Variation in soil properties and crop yield across an eroded prairie landscape

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ABSTRACT: Intensive tillage moves large quantities of soil, resulting in a pattern of soil redistribution where topsoil is depleted from convex slope positions and deposited in concave positions. In these experiments, the variation in erosion estimates, properties of the surface soil, and crop yield (four years) were determined in an undulating landscape that is subject to annual moldboard plowing. Results indicated that areas with high tillage erosion (shoulder slope positions) had high inorganic carbon contents in the surface soil due to the incorporation of calcareous subsoil material. Wheat yields in 2000, 2001, and 2003 were lowest in these areas, demonstrating yield reductions of 50 percent or more. Conversely, wheat yields were highest in areas in which soil translocation by tillage and water results in a net deposition of soil (depressions). These areas had a deeper A horizon, and the surface soils had higher organic carbon contents, lower pH and lower inorganic carbon contents. Soybean yields in 2002 did not show a strong dependence on location within the landscape. These results indicate that the observed variation in crop yield in undulating landscapes may be significantly influenced by removal of topsoil through repeated intensive tillage, and point to opportunities for landscape restoration to reduce yield losses.

Keywords: Erosion, precision agriculture, spatial variability, tillage erosion

Tillage erosion, the progressive downslope movement of soil by mechanical implements, has been identified as a major erosive force (Lindstrom et al., 1990; 1992; Govers et al., 1994; Lobb and Kachanoski, 1999). The net effect of soil translocation by tillage is the loss of soil from convex slope positions and soil accumulation in concave positions. Soil flux due to tillage erosion depends on soil properties (bulk density, moisture, etc.), topography (slope gradients and curvature), and tillage practices (tillage implement, depth and speed of tillage, etc.). Soil translocation by tillage and water erosion induces changes in the physical and chemical properties of the soil, including changes in soil texture, organic matter content, calcium carbonate contents, nutrient concentrations, and bulk density (Kosmas et al., 2001; Li and Lindstrom, 2001; de Alba et al., 2004). Removal of soil from upslope positions can result in the exposure of subsoil material at shoulder positions and soil deposition patterns may result in a deep A horizon in depressions (Kosmas et al., 2001) or a buried A horizon under some conditions (de Alba et al. 2004).

The spatial variability in crop yields and crop quality is often related to the spatial variability in soil quality indicators. In some cases, the spatial variation in soil properties affecting plant growth has been directly linked to changes induced by soil translocation through tillage (Kosmas et al., 2001; Schumacher et al., 1999). Within-field variability in parameters including soil depth, available soil water, nutrients, pH, organic matter content, and indicators of clay content (electrical conductivity and cation exchange capacity) have been reported to affect yield (Bruce et al., 1988; Cox et al., 2003; Johnson et al., 2002; Kosmas et al., 2001; Kravchenko et al., 2003; Sparovek and Schnug, 2001) and crop quality (Johnson et al., 2002; Stewart et al., 2002). Many studies have indicated that grain yields are depressed in areas of a field susceptible to low soil moisture, especially those with coarse soil texture and low organic matter contents. Yields tend to be lowest in eroded areas where calcareous subsoil is exposed and highest in concave positions, which have relatively deep topsoil, especially in dry years (Cox et al., 2003; Kravchenko and Bullock, 2000; Stewart et al., 2002).

In undulating landscapes, tillage and water erosion can combine to induce large variabilities in soil productivity at the field scale (Schumacher et al., 1999). Approaches to manage this variability have been proposed, including the physical movement of soil from areas of net deposition to areas of net soil loss. Assessments of the variability in soil physical and chemical properties in eroded landscapes and the impact of this variability on crop yield are required to evaluate the expected benefits of remediation approaches. The objectives of this work were to characterize the spatial variability in soil properties induced by tillage and water erosion and to investigate the impact of soil variability on crop yield in four consecutive years.

Methods and Materials

Experimental site. Experiments were conducted in a 2.7 ha (6.7 ac) portion of a 16 ha (40 ac) field near Cyrus in west central Minnesota. This field has been cultivated for approximately 100 years, with annual moldboard plowing for more than 40 years; it has been cropped predominantly to wheat, soybean, and corn. 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) in depressions; in middle slope positions, an inverted soil profile may

