ELSEVIER

Soil & Tillage Research 52 (1999) 91–101

Soil & Tillage Research

www.elsevier.com/locate/still

Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany

N. Stockfisch[a], T. Forstreuter[b], W. Ehlers[b,*]

[a]*Institute of Sugar Beet Research, Holtenser Landstr. 77, D-37079 Göttingen, Germany*

[b]*Institute of Agronomy and Plant Breeding, Georg-August-University, Von-Siebold-Str. 8, D-37075 Göttingen, Germany*

Received 19 June 1998; received in revised form 4 November 1998; accepted 14 June 1999

Abstract

Conservation tillage may concentrate organic matter and carbon in the soil, thus improving soil quality and counteracting CO_2-increase in the atmosphere. In parts of Germany however, continuous conservation tillage can cause problems in soil and crop management, resulting in a need to shift to short-term conventional tillage, such as mouldboard ploughing. The objective of the present research was to follow the fate of soil organic matter, when soil is ploughed after long-term minimum tillage in the temperate climate of Lower Saxony. In minimum tillage, shallow cultivation was restricted to stubble cleaning and seedbed preparation, using a rotary harrow or rototiller. After 20 years of shallow cultivation, soil organic carbon, soil nitrogen and microbial biomass carbon were concentrated in the top 5 cm of a loess-derived silt loam (Orthic Luvisol). In the 50 cm soil profile, mass of soil organic carbon tended to be higher by about 5 Mg ha^{-1} as compared to conventionally ploughed soil, which contained roughly 65 Mg ha^{-1}. In the ploughed soil, soil nitrogen amounted to about 6.8 Mg ha^{-1}, whereas in the minimum tilled soil it was roughly 1.0 Mg ha^{-1} higher. Total microbial biomass carbon fluctuated between 800 and 1300 kg ha^{-1}, the differences between tillage systems being less distinct. Ploughing the old minimum tilled land destroyed the stratification of soil organic matter. Moreover, during the winter months (November–March) the surplus of soil organic carbon and nitrogen masses, enriched by conservation tillage, was completely decomposed, presumably a consequence of its labile quality. Inverting the minimum tilled soil did not increase concentrations of organic carbon and nitrogen in the lower part of the A_p-horizon, but it did increase concentration of microbial biomass carbon. We conclude that organic matter stratification and accumulation as a result of long-term minimum tillage were completely lost by a single application of inversion tillage in the course of a relatively mild winter. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Mouldboard ploughing; Conservation tillage; Soil organic matter; Soil nitrogen; Microbial biomass; Organic matter decomposition

1. Introduction

In temperate agroecosystems, conservation tillage like minimum tillage (MT) usually changes soil organic matter distribution in the A_p-horizon compared to conventional tillage (CT). The CT is characterized by a relatively deep tillage that either disrupts (chisel plough, cultivator) or inverts (mouldboard plough) the arable top soil. On the other hand, MT represents any form of tillage with low application frequency and tillage depth (rotary harrow, rotavator)

* Corresponding author. Tel.: +49-551-394357; fax: +49-551-399355.

0167-1987/99/$ – see front matter © 1999 Elsevier Science B.V. All rights reserved.
PII: S0167-1987(99)00063-X

that retains a soil-protecting mulch cover on the surface. Inversion tillage results in a more or less even distribution of soil organic matter in the top soil, but in MT the most conspicuous effect is the concentration of organic matter in the surface soil (0–5 cm) (Staley et al., 1988). Depending on crop rotation, fertilization level, residue input rate and former land-use, the tillage system not only varies the concentration and distribution of organic matter in the top soil, but it also changes the total amount on an area related basis. In many, but not in all instances (Angers et al., 1997), the amount of organic matter increased with the application of conservation tillage (Rasmussen and Collins, 1991; Paustian et al., 1997). In a German loess-derived silt loam, the cumulative increase in the top 30 cm layer was estimated at 7 Mg ha^{-1} of soil organic C and 0.4–0.6 Mg ha^{-1} of soil N, attained after 8–10 years of continuous zero-tillage (Ehlers and Claupein, 1994). Enrichment of organic matter will improve soil quality and counteract soil erosion. Moreover, the C sequestration by minimum tillage is thought to counteract the increase in atmospheric CO_2-concentration that will contribute to global warming (Lal, 1997).

Microbial biomass in the soil is an essential part of soil organic matter and consists of living microorganisms. In contrast to inversion tillage, crop residues in minimum tillage are left on or near the soil surface, where they undergo decomposition. Due to the concentrated C-input in the top few cm, microbial biomass C increases near the soil surface. The microbial biomass C increases much more readily due to changes in the tillage system or residue supply than total organic C (Carter, 1986; Jörgensen, 1995). The ratio of biomass C to total organic C is a measure of C availability (Anderson and Domsch, 1986), where a high ratio indicates an anticipated accumulation of organic matter, long before the actual accumulation can be measured (Anderson and Domsch, 1989; Woods, 1989; Carter, 1991).

Accumulation and stratification of soil organic matter in MT soils is widely documented. Far less documented is the change in organic matter, when MT is reverted to CT. Campbell et al. (1995) observed in Saskatchewan a decline in soil organic C, when no-till soil was tilled with a cultivator to 5–10 cm depth. A 15 cm deep disk-harrowing of short-term no-till land in Georgia reduced the organic C content in the top 1.5 cm, but hardly changed the content in the 1.5–8 cm layer (Bruce et al., 1995). In Michigan a single mouldboard ploughing to 20 cm depth lowered organic C content in the top 5 cm of long-term no-till soil, while between 5 and 20 cm depth the content increased (Pierce et al., 1994). Very similar experiences with short-term mouldboard ploughing of zero-tilled soil were reported from Alberta (Larney et al., 1997).

