Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 93 (2007) 335–345
Soil & Tillage Research
www.elsevier.com/locate/still

Characterization of soil profiles in a landscape affected by long-term tillage

S.K. Papiernik [a,*], M.J. Lindstrom [a], T.E. Schumacher [b], J.A. Schumacher [b], D.D. Malo [b], D.A. Lobb [c]

[a] *USDA-ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Avenue, Morris, MN 56267, USA*
[b] *South Dakota State University, Department of Plant Sciences, 247A SNP, Box 2140C, Brookings, SD 57007-2141, USA*
[c] *University of Manitoba, Department of Soil Science, 276 Ellis Bldg., Winnipeg, Man., Canada R3T 2N2*

Received 10 January 2006; received in revised form 11 May 2006; accepted 20 May 2006

Abstract

Soil movement by tillage redistributes soil within the profile and throughout the landscape, resulting in soil removal from convex slope positions and soil accumulation in concave slope positions. Previous investigations of the spatial variability in surface soil properties and crop yield in a glacial till landscape in west central Minnesota indicated that wheat (*Triticum aestivum*) yields were decreased in upper hillslope positions affected by high soil erosion loss. In the present study, soil cores were collected and characterized to indicate the effects of long-term intensive tillage on soil properties as a function of depth and tillage erosion. This study provides quantitative measures of the chemical and physical properties of soil profiles in a landscape subject to prolonged tillage erosion, and compares the properties of soil profiles in areas of differing rates of tillage erosion and an uncultivated hillslope. These comparisons emphasize the influence of soil translocation within the landscape by tillage on soil profile characteristics. Soil profiles in areas subject to soil loss by tillage erosion >20 Mg ha^{-1} $year^{-1}$ were characterized by truncated profiles, a shallow depth to the C horizon (mean upper boundary 75 cm from the soil surface), a calcic subsoil and a tilled layer containing ~19 g kg^{-1} of inorganic carbon. In contrast, profiles in areas of soil accumulation by tillage >10 Mg ha^{-1} $year^{-1}$ exhibited thick sola with low inorganic carbon content (mean 3 g kg^{-1}) and a large depth to the C horizon (usually >1.5 m below the soil surface). When compared to areas of soil accumulation, organic carbon, total nitrogen and Olsen-extractable phosphorus contents measured lower, whereas inorganic carbon content, pH and soil strength measured higher throughout the profile in eroded landscape positions because of the reduced soil organic matter content and the influence of calcic subsoil material. The mean surface soil organic carbon and total nitrogen contents in cultivated areas (regardless of erosion status) were less than half that measured in an uncultivated area, indicating that intensive tillage and cropping has significantly depleted the surface soil organic matter in this landscape. Prolonged intensive tillage and cropping at this site has effectively removed at least 20 cm of soil from the upper hillslope positions.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Tillage erosion; Erosion; Organic carbon; Inorganic carbon; Soil classification

1. Introduction

Soil loss by erosion is recognized as a factor limiting crop production and plant growth throughout the world. Research has generally demonstrated yield reductions in response to topsoil loss by erosion. The

* Corresponding author. Tel.: +1 320 589 3411; fax: +1 320 589 3787.
E-mail address: papiernik@morris.ars.usda.gov (S.K. Papiernik).

0167-1987/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2006.05.007

extent of yield reduction resulting from soil erosion is dependent on the extent of soil loss through erosion, properties of the surface soil, subsoil and parent material of the soil, management factors (including tillage, crop and fertilizer inputs) and environmental conditions relating to plant growth (Adams, 1949; Battiston et al., 1987; Bruce et al., 1988; Fenton et al., 2005; Kosmas et al., 2001; Olson and Carmer, 1990; Papiernik et al., 2005; Schumacher et al., 1999; Sparovek and Schnug, 2001).

Soil movement by tillage can be a dominant force in redistributing soil within the profile and throughout the landscape. Soil erosion by tillage results in the removal of soil from convex slope positions and soil accumulation in concave slope positions (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995). Net downslope soil flux by tillage erosion is a function of slope gradient, while soil translocation by water erosion is a function of slope steepness and length. Thus, areas with high soil loss resulting from tillage erosion do not always correspond to those with severe water erosion, but tillage and water erosion operate to redistribute soil in the landscape in predictable patterns. Tillage erosion rates are usually highest in crest, shoulder and upper backslope positions while soil movement by water erosion is greatest in the mid to lower backslope region. Tillage erosion is especially evident in hilly landscapes. Soil morphological effects of tillage erosion include truncated soil profiles at convex slope positions, deep topsoil accumulation in concave slope positions and inverted soil profiles, where subsoil material is deposited over original surface horizons (Kosmas et al., 2001; De Alba et al., 2004; Heckrath et al., 2005). Few detailed studies of the effect of tillage erosion on soil properties and soil productivity have been reported.

Previous investigations of the spatial variability in soil properties in landscapes affected by long-term tillage indicate that soil organic carbon and nutrient (nitrogen and phosphorus) contents are lower in areas of soil removal than in areas of soil accumulation (Pennock et al., 1994; Heckrath et al., 2005; Papiernik et al., 2005). In the North American prairies, an increase in pH has been observed in eroded landscape positions as a result of the increased carbonate concentration (Pennock et al., 1994; Papiernik et al., 2005). Previous studies have investigated a limited number of soil properties, but indicate that in some landscapes, tillage erosion has the potential to have large effects on soil properties that determine soil productivity.

Few studies have specifically reported the impact of tillage-induced changes in soil properties on crop production, but these studies consistently report higher grain yields or biomass production in areas of soil accumulation by tillage compared to areas of soil removal by tillage (Kosmas et al., 2001; Tsara et al., 2001; Heckrath et al., 2005; Papiernik et al., 2005). An investigation conducted at the site used in the present studies indicated that low wheat (*Triticum aestivum*) yields were observed in areas affected by high soil loss by erosion, predominately due to tillage erosion on convex slope positions (Papiernik et al., 2005). Wheat yields in these areas of the field averaged 50% of the maximum measured yield in each of 3 years (Papiernik et al., 2005).

Previous studies have suggested that tillage erosion may be partly responsible for changes in soil properties and crop yield in hilly landscapes; they have included qualitative descriptions of soil properties (De Alba et al., 2004) or investigated a small number of soil properties that are expected to affect crop growth (Pennock et al., 1994; Kosmas et al., 2001; Heckrath et al., 2005; Papiernik et al., 2005). Because tillage erosion can have drastic effects on crop yield in the prairies of North America (Papiernik et al., 2005), this study was conducted to more fully investigate the impact of tillage erosion on the variability in soil properties with landscape position and depth in an hilly prairie landscape. Soil cores were collected and characterized from a long-term intensively tilled field and from a nearby grassed hillslope that had no history of tillage to evaluate the effects of soil erosion on soil properties as a function of depth and soil removal/accumulation by tillage. This study provides quantitative measures of soil chemical and physical properties of soil profiles in a landscape subject to prolonged tillage erosion, and provides comparisons of the properties of soil profiles in areas of differing rates of soil loss by tillage and an uncultivated hillslope. These comparisons emphasize the influence of soil translocation within the landscape by tillage on soil profile characteristics.

