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Modeling spatial variation in productivity due to tillage and water erosion☆

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Abstract

The advent of precision farming practices has heightened interest in managing field variability to optimize profitability. The large variation in yields across many producer fields demonstrated by yield–monitor–equipped combines has generated concern about management-induced causes of spatial variation in soil productivity. Soil translocation from erosion processes may result in variation in soil properties across field landscape positions that produce long-term changes in soil productivity. The objective of this study was to examine the relationships between soil redistribution caused by tillage and water erosion and the resulting spatial variability of soil productivity in a soil catena in eastern South Dakota. An empirical model developed to estimate tillage erosion was used to evaluate changes expected in the soil profile over a 50-year period on a typical toposequence found in eastern South Dakota and western Minnesota. Changes in the soil profile due to water erosion over a 50-year period were evaluated using the WEPP hillslope model. The tillage erosion model and the WEPP hillslope model were run concurrently for a 50-year period to evaluate the combined effect of the two processes. The resulting changes in soil properties of the root zone were evaluated for changes in productivity using a productivity index model. Tillage erosion resulted in soil loss in the shoulder position, while soil loss from water erosion occurred primarily in the mid to lower backslope position. The decline in soil productivity was greater when both processes were combined compared to either process acting alone. Water erosion contributed to nearly all the decline in soil productivity in the backslope position when both tillage and water erosion processes were combined. The net effect of soil translocation from the combined effects of tillage and water erosion is an increase in spatial variability of crop yields and a likely decline in overall soil productivity.

Keywords: Tillage erosion; WEPP; Soil catena; Soil translocation; Precision farming

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1. Introduction

Substantial soil translocation occurs on cultivated lands as a result of tillage erosion (Govers et al., 1994; Lindstrom et al., 1992a), water erosion (Frye et al., 1982; Govers et al., 1996), and wind erosion (Lyles,

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1975; Skidmore et al., 1975). The loss of topsoil from any of these processes results in substantial changes in soil properties (Lowery et al., 1995) and reduced crop yields (Schumacher et al., 1994). The effect of erosion processes on crop yield has been shown to be soil specific based on soil properties within the root zone (Schumacher et al., 1994; Shaffer et al., 1995).

The location of soil detachment and deposition zones along the hillslope is dependent on the erosion process. Net soil loss from tillage erosion occurs on shoulder positions as a result of gravity acting on moving soil and is described by diffusion-type equations (Govers et al., 1994). Soil detachment resulting from water erosion occurs in the mid to lower backslope primarily as a result of concentrated flow in rills (Young and Mutchler, 1969). Wind erosion detachment on hillslopes occurs primarily on shoulders facing into the prevailing wind (Chepil et al., 1964). The pattern of soil loss and gain within the landscape will depend on the relative mix of erosion processes and the topography of the hillslope. A mix of erosion processes is likely to occur in most landscapes with complex slope configurations.

The productive capacity of soils within a given catena varies spatially in part as a result of differences in soil properties, landscape location, soil depth, and hydrology (Daniels et al., 1987; Rhoton and Lindbo, 1997; Stone et al., 1985). Soil catenas found in the western Corn Belt commonly contain soils with differing soil properties and yield potentials that are dependent on topographic location within the landscape (Jones et al., 1989). Prolonged soil movement in cultivated landscapes will likely increase the naturally occurring variability of soil properties and yield potential. Studies of spatial variation in yield in these landscapes typically find a wide range in actual yields (Khakural, 1988; Jones et al., 1989). Evaluation of productivity potentials based on soil properties also demonstrate considerable variation (Lindstrom et al., 1992b). The development of site specific farming techniques allows the identification of yield variation and promises to provide the capability of uniquely managing areas with different soil properties (Vanden Heuvel, 1996). Managing spatial variation within the field requires a higher level of management and reduces operational efficiencies.

This study was conducted to determine the relative contributions to variation in productivity of soils that one might expect from the long-term application of moldboard plow based tillage operations on a typical hillslope found in eastern South Dakota and western Minnesota. The objective of this study was to examine the relationship between soil redistribution caused by tillage and water erosion as estimated from computer simulation models and the resulting spatial variability of soil productivity in a soil catena found in eastern South Dakota.

