 % carbonate content, 1.19 % organic C and 0.16 % total N in 0–30 cm. The mean long-term annual temperature is 9.4 °C and the mean long term annual precipitation is 529 mm. The field experiment consisted of a randomised block design with three replicates, the plots measuring 60 m x 12 m (= 720 m^2). The design of the long-term field experiment is given in Figure 1. Fertilisation was done according to the Austrian guidelines for fertilisation (BMLF, 1999). Table 1 shows the crops, the amounts of mineral fertilisers and the yields during 1998–2005. The N was applied in the form of calcium ammonium nitrate, P in the form of triple super phosphate and K in the form of KCl. All crop residues remained in the field. Yields were not different between the tillage treatments, except in 1998 and 2005.

Minimum tillage
Conventional tillage
Reduced tillage
Conventional tillage
Reduced tillage
Minimum tillage
Conventional tillage
Minimum tillage
Reduced tillage

Figure 1: Scheme of the tillage field experiment in Fuchsenbigl
Abbildung 1: Schema des Bodenbearbeitungsversuch Fuchsenbigl

The following tillage treatments were investigated:

The conventional tillage (CT) treatment consisted of regular mouldboard ploughing to 25–30 cm soil depth in autumn. The plough turned the soil over to incorporate crop residues, crumbled and loosened it. At the same date or in spring the seed bed was prepared with a zig-zag drag harrow and a crumbling roller immediately before sowing.

In the reduced tillage (RT) treatment the soils were treated with a cultivator in autumn to a depth of 15–20 cm. The soil was loosened and mixed, but not turned over. At the same date or in spring the seed bed was prepared with a zig-zag drag harrow and a crumbling roller immediately before sowing.

Minimum tillage (MT) plots were treated with a rotary-driller without any primary treatment before sowing cereals in autumn or in spring. The rotovator loosened the soil to a depth of 5–8 cm and whirled it up into the air. The soil

Table 1: Crops, fertilisation and yields of the experimental site Fuchsenbigl during 1998–2005. Different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)
Tabelle 1: Fruchtarten und Düngung am Bodenbearbeitungsversuch Fuchsenbigl 1998 bis 2005

Year	Crop	Fertiliser (kg ha^{-1})			Yields (t ha^{-1})		
		N	P	K	MT	RT	CT
1998	Spring wheat	100	26	50	3.17 a	2.78 a	3.02 a
1999	Spring barley	50	20	75	3.76 a	5.18 b	5.43 b
2000	Winter wheat	120	22	42	2.69 a	2.69 a	3.00 a
2001	Sugar beet	100	39	149	63.32 a	60.31 a	63.21 a
2002	Spring wheat	100	22	42	3.08 a	3.04 a	2.72 a
2003	Maize	120	28	125	6.95 a	6.33 a	7.03 a
2004	Winter wheat	120	0	0	5.24 a	4.98 a	5.13a
2005	Spring wheat	100	22	42	2.44 b	2.10 a	2.50 b

fell upside down, covering the seed (which was precisely broadcasted before) and incorporated crop residues.

As far as sugarbeet and maize are concerned the soil was treated with a rotary in spring, the seed was sown directly by machine immediately afterwards.

2.2 Soil sampling and pretreatment

Soil samples were collected yearly in March or April (before fertilizer application) at depths of 0–10, 10–20 and 20–30 cm over a period of 10 years (normally 1998–2007). In 2001 also samples from 30–40 and 40–60 cm soil depth were drawn. Each type of tillage was replicated 3 times. On each plot, 16 sub-samples were taken with a single-gouge auger (cores of 30 mm diameter), these were mixed and stored in plastic bags. For the analyses the soil samples were air-dried and sieved < 2mm.

2.3 Soil analyses

The pH ($CaCl_2$) value was determined by glass electrode (soil : 0.01 M $CaCl_2$ at 1:2.5). SOC and total-N (N_t) were analysed by dry combustion in a LECO 2000 at temperatures of 650°C (SOC) and 1250°C (N_t). Only the initial values of SOC (1989) were determined by wet combustion (method WALKLEY and BLACK, 1934) and converted by a conversion factor of 1,44 (average ratio of $C_{org\ dry}/C_{org\ wet}$, based on 180 comparing measurements of soils from the experimental site described above). Potential nitrogen mineralisation on dried soils was measured from 2000 to 2007 by the anaerobic incubation method (KEENEY, 1982), modified according to KANDELER (1993). Extractable P and K were determined with CAL (calcium lactate/acetate) according to SCHÜLLER (1969).

