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The relationship between landform and the distribution of soil C, N and P under conventional and minimum tillage

Steven De Gryze [a,b,*], Johan Six [b], Heleen Bossuyt [a], Kristof Van Oost [c], Roel Merckx [a]

[a] Division Soil and Water Management, Katholieke Universiteit Leuven, Leuven, Belgium
[b] Department of Plant Sciences, University of California, Davis, CA, USA
[c] Département de Géologie et de Géographie Université Catholique de Louvain, Louvain-la-Neuve, Belgium

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Abstract

The objective of this study was to examine the interactive effects of tillage and land forms (erodibility) on the redistribution of C, N and P within an agricultural landscape. Soils were sampled from an undulating maize field in central Belgium. Half of the field was under conventional tillage (CT), while the rest was under minimum tillage (MT) management. Based on slope and curvature characteristics, depositional and erodible zones were identified in both tillage treatments. We analyzed 400 surface (0–5 cm) soil samples, and 25 soil profiles (0–100 cm). Concentrations of native C, maize-derived C, total N, Olsen P, and moisture content in the 0–5 cm soil layer showed distinct spatial patterns with variogram ranges from 30 to 90 m. These patterns were related to local differences in texture and landform. In general, nutrient concentrations were greater in lower, depositional areas, and smaller in higher, erodible areas. In addition, the impact of landform was more pronounced in CT than MT. Three years after the implementation of the tillage treatments, native C, total N and Olsen P stocks (0–46 cm) in erodible zones were about 40% less under CT than under MT. However, in depositional zones, nutrient stocks were equal between the tillage treatments. Differences in erosion rates, the distribution of Olsen P and maize-derived C indicated that this pattern was mainly caused by soil transport induced by erosion since the implementation of the tillage treatments, rather than local differences in decomposition rates. We concluded that the influence of landforms on the stabilization and redistribution processes of nutrients is greater within CT than MT. Therefore, interactions between landform and agricultural management need to be considered in regional soil organic matter inventory assessments.

Keywords: Erosion; Deposition; Tillage; Agriculture; Carbon; Soil nutrients

1. Introduction

The loss of agricultural land due to soil degradation poses a very pertinent environmental challenge. Worldwide, soil erosion is one of the most widely spread forms of soil degradation. The negative effects of soil erosion (e.g. soil degradation, nutrient losses and a decline in water quality) have been acknowledged since long (Jacks and Whyte, 1939; Jacobsen and Adams, 1958; Miller, 1986). However, we believe that calculations of nutrient losses induced by erosion are severely biased since most studies pertain to experimental manipulations at the plot level (for a review, see Six et al., 2002). In such studies, nutrient losses by water erosion dominate (Steegen and Govers, 2001). However, at a landscape level, both erosion and deposition occur and most of the nutrients are only translocated within the landscape and hence not lost (Beuselinck et al., 2000, Steegen and Govers, 2001). Therefore, omitting the landscape scale in erosion studies severely biases all attempts to budget net soil nutrient losses from the soil due to erosion (Van Oost et al., 2000; Lal et al., 2000).

The few studies that have taken a comprehensive approach to nutrient budgeting in erodible landscapes are contradicting. According to Jacinthe and Lal (2001), erosion leads to a net loss of soil organic matter (SOM) while Stallard (1998) stated that

* Corresponding author. University of California, One Shields Avenue — mail stop 1, Davis, CA 95616, USA. Tel.: +1 530 752 3450; fax: +1 530 752 4361.
E-mail address: sdegryze@ucdavis.edu (S. De Gryze).

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sedimentation of eroded organic C at a world scale is an important component of the missing C sink. We attribute this discord to the many confounding processes involved. For example, it is unknown how much SOM is decomposed during transport. In addition, the fate of buried SOM in depositional areas is unclear. Erosion may lead to a conveyor belt which constantly transports young SOM from erodible zones to colluvial areas where it is buried and stabilized, thus leading to net C sequestration (Van Oost et al., 2005).

Furthermore, in most studies considering erosion, the effects of soil cultivation are not fully taken into account. First, tillage induces a considerable net downslope movement of soil which can outweigh the effects of water erosion in many cultivated hilly areas (Lindstrom et al., 1992; Govers et al., 1999; Van Muysen et al., 1999; Richter 1999). However, most studies only consider the effect of water erosion on C dynamics (Jacinthe and Lal, 2001), and omit the effects of tillage erosion. Secondly, reducing the intensity of soil cultivation offers the possibility to abate erosion. Practices such as no-tillage or minimal-tillage management (MT), decrease SOM breakdown, which increases soil aggregation, and therefore reduce erosion (De Gryze et al., 2007). However, an exact budgeting of the advantageous effects of reduced tillage intensity at the landscape level is lacking.

We set out to (1) budget the effects of soil translocation on nutrient stocks in an undulating agricultural field due to both water and tillage erosion, and (2) investigate the interactive effects of land form and tillage intensity on surface and depth distributions of nutrients (C, N and available P).

