Annals of Arid Zone 40(3): 337-349, 2001

Tillage Erosion: An Overview

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Abstract: Soil redistribution by tillage is becoming a recognized soil erosion process. Landscapes subject to tillage erosion are topographically complex or have a high number of field boundaries. Tillage erosion contributes to the evolution of landscape heterogeneity through creation of distinct landforms and the relatively rapid redistribution of soils from upland positions to depressions. The resultant variability in soil properties has an important effect on crop production. Our objective is to provide a basic understanding of tillage erosion by describing the tillage erosion process and to discuss the effect of tillage erosion on soil properties and soil productivity, and interaction with water erosion. A brief discussion is included on the subject of future research needs. A soil transport coefficient (k) has been determined as $k = -D\rho b\beta$; where D is tillage depth (m), ρb is the soil bulk density (kg m^{-3}), and β is the slope of the linear regression equation of the relationship between soil displacement and slope gradient. This k-value effectively describes soil transport as a function of slope gradient for a variety of tillage operations; however, the gain or loss in soil mass at any point on the landscape is proportional to hillslope curvature. That is, soil loss from tillage operation will take place on convexities and upper field boundaries, while soil deposition occurs on concavities and lower field boundaries. Soil loss from tillage operations can commonly be greater than what is considered sustainable. As soil is removed from upslope field boundaries or convex slope positions, subsurface soil horizons become exposed. The exposure and subsequent dispersion of this subsoil material, in addition to soil accumulation at lower slope positions, alters soil properties and introduces greater variation in soil properties over the landscape. The recognition of soil translocation by tillage and its subsequent effect on soil properties and variability presents considerable challenges. Soil conservation strategies must be broadened to include tillage erosion to be fully effective.

Key words: Erosion, soil translocation, soil variability, sustainability.

Soil translocation and redistribution in agricultural fields due to the direct action of tillage results in an increase in soil variability and an overall decrease in soil productivity. Tillage erosion is directly related to landscape characteristics. Landscapes subject to tillage erosion are topographically complex or have a high number of field boundaries. Tillage erosion contributes to the evolution of landscape heterogeneity through creation of distinctive landforms, such as lynchets, terraces, and field boundary steps, and through progressive, but relatively rapid

Fig. 1. Relative soil displacement distances when thrust is upslope versus downslope.

redistribution of soil from uplands to depressions. The resultant variability in soil properties has an important effect on crop production.

Evidence of tillage erosion can commonly be observed as the difference in soil color between hilltops and adjacent lower slope positions. The problem has been intensified with increased tillage speed and depth, increased size of tillage tools, and with the tillage of steeper and more undulating lands. When tillage operations are conducted in the upslope direction forward soil movement will be less than when conducted in the downslope direction (Fig. 1). This difference in soil translocation distance is a function of gravity. Assuming that tillage direction occurs equally often in the upslope and downslope directions, it is logical that a net downslope displacement of soil will take place.

Tillage erosion has often been described in qualitative rather than quantitative terms. Evidence of mass downslope movement of soil by tillage has been present for years. One frequently cited example comes from the Palouse region of the Pacific Northwest of the United States (Papendick and Miller, 1977) where soil banks, 3 to 4 m high, have developed at fenceline positions on steep slopes. The fenceline represents a zone of zero soil flux from tillage, i.e., soil does not move through the fenceline. As soil is moved towards the fenceline from above, and away from the fenceline from below, a field border develops. This soil accumulation and removal at field borders can be fairly rapid, leading to development of soil banks several meters high over a time period of a few decades when soil is consistently turned downslope during tillage.

The apparent truncation of hilltops and infilling of historical gullies in southwest France did not follow the pattern expected from water erosion processes and was best explained by long-term downslope soil movement from tillage (Revel and Guiresse, 1995). Examination of stereoscopic aerial photographs taken in 1947 and 1991 in the Loam Belt of Belgium showed a severe surface lowering on the top of hillslopes and on hillslope convexities. Deposition occurred on the lowermost parts of the hillslope concavities and in topographic convergence lines. The observed pattern differed markedly from that expected from water erosion, indicating that soil redistribution was dominated by tillage operations (Vandaele *et al.*, 1995).