Non-inversion tillage like MT may cause problems in the long run in more humid parts of Germany, including residue massing on the soil surface, and infestation with weeds, fungal diseases or pests like slugs and mice. Ploughing is a remedy for these problems with the likely consequence of a decline in organic matter content. The magnitude of this change is unknown for German conditions.

The aim of the present research was to evaluate soil organic C, N and microbial C distribution and their total mass, following mouldboard ploughing a field, which had been under minimum tillage for 20 years. The proportion and rapidity of change of organic matter constituents may influence the decision when to restart conservation tillage after occasional ploughing.

2. Materials and methods

2.1. Site description

A long-term field experiment was established in 1974 in temperate climate (Fig. 1) near Goettingen (Lower Saxony, Germany, 51°30′N, 9°56′E) to study the effect of two contrasting tillage systems on soil characteristics and plant performance. Before 1974 the soil had been mouldboard ploughed for many years. The field consisted of a randomized complete block design with four replicates, the plots measuring 49 m × 18 m. The silt loam soil was a Typic Hapludalf (USDA) or Orthic Luvisol (FAO) derived from loess, with a texture (A_p-horizon) of 160 g kg^{-1} clay (<2 μm), 690 g kg^{-1} silt (2–60 μm) and 150 g kg^{-1} sand (60–2000 μm).

The CT consisted of regular mouldboard ploughing to 25 or 30 cm depth in fall. The MT consisted of shallow cultivation (6–8 cm) with rotary harrow or rototiller for stubble cultivation and seedbed preparation. Out of 21 years, for 15 years small grains were grown, but winter rape (*Brassica napus* L.) (2 years),

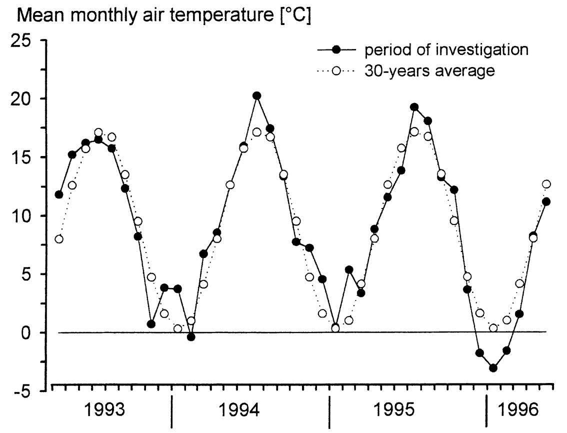

Fig. 1. Mean monthly temperature during the period of investigation as compared to the long-term average. The mean annual temperature at Goettingen is 8.7°C and the mean annual precipitation 645 mm (30-years' average 1961–1990). (Deutscher Wetterdienst, 1993–1996).

sugar beet (*Beta vulgaris* L.), field pea (*Pisum sativum* L.), faba bean (*Vicia faba* L.) and maize (*Zea mays* L.) (all for 1 year) were also cultivated. The average over time of grain or white sugar yield in MT was 98.2% of CT, indicating a nearly identical yearly C input rate for organic matter maintenance in both tillage systems.

This study was conducted from 1993 to 1996 (Table 1) under four consecutive crops, i.e., winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), phacelia (*Phacelia tanacetifolia* Benth.) and winter wheat. On 3 November 1994, the MT plots were broken by mouldboard ploughing to about 30 cm depth. Additional agronomic measures and the yield obtained during this investigation period are listed in Table 1.

2.2. Soil sampling and analyses

For determination of soil bulk density down to 30 or 50 cm depth, undisturbed 100 cm^3 core samples of 5.4 cm in diameter were taken from three plot replicates of MT and CT in April and November 1993 and in March 1994. Six cores were sampled from each depth, except from the top 0 to 5 cm layer, where 10 soil cores were taken in order to take into account higher spatial variability (Stockfisch, 1997). Soil cores were dried at 105°C and bulk density was calculated from net dry weight.

For analysis of soil organic C, soil N and microbial biomass C, additional soil samples (2 cm diameter) were taken with an auger in April 1993, March 1994 and October 1994. After the last sampling the entire

Table 1
Field management operations throughout the study period (CT: conventional tillage; MT: minimum tillage; yield is based on dry matter)

Year	Month	Field operations
1992	November	Sowing of winter wheat
1993	April	Beginning of study
	August	Harvest of winter wheat[a], straw chopped and left on the field. Stubble tillage with rototiller to a depth of 7 cm
	September	Tillage: CT-plots ploughed to a depth of 27 cm. Seedbed preparation: CT-and MT-plots with rotary harrow (7 cm depth) sowing of winter barley
1994	July	Harvest of winter barley[b], straw removed from the field
	September	Stubble tillage with rotary harrow (7 cm depth)
	November	Tillage: CT- and MT-plots ploughed to a depth of 30 cm. Field left as complete fallow over winter
1995	May	Sowing of phacelia ('green fallow')
	July	Phacelia killed chemically[c]
	August	Cultivation with rotary harrow (5 cm depth)
	September	Tillage: CT-and former MT-plots ploughed to a depth of 27 cm. Seedbed preparation: rotary harrow (7 cm depth) sowing of winter wheat
1996	May	End of study