2. Materials and methods

2.1. Site description

The experimental field site is located in the loess belt of central Belgium (50°48′N, 4°35′E) near the town of Huldenberg. The field has a size of 3.2 ha and is characterized by a complex topography with a difference in elevation between the highest and lowest positions of 19.5 m. Slopes vary between 0% and 28% and curvature (i.e. convexity or concavity of the soil surface) between −0.07 and 0.05 m m^{-1}. The main soil types according to the World Reference Base for Soil Resources are Luvisols, Cambisols and Regosols (FAO, 1998), these soils are present on both management sides of the field (see further). Most of the surface is covered by windblown loess deposits from the Quaternary, which contain about 5–10% sand and 15% clay (Van Oost et al., 2000). Due to the silty textural composition (75–80% silt), these soils are very erodible (Bryan and De Ploey, 1983). Severe water and wind erosion at the end of the ice ages exposed the Tertiary sand at some locations (see De Gryze et al., 2007); this substrate contains about 50% sand and 15% clay. Mean annual precipitation at this site is 780 mm, which is equally distributed during the year. Mean annual temperature is 9.8 °C (with a mean daily maximum temperature of 13.5 °C and a mean daily minimum temperature of 6.3 °C). Prior to the experiment, the site was in grass fallow for the last 20 years, and low-intensity agriculture before this. In 2000, before the start of the experiment, the entire field was ploughed to homogenize the soil and remove the grass. Thereafter, the field was split in a CT (25 cm deep moldboard plowing which inverts the complete plow layer) section of 1.7 ha, and a MT (only loosening of the soil using a cultivator to a maximum depth of 20 cm) section of 1.5 ha. At the same time, a mono-culture of maize (*Zea mays* L.) was established. Every year, two weeks before sowing, pig slurry manure (40 Mg ha^{-1} yr^{-1}) was injected at a depth of 15 cm. Seedbed preparation consisted of a rotary harrow and a cross-kill roller. Both sides received equal amounts of herbicides, pesticides and fertilizer. The field next to the experimental field was left under the original grass fallow and served as a reference.

2.2. Soil sampling

All samples were taken after tillage and before manure application plus sowing during the spring of 2003. In total, 400 surface samples and 25 one-meter profiles (13 under CT and 12 under MT) were taken. For the surface samples, standard preweighed 100 ml Kopecki rings were used to sample the 0–5 cm soil depth. We used a combined systematic and randomized sampling strategy. For the systematic soil sampling, 263 samples were taken based on a 10 × 10 m grid to ensure all landscape positions were represented. In addition, another 137 samples were taken at randomly chosen locations to ensure the unbiased construction of variograms. The soil profiles were taken with a 6 cm diameter core sampler up to 1 m depth. The exact location of the profiles was determined using a map of the curvature classes which was calculated using the digital terrain model (see further). Within each of the curvature classes in each of the tillage treatments, we chose the location for the profiles randomly. The depth layers used for analysis were: 0–2 cm, 2–4 cm, 4–6 cm, 8–10 cm, 14–16 cm, 20–22 cm, 30–32 cm, 44–46 cm, 60–80 cm, and 80–100 cm. After sample collection, the cores were weighed and stored at 4 °C until further analysis. Samples were then gently crumbled along the natural planes of weakness to pass an 8-mm sieve. During this procedure, stones >2 mm and visible plant residues were removed. Samples were then air dried and a subsample of 5 g was taken to determine soil moisture (105 °C).

The study area was surveyed with a Trimble 5800 GPS (Trimble, Sunnyvale, California) at a resolution of about 3 m. The precision of the GPS is smaller than 5 cm horizontally. A digital elevation model with a resolution of 1.5 m was constructed using a Delaunay triangulation interpolation method using Surfer 8 (Golden software, Golden, Colorado). After applying a low-pass filter to smoothen the surface, plan-, profile and mean slope curvature were calculated based on the procedures presented by Zevenbergen and Thorne (1987). Because tillage erosion is known to be a very important process in this area (Van Oost et al., 2003) and tillage erosion is proportional to local slope curvature (Quine and Walling, 1993; Govers et al., 1994), we chose slope curvature as the topographic variable for landform classification. The surface sampling locations were classified into 5 classes of curvature (referred to as 'landforms'): very convex (from −0.072 m m^{-1} to −0.013 m m^{-1}), convex (from −0.013 to −0.005 m m^{-1}), linear (from −0.005 to 0.005 m m^{-1}), concave (from 0.005 to 0.017 m m^{-1}), and very concave (from 0.017 to

0.060 m m^{-1}). For the depth sampling locations, samples were divided into convex (curvature < 0 m m^{-1}) and concave (curvature > 0 m m^{-1}).