2. Methods

A soil catena representing a typical toposequence common to eastern South Dakota and western Minnesota was used to evaluate contributions of tillage and water erosion to changes in soil productivity. Soils contained within the catena include the Beadle clay loam (Typic Argiustolls) in the summit and backslope position, Ethan clay loam (Entic Haplustolls) in the shoulder position, Prosper loam (Pachic Argiustolls) in the footslope and Worthing silty clay loam (Typic Argiaquolls) in the toeslope positions. All soils in upslope (summit to footslope) positions were formed from glacial-till parent material, while the parent material for the Worthing series was local colluvium derived from upslope positions. The Worthing series is commonly found in flat enclosed depressions on uplands (Schultz and Driessen, 1973).

Soil development was affected by landscape position. The Beadle soil has an argillic horizon. The Ethan soil is less developed than the Beadle soil and does not have clay accumulation in the B horizon. The Prosper and Worthing soils have deeper topsoil development compared to the soils higher in the landscape. The Worthing soil in the toeslope position is poorly drained and frequently has a high salt content. Portions of this soil catena were used in previous soil management studies (Khakural et al., 1992; Schumacher et al., 1994; Shaffer et al., 1995)

Hillslope topography typical for this soil catena was used for evaluation. The hillslope was idealized by arbitrarily dividing it into five equal segments of 20 m length for each landscape position. The ranges of slope gradients used in the model analysis were 0%—summit; 0.2–8%—shoulder; 8%—backslope; 8–0.1%—footslope; and 0.1–0%—toeslope.

A tillage erosion model (Lindstrom et al., 1992a) was modified to run alone and in combination with the WEPP water erosion hillslope model (Flanagan and Nearing, 1995), version 97.3, using assigned slope gradients, lengths, and elevations. Tillage erosion parameters used included depth of tillage at 0.24 m, bulk density at 1350 kg m^{-3}, and a diffusion constant (k) of 3.3 kg m^{-1} percent $slope^{-1}$ (Govers et al., 1994; Lindstrom et al., 1992a). A computer program was developed to account for slope gradient and elevation changes based on WEPP output of soil detachment and deposition along a hillslope representing a Beadle soil catena. This allowed multi-year runs with a dynamic hillslope component. Soil deposition from the WEPP model was uniformly applied to segments from the initial point of deposition to the end of the toeslope segment. This was necessary to eliminate unrealistic point accumulations of soil caused by treating soil series as discrete units. Deposition of all detached soil was confined within the landscape continuum. This is a reasonable assumption for tillage erosion. For water erosion, this assumption would be true only for enclosed depressions.

Climatic data from Madison, SD, was used as an input into WEPP to develop average annual soil detachment and deposition values for the dynamic hillslope simulation. Annual precipitation at Madison averages 612 mm. The rainfall erosivity (R value in RUSLE) averages 1700 MJ ha^{-1} $year^{-1}$. A 10-year iteration of WEPP was used to represent variation in climatic data at Madison for yearly calculations of soil detachment or deposition in the dynamic hillslope simulation. Soil detachment and deposition values obtained after the 10-year iteration of WEPP were used to modify the soil elevation at 1 m increments annually. New slope gradients based on changes in soil elevation at 1 m increments were calculated and used for the next year's simulation. The tillage erosion model was also run using 1 m increments.

Soil property data for each soil in the catena were used in five overland flow elements as inputs to WEPP. WEPP soil erosion parameters (Table 1) were taken from the WEPP database for soils in the Beadle catena (Flanagan and Livingston, 1995). Parameters included in the published database are texture, bare dry soil albedo, initial saturation, baseline interrill erodibility, baseline rill erodibility, baseline critical shear, and effective hydraulic conductivity at the surface for each soil series. WEPP soil erodibility parameters were unchanged during the simulation. This was in part due to a lack of data on how soil erodibility parameters will change in these series with erosion and a limitation of the model implementation. Soils in WEPP were handled as discrete units and there was no attempt to intergrade soil properties at soil series boundaries. The five overland flow elements in WEPP corresponded to the previously described landscape segments of 20 m length. A continuous corn system with spring moldboard plow using management and dates of operation typical for eastern South Dakota and western Minnesota were used as inputs to the WEPP hillslope model (Gollany et al., 1992).