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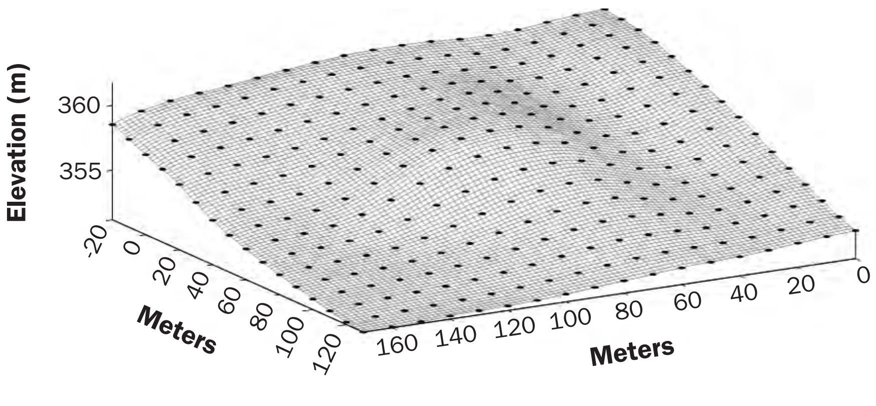
Figure 1
Experimental site: Sampling locations and elevations.



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 288 points on a 10 m (32.81 ft) grid in the 2.72 ha (6.7 ac) field (Figure 1) in August, 2000. Figures present the mirror image of the site to aid in visualization. Each point was located (latitude, longitude, and elevation) using a Trimble AgGPS-132[1] with differential corrections (Omnistar). Soil cores (7.6 cm or 3 in diameter) were collected in 15 cm (5.9 in) depth increments to 30 cm (12 in). The depth of the Ap horizon was determined by a pedologist. A value of 30 cm (12 in) was assigned in cases where the Ap horizon was at least 30 cm (12 in) deep.

Calculation of erosion estimates. To develop tillage and water erosion estimates, a digital elevation model was developed using a Leica survey grade DGPS system, with points located on a 10-m (32.81 ft) grid. Tillage and water erosion estimates were made following the procedure described in Schumacher et al. (2005) and are briefly summarized here.

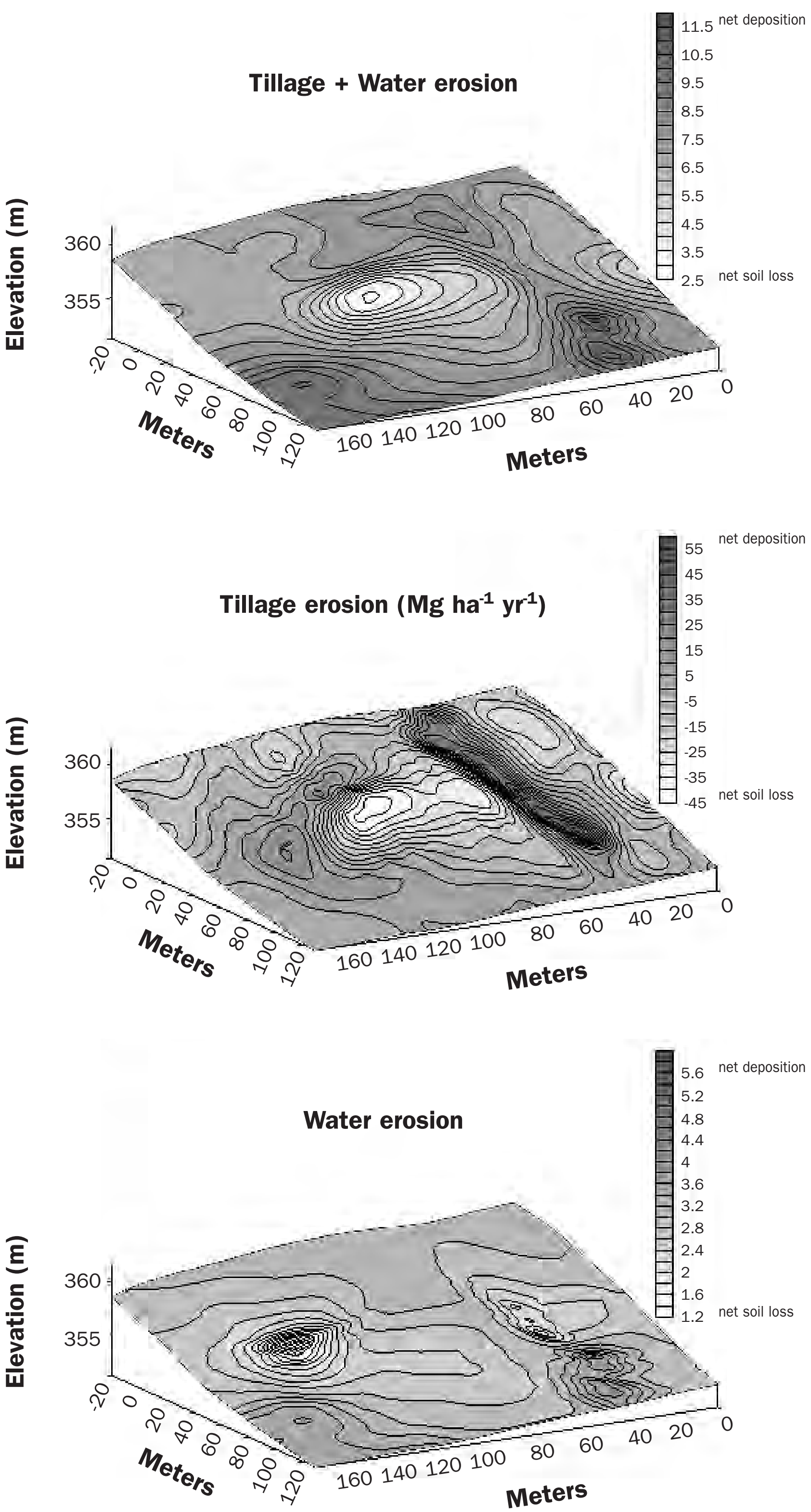
Erosion by tillage, water, and the combined effects of tillage and water was estimated at each node on the grid using the Water and Tillage Erosion Model (WaTEM, van Oost et al., 2000). This model estimates tillage erosion using a diffusion equation and water erosion using a modified version of the Revised Universal Soil Loss Equation (RUSLE). The model assumed a typical tillage of moldboard plowing plus two disking operations annually, giving a tillage transport coefficient (k) of 718 kg m^{-1} (99 lb ft^{-1}). To approximate the RUSLE factors, a corn/soybean/wheat rotation for the past 45 years was assumed. Model coefficients were: a rainfall-runoff erosivity factor (R) of 90, a soil erodibility factor (K) of 0.28, a cover/management factor (C) of 0.21, and a support practice factor (P) of 1. Measured elevation and slope gradients and a bulk density of 1350 kg m^{-3} (17 lb ft^{-3}) were used in the simulation. This produced an estimate of the amount of soil translocated by these processes annually (Mg $ha^{-1}yr^{-1}$).

