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ORIGINAL PAPER

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Soil organic matter dynamics after the conversion of arable land to pasture

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Abstract Conversion of arable land (maize) to pasture will affect the soil organic matter (SOM) content. Changes in the SOM content were studied using a size- and density-fractionation method and ^{13}C analysis. Twenty-six years of maize cropping had resulted in a depletion of carbon stored in the macro-organic fractions ($>150\ \mu\text{m}$) and an increase in the $<20\ \mu\text{m}$ fraction. Maize-derived carbon in the upper 20 cm increased from 10% in the finest fraction ($<20\ \mu\text{m}$) to 91% in the coarse ($>250\ \mu\text{m}$), light (b.d. $<1.13\ \text{g cm}^{-3}$) fractions. Pasture installation resulted in a rapid recovery of the total SOM content. Up to 90% of the pasture-derived carbon that was mineralized during maize cropping was replaced within 9 years. Especially the medium and coarse size ($>150\ \mu\text{m}$) and light (b.d. $<1.13\ \text{g cm}^{-3}$) fractions were almost completely regenerated by input of root-derived SOM. The amount of medium-weight and heavy macro-organic fractions ($>150\ \mu\text{m}$; b.d. $>1.13\ \text{g cm}^{-3}$) in the 0- to 20-cm layer was still 40–50% lower than in the continuous pasture plots. Average half-life times calculated from ^{13}C analyses ranged from 7 years in the light fractions to 56 years in heavy fractions. Fractionation results and ^{13}C data indicated that mechanical disturbance (plowing) during maize cropping had resulted in vertical displacement of dispersed soil carbon from the 0- to 20-cm layer down to 60–80 cm. Conversion of arable land to pasture, therefore, not only causes a regeneration of

the soil carbon content, it also reduces the risk of contaminant transport by dispersed soil carbon.

Key words Organic matter · ^{13}C analyses · Land use change · Fractionation · Pasture · Maize

Introduction

The conversion of arable land to pasture, forest, or wetland has become an important issue in the EC agricultural policy, where attempts are being made to reduce both arable crop production and dairy products. The transition from arable land to non-agricultural destinies is expected to affect both quantity and quality of soil organic matter (SOM) within a few decades, which changes both the nutrient status as well as the soils capacity to retain contaminants (Schulin et al. 1995).

SOM changes brought forth by land-use changes have been studied in great detail. The vast majority of these studies, however, deal with the effects of intensification of land use, such as the conversion of native forest or pasture to arable land (Tiessen and Stewart 1983; Vitorello et al. 1989; Veldkamp 1994; Paul et al. 1997).

Major tools employed in the detection of quantitative changes of carbon in soils include SOM fractionation and stable isotope analysis ($^{13}\text{C}/^{12}\text{C}$). Results from SOM fractionation studies revealed that intensification of land use resulted in a loss of carbon stored in 'macro'-aggregates (Christensen 1992; Feigl et al. 1995; Puges et al. 1995; Magid et al. 1996). Up to 50% of the native soil carbon content is lost due to aggregate disintegration as a result of mechanical impact (e.g. by plowing) and microbial mineralization processes (Balesdent et al. 1988; Christensen 1992; Skjemstad et al. 1994; Miller and Dick 1995). Mineralization rates decrease with a decrease in aggregate size, which is attributed to an increased protection against microbial mineralization as a result of carbon binding to clay and silt particles as well as the incorporation in stable clay- and

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SOM fractions are given relative to the PDB standard (Craig 1957) in $^{13}\delta$ (‰) notation where $^{13}\delta = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \cdot 1000$, and R_{sample} and R_{standard} refer to the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample and the standard, respectively.

Calculation of mean SOM-fraction turnover time from $^{13}\delta$ values

The amount of pasture-derived carbon mineralized during 26 years of maize cropping was calculated based on the loss of pasture-derived carbon in the continuous maize plot:

$$C_{\text{mineralized}} = (C_{\text{pasture}} - C_{\text{pasture-maize}}) \quad (1)$$

where $C_{\text{mineralized}}$ = decrease in the amount of pasture-derived carbon during 26 years of maize cropping (mg C), C_{pasture} = amount of carbon stored in pasture soil (mg C), $C_{\text{pasture maize}}$ = amount of pasture-derived carbon stored in the continuous maize plot (mg C).