[a] Wheat yield (grain/straw in Mg ha^{-1}): CT: 5.0/5.9; MT: 5.2/5.8.
[b] Barley yield (grain in Mg ha^{-1}): CT: 6.3; MT: 5.2.
[c] Phacelia (above ground mass in Mg ha^{-1}): approximately 5.0.

experimental field, including the MT plots, was mouldboard ploughed in November 1994 (Table 1). The first sampling after breaking up the former MT plots took place in March 1995. Soil sampling was continued in October 1995 and May 1996. Auger samples were subdivided into 0–2.5, 2.5–5, 5–10, 10–15, 15–20, 20–30, 30–40 and 40–50 cm layers. Each plot sample was the composite of 6–8 cores. Mixed soil samples were split and either air dried for analysis of organic C and total N or sieved (3 mm) in field moist condition and kept refrigerated at 4°C for the determination of microbial biomass C.

Total C and N content of ground soil samples were measured by dry combustion (vario EL, elementar, Hanau, Germany). Carbonate C as part of total C was determined using a Scheibler-apparatus. Following addition of hydrochloric acid, CO_2 was measured volumetrically.

The microbial biomass C was determined from moist soil (minimum 60% water holding capacity; 15 g dry soil equivalent) using the chloroform-fumigation-extraction-method (Vance et al., 1987). Dissolved organic C in soil extracts was measured with a continuous-flow-analyzer (Flow solution III, Perstorp Analytical Environmental, Wilsonville, OR, USA) using the UV-persulfate oxidation technique of carbonaceous compounds. The biomass C was calculated from the gain in dissolved organic C after fumigation multiplied by 2.22 (Wu et al., 1990).

The mass of organic matter constituents was calculated for individual soil layers using the average over time of the measured bulk density. After breaking MT, the bulk density values were taken from CT. Average bulk density from single layers was also used for calculation of total soil mass in CT and MT down to 50 cm depth.

2.3. Statistical analysis

Statistical analysis was carried out using the Statistical Analysis System (SAS, release 6.11, SAS Institute Inc., Cary, NC). The SAS General Linear Model procedure was used for all calculations with differences significant at $p \leq 0.05$. Variances attributed to effects of tillage systems were considered for each sampling date separately (F-test). Likewise the variances attributed to time were evaluated for each of the two tillage systems separately. The analyses of concentrations were performed individually for single soil layers. The same procedure was followed for calculated masses within combined soil layers, employing the F-test and the Tukey-test.

3. Results

3.1. Organic matter concentration

The concentration profiles of soil organic C in October 1994 (Fig. 2) show an even distribution within the ploughed layer of CT (Fig. 2(a)), and a stratification in MT before breaking the MT soil (Fig. 2(b)). The concentration of organic C within the plough layer of CT varied between 11 and 12 g kg^{-1}, but in MT it increased to 17.5 g kg^{-1} in the surface layer (0–5 cm), which was significantly different from CT. In the subsoil beyond 30 cm depth the concentration decreased in both tillage systems, being generally not significantly different. After ploughing the MT soil, concentrations in March 1995 had diminished significantly in the top 20 cm layer (Fig. 2(b)), whereas in CT the concentrations had decreased uniformly but only slightly (Fig. 2(a)).

The concentration profiles of soil N (Fig. 3) are similar to the profiles of organic C in Fig. 2. Again concentrations decreased only on a small scale and

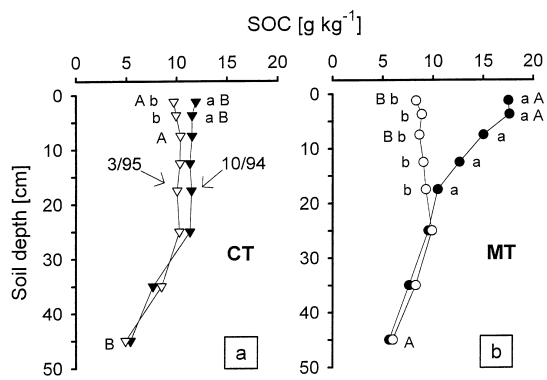

Fig. 2. Concentration profiles of soil organic carbon (SOC) of the conventionally tilled (CT) plots (a) and the minimum tilled (MT) plots (b) before (October 1994) and after (March 1995) breaking the MT plots. Small letters indicate a significant difference in time within a tillage system, capital letters a significant difference between the tillage systems at a fixed date. The analysis refers to individual soil layers.

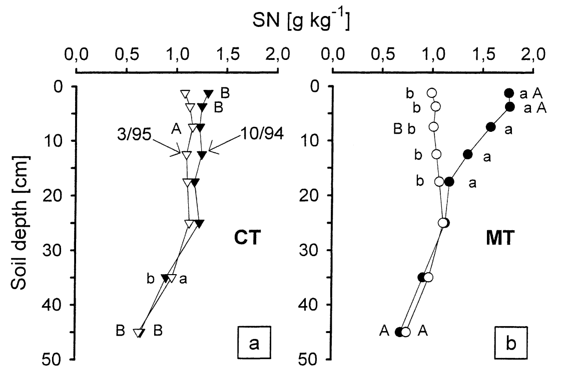

Fig. 3. Concentration profiles of soil nitrogen (SN) of the conventionally tilled (CT) plots (a) and the minimum tilled (MT) plots (b) before (October 1994) and after (March 1995) breaking the MT plots. Small letters indicate a significant difference in time within a tillage system, capital letters a significant difference between the tillage systems at a fixed date. The analysis refers to individual soil layers.