Description of Tillage Erosion Process

A simple linear regression of the form Y = a+ b(S) has been developed (Lindstrom *et al.*, 1992; Govers *et al.*, 1994) where a and b are the regression constant and coefficient, respectively, that describe the relationship between slope gradient (S) and the mean soil translocation distance (Y) in the direction of tillage. Expanding on this relationship, Govers *et al.* (1994) have proposed that tillage translocation could be considered as a diffusion-type geomorphological process similar to raindrop splash and soil creep and characterized by a single constant, the tillage transport coefficient (k):

$$k = - D\rho_b\beta$$

where,
D is the depth of tillage (m), ρb is the soil bulk density (kg m^{-3}), and β is the slope of the linear regression equation of the relationship between soil displacement (m) and slope gradient (m m^{-1}). Using this relationship, the average annual downslope soil transport rate (Qs), assuming that the tillage direction alternates between up- and downslope tillage, at any specific point in the field can be calculated as:

$$Qs = kS$$

where,
S is the slope gradient (m m^{-1}). Representative tillage transport coefficients (k-value) for moldboard plow tillage range between 230 and 330 kg m^{-1} (Govers *et al.*, 1994), roughly two to three orders of magnitude greater than what would be expected from soil creep or raindrop splash. Commonly, intensively tilled agricultural fields undergo a series of tillage operations, resulting in k-values of 400 to 600 kg m^{-1} or greater.

It is not possible to directly calculate soil loss or gain using Qs, since this value essentially represents the soil flux at a cross-section for a specific tillage operation or a series of operations. Soil loss or gain will result when, for an elementary slope segment of unit width, the incoming flux is different than the outgoing flux:

$$E = (Q_{s,in} - Q_{s,out})/X$$

where,
E is the tillage erosion rate (kg m^{-2}), and X is the length (m) of the elementary slope under consideration. Since Qs is directly proportional to the slope gradient, soil loss or gain will be proportional to the change in slope gradient. Soil translocation by tillage will result in soil loss on convex slope positions, such as crests and shoulder slope positions, because there is an increase in slope gradient, thus an increase in soil transport rate. Conversely, soil deposition will take place in concave slope positions in the foot and toeslope positions. When slope gradients between adjacent elemental slope segments are equal, irrespective of their gradient, no net soil loss or gain takes place because Qs,in equals Qs,out. Thus in backslope positions where slope gradients are commonly the greatest, exhibiting the greatest soil transport rate, no net soil loss or gain is observed provided adjacent slope gradients remain equal. Therefore, the rate of soil gain or loss will depend on the unit transport rate and the degree of change in slope gradients.

In less mechanized tillage system, animal power or hand labor, it is common to always direct soil movement towards the downslope direction. This is done to conserve energy. The k-values for animal power or hand labor is less than mechanized tillage, but when the direction of tillage is always downslope an additional constant must be added to account for the unidirectional tillage. Quine *et al.* (1999) concluded that net downslope soil translocation by animal powered tillage always in the downslope direction may exceed those associated with mechanized agriculture.

Measured k-values for individual tillage operation and a series of tillage operations using mechanized equipment, animal power, and hand labor reported in the literature are shown in Table 1. Variations in k-values for similar tillage operations and tools are present. Many factors may be responsible for this variation, including tillage tool and power match, equipment design, soil condition, and depth and speed of operation. Van Muysen *et al.* (2000) reported on the effect of tillage depth, speed, and soil condition on tillage erosivity and showed that the tillage transport coefficient (k-value) increased substantially when the soil was in the unconsolidated state as compared to the consolidated state.

Tillage Erosion and Soil Properties

Lindstrom *et al.* (1992) reported a sustained soil loss of 30 t ha^{-1} y^{-1} from a convex hillslope in southwestern Minnesota from annual moldboard plowing. Lobb *et al.* (1995) reported a soil loss rate of 54 t ha^{-1} y^{-1} from shoulder positions in southwestern Ontario from a moldboard plow, tandem disc (two passes), and a C-tine cultivator. Clearly soil loss rates of this magnitude are not sustainable. Soil loss rates of this magnitude will rapidly expose the underlying subsoil that generally is less productive or desirable on convex slope positions and at upslope field borders. In time the properties of the tilled layer will be determined by the properties of the original subsoil in convexities and upslope field borders. As tillage erosion continues the area of exposed subsoil expands. Subsequent tillage transports the exposed subsoil downslope, which mixes with the original topsoil material in the tilled layer. As this process continues with continued tillage, the tilled layer over a large portion of the landscape will have properties more associated with the subsoil horizons than properties associated with the original topsoil (Fig. 2).