The amount of pasture-derived carbon in the maize plots was calculated based on the difference in the $^{13}\delta$ value of two corresponding fractions in the continuous maize and pasture plots.

$$C_{\text{pasture maize}} = C_{\text{total maize}} \cdot \frac{^{13}\delta_{\text{total maize}} - ^{13}\delta_{\text{maize}}}{^{13}\delta_{\text{pasture}} - ^{13}\delta_{\text{maize}}} \quad (2)$$

where $C_{\text{total maize}}$ = total carbon content in the maize plot (in mg C), $^{13}\delta_{\text{total maize}}$ = $^{13}\delta$ of soil or SOM fraction in the continuous maize plot (in ‰), $^{13}\delta_{\text{maize}}$ = $^{13}\delta$ maize plants (−13‰), $^{13}\delta_{\text{pasture}}$ = $^{13}\delta$ in SOM fractions of pasture soil (ranging from −27.2‰ to −28.8‰).

The average carbon mineralization rate constant of each SOM fraction was calculated assuming an exponential first-order decay rate (Dalal and Mayer 1986; Paul and Clark 1989; Arrouays et al. 1995; Gregorich et al. 1995):

$$C_{\text{pasture maize}} = C_{\text{pasture}} \cdot e^{-k_i \cdot t} \quad (3)$$

where k_i = decay-rate constant (in year^{−1}) of SOM-fraction i and t = time (in years).

The value for $C_{\text{pasture maize}}$ was calculated from Eq. 2, the value for C_{pasture} is equal to the amount of carbon in the fractions from the pasture plot. The average half-life of carbon in each SOM fraction then equals:

$$t_{1/2} = \ln(2) \cdot k^{-1} \quad (4)$$

Results

Effect of land use on total carbon content

The total carbon content in the continuous maize plot decreased from 2.3% to 1.6% in the 0- to 20-cm layer, a loss of 30% compared with the carbon content in the continuous pasture plot. Also in the 30- to 50-cm layer, a carbon loss of 30% had occurred during maize cropping. Apparently, the annual input from maize roots and plant material does not compensate for the increased mineralization that occurs due to the shift from pasture to maize. Termination of maize cropping resulted in a rapid increase in the total carbon content in the 0- to 20-cm layer. Within 4 years after the conversion of maize to pasture, the carbon content in the topsoil had increased from 1.6% to 1.8%. After 9 years, the average carbon content in the topsoil (0–20 cm) had increased 0.6%, which equals 17 mg C ha^{−1} (assuming a soil bulk-density of 1.4 g cm^{−3}).

Impact of land use on the dynamics and the amount of carbon stored in SOM fractions

In Tables 2 and 3, the amount of all SOM fractions (expressed as g fraction 100^{−1} g soil, Table 2) and the carbon content in each SOM fraction (in g carbon 100^{−1} g soil, Table 3) is shown for the four land-use types included in this study. Maize cropping resulted in a loss of carbon stored in the macro-organic SOM fractions (fraction size larger than 150 μm). The amount of SOM fractions larger than 150 μm decreased from 6.4 g fraction 100^{−1} g soil in the pasture plots to 1.6 g fraction 100^{−1} g soil in the maize plots. Despite input from maize roots, a net carbon loss of approximately 60%

Table 2 Amount of fraction retrieved (in g fraction per 100 g soil)

Land use	Depth	Fraction						
		Roots	>250 μm			150–250 μm		20–150 μm
			L ^a	M ^b	H ^c	M	H	<20 μm
Maize	0–20	0.1	0.3	0.2	0.4	0.1	0.5	22.6
Since 1968	30–50	0.0	0.1	0.1	0.3	0.1	0.3	20.3
	60–80	0.0	0.0	0.1	0.6	0.0	0.7	23.3
Pasture	0–20	0.0	0.4	0.3	0.9	0.2	0.4	18.8
Since 1991	30–50	0.0	0.1	0.2	0.5	0.1	0.5	13.3
	60–80	0.0	0.0	0.3	0.3	0.2	0.2	15.7
Pasture	0–20	0.0	0.8	0.6	0.5	0.3	0.8	14.9
Since 1986	30–50	0.0	0.1	0.2	0.3	0.1	0.2	13.4
	60–80	0.0	0.0	0.3	0.3	0.1	0.5	18.0
Pasture	0–20	0.2	0.6	0.6	3.0	0.5	1.5	13.7
Since 1968	30–50	0.0	0.1	0.4	1.6	0.4	0.8	13.0
	60–80	0.0	0.1	0.6	1.3	0.2	0.2	10.1

^a Light (b.d. <1.13 g cm^{−3})