Evaluations of soil redistribution were made for a 50-year period using the tillage erosion model alone, the WEPP hillslope model modified to run dynamically alone, and the two models running interactively. Differences in hillslope elevation after the 50-year period were used to determine depth of topsoil loss or deposition.

Table 1
Soil parameters used for WEPP inputs

Soil series	K_i[a] (kg s m^{-4})	K_r[b] (s m^{-1})	Tau_c[c] (N m^{-2})	Conductivity[d] (mm h^{-1})
Beadle (summit)	4.7×10^6	7.9×10^3	3.5	1.08
Ethan (shoulder)	6.1×10^6	8.2×10^3	3.2	5.11
Beadle (backslope)	4.7×10^6	7.9×10^3	3.5	1.08
Prosper (footslope)	6.1×10^6	7.3×10^3	3.2	4.90
Worthing (toeslope)	4.0×10^6	7.0×10^3	3.5	0.43

[a] Baseline interrill erodibility.
[b] Baseline rill erodibility.
[c] Baseline critical shear.
[d] Effective conductivity of the surface soil.

A productivity index (PI) model (Pierce et al., 1983; Larson et al., 1983) was used to determine productivity of each soil in the catena. The PI model describes the soil environment in terms of the soil's sufficiency for root growth based on the summation of available water capacity, bulk density (adjusted for permeability), and pH as modified by depth increments. Generally as topsoil depth decreases, soil productivity will decrease due to less favorable subsoil characteristics. Soil property data for the respective soil series were based on previously collected data (Khakural et al., 1992 and Gollany et al., 1992) and supplemented with information from the NRCS soil interpretation records (National Cooperative Soil Survey, USDA-NRCS). Soil input values used in the PI simulations are given in Tables 2–5. Initial soil properties were assumed to be uniform within the 20 m segments for each soil series. This assumption also applies to WEPP model input. This assumption is certainly incorrect because of past management and spatial variations in the soil development process (Daniels et al., 1987). However, the assumption of uniform initial conditions within a soil series allowed for a first approximation of how erosion processes change patterns of productivity over

Table 2
Thickness of the principal soil horizons used in computer simulations

Horizon	Beadle (summit)	Ethan (shoulder)	Beadle (backslope)	Prosper (footslope)	Worthing (toeslope)
	(m)				
A_p	0.21	0.17	0.17	0.23	0.17
B_{t1}	0.26	—	0.23	0.38	0.17 (B_{tg})
B_{t2}	0.19	—	0.26	—	—
B_{k1}	0.19	0.27	0.19	0.53	0.75 (B_{kg})
B_{k2}	0.19	0.31	0.19	—	—
C	>1.0	>1.0	>1.0	>1.0	>1.0

Table 3
Bulk density values for the principal horizons of soils used in computer simulations

Horizon	Beadle (summit)	Ethan (shoulder)	Beadle (backslope)	Prosper (footslope)	Worthing (toeslope)
	(kg m^{-3})				
A_p	1190	1190	1190	1200	1200
B_{t1}	1280	—	1280	1250	1300 (B_{tg})
B_{t2}	1370	—	1370	—	—
B_{k1}	1520	1350	1520	1350	1350 (B_{kg})
B_{k2}	1570	1530	1570	—	—
C	1570	1600	1570	1600	1500

Table 4
Water holding capacity values for the principal horizons of soils used in computer simulations

Horizon	Beadle (summit)	Ethan (shoulder)	Beadle (backslope)	Prosper (footslope)	Worthing (toeslope)
	(m^3 m^{-3})				
A_p	0.23	0.21	0.23	0.21	0.20
B_{t1}	0.23	—	0.23	0.20	0.19 (B_{tg})
B_{t2}	0.25	—	0.25	—	—
B_{k1}	0.23	0.23	0.23	0.18	0.12 (B_{kg})
B_{k2}	0.20	0.23	0.20	—	—
C	0.20	0.20	0.20	0.18	0.11

Table 5
pH values for the principal horizons of soils used in computer simulations.