2.3. Analyses

Total soil C, N and $\delta^{13}C$ signature were measured on a 5 g subsample. This subsample was pulverized using a Retsch MM 200 Mixer mill (Retsch Gmbh & Co, Haan, Germany). If the soil pH was above 7, carbonates were removed using acid fumigation (Harris et al., 2001). This material was then analyzed with an ANCA 20–20 GSL mass spectrometer (PDZ Europe Ltd., Cheshire, UK) for organic C, $\delta^{13}C$, and total N. The $\delta^{13}C$ signature of the original grassland soil substrate was found to be −29.1±0.5‰ as measured on the field adjacent to the experimental plots, which was still under the same grassland as the study site before maize cultivation. The average $\delta^{13}C$ signature of the maize biomass, sampled in September 2003, was −12.7±0.5‰. Amounts of native and maize-derived C were calculated according to Cerri et al. (1985). The $\delta^{13}C$ values of the SOM were used to calculate the proportion of new C (f_{new}, i.e. the C derived from the present maize vegetation) and of native C ($f_{native}=1-f_{new}$, i.e. the C derived from the grassland), by using the mass balance equation:

$$f_{new} = (\delta_{new} - \delta_{native})/(\delta_{veg} - \delta_{native})$$

δ_{new} is $\delta^{13}C$ of the SOM of the field site, δ_{native} is the $\delta^{13}C$ of the SOM of the remaining grassland strip (−29.1±0.5‰), and δ_{veg} is the $\delta^{13}C$ of the maize (−12.7±0.5‰). Total N was measured by combustion in O_2. All resulting gases were reduced to N_2 using copper. The N_2 was measured with a TCD detector.

Bulk density was calculated by dividing the stone-free weight of the soil sample by the stone-free volume of the soil sample:

$$BD = \frac{W_{tot} - W_{stone}}{V_{tot} - 2.65/W_{stone}}.$$

Where W_{tot} is the total weight, W_{stone} the weight of the stones, and V_{tot}, the total volume of a kopecki ring (100 ml), the density of the mineral fraction was assumed to be 2.65 g cm^{-3}. Olsen P was determined by extracting air-dry soils for 30 min with 0.5 M $NaHCO_3$ at pH 8.5 (Olsen et al., 1994) and measuring the PO_4^{3-}–P concentration by the molybdenum blue method.

To compare nutrient stocks between the two treatments, we calculated the total amount of C in the upper 46 cm, and not to the UNFCCC standardized depth of 30 cm. This was done to include the C which was buried below 30 cm due to the effects of soil erosion.

2.4. Statistical analyses

The data were analyzed using a general linear model ANOVA, using the SAS statistical package for analysis of variance (PROC GLM, SAS Institute, 2002). Pairwise comparisons were done post-hoc using a Tukey test at a significance level of $\alpha=0.05$. Differences between curvatures within a management treatment or between management treatments within a curvature class were tested post-hoc using contrasts. In each of the 5 different curvature classes, there were about 40 measurements. Using these 40 values directly would lead to a bias due to spatial autocorrelation. Therefore, we calculated averages of 6 randomly sampled values out of the initial 40. These averages could then be regarded as separate and uncorrelated measurements. For the depth samples, samples were divided into convex and concave samples. Using this procedure, we obtained 6 values per depth for convex and 7 for concave positions under CT. Under MT, there were 7 values per depth for convex and 5 for concave positions. Profiles of soil variables were analyzed using a repeated measurements analysis of variance (ANOVA) procedure in which landform, depth, and tillage treatment and their two-way interactions were fixed effects. Depth was considered as a repeated measurements variable with the soil column as a subject. No three-way interactions were considered to avoid over-specification of the model. Since we found no evidence of changes in soil parameters deeper than 46 cm, the effect of depth was considered to be linearly changing until 46 cm, and constant from 46 cm to deeper.

To obtain maps of old and new organic C, total N, Olsen P, moisture content and bulk density, geostatistical analyses were done with VARIOWIN (Pannatier, 1998) and Surfer 8 (Golden Software, Colorado, USA). For each of these variables, the variogram $\gamma(h)$ was calculated so that each point of the variogram was based on at least 80 point couples. The same variogram was used for both tillage treatments. In the kriged maps, specific zones are referenced. These zones were constructed for illustrative purposes only, and are not based on a statistical test.

3. Results

3.1. Native C, maize-derived C, Olsen P, and moisture content in surface samples across the field

Of the four soil variables considered, native C had the shortest variogram range (34 m) and the least amount of spatial autocorrelation (25%) (Table 1). Olsen P and moisture content had much longer ranges (136 m and 93 m respectively) and a higher degree of spatial autocorrelation (both about 60%). Maize-derived C was associated with a medium range (54 m) and degree of spatial autocorrelation (44%).

The highest concentrations of native C in CT were present in the lower, depositional areas of the landscape (zones b and c in Fig. 1a) whereas the lowest concentrations were present on top of the mid slope (zone a). In MT, low concentrations of native C

Table 1
Parameters from kriging analysis of 4 variables measured

	Variogram range (m)	Spatial autocorrelation (%)
Native C	34	25
Maize-derived C	54	44
Olsen P	136	64
Moisture content	93	61

The spatial autocorrelation is calculated as: sill/(nugget variance+sill).