2. Methods

2.1. Experimental site

Experiments were conducted in a 2.7-ha (6.7 acres) portion of a 16-ha (40 acres) field near Cyrus in west central Minnesota (45.68°N, 95.75°W), an area characterized by undulating topography with slopes <10%. The site consists of a low hill and a waterway

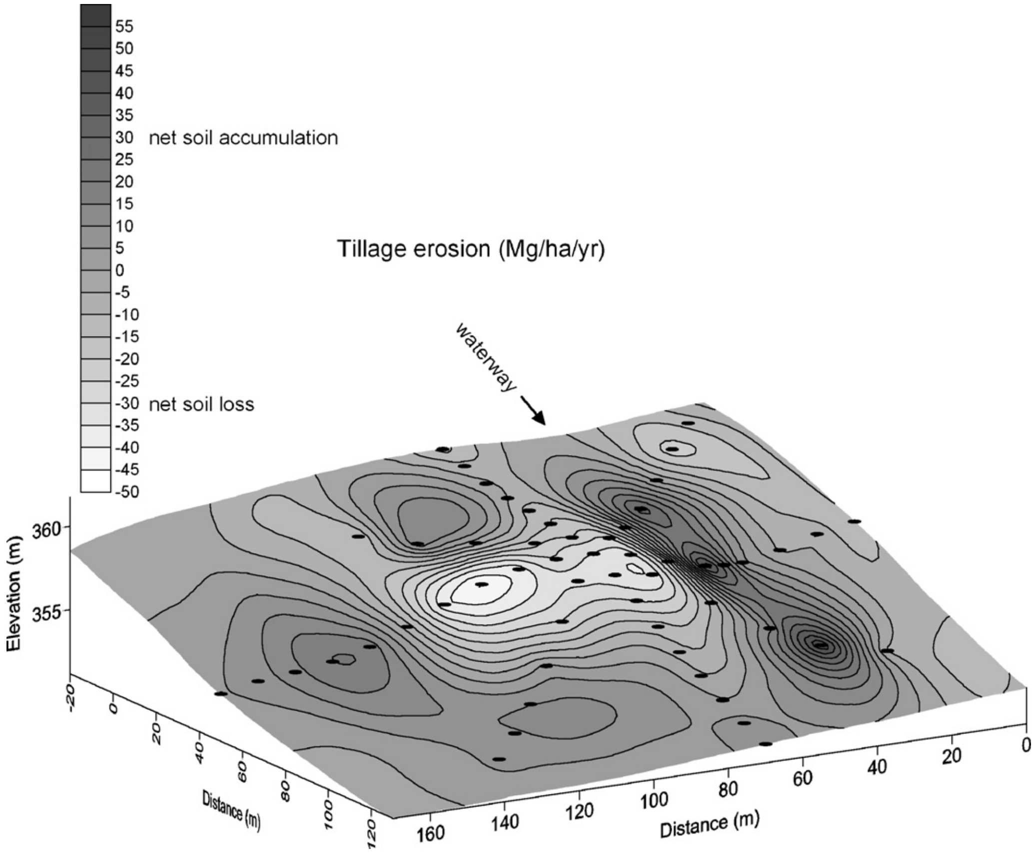

Fig. 1. Estimates of tillage erosion (Mg ha^{-1} year^{-1}) demonstrating the large variability in soil translocation by tillage at a site in west central Minnesota (45.68°N, 95.75°W). Negative values indicate net soil loss and positive values indicate net soil accumulation by tillage erosion. Large soil losses from the shoulder and upper backslope positions and soil accumulation in footslope and toeslope positions and in the linear waterway are predicted based on the site topography.

(Fig. 1). This field has been cultivated for approximately 100 years, with annual moldboard plowing for >40 years; it has been cropped predominantly to wheat, soybean (*Glycine max*) and corn (*Zea mays*). Previous research suggested that soil translocation through tillage was the dominant erosive force at this site (De Alba et al., 2004). Erosion has resulted in the exposure of calcareous subsoil at the shoulder positions and a relatively deep A horizon (with low carbonate content) at footslopes. In middle slope positions, an inverted soil profile may be present, where high-carbonate soil translocated from higher slope positions buries a carbonate-free horizon (De Alba et al., 2004). During these experiments, the field was moldboard plowed each fall with at least one additional tillage operation in the spring prior to planting.

Samples were collected at 10-m spacing along a series of transects (Fig. 1) in August 1999. Figures present the mirror image of the site to aid in visualization. Samples were also collected at five landscape positions (summit to footslope) on an adjacent grassed hillslope with slope >10% that had no documented history of cultivation. These samples provided an indication of the soil profile characteristics in the absence of tillage and cropping.

Each point was located (latitude, longitude and elevation) using a Trimble AgGPS-132[1] with differential corrections (Omnistar). Soil cores (7.6 cm diameter) were collected in two sections to a depth of 140–50 cm. Horizonation was determined by a pedologist using standard methods (Schoeneberger et al., 2002). Soil cores were sectioned by horizon, placed in paper bags and allowed to air dry immediately following collection.

[1] The use of trade, firm or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

2.2. Calculation of erosion estimates

To develop tillage and water erosion estimates, a Digital Elevation Model of the entire field was developed using a Leica survey grade DGPS system, with points located on a 10-m grid. Erosion by tillage, water and the combined effects of tillage and water was estimated at each node on the grid using the Water and Tillage Erosion Model (WATEM, Van Oost et al., 2000) using the approach described in Schumacher et al. (2005).

2.3. Determination of soil properties

Soil samples were air-dried and sieved (<2 mm) and selected properties were determined. The weight fraction consisting of particles >2 mm in diameter was measured. Soil pH was determined in a slurry of 5 g of air-dried soil and 10 mL of 0.01 M $CaCl_2$. Total carbon and nitrogen contents (g kg^{-1}) were determined by Dumas combustion and measured using a LECO 2000 CN analyzer (LECO Corporation, 2003). Inorganic carbon (IC) was determined using a pressure calcimeter and organic carbon (OC) determined by the difference between total and IC (Wagner et al., 1998). Measurements of Olsen-extractable phosphorus, ammonium acetate-extractable potassium, nitrate-N and ammonium-N were determined using standard soil test procedures. Wet aggregate stability was measured using the method described by Kemper and Rosenau (1986).