^b Medium (1.13 < b.d. < 1.37 g cm^{−3})

^c Heavy (b.d. >1.37 g cm^{−3})

Table 3 Amount of carbon in each fraction (in g C 100 g⁻¹ soil). Abbreviations as in Table 2

Land use	Depth	SOM fractions								Sum
		Roots	>250 μm			150–250 μm		20–150 μm	<20 μm	
			L	M	H	M	H			
Maize	0–20	0.02	0.14	0.10	0.04	0.04	0.06	0.46	0.79	1.63
Since 1968	30–50	0.01	0.04	0.05	0.03	0.03	0.03	0.31	0.71	1.19
	60–80	0.00	0.01	0.04	0.04	0.02	0.03	0.24	0.84	1.22
Pasture	0–20	0.01	0.20	0.11	0.04	0.10	0.10	0.50	0.78	1.84
Since 1991	30–50	0.00	0.04	0.10	0.04	0.05	0.05	0.33	0.82	1.42
	60–80	0.00	0.02	0.17	0.05	0.09	0.06	0.50	0.77	1.67
Pasture	0–20	0.02	0.40	0.23	0.09	0.14	0.11	0.58	0.64	2.21
Since 1986	30–50	0.01	0.03	0.08	0.04	0.06	0.05	0.33	0.83	1.42
	60–80	0.00	0.01	0.19	0.06	0.07	0.07	0.57	1.03	2.00
Pasture	0–20	0.07	0.30	0.22	0.19	0.22	0.06	0.69	0.52	2.27
Since 1968	30–50	0.01	0.06	0.15	0.12	0.13	0.08	0.59	0.59	1.72
	60–80	0.00	0.05	0.18	0.09	0.05	0.04	0.53	0.59	1.54

occurred in the >150 μm fractions in the top 20 cm during 26 years of maize cropping. In contrast, the weight of the fine SOM fractions (20–150 μm and <20 μm) increased by 60% (20–150 μm) and 90% (<20 μm) in the topsoil of the continuous maize plots. The amount of carbon in these two fractions, however, showed a different trend. Carbon stored in the 20- to 150- μm SOM fraction decreased from 0.7 g C 100⁻¹ g soil in the pasture plot to 0.5 g C 100⁻¹ g soil in the maize plot, whereas carbon in the <20- μm SOM fraction increased from 0.52 g C 100⁻¹ g soil in the pasture plot to 0.79 g C 100⁻¹ g soil in the maize plot.

Carbon per gram of SOM fraction decreased during maize cropping from 0.05 to 0.02 g C g⁻¹ in the 20- to 150- μm fraction and from 0.26 to 0.21 g C g⁻¹ in the <20- μm fraction. This indicates that the average stability of the aggregates probably decreases due to the lower carbon content in both fractions.

Pasture installation also affected the distribution of carbon among fractions (Fig. 1). In this graph, the relative contribution of the four different size fractions to the total carbon content is shown for all three depth layers. The light and medium-weight SOM fractions showed a rapid recovery and increased from 0.6 g 100 g⁻¹ soil in the maize plot (0–20 cm layer) to 1.7 g 100 g⁻¹ soil (sum of >150- μm light and medium-weight fractions) in the 9-year-old pasture (after 1986). The amount of heavy fractions increased from 1.0 to 1.3 g 100 g⁻¹ soil, which indicates that the recovery of fractions containing strongly humified carbon will take longer. It appears that maize cropping affected carbon distribution among size fractions down to 80 cm. In all depth layers, the amount of carbon stored in the >250- μm classes decreased significantly ($P < 0.001$) due to maize cropping. The decrease in the amount of carbon stored in the larger fractions was largely counterbalanced by an increase in the <20- μm fraction. Conversion of maize to pasture resulted in a partial recovery of the carbon content in all depth layers, although the recovery was fastest in the topsoil. The distribution of

Fig. 1 Contribution of SOM fractions to the total carbon content as a function of land use and sampling depth

carbon among size fractions in the 0- to 20-cm layer of the past-1986 plots roughly resembles that of the continuous pasture plot. In the 30- to 50-cm layer and the 60- to 80-cm layer, the recovery of the >250- μm fraction will take longer due to the limited input of organic matter into the deeper soil layers.