The tillage transport coefficient (k-value) represents the mass of soil per unit width that is moved by tillage across a point on the landscape in a specified direction relative to the direction of tillage. The k-value is dependent on the mean displacement distance of soil as affected by slope gradient. The soil mass is translocated forward in the direction of tillage, but is also translocated in the lateral direction. Determination of k-values has mostly been done in the forward direction. Using the mean displacement distances does not fully describe soil translocation however (Lobb and Kachanoski, 1999). For example, a single pass with a chisel plow may move 70 kg of soil forward per meter width of tillage. The mean forward displacement of this 70 kg of soil may be 40 cm, but significant quantities of soil may be moved as little as 5 cm or as much as 300 cm

Table 1. Comparison of tillage transport coefficients (k-value), available in, or calculated from the literature, for different implements, tillage directions, tillage speed and tillage depth. (after Van Muysen et al., 2000)

Source	Tillage depth (m)	Tillage speed ($m\ s^{-1}$)	Implement	k-value (kg m^{-1} per tillage operation)
Up- and down-slope tillage				
Govers *et al.* (1994)	0.15	1.25	Chisel	111
Govers *et al.* (1994)	0.28	1.25	Moldboard	234
Lindstrom *et al.* (1992)[a]	0.24	2.1	Moldboard	330
Lobb *et al.* (1995)[b]	0.15	1.1	Moldboard	184
Lobb *et al.* (1995)[b]	0.11	1.12	Moldboard + 2 disc + cultivator	473-734
Lobb and Kachanoski (1999)	0.17	2.66	Chisel plough	275
Lobb and Kachanoski (1999)	0.23	1.71	Moldboard	346
Lobb and Kachanoski (1999)	0.17	0.84	Tandem disc	369
Lobb and Kachanoski (1999)	0.15	1.92	Field cultivator	13
Poesen *et al.* (1997)	0.16	0.65	Duckfoot chisel	282
Quine *et al.* (1999)	0.19	2.3	Duckfoot chisel	605-660
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard	425
Turkelboom *et al.* (1999)	0.08	n.a.	Manual tillage (hoe)	77
Van Muysen *et al.* (1999)	0.33	0.5	Moldboard (pre-tiled soil)	254
Van Muysen *et al.* (1999)	0.15	0.75	Moldboard (fallow soil)	70
Controur tillage				
Lindstrom *et al.* (1992)[a]	0.24	2.1	Moldboard	363
Montgomery *et al.* (1999)	0.23	1.0	Moldboard	110
Poesen *et al.* (1997)	0.14	0.65	Duckfoot chisel	139
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard	710
Thapa *et al.* (1999)[b]	0.20	n.a.	1 Moldboard + 2 ridger	260
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard + 1 harrow	424-645
Thapa *et al.* (1999)[b]	0.20	n.a.	2 Moldboard + 1 harrow	299-348

n.a.: data not available; a: Data obtained from Govers *et al.* (1994); b: Reported *k*-values for totals for the sequence of tillage operations given. Tillage depth and speed are average for the tillage sequence.

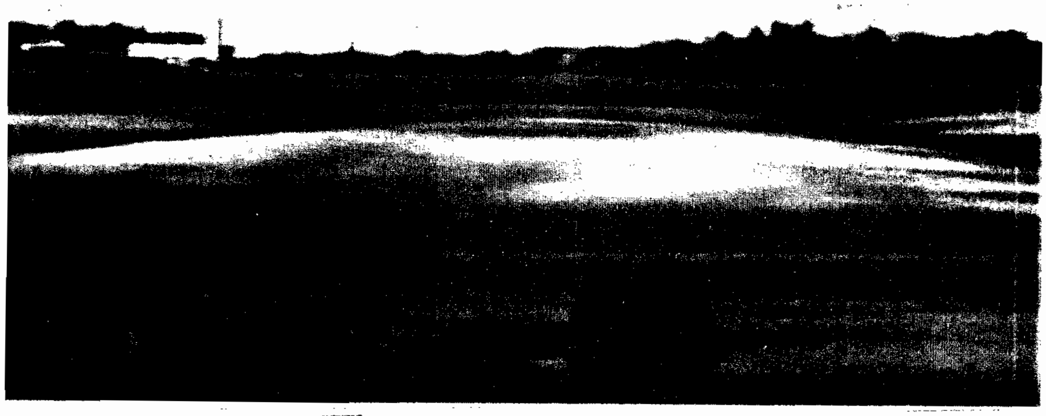

Fig. 2. Intensively tilled landscape showing exposed subsurface horizons on convex slope positions. Annual moldboard plowing and secondary spring tillage has removed the original topsoil, exposing the underlying Bk horizon, resulting in increased field variability and overall reduction in crop productivity.