Soil bulk density was calculated from dry weight (105 °C) after core sampling in March 2001 from each treatment and was used to convert soil chemical properties from a mass to a volume basis (BLAKE, 1965).

2.4 Statistical procedure

All analytical results were given as arithmetic means of results from three plots. If initial values existed (from 1989), these are shown in the figures. Statistical analyses were carried out with a multiple analysis of variance and subsequent multiple range tests (Tukey's honest significant difference). All calculations were performed using the SPSS package.

3 Results and discussion

3.1 Soil organic carbon

Different tillage methods caused significant differences in SOC mainly in 0–10 cm soil depth (Figure 2a). Between 1998 and 2007 SOC in 0–10 cm was highest in the MT plots with the trend (linear regression not shown) to increase. In contrast at RT and CT a trend of decreasing SOC concentrations was observed. Thus the differences in SOC between MT on the one hand and RT and CT on the other hand enlarged. After 19 years of the experiment MT resulted on average in 31 % larger SOC-concentrations than at RT and CT plots in 0–10 cm. No treatment effect occurred in samples taken in the 20–30 cm layer, except significantly lower SOC at RT compared to CT in 2002 and 2004 (Figure 2b).

The distribution of SOC stocks with depth to 60 cm after 13 years of experiment is shown in Figure 3. The results revealed that in the ploughed plots SOC is evenly distributed over 0–30 cm. The cultivator mixes the soil to a depth of 15 cm, the highest SOC in 20–30 cm in this treatment is due to the high bulk density (not shown), probably caused by compaction under the horizon of cultivation. MT showed the most distinct SOC gradient, because most of the residues are concentrated in the first 10 cm.

Averaged over the depth of 0–30 cm, SOC stocks were significantly higher at MT (28.4 t ha^{-1}) and RT (27.7 t ha^{-1}) versus CT (24.8 t ha^{-1}), average SOC stocks from 0–60 cm did not differ between the treatments. MRABET et al. (2001) and HERNANZ et al. (2002) observed higher SOC contents in the surface horizons under minimum and zero tillage, without any depletion at deeper horizons compared to more intensively tilled treatments. Subsurface organic C depletion, as observed for no till treatments by several other authors, e.g. ZIBILSKE et al. (2002), did not occur in this field experiment in Lower Austria. HUTCHINSON et al. (2007) reported about contradictory observations regarding the impact of reduced tillage on soil C.

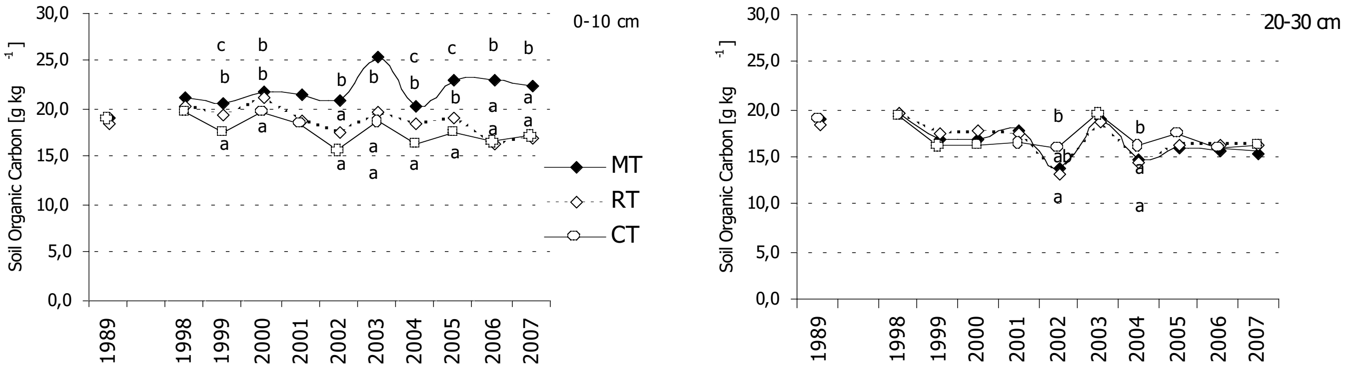

Figure 2: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on Soil Organic Carbon (SOC, g kg^{-1}) in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 1998–2007. Different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey). 1989: initial values in 0–25 cm

Abbildung 2: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf den Gehalt an C_{org} (g kg^{-1}) in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 1999–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey). Die Werte 1989 zeigen die zu Versuchsbeginn gemessenen Anfangsgehalte in 0–25 cm Bodentiefe