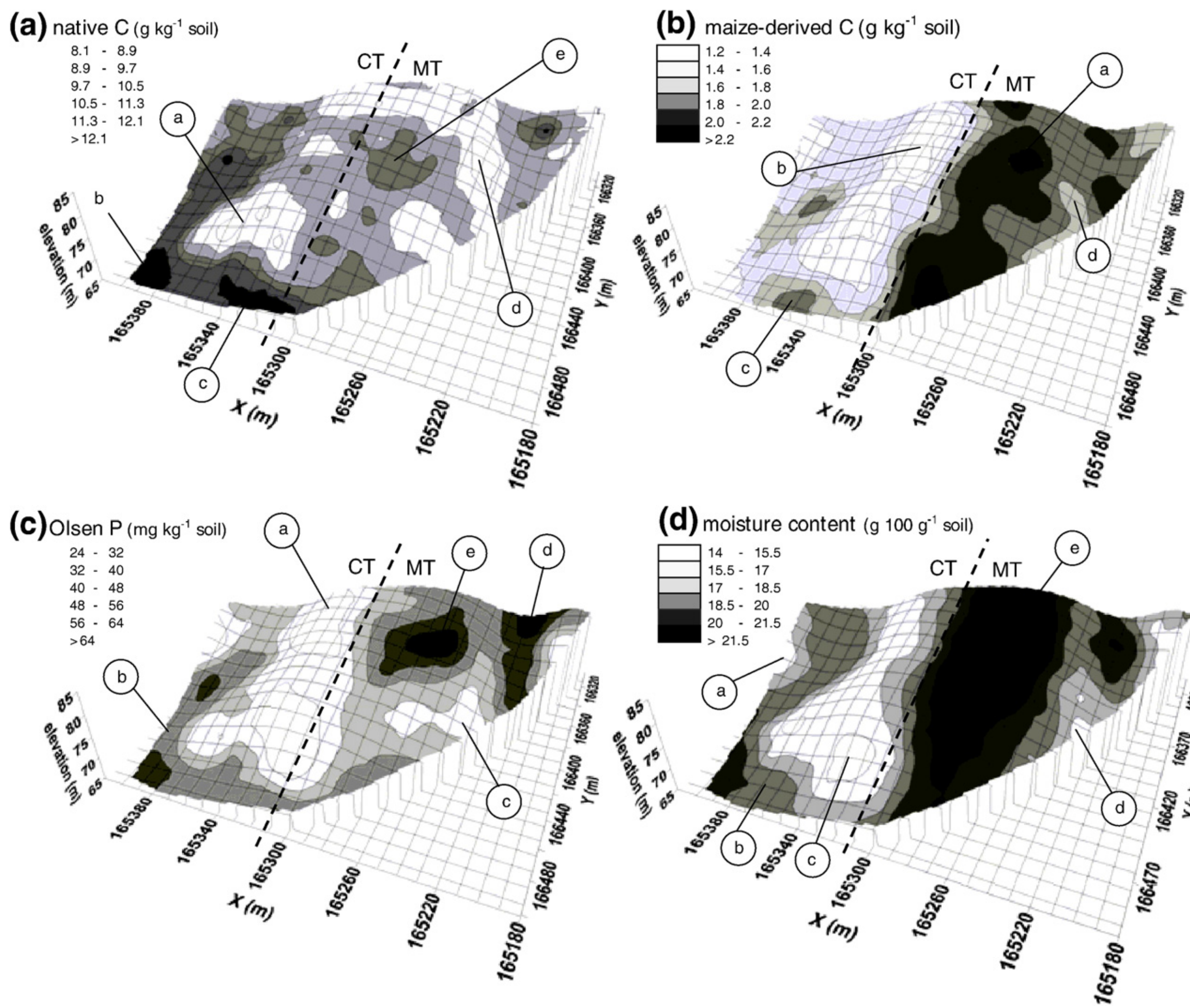

Fig. 1. Maps of kriged soil parameters at the 0–5 cm surface layer of the Huldenberg field site. This site is split into minimum tillage (MT) and conventional tillage (CT) systems. For illustrative purposes, the area was divided in zones differing in magnitude of soil parameters. These are indicated with different letters (see text). The *X* and *Y* coordinates (respectively easting and northing values) follow the UTM Lambert zone 24 coordinate system.

were found in the sandy outcrop area (De Gryze et al., 2007) (zone d). Higher native C concentrations were present in zone e.

In CT, the highest concentrations of maize-derived C were present again in the lower, depositional areas (zone c in Fig. 1b) and lower concentrations were located at the top of the slope (zone b). Intermediate values were found in the rest of the field. In MT, the lowest concentration of maize-derived C was found again in the sandy outcrop (zone d) whereas higher concentrations were present on top of the mid slope (zone a). Nitrogen followed the same pattern as native C, with higher concentrations in the depositional sites in CT and lower concentrations on the mid slope and up slope (data not shown). Olsen P generally increased from the top to the lower zones in CT (from zone a to zone b in Fig. 1c). In MT, highest concentrations of Olsen P were found on the top of the slope and in the sandy outcrop (zones d and e, respectively). Lowest concentrations were found on the lower slope (zone c). In CT, moisture roughly decreased with increasing elevation (Fig. 1d). The driest parts were located on the steep slopes of the middle part (zones a and c). The lower areas (zone b) were generally wetter. This is in contrast with the situation in MT where the moisture content was generally highest on top of the middle slope (zone e) and decreased with decreasing elevation (towards zone d). The average bulk density was equal in CT and MT (1.29 g cm^{-3} versus 1.32 g cm^{-3}). In CT, bulk density decreased from the top to the lower parts. However, in MT, there was no obvious trend in bulk density.