Soil strength and bulk density were determined along the same transects under relatively dry conditions in August 2000. Soil cores (5.7-cm diameter) were collected to 76 cm depth and sectioned into 0–15, 15–30, 30–60 and 60–76 cm increments. The bulk density was estimated by dividing the mass of soil (calculated from the difference in sample mass before and after oven-drying) by the volume of soil (386.3 cm^3 for 15-cm increments, 772.6 cm^3 for 30-cm increments). Soil strength was measured by the resistance to penetration using a Veris 3000 Profiler with a 30° angle cone tip with a maximum diameter of 1.6 cm. The rate of penetration was 1.8 m min^{-1}. Three soil strength profile measurements were taken adjacent to each transect point.

Relationships between variables were examined using Kendall correlation. Differences in the least-squares means of the properties of different soil horizons were detected using PROC MIXED in SAS (SAS Institute, 2003). Based on the erosion estimates, sampling locations were classified into groups based on the tillage erosion rate: soil loss >20 Mg ha^{-1} $year^{-1}$; loss 10 to 20 Mg ha^{-1} $year^{-1}$; loss 0 to 10 Mg ha^{-1} $year^{-1}$; soil accumulation 0 to 10 Mg ha^{-1} $year^{-1}$; accumulation >10 Mg ha^{-1} $year^{-1}$; uncultivated. Differences in properties of the surface soil were detected using PROC MIXED in SAS. In both cases, the MIXED model assumed an unbalanced design with individual cores representing repeated measures.

3. Results and discussion

3.1. Erosion estimates

Erosion rates predicted from the site topography indicated that soil removal rates by tillage were highest in the shoulder and upper backslope positions, with net soil accumulation in lower slope positions and throughout the linear waterway (Fig. 1). The transect points monitored in this study spanned the range of erosion rates predicted for the entire field (Papiernik et al., 2005). Predicted tillage erosion rates at the transect points monitored in this study varied from a net loss of 46 Mg ha^{-1} $year^{-1}$ to a net gain of 51 Mg ha^{-1} $year^{-1}$ (Fig. 1); water erosion rates from a loss of 46 Mg ha^{-1} $year^{-1}$ to a gain of 155 Mg ha^{-1} $year^{-1}$; tillage + water erosion rates from a loss of 66 Mg ha^{-1} $year^{-1}$ to a net gain of 207 Mg ha^{-1} $year^{-1}$. The major features of the total erosion reflect the removal of soil from the shoulder positions by tillage and accumulation at footslope positions by tillage and water (Papiernik et al., 2005). At this site, tillage erosion has a dominant impact over a larger portion of the field compared to water erosion (Papiernik et al., 2005). Similar tillage erosion rates and erosion patterns have been observed in other undulating landscapes (Heckrath et al., 2005).

3.2. Properties of soil horizons

The IC content of the Ap horizon was highly variable at this site (Table 1). Soil redistribution by erosion has incorporated subsoil into the tilled layer and mixed soil from different landscape positions with different calcium carbonate contents (De Alba et al., 2004). As observed in extensive sampling of the surface soil at this site (Papiernik et al., 2005), soil pH, IC and OC contents were significantly correlated (Table 2). Expanded soil characterization in this study indicated that total N and Olsen-extractable P contents decreased with increasing pH and IC content and increased with increasing OC content (Table 2). The properties of the tilled layer are typically most affected by erosion processes. Areas of high estimated soil loss by tillage

Table 1
Soil properties (arithmetic mean ± standard deviation) by horizon for profiles in cultivated areas

	Ap	A	AB	Bt	Bw	Bk	BC	C
n	60	13	23	4	32	51	11	41
Upper boundary (cm)	0 a	21 ± 4 b	33 ± 12 bc	60 ± 25 cde	46 ± 18 cd	51 ± 35 d	86 ± 23 e	91 ± 24 e
Lower boundary (cm)	23 ± 4 a	45 ± 5 b	59 ± 14 b	136 ± 16 ef	81 ± 32 c	98 ± 32 d	118 ± 22 e	144 ± 5 f
pH in $CaCl_2$	7.4 ± 0.2 c	7.1 ± 0.1 b	7.0 ± 0.2 b	6.4 ± 0.1 a	7.1 ± 0.4 b	7.6 ± 0.2 de	7.4 ± 0.5 cd	7.7 ± 0.2 e
Olsen P (mg kg^{-1})	15 ± 8 d	9 ± 5 c	6 ± 2 bc	9 ± 2 abcd	4 ± 2 ab	2 ± 3 a	2 ± 3 ab	3 ± 4 a
Extractable K (mg kg^{-1})	143 ± 30 c	125 ± 30 bc	135 ± 39 c	139 ± 12 bc	128 ± 39 bc	109 ± 33 ab	117 ± 40 ac	91 ± 32 a
Total N (g kg^{-1})	1.2 ± 0.3 d	1.6 ± 0.3 e	1.1 ± 0.1 d	0.7 ± 0.1 c	0.6 ± 0.2 c	0.3 ± 0.3 b	0.2 ± 0.1 ab	0.11 ± 0.04 a
Inorganic carbon (g kg^{-1})	9 ± 9 b	0.1 ± 0.1 a	0.1 ± 0.1 a	0.1 ± 0.1 ab	2 ± 4 a	24 ± 7 c	20 ± 11 c	21 ± 5 c
Organic carbon (g kg^{-1})	13 ± 5 c	20 ± 4 d	13 ± 2 c	7 ± 1 b	6 ± 2 b	2 ± 2 a	1 ± 1 a	0.5 ± 0.8 a
Nitrate-N (mg kg^{-1})	4 ± 4 b	3 ± 1 ab	3 ± 2 a	1.5 ± 0.8 ab	1 ± 1 a	2 ± 2 a	3 ± 2 ab	2 ± 1 a
Ammonium-N (mg kg^{-1})	8 ± 3 d	6 ± 2 c	6 ± 2 c	5.0 ± 0.9 ac	5 ± 2 bc	4 ± 2 ab	4 ± 2 ab	3 ± 2 a
Mass fraction > 2 mm (g g^{-1})	0.13 ± 0.09 a	0.10 ± 0.09 a	0.15 ± 0.11 a	0.27 ± 0.05 b	0.15 ± 0.08 a	0.13 ± 0.08 a	0.16 ± 0.08 ab	0.13 ± 0.05 a
Wet aggregate stability (g g^{-1})	0.90 ± 0.03 c	0.94 ± 0.02 c	0.93 ± 0.03 c	0.94 ± 0.01 c	0.86 ± 0.08 c	0.72 ± 0.16 b	0.69 ± 0.14 b	0.54 ± 0.16 a

Within each measured parameter (each row), values followed by different letters (a–f) are significantly different ($\alpha = 0.01$).

and tillage + water erosion had relatively high surface soil pH, high IC contents, low OC contents and low total N and Olsen P concentrations (Table 2). The measured soil properties were not strongly correlated with water erosion estimates (Table 2). Other measured properties of the surface soil, including extractable K, wet aggregate stability, soil strength and bulk density were not significantly correlated with other soil properties or erosion estimates (Table 2). Other researchers have reported significant correlations between tillage erosion rates and surface soil clay, OC and total P concentrations (Heckrath et al., 2005).