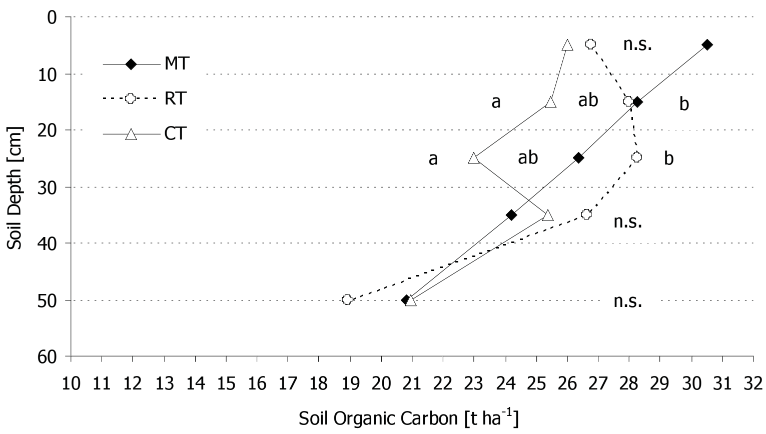

Figure 3: Vertical distribution of SOC (t ha^{-1}) after 13 years of minimum (MT), reduced (RT) and conventional (CT) tillage. At each depth different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 3: Vertikale Verteilung von C_{org} (t ha^{-1}) nach einer Versuchsdauer von 13 Jahren bei minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung. Verschiedene Buchstaben in derselben Bodentiefe zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

3.2 Total nitrogen and potential nitrogen mineralisation

Soil nitrogen is closely related to soil organic carbon and, therefore, tillage-induced changes in N_t followed similar pattern as SOC. Due to the accumulation of crop residues near the soil surface, N_t contents in 0–10 cm were significantly larger in MT plots compared to RT and CT. As it was stated for SOC also N_t showed a tendency (linear regression not shown) to increase with time at MT while it remained unchanged with RT and CT (Figure 4). Thus the gap between soil N_t contents of the management practice with shallow tillage once a year (before sowing) and those of recurred tillage after the harvest (stubble breaking, incorporation of weeds) increased. In 20–30 cm N_t revealed no clear trend in all described years of investigation. Larger N_t contents in the upper soil layer with minimum tillage were reported from several researchers at various locations (UNGER, 1991, SALINAS-GARCIA et al. 2002). In 2001 N_t stocks showed a uniform distribution with depth under plough and cultivator and the greatest decrease at MT (Figure 5).

C/N ratios (not shown) did not reveal statistically significant differences over the investigation period.

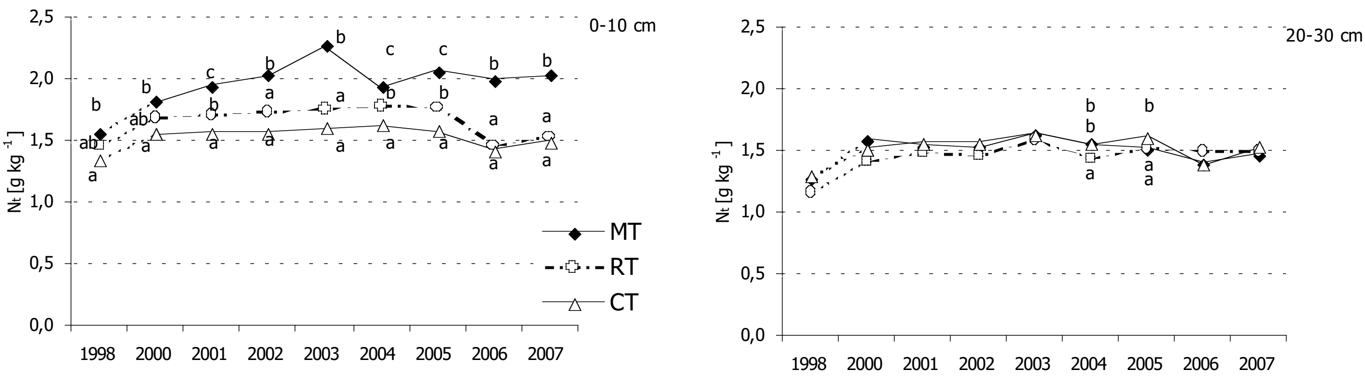

Figure 4: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on the total N content (N_t, g kg^{-1}) in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 1998–2007. Different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 4: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf den Gehalt an N_t (g kg^{-1}) in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 1998–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