3.2. Surface C, N, P, moisture and bulk density across curvature classes

There was no difference in native C content of surface samples between CT and MT samples, except in the very concave curvature class (Fig. 2a). Native C content increased from 9.1 g kg^{-1} soil to 12.1 g kg^{-1} soil with an increasing curvature from erodible (i.e. very convex) to depositional (i.e. very concave) sites under CT. No differences among curvature classes were found under MT. The N content of surface samples followed a similar trend (data not shown). Across all curvature classes, maize-derived C content of surface samples was higher under MT than under CT (Fig. 2b). No significant differences were detected among the different curvature classes in both CT and MT. Olsen P content was significantly higher in MT than in

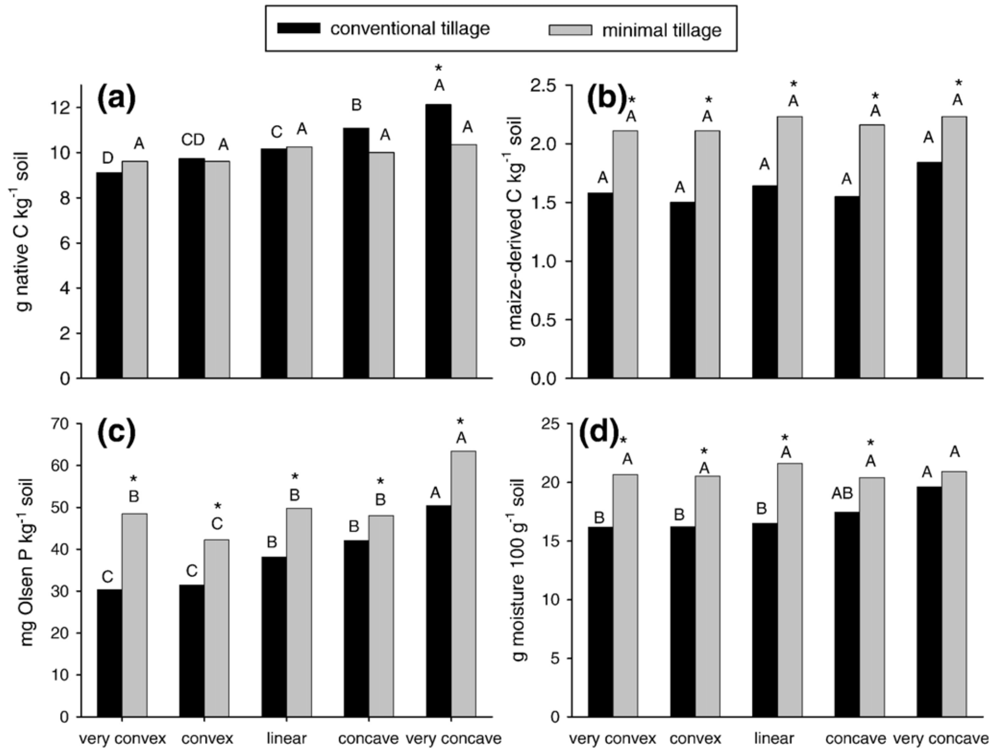

Fig. 2. Concentrations of native C, and maize-derived C, Olsen P and moisture content in surface samples (0–5 cm) across curvature classes within a conventional (CT) and minimum tilled (MT) plot at the Huldenberg field site. The statistical analysis is based on a re-sampling procedure as described in the Materials and methods section. Values followed by a different uppercase letter are significantly different among curvature classes within a tillage treatment. Values indicated by a '*' are significantly different between the two tillage treatments and within a curvature class.

CT for each curvature class and increased significantly for both CT and MT systems with increasing curvature (from 30.3 to 50.6 mg kg^{-1} soil and from 48.3 to 63.6 mg kg^{-1} soil in CT and MT, respectively) (Fig. 2c). Moisture content was higher in MT than in CT for all curvature classes, except in the very concave curvature class (Fig. 2d). Moisture content in CT increased slightly with increasing curvature from 16.1% to 19.8%. There were no differences in moisture content within MT among the different curvature classes. There were no differences at all in bulk density between tillage treatments or among curvature classes (data not shown).