The A horizon (below the Ap horizon in areas of soil accumulation) had significantly higher OC, lower IC content and lower pH than the mean of the Ap horizons (Table 1). In profiles in which the Ap horizon was underlain by an A horizon (areas of soil accumulation), the mean OC content of the Ap horizon was similar to that in the A horizon, whereas the mean pH, the weight fraction >2 mm and the aggregate stability were similar to the mean of all Ap horizons. The mean IC content of the Ap horizon in profiles with an underlying A horizon was greater than that in the A horizon (0.26% compared to 0.01%), most likely due to the redistribution of topsoil within the landscape described by De Alba et al. (2004) where topsoil mixed with carbonate-containing subsoil is imported from shoulder and upper backslope positions, resulting in an elevated carbonate content in the tilled layer.

Compared to other B horizons, the Bt horizon tended to have lower IC content, lower pH, higher OC content, higher aggregate stability and a higher weight fraction comprised of particles larger than 2 mm (Table 1). The Bk horizon tended to have higher IC content, higher pH, lower OC content, lower aggregate stability and lower weight fraction >2 mm than other B horizons (Table 1). No large differences in nitrate-N and ammonium-N concentrations were observed throughout the A and B horizons (Table 1), as has been observed for other soils under long-term cultivation (Malo et al., 2005). As expected, the calcareous C horizon had relatively high pH and IC content, low OC and macronutrient content and low aggregate stability (Table 1).

3.3. Effects of erosion on properties of soil profiles

Profiles in areas subject to high soil loss by tillage erosion – samples collected at shoulder and upper backslope positions – were characterized by truncated profiles, a shallow depth to the C horizon, a calcic subsoil (Bk) (Fig. 2A) and a tilled layer containing significant amounts of IC (Table 3). Soils in convex

Table 2
Kendall correlation coefficients for surface soil (Ap horizon) properties in cultivated areas

	pH	N	P	K	IC	OC	WAS	>2 mm	BD	SS	TE	WE	TE + WE
pH in $CaCl_2$ (pH)	1												
Total N (N)	**−0.56**	1											
Olsen P (P)	**−0.41**	**0.43**	1										
Extractable K (K)	0.05	0.11	−0.00	1									
Inorganic carbon (IC)	**0.76**	**−0.61**	**−0.49**	0.05	1								
Organic carbon (OC)	**−0.56**	**0.86**	**0.46**	0.05	**−0.62**	1							
Wet aggregate stability (WAS)	−0.12	0.21	0.05	0.20	−0.12	0.21	1						
Mass fraction >2 mm (>2 mm)	0.22	−0.19	−0.17	0.03	0.25	−0.20	0.03	1					
Bulk density 0–15 cm (BD)	0.15	−0.06	0.04	0.06	0.14	−0.06	−0.05	−0.04	1				
Soil strength 0–20 cm (SS)	0.20	−0.18	−0.11	−0.05	0.22	−0.18	−0.13	0.00	0.30	1			
Tillage erosion (TE)	**0.36**	−0.32	**−0.34**	0.12	**0.38**	**−0.39**	−0.18	−0.00	0.06	0.23	1		
Water erosion (WE)	0.07	−0.21	−0.04	−0.12	0.07	−0.17	0.10	0.16	0.00	−0.01	0.21	1	
Tillage + water erosion (TE + WE)	**0.46**	**−0.52**	**−0.39**	0.00	**0.46**	**−0.57**	−0.13	0.10	0.04	0.23	**−0.63**	−0.15	1

Bold values indicate significance at $\alpha < 0.0005$. Positive correlation with erosion estimates indicates that the property was positively associated with loss of soil.

landscape positions were classified as Barnes, Buse and Langhei series (Table 4). Profiles in areas of soil accumulation exhibited thick sola with a deep C horizon (Fig. 2B). Soils in concave landscape positions were described as belonging to the Darnen, Svea and Parnell series (Table 4). Soil profiles characterized by high soil loss by tillage demonstrated a C horizon with a mean upper boundary 75 cm from the soil surface, and all profiles in areas of high soil loss had a C horizon within 1.5 m of the soil surface (Fig. 2A). In contrast, only three of the eight cores collected in areas of soil accumulation showed a C horizon within the top 1.5 m (Fig. 2B).

The Ap horizon in areas of high (>10 Mg ha^{-1} $year^{-1}$) soil accumulation resulting from tillage erosion had significantly lower IC content, higher OC content, higher wet aggregate stability, lower soil strength and higher concentrations of total N and Olsen P than the Ap horizon in areas of high (>20 Mg ha^{-1} $year^{-1}$) soil loss by tillage (Table 3).

Areas with intermediate rates of soil erosion by tillage generally did not show statistically significant

Table 3
Properties of Ap horizon at sampling points classified by estimated tillage erosion rates; properties of A horizon on uncultivated hillslope (arithmetic mean ± standard deviation)