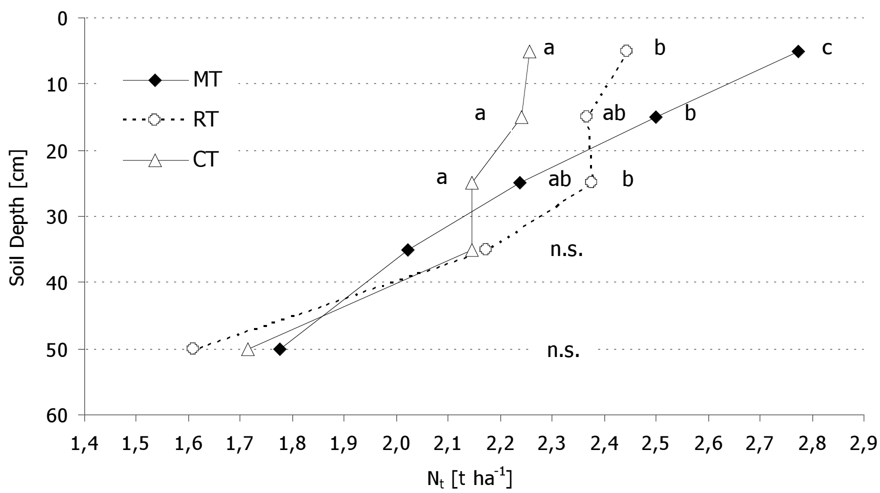

Figure 5: Vertical distribution of N_t (t ha^{-1}) after 13 years of minimum (MT), reduced (RT) and conventional (CT) tillage. At each depth different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 5: Vertikale Verteilung von N_t (t ha^{-1}) nach einer Versuchsdauer von 13 Jahren bei minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung. Verschiedene Buchstaben in derselben Bodentiefe zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

Besides influencing N_t, different tillage systems affected N dynamics in the soil. The potential N mineralisation in 0–10 cm was significantly larger at MT compared to RT and CT soils due to the accumulation of organic substances (Figure 6). In 2001–2007 N mineralisation at MT was classified as high (> 70 mg N kg^{-1} 7 d^{-1}), according to the classification of the Austrian guidelines (BMLFUW, 2006). This indicated large contents of easily decomposable organic matter in these soils. In contrast, potential N mineralisation was classified as low to medium (≤ 35 and 35–70 mg N kg^{-1} 7d^{-1}, respectively) in the ploughed plots. In the 20 to 30 cm layer, N mineralisation rates were highest in the CT plots in 2000 (with smaller differences between the treatments than in the uppermost layer). KANDELER et al. (1999) accounted buried organic material for this matter of fact. However, larger SOC and N_t were not always detected at CT in this soil depth. This confirms former findings (e.g. FRIEDEL et al., 1996, TSCHERKO and KANDELER, 1999), that microbial analyses are more sensitive indicators for management changes than element contents. No significant differences could be detected in the subsoil below 30 cm (not shown).

MRABET et al. (2001) supposed that higher N_t values near the soil surface under reduced tillage compared with conventional ploughing lead to the incorporation of N in microbial biomass. From this it follows that N is initially less available for mineralisation and leaching. This could be one reason why the danger of soil N losses by seepage water was significantly lower in MT plots, as could be deduced from smaller NO_3-N und NH_4-N contents in the soil of our experiment (SPIEGEL et al., 2002). A more important reason could have been that mineralised N might immediately have been taken up by the plant cover in the MT plots in contrast to the ploughed and cultivated plots.

On the other hand DALAL et al. (2007) did not find any significant effect on the amount of presowing NO_3-N in the soil profile over a 10-year period between NT and CT practices.