Soil properties determined for 0 to 15 cm (5.9 in) depth. Soil samples were air-dried and sieved (< 2 mm or 0.08 in) and selected properties of the surface soil were determined as described in Stephens (2003). Briefly, soil pH was determined in a slurry of 10 g (0.35 oz) of air-dried soil and 20 mL (0.67 fl oz.) of 0.01 M $CaCl_2$. Organic carbon content (weight percent) was measured using a LECO 600 CN analyzer following removal of inorganic carbon [by addition of 10 mL (0.34 fl oz) of 6 N HCl] from a 0.12-g (0.004 oz) sample of oven-dried, ground soil. Calcite content (weight percent) was measured by addition of HCl-$FeCl_2$ to the sample and measuring the evolved CO_2 after 30 seconds of shaking; dolomite content (weight percent) was measured after 30 minute of shaking. The weight percent of total carbonates was calculated as the sum of calcite and dolomite.

Table 1. Descriptive statistics of the distribution of erosion estimates, measured soil chemical properties, and yield.

Property	Range (min-max)	Mean	CV (%)	Skew	Kurtosis
Elevation (m)	351.1 to 361.8	356.5	<1	-0.1	-1.3
Tillage erosion (Mg ha^{-1} yr^{-1})	-46 to 53	-2	683	0.2	1.2
Water erosion (Mg ha^{-1} yr^{-1})	-49 to 155	-13	166	3.6	20.4
transformed values	*0.2 to 4*	*2.9*	*13*	*-1.6*	*10.2*
Tillage + water erosion (Mg ha^{-1} yr^{-1})	-67 to 207	-15	181	3.0	17.7
transformed values	*1 to 15*	*7.5*	*21*	*0.1*	*3.8*
Depth of Ap (cm)	17 to 30	25	14	-0.2	-0.7
pH	6.9 to 7.9	7.5	2	-0.7	0.4
Organic carbon (%)	0.4 to 2.0	1.0	28	0.8	0.8
Total carbonates (%)	0 to 26	5	109	1.3	0.7
transformed values	*-2.1 to 2.1*	*0.8*	*117*	*-0.2*	*-1.0*
2000 Wheat yield (Mg ha^{-1})	2.3 to 5.3	4.2	13	-0.3	-0.3
2001 Wheat yield (Mg ha^{-1})	1.5 to 6.5	3.9	19	0.3	0.2
2002 Soybean yield (Mg ha^{-1})	1.6 to 4.9	2.8	12	0.6	6.0
2003 Wheat yield (Mg ha^{-1})	1.9 to 6.5	4.6	22	-0.3	-0.9
Mean normalized yield	0.4 to 0.9	0.7	14	-0.3	-0.6

Figure 2
Erosion estimates as a function of field position. Tillage+water and water erosion estimates are transformed values; see Table 1 for range in untransformed values.