Horizon	Beadle (summit)	Ethan (shoulder)	Beadle (backslope)	Prosper (footslope)	Worthing (toeslope)
A_p	6.2	7.1	6.2	6.8	7.0
B_{t1}	7.1	—	7.1	7.0	7.1 (B_{tg})
B_{t2}	7.8	—	7.8	—	—
B_{k1}	8.0	7.6	8.0	7.8	7.1 (B_{kg})
B_{k2}	8.0	7.9	8.0	—	—
C	8.0	8.0	8.0	7.9	8.0

landscape positions. The effects of soil redistribution on spatial variation of soil productivity were measured assuming optimum management inputs (fertilizer application, weed control, and pest management) under dryland production. Soil deposition on the toeslope was assumed to have 33% less influence on productivity than predicted by the PI model due to the effects of high water tables and accumulated salts which are not accounted for in the PI model (Westin and Malo, 1978).

3. Results and discussion

Tillage erosion after a 50-year simulation resulted in two zones of change, soil loss from the shoulder position and deposition of soil in the footslope (Fig. 1). In contrast, water erosion caused a net soil loss in the lower shoulder, backslope, and upper footslope positions while net soil gain occurred in the mid to lower footslope and toeslope positions. (Fig. 2). The results of the combined processes of tillage and water erosion after a 50-year period are shown in Fig. 3. Soil loss occurred from the shoulder through the backslope positions into the upper footslope position when both processes were simulated together (Fig. 3). These combined processes resulted in a more uniform loss of soil in the backslope position than when simulating water erosion alone.

Soil translocation occurring at each point along the hillslope for the combined erosion processes and the individual processes alone are given in Fig. 4. Soil loss is enhanced in the shoulder position and soil gain is increased in the footslope position when both processes occur concurrently. Soil loss in the backslope position was moderated by the inclusion of

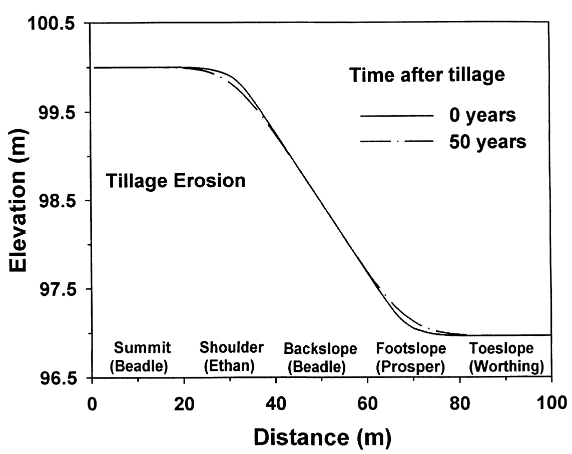

Fig. 1. Soil redistribution from tillage erosion. Based on a 50-year simulation using a modified tillage erosion model (Lindstrom et al., 1992a).

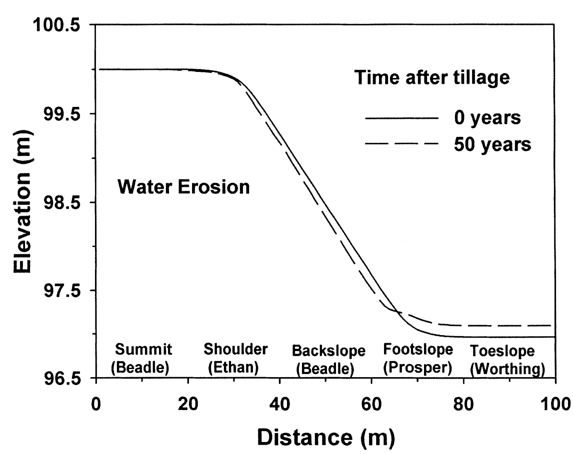

Fig. 2. Soil redistribution from water erosion. Based on a 50-year simulation using a dynamic WEPP hillslope water erosion model.