3.3. Nutrient stocks

Native C stocks (down to 46 cm) were significantly larger in MT (5596 ± 424 g m^{-2}) than in CT (3658 ± 387 g m^{-2}) at erodible sites ($P=0.003$) (Table 2). No differences in native C stocks were detected between MT and CT at depositional sites (7021 ± 424 g m^{-2} compared to 6879 ± 358 g m^{-2}). Depositional sites had larger native C stocks than erodible sites under both CT ($P<0.0001$) and MT ($P=0.03$), but a significant interaction between tillage management and landform ($P=0.03$) showed that the difference between erodible sites and depositional sites is greater in CT than in MT. There were no differences in maize-derived C stocks between CT and MT, neither for erodible nor for depositional sites. Under CT, depositional sites contained more maize-derived C than erodible sites (669 ± 40 g m^{-2} compared to 512 ± 43 g m^{-2}). In contrast, there was no significant difference in maize-derived C stock between erodible and depositional sites under MT (532 ± 43 g m^{-2} compared to 638 ± 61 g m^{-2}). Furthermore, no significant interaction between curvature and management practices was

Table 2
Stocks of native C, maize-derived C and Olsen P in depth profiles up to 46 cm of erodible versus depositional sites within a conventional (CT) and a minimum tilled (MT) field at the Huldenberg field site

	Stock values (g m^{-2})				ANOVA effects			Post-hoc contrasts			
	CT		MT					Difference CT−MT		Landform difference	
	Erodible	Depositional	Erodible	Depositional	Tillage	Landform	Tillage × landform	Within erodible	Within depositional	Within CT	Within MT
Native C	3658±387	6879±358	5596±424	7021±424	*	***	*	**		***	*
Maize-derived C	512±43	669±40	532±43	638±61		**				*	
Olsen P	12.2±1.3	22.9±1.3	21.1±1.8	22.5±1.6	*	***	**	**		***	*

Values are reported ± standard error. *: $0.01<P<0.05$, **: $0.001<P<0.01$, ***: $P<0.001$.