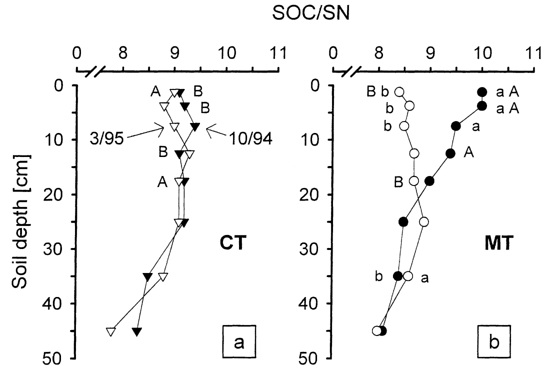

Fig. 5. Profiles of the ratio of soil organic carbon (SOC) to soil nitrogen (SN) of the conventionally tilled (CT) plots (a) and the minimum tilled (MT) plots (b) before (October 1994) and after (March 1995) breaking the MT plots. Small letters indicate a significant difference in time within a tillage system, capital letters a significant difference between the tillage systems at a fixed date. The analysis refers to individual soil layers.

insignificantly in 0–30 cm of CT between sampling dates (Fig. 3(a)), but in MT the concentration change due to ploughing was much more dramatic and significant (Fig. 3(b)).

In October 1994 microbial biomass C (Fig. 4) showed a distinct stratification in MT (Fig. 4(b)). The values decreased sharply with increasing depth. In contrast to total organic C or N, biomass C in 20–30 cm depth was significantly lower than in CT

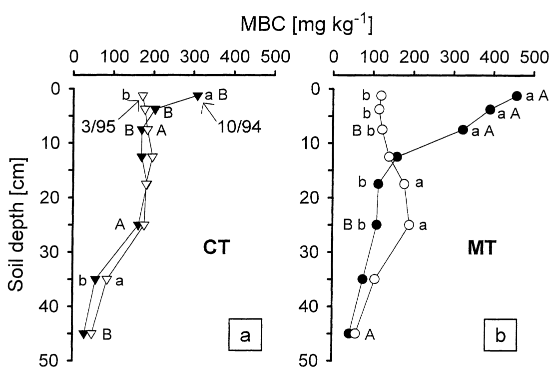

Fig. 4. Concentration profiles of microbial biomass carbon (MBC) of the conventionally tilled (CT) plots (a) and the minimum tilled (MT) plots (b) before (October 1994) and after (March 1995) breaking the MT plots. Small letters indicate a significant difference in time within a tillage system, capital letters a significant difference between the tillage systems at a fixed date. The analysis refers to individual soil layers.

(Fig. 4(a) and (b)). In the ploughed top 5 cm of CT, biomass C was also stratified (Fig. 4(a)). Between October 1994 and March 1995 concentrations changed only slightly in CT (Fig. 4(a)). In MT on the other hand, the ploughing up caused distinct alterations in the concentration profile (Fig. 4(b)). In the top 10 cm biomass C dropped significantly from fall to spring, attaining a concentration in the 5–10 cm layer significantly lower than in CT. Such a distinct decline due to ploughing was not observed in organic C (Fig. 2(a) and (b)) and N (Fig. 3(a) and (b)). This decline of biomass C was contrasted with a significant increase in the 15–20 cm and 20–30 cm layer (Fig. 4(b)), attaining the level of CT in March 1995 (Fig. 4(a)).

In the 0–30 cm layer of CT the organic C to N ratio varied around 9 (Fig. 5(a)), and decreased in the subsoil. In the 0–5 cm layer of MT the ratio approached the value of 10 in October 1994 (Fig. 5(b)), which was significantly different from CT. After ploughing up, the ratio decreased significantly to around 8.5.

The ratio of microbial biomass C to soil organic C is a measure of C availability to microorganisms. In CT the ratio was generally slightly higher in March 1995 than in October 1994, but not at 0–2.5 cm depth (Fig. 6(a)). Breaking MT caused a significant decrease of the ratio in the top 10 cm zone but a significant increase in the 15–30 cm zone (Fig. 6(b)).

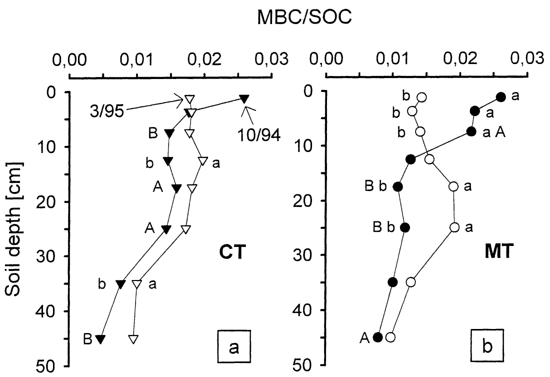

Fig. 6. Profiles of the ratio of microbial biomass carbon (MBC) to soil organic carbon (SOC) of the conventionally tilled (CT) plots (a) and the minimum tilled (MT) plots (b) before (October 1994) and after (March 1995) breaking the MT plots. Small letters indicate a significant difference in time within a tillage system, capital letters a significant difference between the tillage systems at a fixed date. The analysis refers to individual soil layers.