^{13}C content in soils and fractionated SOM and turnover of SOM fractions

$^{13}\delta$ values for soil and SOM fractions are shown in Table 4 in combination with the calculated percentage of maize-derived carbon in each SOM fraction and soil sample (Table 5). The calculated contribution of maize to the total carbon content in the continuous maize plot decreased with depth from 23% in the 0- to 20-cm layer to 7% in the 30- to 50-cm layer and 1% in the 60- to 80-cm layer. The amounts of maize-derived carbon are in line with previously reported data by Gregorich et al. (1996), who found that the contribution of C4-carbon ranged between 22% and 30% in the topsoil of a fertilized maize plot. The effect of maize cropping on $^{13}\delta$

values was most pronounced in the >250- μm , light fractions. The percentage of maize-derived carbon in SOM fractions decreased with a decrease in fraction size and an increase in fraction density, from 91% in the >250- μm light fraction to 10% in the <20- μm fraction. The decreased incorporation of maize-derived carbon in the heavy, fine fractions reflects the slow transformation of soil carbon from coarse fractions towards finer fractions with time. After conversion from maize to pasture, a rapid mineralization of maize-derived carbon occurred in all fractions and depth layers. Similar to incorporation of maize-derived carbon, mineralization of maize-derived carbon was fastest in the coarse, light and medium-weight fractions. After 9 years of pasture, the contribution of maize-derived carbon decreased from 91% to 11% in the light SOM fraction and from 48% (respectively 47%) to 11% (respectively 10%) in the medium-weight fractions. However, due to the increased total carbon content in these fractions after the change from maize to pasture, the absolute loss of maize-derived carbon is less and ranges from 66% in the >250- μm , light fraction to 12.5% in the >250- μm , heavy fraction. In general, the loss of

Table 4 $^{13}\delta$ (‰) of soil samples and SOM fractions. Abbreviations as in Table 2

Land use	Depth	SOM fractions								
		Soil	Roots	>250 μm			150–250 μm		200–150 μm	<20 μm
				L	M	H	M	H		
Maize	0–20	–25.88	–13.00	–16.25	–21.52	–24.88	–21.77	–24.26	–25.43	–26.35
Since 1968	30–50	–27.30	–15.01	–15.84	–25.17	–26.40	–25.25	–26.69	–27.01	–27.53
	60–80	–27.48	n.a.	–16.89	–27.08	–27.30	–27.61	–27.50	–27.34	–27.60
Pasture	0–20	–26.04	–27.46	–24.90	–25.21	–25.90	–25.27	–25.69	–26.23	–26.86
Since 1991	30–50	–27.42	–27.19	–23.39	–27.11	–26.94	–27.35	–27.06	–27.43	–27.53
	60–80	–27.91	n.a.	–27.58	–27.66	–27.35	–28.17	–27.71	–27.95	–28.07
Pasture	0–20	–26.69	–28.08	–26.71	–26.07	–26.36	–26.48	–26.40	–26.43	–26.98
Since 1986	30–50	–27.53	–28.76	–24.83	–26.89	–27.20	–27.07	–27.09	–27.45	–27.81
	60–80	–27.89	–29.00	–27.20	–27.92	–27.40	–28.24	–27.67	–27.95	–28.04
Pasture	0–20	–27.63	–28.78	–28.23	–27.48	–27.30	–27.78	–27.23	–27.66	–27.59
Since 1968	30–50	–27.90	–28.83	–28.43	–28.00	–27.55	–28.35	–27.84	–27.98	–27.84
	60–80	–27.73	n.a.	–28.64	–28.04	–27.99	–28.09	–27.93	–27.98	–27.50

Table 5 Percentage of maize-derived carbon in soils and SOM fractions. Abbreviations as in Table 2

Land use	Depth	SOM fractions								
		Soil	Roots	>250 μm			150–250 μm		20–150 μm	<20 μm
				L	M	H	M	H		
Maize	0–20	23	100	91	48	20	47	24	18	10
Since 1968	30–50	7	85	94	19	7	20	4	5	0
	60–80	1	n.a.	86	3	0	1	1	3	0
Pasture	0–20	11	10	25	18	11	20	13	11	6
Since 1991	30–50	2	5	37	3	3	3	1	2	0
	60–80	<1	n.a.	5	1	0	1	0	0	0
Pasture	0–20	9	5	11	11	8	10	7	10	5
Since 1986	30–50	1	2	26	5	1	6	1	2	0
	60–80	<1	n.a.	3	1	0	1	0	0	0

Table 6 Calculation of decay-rate constants of SOM fractions (0–20 cm). Abbreviations as in Table 2