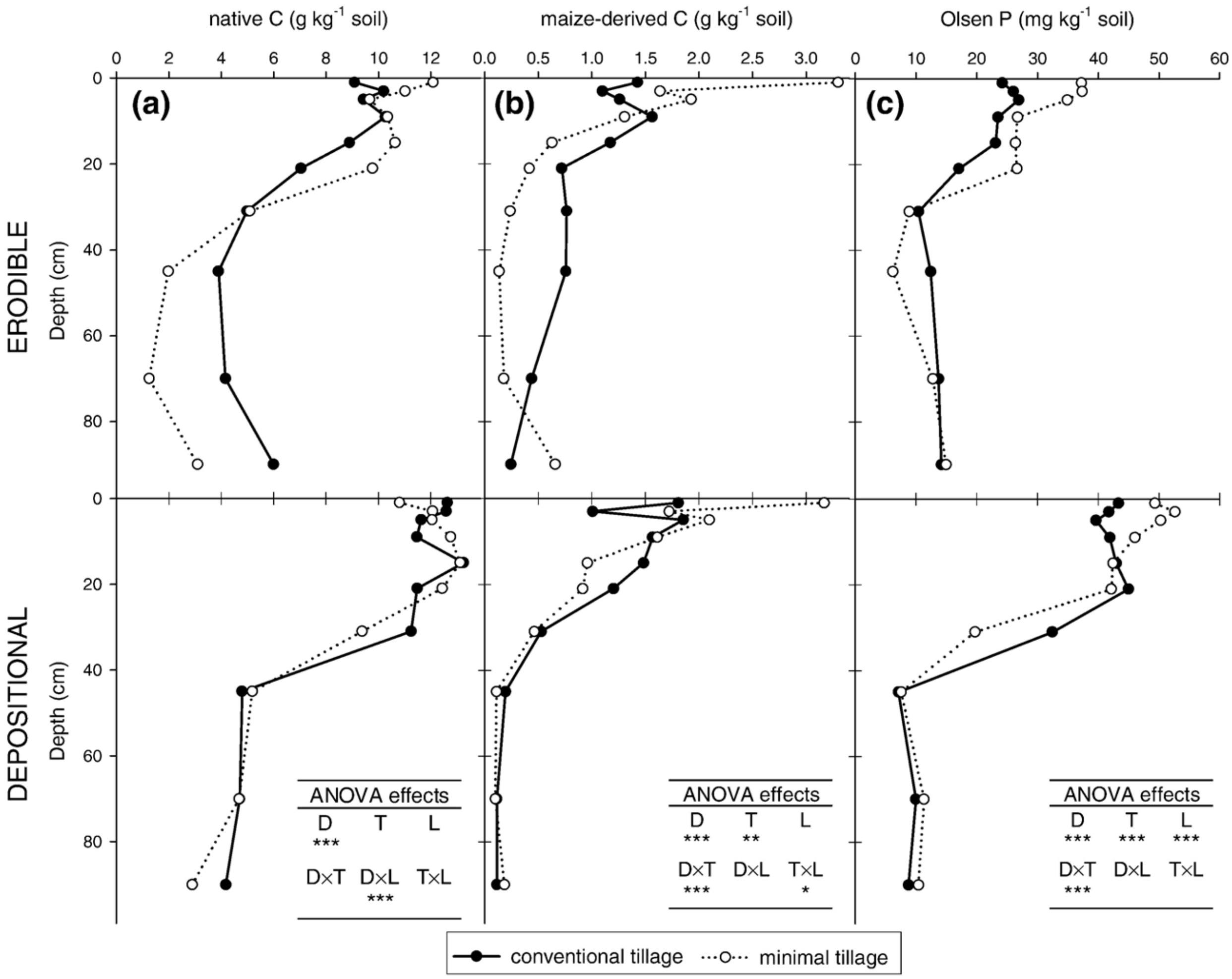

Fig. 3. Moisture content and bulk density in depth profiles of erodible versus depositional sites within a conventional (CT) and a minimum tilled (MT) plot at the Huldenberg field site. D = depth, T = tillage effect, L = landform position effect (erodibility), $D \times L$ indicates the interaction between depth and landform position, etc. *: $0.01 < P < 0.05$, **: $0.001 < P < 0.01$, ***: $P < 0.001$.

found, meaning that the effect of curvature on maize-derived C stocks was identical in the two tillage treatments. Olsen P stocks were significantly larger in MT (21.1 ± 1.8 g m^{-2}) than in CT (12.2 ± 1.3 g m^{-2}) in erodible sites ($P = 0.001$), but no differences in Olsen P stocks were detected between CT and MT at depositional sites (22.9 ± 1.3 g m^{-2} compared to 22.5 ± 1.6 g m^{-2}). Depositional sites had larger Olsen P stocks than erodible sites under CT ($P < 0.0001$), while no difference in Olsen P between depositional and erodible sites was found under MT. A significant interaction between curvature and management practices ($P = 0.009$) was found, indicating that the differences induced by curvature were different between CT and MT.

3.4. Depth profiles of native C, maize-derived C and Olsen P

Concentrations of native C, maize-derived C, and Olsen P decreased from the soil surface until a depth of about 46 cm, from which concentrations became constant. Profiles of native C were not affected by tillage intensity in both depositional and erodible sites (Fig. 3a). However, the significant interaction between depth and landform indicates that the depth profile of native C was different at erodible and depositional sites. In depositional sites, there was a steeper decrease in native C concentrations than in depositional sites. The depth profile of maize-derived C was significantly affected by tillage intensity (interaction between depth and tillage intensity is significant) (Fig. 3b). In addition, the effect of tillage was different for erodible and depositional sites (significant interaction of landform and tillage intensity). While there was almost no difference between CT and MT for depositional sites, in erodible sites the decrease of maize-derived C with depth was much steeper for MT than for CT. Olsen P was significantly affected by both tillage intensity and landform (Fig. 3c). The effect of landform on Olsen P was identical for both tillage treatments (no significant interaction between landform and tillage intensity).

4. Discussion

Erosion induces displacement of surface soil from higher to lower parts of the landscape, where the soil may be deposited or further transported into rivers and streams. This net transport has severe impacts on soil organic matter (SOM) dynamics and its spatial distribution in both horizontal and vertical directions. Here, we investigate differences in stocks and the spatial distribution of nutrients (C, N, and P) across different landforms (from erodible to depositional zones) under two different tillage management types (conventional and minimal tillage: CT and MT). Our approach is novel since most studies investigate either erosion or management practices at a plot level (Kwaad, 1994; Myers and Wagger, 1996; Basic et al., 2004), while we investigated the interaction of both factors across an agricultural landscape (Moorman et al., 2004).

Generally, we observed a greater amount of macronutrients (C, N, and P) and moisture in depositional areas compared to erodible areas. This has been reported before; for example, Ellis found already in 1938 that C content increased from upper to lower slopes (Ellis, 1938). Similarly, Gregorich (1996), Gregorich et al. (1998), Vandenbygaart (2001) and Yoo et al. (2005) found that erosion can concentrate organic C in depositional areas. On eroded sites, C concentration is smaller as SOM-poor subsoil is incorporated into surface horizons (Pennock, 1997). Li et al. (2004) studied, next to organic C, also N and Olsen P and found that these nutrients were also redistributed due to erosion and accumulated on the lower slope of a steep backslope.

In addition, we found that this effect of landform was profoundly influenced by tillage management practices. Most obviously, because crop residues stay on the surface under MT while they are mixed into the plow layer under CT, recent soil C and Olsen P concentrations are enriched in the top soil layer under MT and diluted over the plow layer under CT. This enrichment versus dilution is mostly observed in the profiles of recent C: there is a steeper decrease in MT in the top 20 cm (the tillage depth) compared to CT, reflecting the homogenizing effect of tillage in CT. However, nutrient stocks reported up to 46 cm (and therefore not influenced by this effect) were still different between the CT and MT management treatments, indicating that another mechanism than tillage mixing is also inducing differences in nutrient stocks across the profile. More specifically, both differences in total C stocks from the depth profiles (0–46 cm) and surface samples (0–5 cm) induced by landform were much more pronounced under CT than under MT.