3.2. Bulk density

In the 0–5 cm layer of MT the bulk density was lower (Fig. 7(b)) than in CT (Fig. 7(a)), apparently the consequence of loosening MT by rotary harrow during stubble cultivation and seedbed preparation. In the center of the topsoil layer, however, bulk density was higher in MT than in CT. In the 25–30 cm layer of CT, the bulk density surpassed that of MT, indicating a tillage-traffic pan.

3.3. Mass of organic matter

Masses of organic matter constituents are based on their concentrations (Figs. 2–4) and the bulk density (Fig. 7) of individual soil layers. In the 0–50 cm soil profile of CT total mass of organic C ranged between 62 and 67 Mg ha^{-1} from April 1993 to May 1996 (Table 2). On average, the subsoil between 30 and 50 cm depth contained 29% of the total mass. Total mass tended to be higher in October 1994 and 1995 than in spring of 1993, 1995 and 1996 (Table 2). Before ploughing up MT, total mass of organic C in the 0–50 cm layer tended to be higher by 4–5 Mg ha^{-1} as compared to CT. Ploughing MT diminished significantly the mass to 86% of the original mass measured in April 1993 (Table 2). On the contrary in CT total mass of organic C varied only between 96% and 102% of the mass measured in April 1993. After ploughing, the total mass in MT fell below the level of CT by 2–3 Mg ha^{-1}, but differences were not significant.

The total mass of soil N in the 0–50 cm layer of CT ranged between 6.1 and 7.4 Mg ha^{-1} (Table 2). Very similar to organic C, again 29% of the mass of N was contained in the 30–50 cm layer, and also very much like organic C, the October values of soil N were (with one exception) significantly higher than the spring values. Before breaking MT by ploughing, MT seemed to conserve 0.7–1.3 Mg ha^{-1} more of N than

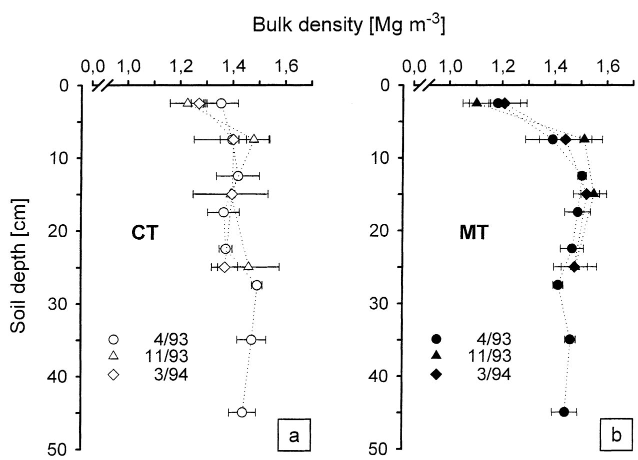

Fig. 7. Bulk density profiles of the conventionally tilled (CT) plots (a) and of the minimum tilled (MT) plots (b) at three dates before ploughing up MT. Bars indicate the standard deviation.

Table 2
Masses of soil organic carbon, soil nitrogen and microbial biomass carbon in the conventionally tilled (CT) plots and in the minimum tilled (MT) plots (directly after the sampling in October 1994 the MT plots (like the CT plots) were ploughed)

Tillage	Depth (cm)	Date						Mean[a] (%)
		4/93	3/94	10/94	3/95	10/95	5/96	
Soil organic carbon (Mg ha^{-1})								
CT	0–30	47.4 a	45.6 ab	47.9 a[c]	42.6 b	45.5 ab	43.8 ab	46 (71)
	30–50	17.6 b	n.d.[b]	19.1 ab	19.7 ab	20.6 a	19.6 ab	19 (29)
	0–50	65.0 a	n.d.	67.0 a	62.3 a	66.1 a	63.4 a	65 (100)
	0–50 (%)	100	n.d.	103	96	102	98	
	0–30	47.3 b	47.0 b	52.8 a	38.5 d	44.2 bc	42.0 cd	
MT	30–50	21.6 a	n.d.	19.3 a	20.8 a	20.2 a	19.3 a	
	0–50	68.9 ab	n.d.	72.1 a	59.3 c	64.4 bc	61.3 c	
	0–50 (%)	100	n.d.	105	86	93	89	
Soil nitrogen (Mg ha^{-1})								
CT	0–30	4.79 ab	5.01 ab	5.14 a B	4.69 b	4.98 ab	4.17 c	4.8 (71)
	30–50	1.43 b	n.d.	2.26 a	2.32 a	2.35 a	1.90 ab	2.0 (29)
	0–50	6.22 bc	n.d.	7.40 a	7.01 ab	7.33 a	6.07 c	6.8 (100)
	0–50 (%)	100	n.d.	119	113	118	98	
	0–30	5.04 ab	5.19 ab	5.76 a A[c]	4.42 bc	4.96 ab	4.00 c	
MT	30–50	2.45 a	n.d.	2.23 ab	2.51 a	2.36 ab	1.93 b	
	0–50	7.49 ab	n.d.	8.09 a	6.93 bc	7.32 ab	5.93 c	
	0–50 (%)	100	n.d.	108	93	98	79	
Microbial biomass carbon (kg ha^{-1})								
CT	0–30	769 ab	852 ab	762 ab	758 ab	648 b	1000 a	790 (81)
	30–50	127 b	n.d.	126 b	196 ab	143 ab	296 a	180 (19)
	0–50	896 b	n.d.	888 b	954 ab	791 b	1296 a	970 (100)
	0–50 (%)	100	n.d.	99	106	88	145	
	0–30	694 bc	761 bc	851 ab	655 bc	590 c	988 a	
MT	30–50	182 bc	n.d.	174 bc	241 ab	111 c	329 a	
	0–50	876 bc	n.d.	1025 b	896 bc	701 c	1317 a	
	0–50 (%)	100	n.d.	117	102	80	150	