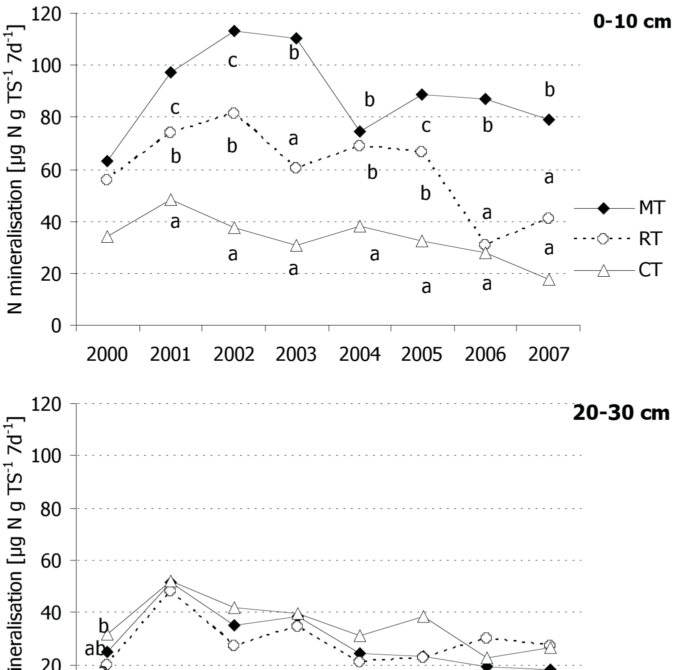

Figure 6: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on the N- mineralisation (µg N g DM^{-1} $7d^{-1}$) in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 2000–2007. Different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 6: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf die N-Mineralisierung (µg N g TS^{-1} $7d^{-1}$) in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 2000–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

3.3 Extractable soil potassium and phosphorus

The results of soil P and K analyses in 0–10 cm (see Figures 7 and 8) showed that in 2007, nineteen years after the beginning of the field experiment, soil P and K contents in MT (P: 179 mg kg^{-1}, K: 405 mg kg^{-1}) as well as in RT (P: 119 mg kg^{-1}, K: 285 mg kg^{-1}) increased the supply class to very high and high, respectively. Initial values (P: 97 mg kg^{-1}, K: 178 mg kg^{-1}) were situated in the "sufficient" supply class according to the Austrian guidelines (BMLFUW, 2006), see Figures 7 and 8. A similar development can be observed, if the averages of the first two soil depths were compared (0–20 cm is the soil layer to which the guidelines refer to). With MT this accumulation of nutrients near the soil surface was probably caused by the lack of incorporation of the mineral fertilisers used and of the crop residues. With ploughing the P and K levels remained within the initial "sufficient" supply class. In 20–30 cm P_{CAL} and K_{CAL} were similar in all three variants, in some years P_{CAL} and K_{CAL} were even significantly higher with CT (Figures 7 and 8).

Figures 9 and 10 show the depth distribution of CAL-soluble P and K stocks thirteen years after the beginning of the field experiment. In the uppermost soil layer P_{CAL} was 50 % higher with MT and K_{CAL} twice as high as with ploughing, RT showed intermediate contents. Higher stocks in the second layer of RT compared with CT are in each case connected with the depth of disturbance under the studied tillage systems.

With ploughing, crop residues and fertilisers were incorporated and mixed to a depth of approximately 30 cm. Underneath the plough layer (30–40 cm) P_{CAL} showed higher levels in the CT plots (Figure 9). The P_{CAL} and K_{CAL} stocks of the last investigated soil depth 40–60 cm were not affected by different tillage.

A depletion of nutrients in MT and RT from this layer is possible, because plant roots extracted the nutrients. A "mining" of P from lower soil depths and retention in upper depths in conservation systems were also reported by ZIBILSKE et al. 2002.

The strong increase of P_{CAL} and K_{CAL} in 0–10 cm at MT and RT compared to CT could also be explained by a slower transfer of the added nutrients from the readily available pool to the slowly available pool (according to JOHNSTON et al., 2001) and the shallow depth of disturbance.