Assessment of soil productivity. Yield was determined in each of four years (2000 to 2003) using a yield-monitoring plot combine. The field was cropped to wheat in 2000, 2001, and 2003 and to soybean in 2002. The GPS-referenced data point was located at the center of the area harvested. A 1.5 m (5 ft) wide head was used for both wheat and soybean harvesting. Each yield data point was based on a ~13 m^2 (140 ft^2) harvested area, with the exact area measured for each location. Yield was determined on a mass basis, and was corrected for the moisture content of the grain. Yield was also normalized to the highest yield observed in each year, and the mean normalized yield was computed for each sampling point.

Data analysis. The Kolomogorov-Smirnov test for goodness of fit for a normal distribution indicated that elevation, tillage erosion, depth of Ap horizon, soil pH, organic carbon content, and all yield data were normally distributed. A Box-Cox transformation

$$[T(y) = (y^{\alpha}-1)/\alpha \quad (1)$$

where,

T(y) = transformed value,
y = original value, and
α = transformation parameter

was used for the total carbonate (α = -0.3), water erosion (α = -0.1), and tillage+water erosion (α = 0.3) data to obtain a normal distribution. A constant was added to each erosion estimate to make all values greater than 0. These data were used for statistical analysis.

Pearson correlation coefficients (SAS, SAS Institute, Cary, North Carolina) were calculated for each pair of measured properties to indicate correlation of soil properties and the correlation between measured soil properties and yield. Preliminary geostatistical analysis was used to indicate the spatial relationships of the parameters. A linear or spherical variogram was calculated using a maximum lag distance of 80 m (262 ft), a 30° tolerance and a 45° step interval for each measured soil property and yield parameter (Surfer, Golden Software, Golden, Colorado). The resulting variogram was used with ordinary kriging to construct a contour plot for each parameter (Surfer, Golden Software, Golden, Colorado) to indicate patterns in the spatial distribution of each property.

Results and Discussion

Site characterization. The area is characterized by rolling topography. The site consists

Table 2. Variogram properties for erosion estimates, soil properties, and yield.

Property	Nugget	Sill	Range	Anisotropy ratio	Anisotropy angle
Tillage erosion	0	300	80	2	97
Water erosion*	0	0.2	150	2	156
Tillage + water erosion*	0.6	4.5	240	1.9	154
pH	0	0.03	70	2	161
Depth of Ap†	10	slope = 0.03		2	174
Organic carbon†	0.06	slope = 0.0002		2	154
Total carbonates*,†	0.4	slope = 0.004		2	144
2000 Wheat yield	0.09	0.3	130	2	164
2001 Wheat yield	0.3	0.3	130	2	163
2002 Soybean yield†	0.08	slope = 0.0003		2	3
2003 Wheat yield	0.5	1.1	200	2	146
Mean normalized yield	0.003	0.008	170	2	157

*** Data transformed to obtain a normal distribution.**

† Linear variogram.

of a low hill and a waterway (Figure 1). Tillage erosion results in a pattern of soil redistribution such that soil is removed from shoulder positions and deposited in depressional areas with net soil loss exceeding 60 Mg ha^{-1} yr^{-1} (greater than 27 t ac^{-1} yr^{-1}) in some areas (Figure 2). At this site, water erosion generally results in lower soil removal rates [net soil loss < 20 Mg ha^{-1} yr^{-1} (<9 t ac^{-1} yr^{-1}) for most of the field] than tillage erosion. Both tillage erosion and water erosion produced large net deposition (>40 Mg ha^{-1} yr^{-1} or >18 t ac^{-1} yr^{-1}) in some areas, but tillage erosion has a larger impact on a larger portion of the field than water erosion. Estimates of tillage erosion predicted net soil loss at 53 percent of the points in the grid and net soil deposition at 47 percent of the points. For water erosion, the WaTEM model predicted net soil loss at 88 percent of the points and net deposition at only 12 percent of the points. Estimates of cumulative tillage+water erosion predicted net soil loss at 84 percent of the points and net soil deposition at 16 percent of the points.

Net soil flux by tillage erosion increases with increasing slope gradient (change in slope), while soil translocation by water erosion is a function of slope steepness and length. Combining the tillage and water erosion models indicates that the major features of the total erosion reflect the removal of soil from the shoulder positions by tillage and deposition at footslope positions by tillage and water (Figure 2). The combined effects of deposition of soil in the linear depression by tillage and removal of soil within the upper waterway by water result in very high deposition rates in the lower waterway (Figure 2). Although in this study, the depth of the Ap horizon was only monitored to 30 cm (11.81 in), other soil cores collected in the waterway indicate that the average depth of the A horizon exceeds 60 cm (24 in) near these sample points.