Fraction	C_i^a	C_f^b	$^{13}\delta_i^c$	$^{13}\delta_f^d$	C_f		C_{min}^e	k	$t_{1/2}$
	g C 100 ⁻¹ soil		‰	‰	Maize	Past.		Day ⁻¹	Year
>250-L	0.20	0.09	-28.23	-16.25	0.07	0.02	0.18	-0.000236	8
>250-M	0.15	0.07	-27.48	-21.52	0.03	0.04	0.11	-0.000138	14
>250-H	0.13	0.03	-27.30	-24.88	0.01	0.02	0.11	-0.000172	11
150/250-M	0.15	0.03	-27.78	-21.77	0.01	0.02	0.13	-0.000216	9
150/250-H	0.04	0.04	-27.23	-24.26	0.01	0.03	0.01	-0.000034	56
201/50	0.47	0.31	-27.66	-25.43	0.05	0.26	0.21	-0.000057	33
<20	0.36	0.54	-27.59	-26.35	0.05	0.49	-0.13	0.000032	-59
<20*	0.36	0.54	-27.59	-26.35	0.05	0.22	0.14	-0.000048	39

^a $C_{pasture}$
^b C_{maize}
^c $^{13}\delta_{pasture}$

^d $^{13}\delta_{maize}$
^e $C_{mineralized}$

Table 7 Decay-rate constants of weight fractions (0–20 cm)

Fraction	C_i	C_f	$^{13}\delta_i$	$^{13}\delta_f$	C_f		C_{Min}	k	$t_{1/2}$
	g C 100 ⁻¹ soil		‰	‰	Maize	Past.		Day ⁻¹	Year
Light	0.25	0.09	-28.34	-16.25	0.07	0.02	0.23	-0.000261	7
Medium	0.30	0.10	-27.63	-21.60	0.04	0.06	0.24	-0.000165	11
Heavy	0.17	0.07	-27.28	-24.52	0.01	0.06	0.11	-0.000112	17
20–150 μ m	0.47	0.31	-27.66	-25.43	0.05	0.26	0.21	-0.000059	32
<20 μ m	0.36	0.54	-27.59	-26.35	0.05	0.22	0.14	-0.000048	39

maize-derived carbon was more pronounced in the light and coarse fractions, which also confirms the hypothesis that carbon attached to the heavy, fine fraction is more protected from microbial degradation processes than carbon stored in the light, coarse fractions (Tisdall and Oades 1982).

In Table 6, the calculation of k and $t_{1/2}$ is shown for all fractions from the topsoil (0–20 cm). In order to compare the results with previous results from Hassink (1995), the half-life time was calculated per weight class as well (Table 7). Average half-life times decreased from 8 years in the >250- μ m light fraction to 56 years in the 150- to 250- μ m, heavy fraction. This trend confirms the hypothesis that carbon turnover decreases with an increasing degree of 'protection' in small aggregates as well as an advanced degree of humification (Tisdall and Oades 1982). A striking feature is the initial negative value of $t_{1/2}$ in the <20- μ m fraction. This is a logical consequence of the increase in the amount of carbon stored in this SOM fraction during maize cropping, which reflects the carbon transfer from macro-organic matter (>150 μ m) to the <20- μ m fraction. Assuming that the amount of carbon transferred from other fractions is roughly 50% of the total amount of carbon stored in the <20- μ m fraction (0.27 g C 100⁻¹ g soil), the corrected value for $t_{1/2}$ in the <20- μ m fraction is 39 years. It also implies that carbon mineralization of the macro-organic matter was overestimated: part of the carbon from the >150- μ m fractions is not mineralized, but stored in the <20- μ m fraction. The average

half-life times calculated for the >150- μ m fractions are higher than those found by Hassink (1995) in a similar soil where $t_{1/2}$ ranged from 1 year in the light fraction to 5 years in the heavy fraction. However, in the study by Hassink (1995), no fresh organic matter was added, as was the case during maize cropping in the present study. The addition of new organic material probably reduced mineralization rates of native organic matter present in the soil. The differences in $t_{1/2}$ for the 20- to 150- μ m and <20- μ m fraction were small: 32 years versus 37 years for the 20- to 150- μ m fraction and 39 years versus 27 years in the <20- μ m fraction. Apparently, the input of organic matter during maize cropping had only a minor effect on the mineralization of carbon stored in the finest fractions. This confirms that input of organic material affects carbon turnover stored in larger fractions more than carbon stored in fine fractions.