(Lobb *et al.*, 2000). Soil displacement will vary across the width of a tillage implement due to the spacing and arrangement of the individual tillage tools. This variation in distance over which soil is translocated is important as it affects the distance that soil constituents (amendments and contaminants) are dispersed or mixed by tillage.

Sibbesen *et al.* (1985) demonstrated the significance of tillage translocation and the mixing of soil within the till-layer by predicting the rate and extent of cross-contamination of soil amendments by tillage translocation in long-term fertility research plots on level land. Lobb and Kachanoski (1999) have expanded on this concept by using various functions to describe the distances soil is displaced. In this analysis, an exponential function provided superior results over a step or linear-plateau function in describing the magnitude of translocation and the redistribution pattern of the soil in the tilled layer. In both cases, dispersion of a finite amount of known tracer by tillage was rapid and extended over several meters within a short time period (years). Van Oost *et al.* (2000) measured movement of sand from a sand outcrop situated at the upper slope boundary a distance of 45 m downslope in a field that had been cultivated for approximately 130 years. Soil dispersion by tillage, direction of tillage, and topography were factors considered in development of a model to describe the progression of sand movement downslope. Best correlation for dispersion of the sand required consideration of soil transport by water; however, soil translocation and dispersion by tillage accounted for the major portion of the redistribution of the sand.

Exposure of underlying subsoil to the surface and subsequent redistribution over the landscape by tillage modifies existing soil properties. Commonly the structural stability of the underlying subsoil is lower and combined with lower inherent soil organic matter content makes the soil more vulnerable to wind and water erosion. Furthermore, the redistribution of soil by tillage erosion delivers soil to areas of concentrated overland flow on both the microtopograhic scale, i.e., rills, and the macrotopograhic scale, i.e., convergent landforms (Lobb *et al.*, 1995; Govers *et al.*, 1996). As such, tillage erosion acts as a delivery mechanism of soil, which is then subject to water erosion. Water erosion is greatest along the central axis of hillslope concavities or draws where a large volume of surface runoff is concentrated, commonly leading to ephemeral gullies. This is also the zone of deposition by tillage erosion. While soil is not moved past field boundaries by tillage erosion, when soil is deposited in zones of concentrated runoff, it becomes subject to field loss.

The balance between deposition and removal depends on the relative intensity of the two processes and landscape morphology. Deposition by tillage will increase with increasing concavity; soil removal will increase with increasing slope gradient and upslope water contributing area. Thomas and Welch (1988) in the southern Great Plains, USA, using stereoscopic techniques found that more soil material was moved into two major ephemeral gullies by tillage than was removed by water erosion.

Tillage Erosion and Water Erosion

The magnitude of soil erosion rates by tillage versus water is affected by many variables, i.e., topography, rainfall intensity, tillage intensity (depth and frequency), and land use. After examining the relationship between a range of topographic parameters and ^{137}Cs-derived erosion rates, Quine and Walling (1993) showed that the highest correlation was between erosion rate and landscape curvature at four of the five sites investigated. These results were not consistent with the dominance of water erosion, where slope angle and upslope lengths or areas are the primary influences. Quine and Walling *et al.* (1994) compared the roles of tillage and water erosion on landform development on agricultural land in Belgium. If water erosion was the dominant process, they hypothesized that the landscape would be characterized by increased incision of the concavities and convergent waterways and a gradual increase in slope angles on upland convex slopes. In contrast, tillage produces maximum erosion on convex slopes leading to reduced slope angles and infilling of concavities and hollows. The pattern of landform development observed was an infilling of slope concavities and convergent waterways by sediment displaced through tillage that more than compensated for the less frequent but more visible rill and gully incision. Overall, the pattern indicates that despite the high susceptibility of this area to water erosion, landform development in this agricultural landscape is currently dominated by tillage erosion processes. A gradual obliteration of topographic features was found, rather than the expected landscape evolution if water erosion was the major contributing agent for landform development.

Quine *et al.* (1999) differentiated between erosion processes (tillage and water) at three field sites in China, Lesotho, and Zimbabwe. Tillage systems ranged from manual to mechanized. Soil movement rates from tillage translocation were determined through an iterative process to determine the best-fit k-value explaining the loss of ^{137}Cs at upper field boundaries and landscape positions where soil movement due to water erosion would be minimal. Using the best-fit k-value and water erosion equations the predicted soil movement levels were highly correlated with observed ^{137}Cs redistribution. In these analyses, soil movement by tillage was responsible for approximately 50% of the observed soil erosion measured in the three field situations.