Soil erosion, primarily resulting from long-term tillage (based on annual moldboard plowing for more than 40 years) has resulted in a large variation in soil physical and chemical properties. The variation in calcite and total carbonate content was more than one order of magnitude, because long-term tillage has exposed high-carbonate subsoil at the shoulder positions. Other parameters also show high variation (Table 1). Estimates of tillage erosion were more variable than those for water erosion (Table 1).

A spherical variogram model, in which the variance increases with distance between samples to a maximum (sill) described the variograms of erosion estimates and wheat yield well, indicating that these factors were spatially variable. In these experiments, nugget values (variance at very small separation distances) were a small proportion of the total variance in erosion estimates (Table 2), suggesting that the 10 m (32.81 ft) grid sampling captured much of the spatial variability at this site. Nugget values for wheat yield variograms were a larger proportion of the total variance (Table 2), suggesting that a significant portion of the variance in yield was unexplained. The variance in some soil

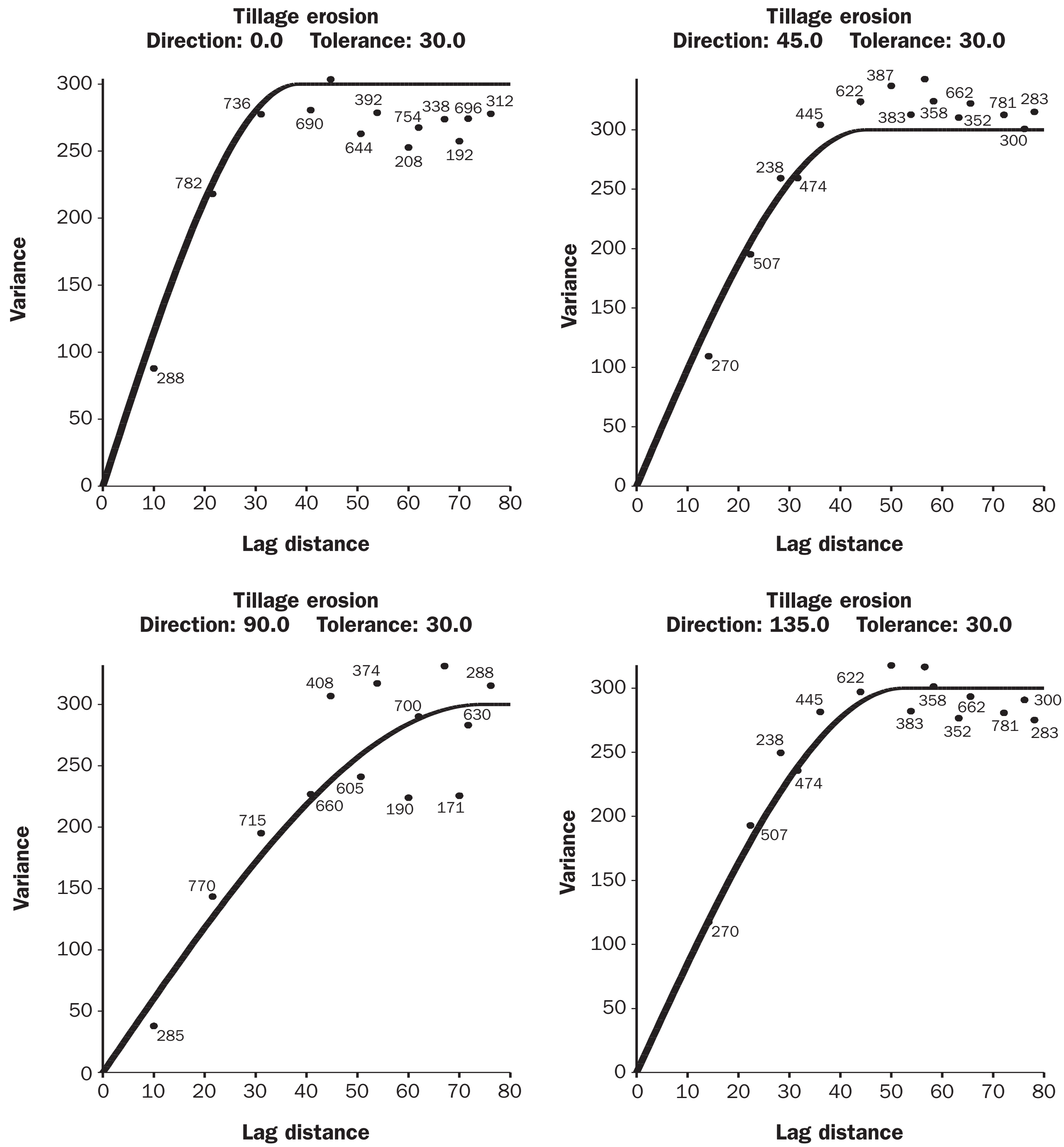
Table 3. Pearson correlation coefficients for erosion estimates and soil properties. Values in bold indicate significance at the 0.0001 level.