Discussion

The shift from maize cropping to pasture induces a rapid recovery in the quantity of SOM in the topsoil due to input from grass roots and the termination of physical disturbances of the soil. Carbon dynamics were most pronounced in the coarse, light and medium-weight fractions and decreased with fraction density and a decrease in fraction size. This was most likely due to the nature of organic matter present in the SOM fraction

separated here. Both the fractionation results and the calculated half-life times indicate that three distinctly different SOM pools can be distinguished. The first 'pool' contains the light and medium-weight SOM fractions (b.d. $<1.37 \text{ g cm}^{-3}$) and can be considered to be a highly 'reactive' pool with a short turnover time and that mainly contains moderately decomposed plant material and roots. The second pool contains more-humified organic matter attached to soil particles and present in stable medium-to-large aggregates ($>150 \mu\text{m}$) with a high density (b.d. $>1.37 \text{ g cm}^{-3}$). The third pool contains the 20- to $150\text{-}\mu\text{m}$ and $<20\text{-}\mu\text{m}$ fractions and contains strongly humified organic material attached to silt and clay particles. Under 'stable' conditions (e.g. continuous pasture), carbon is transferred slowly from the light fractions to the heavy or fine fractions. This was confirmed by the degree of incorporation of maize-derived carbon, which was highest in the reactive pool and lowest in the finest SOM fraction. This reflects the slow transition of SOM from plant residues to humified organic matter attached to clay and silt particles. After the transition from agriculture to pasture, the recovery was fastest in the light fractions and decreased with fraction density and a decrease in fraction size. This also reflects the slow build-up of SOM in the humified fractions. Initially, organic matter from plant roots mainly contributes to the coarse, light fractions and is converted to more-humified SOM in the course of time. From the fractionation results, it was concluded that the distribution of carbon among fractions in the 0- to 20-cm layer of the 9-year-old pasture roughly resembled that of the continuous pasture site. In the lower soil horizons, however, the recovery of the SOM content takes longer due to the limited input of carbon from pasture roots in the lower soil horizons.

Effect of maize cropping and pasture installation on organic matter dynamics: indication of carbon displacement?

The increase in both fraction weight and amount of carbon in the $<20\text{-}\mu\text{m}$ fraction in the maize plots is likely to be the result of carbon transfer from macro-organic matter fractions ($>150 \mu\text{m}$) towards finer fractions as a result of mechanical destruction (e.g. plowing). The increase in the $<20\text{-}\mu\text{m}$ fraction was observed throughout the soil. It is unlikely, however, that plowing is responsible for this effect in the 30- to 50-cm and the 60- to 80-cm layer, since its direct impact is limited to a soil depth of 30 cm. ^{13}C data revealed that the majority of carbon stored in both the 20- to $150\text{-}\mu\text{m}$ and the $<20\text{-}\mu\text{m}$ fractions is of pasture (C3) origin. This excludes the possibility that the increase is due to carbon input from maize roots. Furthermore, radiocarbon analysis showed that the average age of carbon attached to both the 20- to $150\text{-}\mu\text{m}$ and $<20\text{-}\mu\text{m}$ fractions in the maize plots was substantially lower than carbon in the corresponding fractions in the pasture plots (Römken et al., in press).

It is, therefore, reasonable to assume that the increase in the amount of carbon in the finest fractions in the subsoil of the maize plots is due to vertical displacement of (young) pasture-derived carbon from the topsoil. The possibility of enhanced vertical displacement of carbon from physically disrupted macroaggregates is strengthened by recent results from Follett et al. (1997), who found that plowing had resulted in enhanced vertical transport of destabilized macro-organic matter. Apart from this, manure additions may also have contributed to the increased amount of carbon in the $<20\text{-}\mu\text{m}$ fractions. This seems less likely, since manure was applied to the pasture plots as well. Preferential flow-paths created by maize roots, however, may have contributed to the increased vertical displacement of manure-derived carbon in the maize plots compared with the pasture plots. Both mechanisms are in line with the hypothesis that part of the carbon stored in the 20- to $150\text{-}\mu\text{m}$ and the $<20\text{-}\mu\text{m}$ fractions in the lower soil horizons of the maize plots originated in the topsoil. Whether this carbon originates from carbon originally present in the soil (larger aggregates) or from manure additions remains unclear. The mechanism of enhanced vertical transport of particulate carbon under intensive agriculture, therefore, can form an important contribution to carbon and contaminant translocation in soils. Stabilization of the system, as was achieved by pasture installation, not only leads to a recovery of the macro-organic fractions, but may also reduce the risk of enhanced transport of contaminants attached to carbon.

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