	Soil loss (Mg ha^{-1} $year^{-1}$)			Soil accumulation (Mg ha^{-1} $year^{-1}$)		Uncultivated hillslope
	>20	10–20	0–10	0–10	>10	
n	13	10	14	10	8	10
pH in $CaCl_2$	7.6 ± 0.1 c	7.4 ± 0.2 bc	7.4 ± 0.2 bc	7.3 ± 0.1 b	7.3 ± 0.1 bc	6.7 ± 0.6 a
Olsen P (mg kg^{-1})	10 ± 8 a	11 ± 5 a	12 ± 8 a	21 ± 5 b	21 ± 7 b	7 ± 4 a
Extractable K (mg kg^{-1})	142 ± 19 ab	149 ± 22 ab	144 ± 28 ab	126 ± 34 a	157 ± 38 b	144 ± 38 ab
Total N (g kg^{-1})	0.9 ± 0.2 a	1.3 ± 0.3 b	1.2 ± 0.3 b	1.3 ± 0.2 b	1.4 ± 0.2 b	3.1 ± 0.3 c
Inorganic carbon (g kg^{-1})	19 ± 7 d	8 ± 8 bc	10 ± 9 b	2 ± 3 a	3 ± 2 ab	3 ± 4 ac
Organic carbon (g kg^{-1})	9 ± 3 a	14 ± 4 bc	12 ± 4 b	15 ± 3 c	16 ± 2 c	36 ± 4 d
Total carbon (g kg^{-1})	28 ± 4 c	22 ± 5 b	22 ± 6 b	18 ± 4 a	19 ± 3 a	39 ± 5 d
Nitrate-N (mg kg^{-1})	3 ± 4 a	4 ± 2 a	4 ± 3 a	5 ± 4 a	6 ± 6 a	4 ± 6 a
Ammonium-N (mg kg^{-1})	8 ± 3 a	8 ± 3 a	8 ± 2 a	8 ± 2 a	8 ± 2 a	8 ± 3 a
Mass fraction >2 mm (g g^{-1})	0.13 ± 0.04 a	0.14 ± 0.10 ab	0.13 ± 0.08 a	0.09 ± 0.05 a	0.21 ± 0.16 b	0.15 ± 0.09 ab
Wet aggregate stability (g g^{-1})	0.88 ± 0.03 a	0.89 ± 0.03 ab	0.91 ± 0.03 b	0.88 ± 0.03 a	0.91 ± 0.02 b	0.95 ± 0.02 c
Bulk density 0–15 cm (g cm^{-3})	1.50 ± 0.10 b	1.49 ± 0.09 b	1.44 ± 0.12 b	1.47 ± 0.09 b	1.47 ± 0.08 b	1.19 ± 0.07 a
Soil strength 0–20 cm (MPa)	2.2 ± 1.1 c	1.8 ± 0.9 ac	1.6 ± 0.7 ac	1.4 ± 0.5 ab	1.3 ± 0.3 a	2.0 ± 0.3 bc

Within each measured parameter (each row), values followed by different letters (a–d) are significantly different ($\alpha = 0.05$).

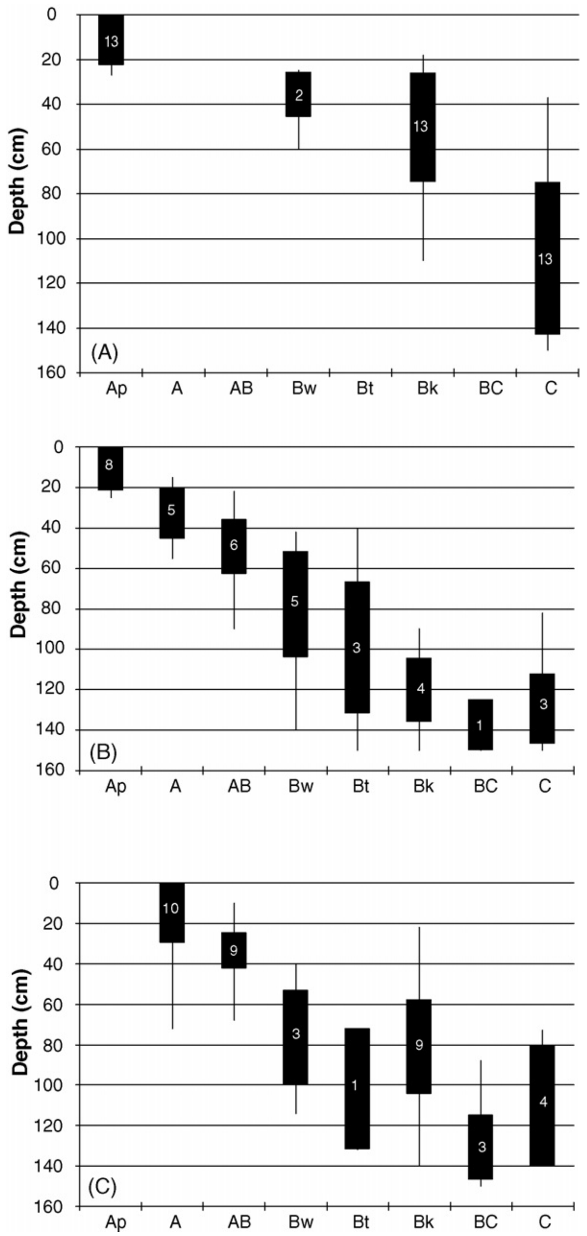

Fig. 2. Identification and depth distribution of soil horizons in (A) areas of high soil loss (soil loss by tillage >20 Mg ha^{-1} year^{-1}, $n = 13$); (B) areas of soil accumulation (soil accumulation by tillage >10 Mg ha^{-1} year^{-1}, $n = 8$); (C) uncultivated hillslopes ($n = 10$). Upper limit of each bar indicates the mean upper boundary of the horizon; lower limit of each bar indicates the mean lower boundary of the horizon. Vertical lines indicate minimum and maximum values. Values within bars indicate the number of soil cores exhibiting each horizon. Observations are limited to the upper 1.5 m of the soil profile.

differences, but in most cases, values of soil properties in these areas were between those observed for the highest rates of soil loss and accumulation by tillage (Table 3). Sampling points were classified only by tillage erosion rates, although the landscape is impacted by other erosion processes that affect soil movement and soil properties, most notably water erosion in the backslope. Decreasing Ap-horizon OC contents with increasing soil loss by erosion have been observed in other till- and loess-derived soils in the Midwestern United States (Lowery et al., 1995). We did not observe a difference in the bulk density of the surface soil in areas of soil loss and accumulation by tillage erosion (Table 3), although others have reported that surface soil bulk density tends to increase with increasing soil loss by erosion (Lowery et al., 1995).

Soil property information, described by horizon, was converted to a depth basis to allow comparisons between profiles. The value for each horizon was weighted (based on depth) by the fraction of the total that it contributed to the assigned depth increment. Profiles for uncultivated hillslopes and cultivated areas impacted by soil removal or accumulation by tillage erosion exhibited widely differing chemical (Fig. 3) and physical (Fig. 4) characteristics. Some properties, including OC, total N and Olsen P were consistently higher throughout the profile in areas of soil accumulation than in areas of soil removal (Fig. 3B–D). The accumulation of organic-rich topsoil in areas of soil accumulation (Fig. 2B) results in relatively high OC, total N and Olsen P contents throughout the upper profile (Fig. 3B–D). These properties tended to become more uniform at depths >50 cm due to the increasing parent material influence in the lower B and C horizons in all profiles. In contrast, soil properties, such as IC content (Fig. 3A), pH, bulk density, resistance to penetration and wet aggregate stability (Fig. 4A–C) tended to become more variable with depth in cultivated areas because highly-eroded profiles are impacted by a shallow C that has high IC content and pH and low aggregate stability while profiles in areas of soil accumulation are characterized by Bw or Bt horizons at depths >50 cm with low carbonate and high aggregate stability (Figs. 2–4; Table 1). Eroded profiles showed elevated resistance to penetration (Fig. 4C), IC content (Fig. 3A) and pH (data not shown) throughout the soil profile compared to areas of soil accumulation, conditions unfavorable to crop growth.