		Erosion estimates			Soil properties			
	Elevation	Tillage	Water*	Tillage + Water*	Depth Ap	pH	OC	Total carbonates*
Elevation	1							
Tillage erosion	**-0.43**	1						
Water erosion*	-0.09	-0.10	1					
Tillage + Water erosion*	**-0.40**	**0.72**	**0.53**	1				
Depth of Ap	-0.11	**0.32**	-0.04	0.23	1			
pH	**0.27**	**-0.27**	-0.21	**-0.39**	**-0.31**	1		
OC	-0.15	**0.26**	0.21	**0.35**	0.15	**-0.39**	1	
Total carbonates*	**0.39**	**-0.47**	**-0.28**	**-0.55**	-0.27	**0.69**	**-0.41**	1

*** Data transformed to obtain a normal distribution.**

Figure 3

Variogram for tillage erosion. Number of pairs are given for each point. An anisotropic spherical model was fitted to the data. This variogram was used in kriging to construct contour plots in Figure 2.



properties showing a linear variogram (depth of Ap, organic carbon and total carbonate contents) is not defined using this sampling scheme. An example set of variograms for tillage erosion is given in Figure 3.

Calculation of directional variograms indicated that variation in erosion estimates, soil chemical properties, and yields were direction-dependent, leading to variograms that had an anisotropy ratio of ~2 (Table 2). This is expected because of the presence of an approximately linear depression in the field (Figure 1), which affected erosion estimates and all measured properties. Contours demonstrate elongation along the direction of anisotropy (Figures 2, 4, and 5).

Correlation of soil properties. Pearson correlation coefficients (Table 3) indicate some general relationships. Tillage+water erosion estimates were highly correlated with tillage erosion estimates, but less so with water

Table 4. Pearson correlation coefficients for tillage estimates, soil properties, and crop yield. Values in bold indicate significance at the 0.0001 level.

	Yield				
	2000 Wheat	2001 Wheat	2002 Soybean	2003 Wheat	Mean normalized
Elevation	-0.21	**-0.26**	0.11	**-0.38**	**-0.29**
Tillage erosion	**0.57**	**0.44**	0.17	**0.59**	**0.58**
Water erosion*	0.19	0.14	0.07	**0.24**	**0.22**
Tillage + Water erosion*	**0.62**	**0.45**	**0.24**	**0.64**	**0.64**
Depth of Ap	**0.34**	**0.35**	**0.35**	**0.35**	**0.42**
pH	**-0.48**	**-0.41**	-0.21	**-0.61**	**-0.58**
OC	**0.38**	**0.29**	0.14	**0.41**	**0.41**
Total carbonates*	**-0.58**	**-0.47**	-0.18	**-0.74**	**-0.67**
2000 yield		**0.68**	**0.41**	**0.75**	**0.89**
2001 yield			**0.31**	**0.63**	**0.83**
2002 yield				**0.36**	**0.54**
2003 yield					**0.91**

* Data transformed to obtain a normal distribution.

erosion estimates. Estimates of total erosion at this site are dominated by the tillage erosion component. Tillage erosion was not correlated to water erosion as predicted by the WaTEM model, indicating that areas with high tillage erosion did not necessarily correspond with areas of high water erosion. Soil pH increased and organic carbon content decreased with increasing carbonate content. High soil loss by tillage erosion was correlated with high carbonate content in the soil, because long-term tillage has resulted in the exposure of calcareous subsoil in shoulder slope positions. This also results in a high correlation between tillage+water erosion and carbonate contents. (These regression coefficients are negative because erosion estimates for net soil loss are indicated by negative values.)

These relationships are also demonstrated by comparing plots of soil properties, which indicate that total carbonate (Figure 4) is highest in areas of high soil loss by erosion, and lowest in areas of high soil deposition (Figure 2). Areas of high carbonate content in the surface soil correspond to areas with high surface-soil pH and low organic carbon content. Other studies have indicated general agreement between classical and spatial correlation coefficients for soil properties at the field scale (Borůvka et al., 2002).

Impact of soil properties on yield. Correlation analysis (Table 4) indicated that wheat yield was positively correlated with tillage erosion and tillage+water erosion estimates (positive erosion values indicate net soil deposition), organic carbon content, and depth of the Ap horizon; wheat yields were inversely correlated with carbonate content and pH. Wheat yields were not strongly correlated with water erosion estimates. Soybean yields appeared to be less affected by these soil properties than wheat yields were, but only one year of yield data was available for soybean in this field. Yields were highly correlated with each other (Table 4), indicating that certain areas of the field produced consistently high/low yields.