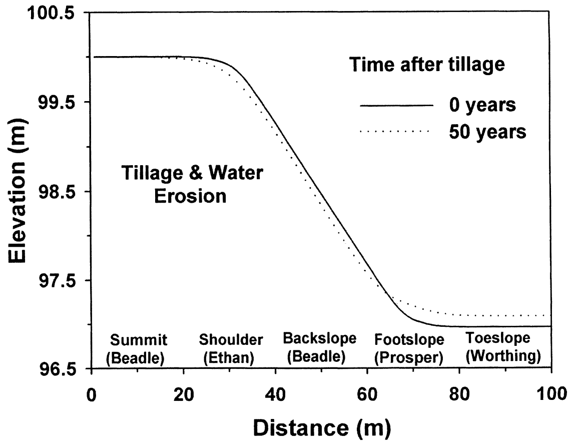

Fig. 3. Soil redistribution from tillage and water erosion occurring concurrently during a 50-year period. Based on a 50-year simulation using a modified tillage erosion model linked to a dynamic WEPP erosion model.

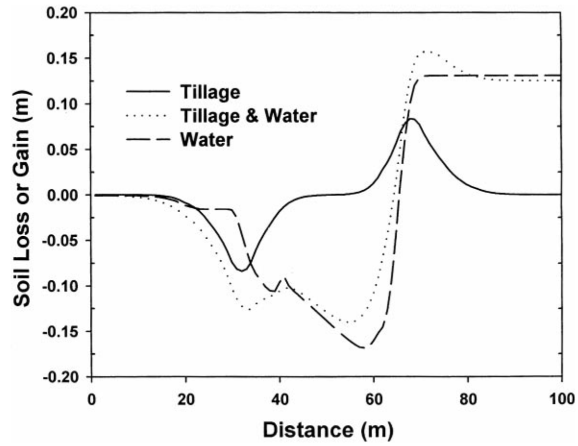

Fig. 4. A comparison of independent evaluations of tillage and water erosion with combined tillage and water erosion processes on simulated soil loss and gain in a Beadle catena during a 50-year period.

tillage erosion in the erosion process model. The change in slope gradient in the lower portions of the landscape continuum (lower backslope and upper footslope) by soil deposition due to both tillage and water erosion processes results in a continuous shift upslope for soil deposition. Soil gain in the toeslope assumes no loss of soil from the landscape as expected in a landscape containing enclosed depressions similar to the modeled research site. The pattern of hillslope morphology after the 50-year period differed depending on erosion process similar to observations made by Govers et al. (1996).

A small peak in the water erosion plot occurs at 40 m at the transition from the Ethan to Beadle soil series in Fig. 4. This is most likely an artifact of the simulation resulting from the treatment of soils as discrete units by WEPP combined with differences in the soil erodibility parameters of these two soils (Table 1).

There was an interaction between tillage and water erosion when both processes were modeled together. A comparison of the tillage erosion process individually and as a component in the combined process model is shown in Fig. 5(a). An increase in the