[a] Mean without data from March 1994.
[b] Not determined.
[c] Means within rows followed by the same small letter are not significantly different in time within a tillage system. Capital letters within columns indicate a significant difference between tillage systems at a fixed date.

CT. After ploughing MT, the N masses approximated the values of CT (Table 2).

In CT the total mass of microbial biomass C in 0–50 cm depth amounted to 790 up to 1300 kg ha^{-1} (Table 2). On average, 19% was in the subsoil from 30 to 50 cm depth. In contrast to total organic C and N in CT, spring values of biomass C mass tended to be higher than the October values. Immediately before ploughing the old MT land, mass of biomass C seemed to be higher than in CT (Table 2). After ploughing, the mass of the former MT came close to the values of CT.

4. Discussion

4.1. Before ploughing minimum tilled soil

Conventional tillage like mouldboard ploughing mixes plant residues causing soil organic matter to be evenly distributed within the top soil (Figs. 2 and 3). Leaving plant material to the uppermost soil layer as with MT lowers the local accessability to soil micro-organisms. This may withhold the decomposition of the organic material and its transformation into humic substances. Decomposition and transformation processes may be slowed down additionally as compared to CT by lower temperatures near the soil surface during rainy seasons or by comparatively low water contents during dry weather. Conservation tillage also seems to protect part of organic matter in the top layer physically from mineralization by inclusion within macroaggregates. In CT, on the other hand, aggregates will be more thoroughly disrupted, assisting loss of organic matter (Beare et al., 1994). Whatever the reason is for decreased breakdown and transformation rates, the concentrations of soil organic C and N in MT increase steeply near the soil surface (Figs. 2 and 3). This result corresponds with an overwhelming number of reports from various climatic regions (Rasmussen and Collins, 1991).

Much more uncertain is the question whether the transition of any form of CT to a form of conservation tillage will increase the mass of soil organic matter per unit area, giving chance to sequester C and N in the soil profile in view of environmental concerns. The number of contributions on this subject is much lower, probably due to the practical difficulties related to soil sampling at depth. Quite often the observations on soil organic matter concentrations are confined to the top layers, sometimes extending to the depth of tillage. For a total mass evaluation in differently treated soils, it is important to extend the sampling depth to the subsoil, where soil organic matter contents will converge (see Fig. 2). Otherwise differences in the mass of organic matter due to soil management will be truncated by depth. Another prerequisite for mass evaluation on an area related basis is a reliable determination of bulk density profiles. Finally, comparisons in total stock should be made on an equivalent soil mass basis (Ellert and Bettany, 1995; Angers et al., 1997; Stockfisch, 1997), which differed in the 50 cm profile of MT (i.e. 721 kg m^{-2}) by less than 2% from CT (709 kg m^{-2}).

On eight sites in eastern Canada, total soil organic C and N reserves in 0–60 cm depth were not significantly different due to mouldboard ploughing as compared to conservation tillage practices (Angers et al., 1997). This was also true for crop yield and therefore probably for C input. However, on most sites there was a tendency for higher C and N masses in autumn mouldboard ploughed plots. On the contrary, on one site in Ontario with continuous maize and continuous spring wheat, a higher organic C mass was found under no-till, although the average yield was lower compared to ploughing. In the Canadian study, mass of organic C ranged from 27 to 115 Mg ha^{-1} and mass of total N from 3.6 to 10.1 Mg ha^{-1}, a range comprising the data in the present study (Table 2). Our study agrees with experiences from Ohio (Dick, 1983), Kansas (Havlin et al., 1990) and Kentucky (Ismail et al., 1994) that conservation tillage can increase the mass of organic C per unit area as compared to mouldboard ploughing (Table 2). In Germany, this apparent enrichment was attained, although the average yield was not higher than in conventional mouldbourd ploughing during the period from 1974 to 1994 (see Section 2.1).

Masses of soil organic C and N in the 0–30 cm or 0–50 cm layer of both tillage systems were generally higher in fall than in spring (Table 2). Both soil constituents will change in time with the supply of plant residues left on the soil surface (Havlin et al., 1990). The higher masses of soil organic matter in fall were probably produced by the previous crops, which usually contribute to the maintenance of organic matter by decaying stems, leaves and roots. In spring most of the incorporated plant residues have been decayed, bringing the masses of organic matter back near the long-term equilibrium. The large drop in mass of soil organic C between October 1994 and March 1995 in the regularly ploughed CT plots (Table 2) was probably caused by the removal of barley straw followed by bare fallow (Table 1).