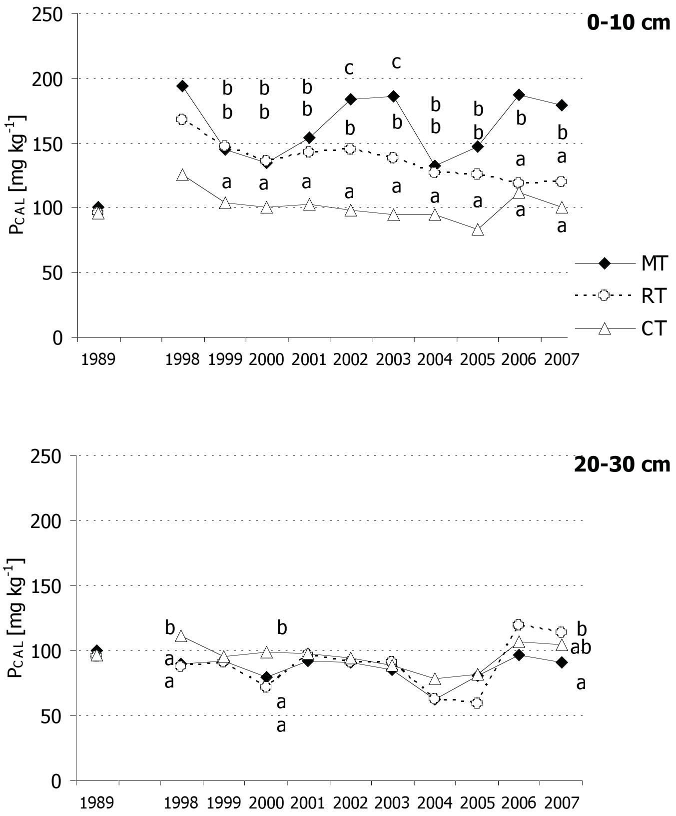

Figure 7: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on P_{CAL} (mg kg^{-1}) in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 1999–2007. Different letters indicate significant differences between treatments at the p < 0.05 level (Tukey). 1989: initial values in 0–25 cm

Abbildung 7: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf die P_{CAL}-Gehalte (mg kg^{-1}) in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 1999–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau P < 0.05 (Tukey). Die Werte 1989 zeigen die zu Versuchsbeginn gemessenen Anfangsgehalte in 0–25 cm Bodentiefe

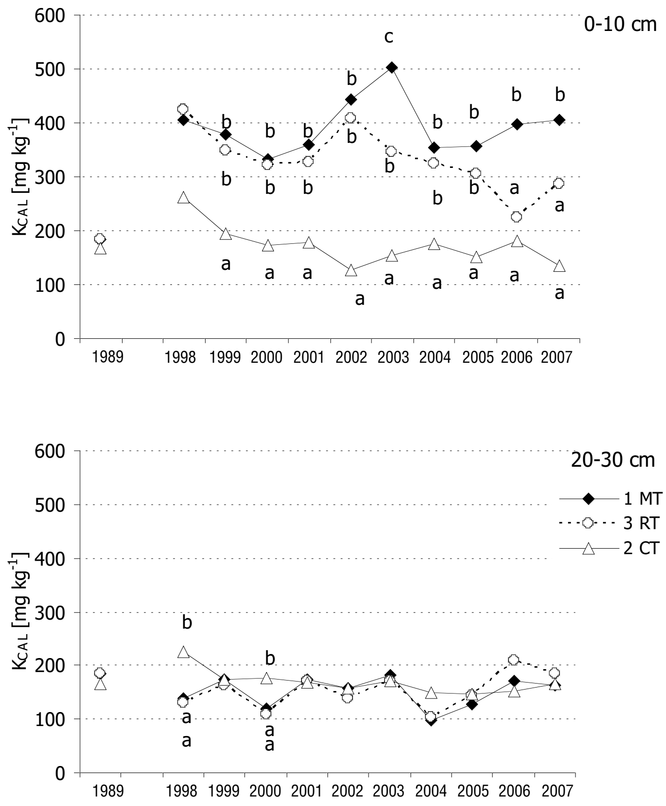

Figure 8: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on K_{CAL} (mg kg^{-1}) in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 1998–2007. Different letters indicate significant differences between treatments at the p < 0.05 level (Tukey). 1989: initial values in 0–25 cm

Abbildung 8: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf die K_{CAL}-Gehalte (mg kg^{-1}) in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 1998–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau P < 0.05 (Tukey). Die Werte 1989 zeigen die zu Versuchsbeginn gemessenen Anfangsgehalte in 0–25 cm Bodentiefe

3.4 pH ($CaCl_2$)

pH values in the period of investigation ranged from 7.3 to 7.9, which is due to the calcareous parent material of the soil (loess). Eleven years after the beginning of the experiment, the soil pH in 0–10 cm was lowest in MT, in some years the differences to the other treatments were statistically significant ($p < 0.05$), (Figure 11). This could be due to the accumulation of organic matter on the soil surface, increased microbial biomass and microbial processes (KANDELER et al., 1999) and thus an enhanced production of carbonic and organic acids. Also the missing incorporation of the slightly acidifying P- and K-fertilisers may possibly have contributed to this effect. However, it must be stated, that generally pH-differences were quite low and the temporal spread was larger than that of the treatments.