In surface soil horizons, total (organic + inorganic) carbon contents followed the trend uncultivated > soil loss > soil accumulation (Table 3). While OC contents tend to decrease with increasing soil loss by erosion (Table 3; Fig. 3B; Lowery et al., 1995; Heckrath et al., 2005; Shukla and Lal, 2005), some observations of increasing total carbon concentration with increasing soil loss by erosion have been reported in other

Table 4
Soil series (Soil Survey Staff, 2006) in the studied landscape

	Series	Description
Convex landscape positions	Barnes	Fine-loamy, mixed superactive, frigid Calcic Hapludolls
	Buse	Fine-loamy, mixed, superactive, frigid Typic Calciudolls
	Langhei	Fine-loamy, mixed, superactive, frigid Typic Eutrudepts
Concave landscape positions	Darnen	Fine-loamy, mixed, superactive, frigid Cumulic Hapludolls
	Svea	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls
	Parnell	Fine, smectitic, frigid Vertic Argiaquolls
Nearly level landscape positions	Estelline	Fine-silty over sandy or sandy-skeletal, mixed, superactive, frigid Calcic Hapludolls

cultivated Midwestern soils with a high-clay Bt horizon (Arriaga and Lowery, 2005). At this site, total carbon contents throughout the profile in highly eroded areas are strongly impacted by IC contents (Fig. 3A and B; Table 3) due to the high IC content (mean 24 g kg^{-1}) of the Bk horizon (Table 1).

Surface soil horizons of uncultivated areas had significantly higher OC, total N (Fig. 3B and C) and wet aggregate stability (Fig. 4A) than in all cultivated areas, indicating loss of organic matter through prolonged cropping. Mean OC and total N contents were approximately 2.5-fold higher in the upper 15 cm of uncultivated soil than in cultivated soils (Fig. 3B and C). Bulk density and pH were significantly lower in uncultivated surface soils than in cultivated areas (Fig. 4B; Table 3). Nitrate-N (data not shown) and

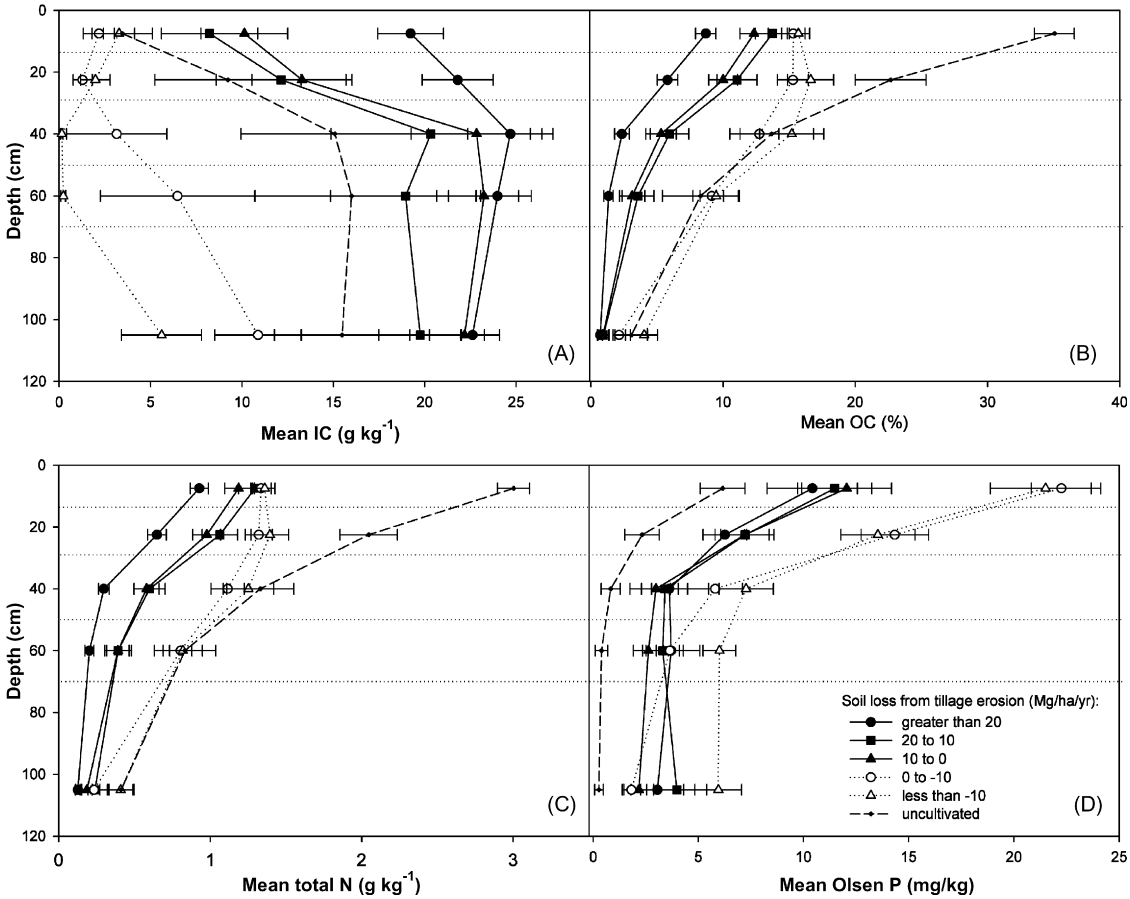

Fig. 3. Mean (±standard error) (A) inorganic carbon, (B) organic carbon, (C) total nitrogen and (D) Olsen-extractable phosphorus in soil profiles as affected by tillage erosion. Positive tillage erosion values indicate net soil loss; negative values indicate net soil accumulation. Horizontal dotted lines indicate the extent of the depth increment represented by each point.