The soil microbial biomass utilizes plant material mixed into the soil. From the contrasting profiles of microbial biomass C in the MT and CT systems (Fig. 4(a) and (b)) one may deduce that the high total organic C concentrations near the soil surface in MT will be maintained or that the enrichment will be even continued. On the other hand, in deeper MT layers (15–20 cm, 20–30 cm) low biomass C values indicate an on-going decline in the organic matter concentration. Here the ratio of biomass C to total organic C is relatively low (Fig. 6(b)), indicating a reduction in C available for the microbial biomass. In the top 10 cm of MT and the uppermost 0–30 cm layer of CT the ratio is much higher (Fig. 6(a) and (b)), which suggests C availability to be higher. Quite similar relations with microbial biomass C in contrasting tillage systems were reported from central USA (Doran, 1987; Staley et al., 1988) and from Prince Edward Island, Canada (Carter, 1991).

The comparatively high ratio of organic C to N in the top 5 cm of MT (Fig. 5) may be the consequence of a less advanced decomposition of organic matter. Several researchers have likewise reported on higher C to N ratios in the top soil with conservation tillage as compared to CT (Dick, 1983; Wood et al., 1991).

4.2. After ploughing minimum tilled soil

Ploughing under the 20 years old MT soil resulted in dramatic changes in organic matter concentrations (Fig. 2(b) and Fig. 3(b), Table 2). These changes within layers of the soil profile may be caused by redistribution or decomposition. Redistribution of soil material from upper horizons rich in organic matter should cause an enrichment in lower horizons. Within the 30 cm deep layer of MT, inverted by the mouldboard plough (Table 1), such signs of enrichment were not detectable, neither for organic C (Fig. 2(b)) nor for N (Fig. 3(b)). At later dates in October 1995 and May 1996, the concentration of organic C and N in the 20–30 cm layer also stayed at the same level (not shown). Table 2 explains that one single tillage operation on 3 November 1994 on MT plots caused the complete disintegration of all the organic matter that had been accumulated for 20 years. Ploughing up MT reduced the mass of soil N per area during five winter months to the level of CT. The mass of organic C was diminished to even lower levels than in CT (Table 2). The rapid decomposition might have been promoted by the mild temperatures that dominated the winter in 1994/1995. Monthly temperatures were higher than in winter 1993/1994 and 1995/1996 and higher than the long-term average (Fig. 1).

The microbial biomass C in MT showed a different reaction on ploughing up the soil. Turning the soil decreased concentrations in the upper soil layers dramatically (Fig. 4(b)), but increased concentrations in lower layers. In summary, the total mass of biomass C decreased insignificantly over winter 1994/1995 in ploughed MT, whereas the mass in CT slightly increased (Table 2).

Ploughing up MT diminished the ratio of organic C to N (Fig. 5(b)) and also the ratio of biomass C to total C (Fig. 6(b)) in the upper layers. The increased ratio of biomass to total C in the 15–20 cm and 20–30 cm layers, which was also observed in May 1996 (not shown), is thought to be an early indication of total C increase in these layers (Anderson and Domsch, 1989), if ploughing will be continued on the former MT. But on the other hand, the minor differences in total organic C levels between long-term CT and former MT (Fig. 2) calls this view in question.

The rapid and complete destruction of organic C accumulated in MT by one ploughing action happened unexpectedly. On the other hand, it is well known that after cultivation of permanent range and grassland organic matter decreases rapidly (Jenny, 1941). In northeast Colorado 60 years of cultivation (''clean'' tillage) of native rangeland (short-grass prairie steppe) caused a 62% reduction of organic C in the top 15 cm soil layer (Bowman et al., 1990). More than half of it was lost during the first three years of cultivation. The decline of potentially mineralizable C occurred still more rapidly (Bowman et al., 1990), most of which had been concentrated in the top 2 cm (Woods, 1989).

Larney et al. (1997) observed a percentage increase of a ''light'' fraction of organic C with a reduced specific gravity and of mineralizable N in zero-tilled soils in Alberta, which was greater than the increase in total organic C and N compared to CT. Recently Angers et al. (1993) from Québec reported that organic C, associated with the sand fraction, was enriched in conservation tillage systems as compared to mouldboard ploughing. This ''particulate'' organic C, rich on native grassland, was reduced much more by CT than by zero-till (Cambardella and Elliott, 1992). The particulate C fraction has a more rapid turnover rate than the C fractions associated with silt and clay. It is a more labile form of organic C (Angers et al., 1993), belonging to the 'slow' or 'decomposable' pools of organic matter (Cambardella and Elliott, 1992). This pool was increased by zero-till in the top 5 cm soil as compared to chisel ploughing in Alberta and British Columbia (Franzluebbers and Arshad, 1997). As particulate organic C combines greater potential decomposability with lower actual in situ decomposition, authors concluded that zero-till increases the residence time of this labile pool. This fraction contains a higher organic C to N ratio than the organic matter of silt and clay with greater microbial alterations (Amelung et al., 1998). The high ratio in our MT soil before ploughing up (Fig. 5(a,b)) supports the idea of an enrichment of particulate organic C under conservation tillage.

5. Conclusion

From this long-term field experiment it is concluded that silt loam soils in Germany will concentrate soil organic matter near the soil surface when inversion tillage is abandoned and conservation tillage is adopted. It is also concluded that this accumulated organic matter is of labile character as it decomposes rapidly and completely after re-starting mouldboard ploughing. This enriched fraction is more easily decomposable than other fractions of organic matter. Due to its surface position in MT soil the fraction is prevented from rapid disintegration due to less accessability and due to temperature and moisture fluctuations. When ploughed, these limitations are neutralized and microbial decomposition of the stored organic matter is rapid when weather conditions are favorable during exceptionally mild winter months in the temperate climate of Germany. Hence, periodic inversion tillage can readily destroy the surplus of organic matter accumulated during years of conservation tillage.