The observed difference in spatial patterns in macronutrients might be caused by: (1) differences in soil C input. If there would have been a greater C input in depositional areas due to a possible higher crop growth in these areas, this might have led to a higher input of C to the soil. However, the differences in crop biomass growth between CT and MT or among landform positions were minimal (data not shown). In addition, it is unlikely that there was a difference in grass productivity between the two tillage treatments before the establishment of the experiment. Because even the non-crop derived soil C was different in the tillage treatments, it is improbable that the observed differences are solely caused by differences in soil C input. (2) Spatial differences in soil C dynamics might have been caused by landform-induced differences in micro-climatic conditions. For example, conditions in depositional areas might lead to increased protection of SOM. De Gryze et al. (2007) observed an increased amount of macroaggregates in depositional areas. They hypothesized that the higher presence of organic components and macronutrients in depositional areas increased the formation of binding agents for soil aggregates. These aggregates can then physically protect organic matter inside them, slowing down the turnover of organic matter in these depositional zones (Elliott, 1986). In addition, moisture contents were greater at lower positions in the landscape for CT, which can profoundly affect SOM dynamics. (3) Soil erosion might have induced horizontal transport of soil from erodible parts of the field to depositional areas.

Based on the soil phosphorus (P) profiles in CT and MT, we hypothesize that the observed differences in soil C must be (at least partly) due to soil transport induced by erosion. Since phosphorus (P) is even stronger adsorbed to mineral soil particles than C or N, it can be used as a tracer for mineral soil particles in soil erosion studies (Steegen et al., 2000, 2001). First, more P was present in depositional sites compared to erodible sites. In addition, in depositional sites, P accumulated up to a depth of 20 cm, and decreased rapidly at greater depth. There was a much more gradual decrease in P with depth in erodible zones. Furthermore, these effects were more pronounced in CT compared to MT. These observations indicate that the tillage-induced erosion in the CT system moves soil mineral particles from erodible to depositional positions and validates the observed patterns in soil C. However, it cannot be negated that landform-induced changes in decomposition rate have also led in part to the spatial patterns in soil C. Nevertheless, we observed that tillage intensity did not affect total stocks of recent C up to 46 cm, which indicates that landform-induced differences in soil C decomposition are probably minimal.

The question remains whether the observed spatial patterns in soil nutrients are caused by erosion events before the establishment of the experiment in 2000, or after 2000. To investigate this, the spatial distribution of maize-derived soil C and the differences between CT and MT can be used. We hypothesize that the CT management induced a significant amount of soil transport after 2000. First, there is morphological evidence that recent erosion rates under CT were much larger than under MT: the CT part contained rills, whereas the MT part did not (see photographs in the supplementary online materials). In addition, the tillage erosion rates for the CT treatment are substantially higher than those for the MT treatment. The tillage transport coefficient, which is a measure for the erosivity of the implement, equals 169 kg m^{-1} for a moldboard operation used in the CT treatment (Van Muysen et al., 2002) and only 13 kg m^{-1} for a cultivator, used in the MT treatment (Lobb and Kachanoski., 1999). Furthermore, an erosion survey on this field calculated the total amount of soil loss based on the size of rills (Gillijns et al., 2007). It was found that in the CT part of the field, 76.3, 15.7, and 8.6 Mg ha^{-1} was lost during 2002, 2003, and 2004 respectively, while this was only 4.1, 0, and 0 Mg ha^{-1} in the MT part. Secondly, landform did affect recent soil C stocks: more recent C was present in depositional areas than erodible areas, but this was only the case in the CT treatment. Also the recent C profile was similar between depositional and erodible positions for MT, but there were much more differences between the landscape positions for the CT treatment. Therefore, we conclude that the relatively short duration of the experiment (about 4 years) was sufficient to create erosion-induced spatial variation in SOM accumulation. However, due to the greater amount of grass-derived C versus maize-derived C, changes in the former were more outspoken than changes in the latter. It is known that the majority of organic C changes only occur after 5–10 years of conversion from conventional to reduced tillage management (West and Post, 2002).

Comparing the results of our study with the factor analysis and multiple regression analysis done by De Gryze et al. (2007), we observe that in their study, the correlation between C and macroaggregates was more dependent on erodibility in the landscape under CT than under MT. This analysis corresponds well with the results of our study, confirming that effects of erosion and deposition play a more important role in CT than in MT. More specifically, in CT there seems to be much more destructive forces, leading to the break-up of unstable soil macroaggregates. Only aggregates that are stable and contain new SOM inside are able to withstand these forces. A study done by Jacinthe et al. (2001) showed that erosion breaks down the less stable aggregates, releasing organic matter for decomposition. Therefore, this corroborates our results of a higher sensitivity of SOM to erodibility in CT compared to MT soils.

5. Conclusions

Based on the results of this study, we found indications that the redistribution processes from erodible to depositional sites in an agricultural field are dependent on tillage intensity. Organic matter (C, N, P) content and moisture content were generally greater in depositional sites than in erodible sites and this effect was much more pronounced in the CT part of the field than in the MT part of the field. The findings of this study confirm the need to include the topographic characteristics of an agricultural field and their interactions with management when budgeting soil nutrients.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geoderma.2007.11.013.

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