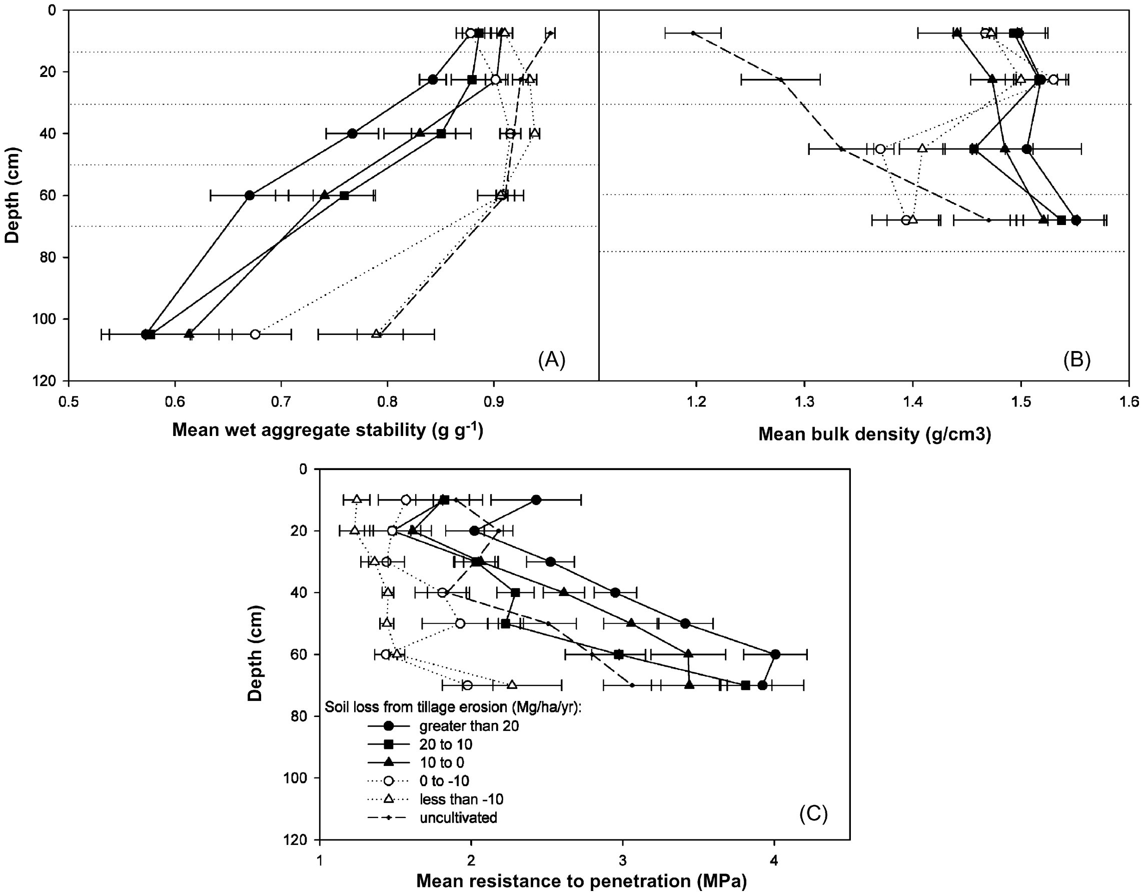

Fig. 4. Mean (±standard error) (A) wet aggregate stability, (B) bulk density and (C) resistance to penetration in soil profiles as affected by tillage erosion. Positive tillage erosion values indicate net soil loss; negative values indicate net soil accumulation. Horizontal dotted lines indicate the extent of the depth increment represented by each point.

Olsen P (Fig. 3D) were low throughout the soil profile in uncultivated areas (receiving no fertilizer) and decreased with depth. In uncultivated areas, bulk density, soil strength (Fig. 4B and C), IC (Fig. 3A) and pH (data not shown) tended to increase with depth, influenced by the higher calcium carbonate content, lower humus contents, reduced structural development and bulk density of subsoil material below 50 cm. Pennock et al. (1994) also reported significantly higher OC and total N and lower pH and bulk density in surface soils of an uncultivated site compared to areas subject to long-term cultivation.

Comparing soil profiles in cultivated and uncultivated areas emphasizes the importance of soil translocation within the landscape in determining soil profile characteristics. More than 50 cm of topsoil material low in calcium carbonate accumulated at some sampling locations in areas of soil deposition (Fig. 2B). This accumulation, coupled with carbonate leaching during soil genesis in these relatively wet landscape positions, leads to very low IC contents throughout the soil profile in areas of soil deposition that are consistently lower than those measured in uncultivated soil (Fig. 3A). Removal of the OC-rich mineral horizons in eroded landscape positions leads to IC contents that are higher throughout the soil profile than in uncultivated areas and areas of soil accumulation (Fig. 3A).

The IC content measured in the Ap horizon at each sampling location was used to estimate the fraction of the Ap horizon comprised of Bk and A material using the mean IC content in the Bk and A horizons (Table 1). Results indicate that the IC content of the Ap horizon varied from essentially 100% similarity to the buried A horizon in areas of soil accumulation to 100% similarity to the Bk horizon in highly eroded areas. The properties of the rooting zone in eroded areas, combined with other processes influenced by landscape position, such as water infiltration and availability, result in significant yield reductions in eroded landscape positions as reported in Papiernik et al. (2005). The depth of the A + AB horizons in the summit, shoulder and upper backslope positions of uncultivated areas ranged from 22 to 38 cm (data not shown). Prolonged intensive tillage and cropping at this site has effectively removed at least 20 cm of soil from the upper hillslope positions.

The large difference in OC content found between the uncultivated and cultivated hillslopes is in part a reflection of the relatively high OC content of the uncultivated topsoil (Fig. 3B). Soil OC contents below 20 cm depth on the uncultivated hillslope are similar to those of the cultivated topsoil (Fig. 3B). Soil loss by erosion (approximately 20 cm) on the cultivated hillslope could account for most of the reduction in OC concentration in the upper shoulder position. Our observations are consistent with other studies examining the effects of cultivation on soil properties in the prairie region (Pennock et al., 1994; Malo et al., 2005), which report a large decrease in surface soil OC contents in soils subject to long-term cultivation compared to uncultivated soils. Malo et al. (2005) indicated that the OC content of the surface soil was similar to that of the underlying B horizon in the upper shoulder position of cultivated areas. Pennock et al. (1994) report a >2-fold reduction in OC content in the upper 0.45 m following 80 years of cultivation in Saskatchewan, Canada, similar to the reduction in surface soil OC reported here. The reported reduction in OC content was smaller in Malo et al. (2005) than in our study because of the lower OC content of the uncultivated topsoil, a reflection of the drier and warmer climate associated with the experimental sites in that study. Organic carbon concentrations in B horizons were similar to those observed in this study.

Redistribution of soil by tillage is being increasingly recognized as a major erosive force in undulating landscapes, as evidenced by recent efforts to include tillage erosion in descriptive and predictive erosion models (Van Oost et al., 2000). Information regarding carbon and organic matter dynamics in eroding landscapes is required to allow more accurate predictions of carbon sequestration and carbon dioxide emissions from agricultural sources (Liu et al., 2003; Van Oost et al., 2004). The global carbon budget is not currently balanced, and current estimates of agricultural sources and sinks may be inaccurate, since they do not account for soil movement within the landscape (Van Oost et al., 2004). In order to accurately model carbon sequestration in the landscape, processes including wind, water and tillage erosion that redistribute carbon within the landscape must be accurately described. In addition, this study emphasized that total carbon is not a robust indicator of soil quality or carbon sequestration, because IC contents can greatly exceed OC contents in areas of severe erosion (Table 3), resulting in significantly higher total carbon concentrations in eroded landscape positions than in accumulating (sequestering) landscape positions (Table 3).