Comparison of contour plots indicated the same trends: wheat yields (Figure 5) were lowest in areas characterized by high soil loss by erosion (tillage+water, dominated by tillage erosion, Figure 2), high carbonate content (Figure 4), and high pH. In each year, the minimum yield was 23-43 percent (average 32 percent) of the maximum yield (Figure 5). In 2001, 2002, and 2003, more than 10 percent of the field area produced yields less than 50 percent of the highest yield

Figure 4

Total carbonate content (transformed values) in top 15 cm of soil as a function of field position. Carbonate contents ranged from 0 to 26 percent by weight. Carbonate contents are highest in shoulder slope positions where long-term tillage has exposed calcareous subsoil and lowest in areas of high soil deposition.

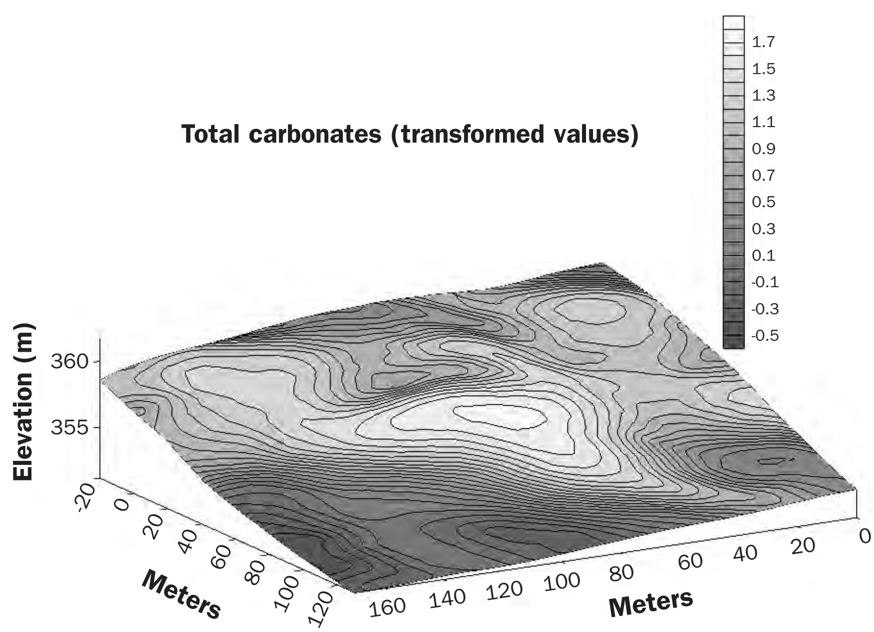
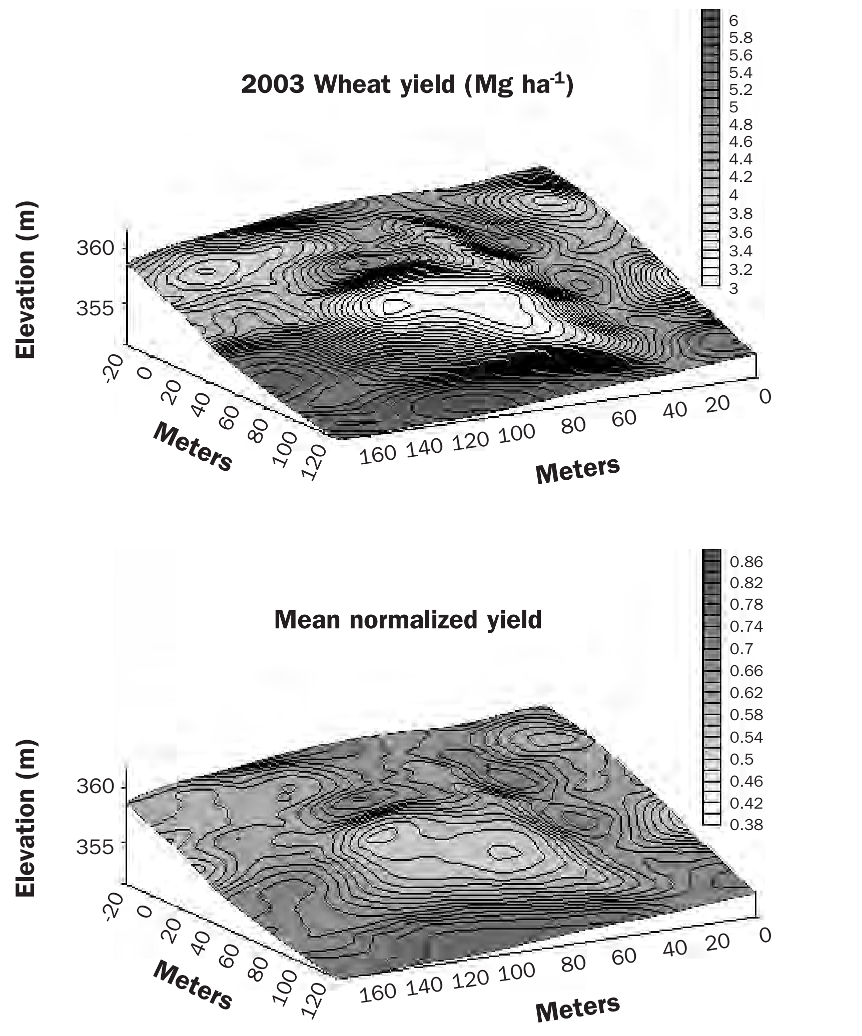