With depth (Figure 12) pH showed a more distinct gradient in the MT plots than in the ploughed soils after 13 years of investigation due to the depth of disturbance. Some researcher observed a decrease of soil pH near the soil surface at MT (e.g. MAILLARD et al., 1994, SALINAS-GARCIA et al., 1997, RASMUSSEN and ARSHAD, 1999, MRABET et al. 2001, LIMOUSIN and TESSIER, 2007), others did not (ED-

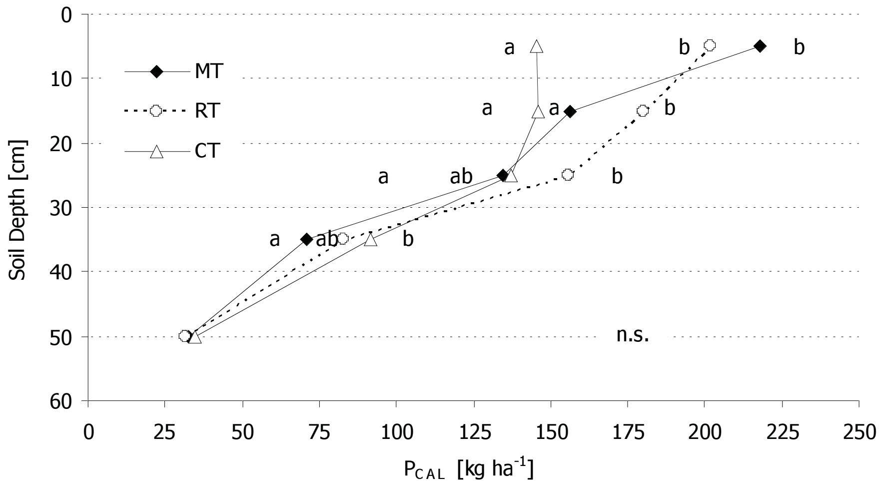

Figure 9: Vertical distribution of P_{CAL} (kg ha^{-1}) after 13 years of minimum (MT), reduced (RT) and conventional (CT) tillage. At each depth different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 9: Vertikale Verteilung der P_{CAL}-Gehalte (kg ha^{-1}) nach einer Versuchsdauer von 13 Jahren bei minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung. Verschiedene Buchstaben in derselben Bodentiefe zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

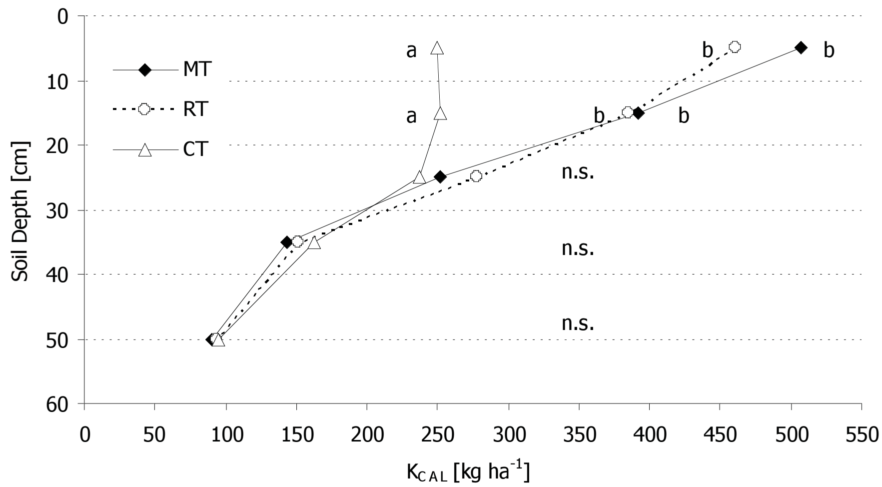

Figure 10: Vertical distribution of K_{CAL} (kg ha^{-1}) after 13 years of minimum (MT), reduced (RT) and conventional (CT) tillage. At each depth different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 10: Vertikale Verteilung der K_{CAL}-Gehalte (kg ha^{-1}) nach einer Versuchsdauer von 13 Jahren bei minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung. Verschiedene Buchstaben in derselben Bodentiefe zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

WARDS et al. 1992, HULUGALLE et al. 1999). These different results depended on various factors (site, soil and plant).

4 Conclusions

Based on the investigated soil parameters, an assessment of soil fertility leads to the following findings: After nineteen years in the MT treatment a distinct accumulation of organic substance and plant available P and K as well as the highest potential N mineralisation near the soil surface have occurred. A possible higher risk of leaching (especially N and P) is assumed to be compensated by the nutrient uptake of the permanent plant cover at this variant.