4. Conclusion

At this site in west central Minnesota, cultivation for the past ~100 years has resulted in a pattern of soil redistribution within the landscape such that topsoil has been removed from shoulder and upper backslope positions and accumulated in footslope and toeslope positions. Tillage erosion, the primary erosive force at this site, has altered the characteristics of the soil profiles across the landscape. Low organic matter contents throughout the soil profile in eroded landscape positions leads to low OC, total N and Olsen-extractable P contents relative to areas of soil accumulation. The influence of shallow subsoil material in upper landscape positions results in increased soil strength, low aggregate stability, high IC content, high pH, low OC content and low concentrations of total N and Olsen P throughout the profile in areas of soil loss by tillage erosion compared to areas of soil accumulation by tillage. The mean surface soil OC and total N contents in cultivated areas (regardless of erosion status) were less than half that measured in an adjacent uncultivated hillslope, indicating that intensive tillage and cropping has significantly depleted the surface soil organic matter in this landscape. These results provide a detailed documentation of the effects of soil translocation by tillage on the physical and chemical properties of soil profiles in hilly landscapes, and are important for continued efforts to incorporate tillage erosion into soil erosion and crop productivity models.

References

Adams, W.E., 1949. Loss of topsoil reduces crop yields. J. Soil Water Conserv. 4, 130.

Arriaga, F., Lowery, B., 2005. Spatial distribution of carbon over an eroded landscape in southwest Wisconsin. Soil Tillage Res. 81, 155–162.

Battiston, L.A., Miller, M.H., Shelton, I.J., 1987. Soil erosion and corn yield in Ontario. I. Field evaluation. Can. J. Soil Sci. 67, 731–745.

Bruce, R.R., White Jr., A.W., Thomas, A.W., Snyder, W.M., Langdale, G.W., Perkins, H.F., 1988. Characterization of soil-crop yield relationships over a range of erosion on a landscape. Geoderma 43, 99–116.

De Alba, S., Lindstrom, M., Schumacher, T.E., Malo, D.D., 2004. Soil landscape evolution due to soil redistribution by tillage: a new conceptual model of soil catena evolution in agricultural landscapes. Catena 58, 77–100.

Fenton, T.E., Kazemi, M., Lauterbach-Barrett, M.A., 2005. Erosional impact on organic matter content and productivity of selected Iowa soils. Soil Tillage Res. 81, 163–171.

Govers, G., Vandaele, K., Desmet, P., Poesen, J., Bunte, K., 1994. The role of tillage in soil redistribution on hillslopes. Eur. J. Soil Sci. 45, 469–478.

Heckrath, G., Djurhuus, J., Quine, T.A., Van Oost, K., Govers, G., Zhang, Y., 2005. Tillage erosion and its effect on soil properties and crop yield in Denmark. J. Environ. Qual. 34, 312–324.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. second ed. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 425–442.

Kosmas, C., Gerontidis, S., Marathianou, M., Detsis, B., Zafiriou, T., Van Muysen, W., Govers, G., Quine, T., Van Oost, K., 2001. The effects of tillage displaced soil on soil properties and wheat biomass. Soil Tillage Res. 58, 31–44.

LECO Corporation, 2003. Total/organic carbon and nitrogen in soils. LECO Corporation, St. Joseph, MO, Organic Application Note 203-821-165.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to moldboard plowing. Soil Tillage Res. 24, 243–255.

Liu, S., Bliss, N., Sundquist, E., Huntington, T.G., 2003. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. Global Biogeochem. Cycles 17, 1074.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. Can. J. Soil Sci. 75, 211–218.

Lowery, B., Swan, J., Schumacher, T., Jones, A., 1995. Physical properties of selected soils by erosion class. J. Soil Water Conserv. 50, 306–311.

Malo, D.D., Schumacher, T.E., Doolittle, J.J., 2005. Long-term cultivation impacts on selected soil properties in the northern Great Plains. Soil Tillage Res. 81, 277–291.

Olson, K.R., Carmer, S.G., 1990. Corn yield and plant population differences between eroded phases of Illinois soils. J. Soil Water Conserv. 45, 562–566.

Pennock, D.J., Anderson, D.W., de Jong, E., 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma 64, 1–19.

Papiernik, S.K., Lindstrom, M.J., Schumacher, J.A., Farenhorst, A., Stephans, K.D., Schumacher, T.E., Lobb, D.A., 2005. Variation in soil properties and crop yield across an eroded prairie landscape. J. Soil Water Conserv. 60, 388–395.

SAS Institute, 2003. SAS version 9.1 for Windows. SAS Institute, Inc., Cary, NC.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D. (Eds.), 2002. Field book for describing and sampling soils, version 2.0. Natural Resources Conservation Service, United States Department of Agriculture, National Soil Survey Center, Lincoln, NE.

Schumacher, J.A., Kaspar, T.C., Ritchie, J.C., Schumacher, T.E., Karlen, D.L., Ventris, E.R., McCarthy, G.M., Colvin, T.S., Jaynes, D.B., Lindstrom, M.J., Fenton, T.E., 2005. Identifying spatial patterns of erosion for use in precision conservation. J. Soil Water Conserv. 60, 355–362.

Schumacher, T.E., Lindstrom, M.J., Schumacher, J.A., Lemme, G.D., 1999. Modeling spatial variation in productivity due to tillage and water erosion. Soil Tillage Res. 51, 331–339.

Shukla, M.K., Lal, R., 2005. Erosional effects on soil organic carbon stock in an on-farm study on Alfisols in west central Ohio. Soil Tillage Res. 81, 173–181.

Sparovek, G., Schnug, E., 2001. Temporal erosion-induced soil degradation and yield loss. Soil Sci. Soc. Am. J. 65, 1479–1486.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2006. Official soil series descriptions. Available at http://soils.usda.gov/technical/classification/osd/index.html. Accessed 19 April, 2006.

Tsara, M., Gerontidis, S., Marathianou, M., Kosmas, C., 2001. The long-term effect of tillage on soil displacement of hilly areas used for growing wheat in Greece. Soil Use Manage. 17, 113–120.

Van Oost, K., Govers, G., Desemet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecol. 15, 577–589.

Van Oost, K., Govers, G., Quine, T.A., Heckrath, G., 2004. Comment on ‘‘Managing soil carbon’’ (1). Science 305, 1567b, http://www.sciencemag.org/cgi/reprint/305/5690/1567b.pdf.

Wagner, S.W., Hanson, J.D., Olness, A., Voorhees, W.B., 1998. A volumetric inorganic carbon analysis system. Soil Sci. Soc. Am. J. 62, 690–693.