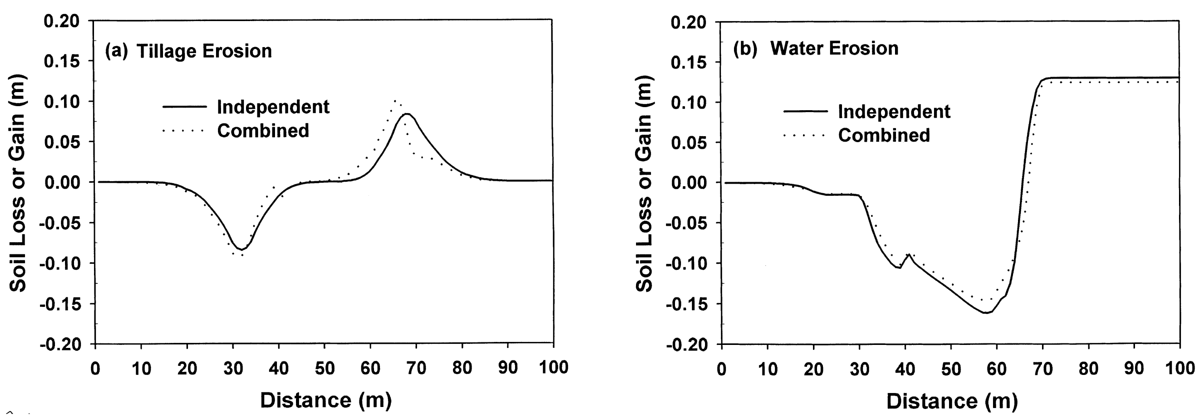

Fig. 5. Soil loss and gain occurring from independent simulations of each erosion process compared to the contribution of each respective erosion process to the combined model after a 50-year simulation of a Beadle catena, (a) tillage erosion, and (b) water erosion.

magnitude and a shift upslope in the distribution of the detachment and deposition peak occurred in the combined model due to tillage. The magnitude of the water erosion detachment peak was somewhat reduced when evaluated as a component of the combined model (Fig. 5(b)).

Soil PI values varied depending on the initial soil properties within the root zone (Tables 2–5). Soil properties measured from a field experiment in a Beadle catena were used and assumed to be uniform within the 20 m segment. Although this is not a correct assumption, it does allow for a first approximation of how erosion processes change patterns of soil productivity over discrete soil series located in specific landscape positions. Soil productivity based on soil properties and the application of a PI model showed the lowest PI in the shoulder and highest PI in the footslope positions (Fig. 6(a)–(d)). The changes in soil productivity reflect a reduction in topsoil depth and root zone depth in the shoulder and backslope positions, and a corresponding increase in topsoil and root zone depth in the footslope and toeslope positions. The high bulk densities in the B_k and C horizons (Table 3) are due to dense glacial-till parent material and represent root restricting subsoils (Olson et al., 1998). Crop production potential as estimated by PI will decline or increase as the volume of the root zone is reduced or increased through erosion processes.

The summit position had the least effect from the erosion processes on PI estimates (Fig. 6(a)). A large change in PI was observed at the shoulder position from both water and tillage erosion processes (Fig. 6(b)). A reduction in PI in the backslope position