Acknowledgements

The authors thank Mrs. A. Bartlitz and Mrs. G. Kolle for their technical assistance. Mrs. W. Meyer was helpful in improving the English text.

References

Amelung, W., Zech, W., Zhang, X., Follett, R.F., Tiessen, H., Knox, E., Flach, K.-W., 1998. Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. Soil Sci. Soc. Am. J. 62, 172–181.

Anderson, T.-H., Domsch, K.H., 1986. Carbon link between microbial biomass and soil organic matter. In: Megusar, F., Gantar, M. (Eds.), Proceedings of the Fourth International Symposium on Microbial Ecology. Slovene Society for Microbiology, Ljubljana, Slovenia, pp. 467–471.

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

Angers, D.A., Ndayegamiye, A., Côté, D., 1993. Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Sci. Soc. Am. J. 57, 512–516.

Angers, D.A., Bolinder, M.A., Carter, M.R., Gregorich, E.G., Drury, C.F., Liang, B.C., Voroney, R.P., Simard, R.R., Donald, R.G., Beyaert, R.P., Martel, J., 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res. 41, 191–201.

Beare, M.H., Cabrera, M.L., Hendrix, P.F., Coleman, D.C., 1994. Aggregate-protected and unprotected organic matter pools in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 58, 787–795.

Bowman, R.A., Reeder, J.D., Lober, R.W., 1990. Changes in soil properties in a Central Plains rangeland soil after 3, 20 and 60 years of cultivation. Soil Sci. 150, 851–857.

Bruce, R.R., Langdale, G.W., West, L.T., Miller, W.P., 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. Am. J. 59, 654–660.

Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777–783.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Dyck, F.B., Selles, F., Curtin, D., 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. Can. J. Soil Sci. 75, 449–458.

Carter, M.R., 1986. Microbial biomass as an index for tillage-induced changes in soil biological properties. Soil Tillage Res. 7, 29–40.

Carter, M.R., 1991. The influence of tillage on the proportion of organic carbon and nitrogen in the microbial biomass of medium-textured soils in a humid climate. Biol. Fertil. Soils 11, 135–139.

Deutscher Wetterdienst, 1993–1996. Monatlicher Witterungsbericht 41–44. Offenbach/Main, Germany.

Dick, W.A., 1983. Organic carbon, nitrogen and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.

Doran, J.W., 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5, 68–75.

Ehlers, W., Claupein, W., 1994. Approaches towards conservation tillage in Germany. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, USA, pp. 141–165.

Ellert, B.H., Bettany, J.R., 1995. Methods to express the amounts of organic matter stored in soils under constrasting management regimes. Can. J. Soil Sci. 75, 529–538.

Franzluebbers, A.J., Arshad, M.A., 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Sci. Soc. Am. J. 61, 1382–1386.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claassen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54, 448–452.

Ismail, I., Blevins, R.L., Frye, W.W., 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58, 193–198.

Jenny, H., 1941. Factors of Soil Formation. McGraw-Hill, New York, 281 pp.

Jörgensen, R.G., 1995. Die quantitative Bestimmung der mikrobiellen Biomasse in Böden mit der Chloroform-Fumigations-

Extraktionsmethode (Quantitative determination of microbial biomass in soils by use of the chloroform-fumigation-extraction method). Göttinger Bodenkdl. Ber. 104, 229 pp.

Lal, R., 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2-enrichment. Soil Tillage Res. 43, 81–107.

Larney, F.J., Bremer, E., Janzen, H.H., Johnston, A.M., Lindwall, C.W., 1997. Changes in total, mineralizable and light fraction soil organic matter with cropping and tillage intensities in semiarid southern Alberta, Canada. Soil Tillage Res. 42, 229–240.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, USA, pp. 15–49.

Pierce, F.J., Fortin, M.-C., Staton, M.J., 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58, 1782–1787.

Rasmussen, P.E., Collins, H.P., 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. Adv. Agron. 45, 93–134.

Staley, T.E., Edwards, W.M., Scott, C.L., Owens, L.B., 1988. Soil microbial biomass and organic component alterations in a no-tillage chronosequence. Soil Sci. Soc. Am. J. 52, 998–1005.

Stockfisch, N., 1997. Strohabbau durch Mikroorganismen und Regenwürmer in zwei Bodenbearbeitungssystemen (Straw decomposition by microorganisms and earthworms in two tillage systems). Ph.D. Thesis, University of Göttingen. In: Agrarwissenschaftliche Forschungsergebnisse, Dr. Kovac Publ., Hamburg, 189 pp.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass. C. Soil Biol. Biochem. 19, 703–707.

Wood, C.W., Westfall, D.G., Peterson, G.A., 1991. Soil carbon and nitrogen changes on initiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55, 470–476.

Woods, L.E., 1989. Active organic matter distribution in the surface 15 cm of undisturbed and cultivated soil. Biol. Fertil. Soils 8, 271–278.

Wu, J., Joergensen, R.G., Pommerening, B., Chaussod, R., Brookes, P.C., 1990. Measurement of soil microbial biomass C by fumigation–extraction — an automated procedure. Soil Biol. Biochem. 22, 1167–1169.