Figure 5

Yield as a function of field position. Yields are lowest in shoulder slope positions were long-term tillage has exposed calcareous subsoil and highest in areas of high soil deposition.



(Figure 5). In each year, the lowest yields (less than 10th percentile) were in areas with predicted high soil loss through erosion (tillage, water, and combined), high total carbonates, low organic carbon, and relatively high pH (Table 5). In contrast, the highest-yielding areas (greater than 90th percentile) in each year were characterized by lower soil loss through water erosion, soil deposition by tillage, low total carbonates, higher organic carbon contents, and slightly lower pH (Table 5).

The effects of within-field landscape position and soil properties on wheat yield have been noted by researchers in a variety of locations. For example, Stewart et al. (2002) found that wheat yield in New South Wales, Australia was affected by water stress; in their study, wheat yield was positively correlated with water holding capacity, clay content, and organic carbon content, and negatively correlated with coarse sand content. They also suggest the importance of erosion in determining soil properties that affect yield, but did not calculate tillage or water erosion rates. Similar results were reported by Kosmas et al. (2001) in Greece, where large topsoil depth and water holding capacities in concave landscape positions corresponded with high wheat biomass production.

Multiple factors interact to determine soil productivity in a given year. These experiments addressed only erosion estimates and selected properties of the surface soil. Other soil physical, chemical, and biological properties, landscape position, and climatic variables affect yield through their impact on soil water content, plant water relations, physiological processes, nutrient availability, pest pressure, and other processes. The results of these experiments suggest that the depletion of topsoil by repeated intensive tillage may be a critical factor in determining the variation in soil productivity at the field scale.

Summary and Conclusion

This site is characterized by a large variability in soil properties, with some parameters exhibiting coefficients of variation (CV) greater than 100 percent. Results indicated that wheat yields were decreased in areas affected by high soil loss, predominately due to tillage erosion on convex slope positions. These slope positions were areas with high soil pH, low organic matter contents, and high surface soil carbonate content resulting from exposure of subsoil material by tillage at these locations. Yield depressions in these areas of the field averaged 50 percent of the maximum measured yield in each year. The environmental and economic impacts of remediation approaches to increase yield at these degraded locations (for example, by moving translocated topsoil upslope from areas of net deposition) should be investigated.

Endnote

[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.

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Table 5. Average values of erosion estimates and selected soil properties for low-yielding (<10th percentile) and high-yielding (>90th percentile) locations.

	2000	2001	2002	2003	Mean
Low-yielding areas (yield <10th percentile)					
Tillage + water erosion (Mg ha^{-1} yr^{-1})	-40.4	-23.7	-30.6	-43.4	-34.5
Tillage erosion (Mg ha^{-1} yr^{-1})	-16.9	-10.2	-13.7	-18.6	-14.9
Water erosion (Mg ha^{-1} yr^{-1})	-23.5	-13.4	-16.9	-24.8	-19.6
Total carbonates (weight %)	13.7	8.7	11.2	14.6	12.0
pH	7.6	7.5	7.6	7.6	7.6
Organic carbon (weight %)	0.83	0.94	0.86	0.86	0.87
High-yielding areas (yield >90th percentile)					
Tillage + water erosion (Mg ha^{-1} yr^{-1})	-2.8	-2.7	-13.8	-0.3	-4.9
Tillage erosion (Mg ha^{-1} yr^{-1})	9.0	3.9	-0.3	5.6	4.6
Water erosion (Mg ha^{-1} yr^{-1})	-11.8	-6.5	-13.5	-5.9	-9.4
Total carbonates (weight %)	1.7	2.1	3.9	1.3	2.2
pH	7.3	7.4	7.4	7.3	7.3
Organic carbon (weight %)	1.2	1.1	1.0	1.2	1.1

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