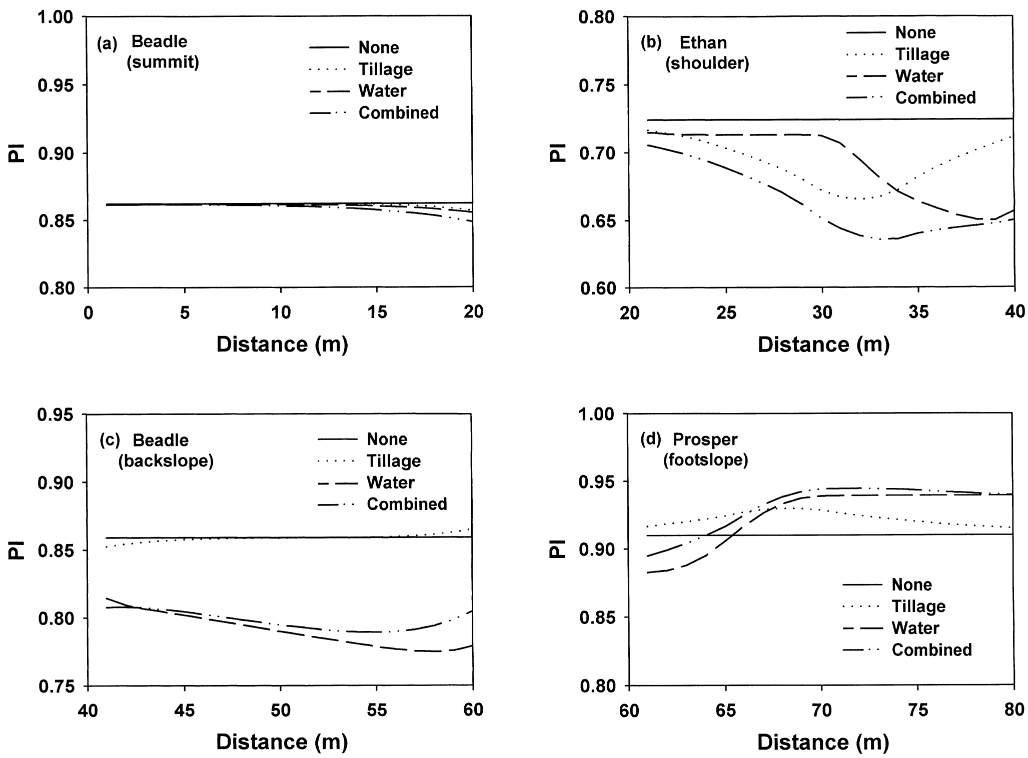

Fig. 6. Spatial distribution of soil productivity in a Beadle catena for the (a) summit; (b) shoulder; (c) backslope; and (d) footslope positions for a 50-year period of erosion from water erosion alone, tillage erosion alone, and both processes occurring together. Soil productivity was estimated using a PI model (Pierce et al., 1983) that evaluated productivity of the root zone on a scale of 0 to 1 based on changes in soil properties within the root zone resulting from the loss or gain of topsoil simulated by a tillage erosion model, a modified WEPP hillslope model, and the linkage of the two models.

appeared to be due to soil loss primarily from water erosion (Fig. 6(c)). An increase in PI was observed in the footslope region due to the combined effects of soil deposition from tillage and water erosion, which increased topsoil depth (Fig. 6(d)). Deposition of soil in the toeslope resulted in an increase in PI from 0.65 to a PI of 0.76. However, the relationship of PI to yield potential is likely to be moderated by the effects of poor drainage and salinity typically found in this position in the Beadle soil catena. Available information suggests a 33% loss in productivity in the Worthing soil (Westin and Malo, 1978) not accounted for by the PI model resulting in an estimated PI of 0.72 after the 50-year simulation.

This analysis of soil productivity changes due to model estimations of soil translocation from tillage and water erosion demonstrates how an increase in spatial variability of soil productivity may develop in fields with complex topography. Knowledge of the cause and direction of spatial variability in soil productivity may be used to help improve geostatistical analysis of yield trends in precision farming (Crawford and Hergert, 1997).

4. Conclusions

This attempt at simulating the effects of tillage and water erosion on crop production potential must be viewed as a first approximation. The treatment of soils as discrete units and the static treatment of soil properties in the WEPP component of the simulation are simplifications that are unlikely to describe most landscapes and need to be accounted for in future simulation efforts.

Tillage erosion predominates in summit and shoulder positions (convex slopes) where the slope gradients begin to increase downslope. Water erosion predominates in the backslope position, the area of maximum slope gradient. There was an interaction between the two erosion processes in soil translocation when both processes occurred concurrently. When processes were combined, soil loss increased in the shoulder position relative to when either erosion process was evaluated alone. The zone of deposition from tillage erosion shifted upslope when combined with water erosion due to changes in hillslope morphology caused by water erosion. Both processes deposit soil when slope gradients begin to decrease (concave slopes).

The simulation of soil redistribution within the Beadle catena resulted in spatial changes in soil productivity due to loss or gain in topsoil thickness. An evaluation of PI based on the simulated redistribution of soil on the hillslope showed an increase in spatial variability of soil productivity in the shoulder, backslope, and upper footslope positions. The reduction in PI on the shoulder position occurred primarily as a result of tillage erosion with some additional effect of water erosion in the lower part of the shoulder segment. In the backslope position, the reduction in PI occurred primarily from water erosion. The pattern of spatial variability in PI observed in the footslope position depended on the occurrence of detachment or deposition. The net effect of simulated soil translocation from the combined effects of tillage and water erosion was an increase in spatial variability of crop production potential.

5. List of symbols

WEPP	water erosion prediction project
RUSLE	revised universal soil loss equation
R	rainfall erosivity value in RUSLE
k	diffusion constant in tillage erosion equation
PI	productivity index model
USDA-NRCS	United States Department of Agriculture-National Resource Conservation Service
K_i	baseline interrill erodibility value in WEPP
K_r	baseline rill erodibility value in WEPP
Tau_c	baseline critical shear value in WEPP

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