If tillage is reduced to a minimum, an adjustment of fertilisation (depending on the crop needs) should be considered to avoid nutrient losses to the ground water in the future.

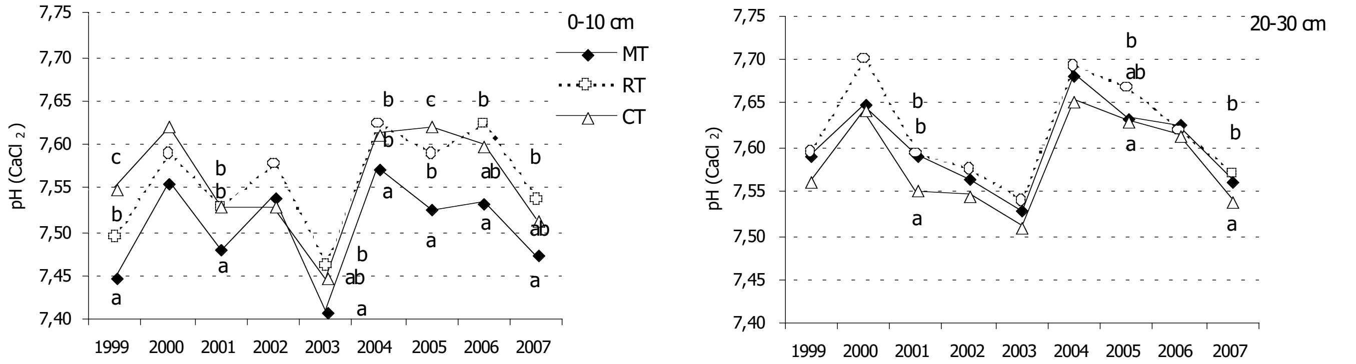

Figure 11: Effect of minimum (MT), reduced (RT) and conventional (CT) tillage on pH-value in (a) the 0–10 cm soil layer and (b) the 20–30 cm soil layer during 1999–2007. Different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 11: Auswirkungen mehrjähriger minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung auf die pH-Werte in (a) 0–10 cm Bodentiefe und (b) 20–30 cm Bodentiefe von 1999–2007. Verschiedene Buchstaben zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

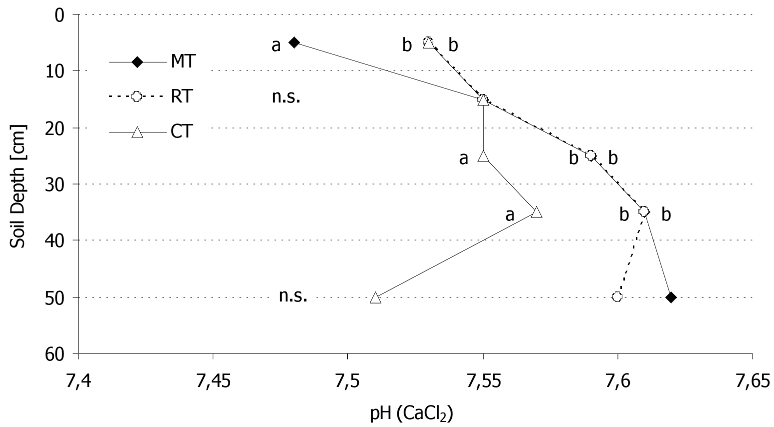

Figure 12: Vertical distribution of pH after 13 years of minimum (MT), reduced (RT) and conventional (CT) tillage. At each depth different letters indicate significant differences between treatments at the $p < 0.05$ level (Tukey)

Abbildung 12: Vertikale Verteilung der pH-Werte nach einer Versuchsdauer von 13 Jahren bei minimaler (MT), reduzierter (RT) und konventioneller (CT) Bodenbearbeitung. Verschiedene Buchstaben in derselben Bodentiefe zeigen signifikante Unterschiede an, Signifikanzniveau $P < 0.05$ (Tukey)

More frequent tillage measures with the plough and the cultivator show a tendency for decreasing levels of organic substance in the long term and therefore lower carbon sequestration. Enhanced C stocks, as detected in the 0–30 cm soil layer with MT compared to RT and CT, contribute to diminish CO_2 emissions. However, we have to bear in mind, that these gains in SOC as well as the other investigated soil quality parameters can deteriorate if proper management is not maintained. Regular soil investigations are necessary to identify the changes. The analysed parameters, which can also be used by farmers to control soil fertility measures, have been proven satisfactory indicators for soil fertility.

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