Tillage Erosion and Soil Productivity

The impact of tillage erosion on soil productivity is primarily related to soil removal from a specific landscape position and deposition in another part of the landscape. Many of the causes of changes in soil productivity attributed to wind and water erosion also apply to tillage erosion. Lal (1988) lists several direct effects of soil erosion on crop yield, including a reduction in rooting depth, loss of plant nutrients, loss of available plant water, loss of land area, and damage to seedlings. Of these, tillage erosion acts on soil productivity through the first three: loss of effective rooting depth, loss of plant nutrients, and loss of plant-available water. Li and Lindstrom (2001) report changes in soil quality parameters, i.e., soil organic matter, plant-available nutrients, and bulk density, in terraced fields and along a steep cultivated hillslope in the Loess Plateau of China and attribute the changes in soil quality to soil deposition by tillage. In the terraced fields, soil organic matter content was lowest at the upper terrace boundaries and increased towards the lower terrace boundary. Soil bulk density was highest at the upper terrace boundary and lowest at the lower terrace boundary. In the steep cultivated hillslope, soil organic matter content and available plant nutrients were observed to increase in concave landscape position, most notably in the foot and toeslope areas, but also in the mid-backslope position where a discernable concave slope was present.

In the Philippines uplands, Thapa *et al.* (2001) measured changes in nutrient gradients on a steep hillslope (16 to 22%) and on terrace systems within a four-year-period with animal tillage systems. The extractable P concentration gradient became steeper for management systems utilizing grass barriers, with the highest concentration at the base of the terrace. Thapa *et al.* (1999) estimated that as much as 40% of the cropped area between terraces might eventually be degraded physically, chemically, or biologically if moldboard plowing continues. Downslope soil movement in the upland portion of the terrace was 42 t ha^{-1} y^{-1}, exposing an acidic subsoil with high Al saturation. In narrow spaced (5 m) terrace systems on steep uplands in Rwanda, Lewis (1992) describes the techniques used by local farmers to partially maintain fertility on the upslope portion of the terraces. The grass terrace was annually undercut to add nutrient-rich soil to the severely degraded soil that has developed from downslope soil movement with hand tillage operations.

Schumacher *et al.* (1999), using a tillage erosion model (Lindstrom *et al.*, 1992) and a water erosion model (Flanagan and Nearing, 1995) evaluated the effects of erosion patterns on soil property distribution on a landscape representative of glacial till landforms common to eastern South Dakota and western Minnesota. Summit, shoulder, backslope, footslope, and toeslope positions were represented in the landscape with representative soil series for each landscape position. The resulting changes in soil properties of the root zone, due to movement by the two eroding processes, were evaluated for each landscape position for change in productivity using a productivity model (Piece *et al.*, 1983).

This simulation of soil redistribution within the soil catena resulted in spatial changes in soil productivity due to loss or gain in topsoil thickness. An evaluation of productivity 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 net effect of soil redistribution from the combined effects of tillage and water erosion was a decrease in crop productivity in the shoulder and upper backslope positions and an increase in crop production potential in the footslope position. The increase in the footslope position did not compensate for the loss in crop production potential in the shoulder and upper backslope positions.

Research Needs

The most effective way to arrest tillage erosion and its adverse impacts is to eliminate tillage. However, tillage is an integral part for most forms of crop production. At a minimum, tillage is required for placement of seeds and nutrients. Tillage may be required for crop management and harvesting, i.e., root crops such as potatoes. Although the intensity of tillage has been dramatically reduced in many regions of the world over the past couple of decades, no-till or zero-till-cropping systems account for only a minor percentage of total cropped land in most parts of the world. The challenge will be to develop equipment and practices that provide the desired effect of tillage while minimizing soil erosion by wind, water, and tillage.

While some degree of tillage is necessary, tillage frequency and intensity (speed and depth), implement size and design, tillage pattern, and soil condition are factors that may be adjusted to minime tillage erosion. Data from Van Muysen *et al.* (2000) show the additive effects of increased speed and depth to the tillage transport coefficient for a chisel plow. Additional data from Van Muysen *et al.* (1999) showed an increase in the tillage transport coefficient with moldboard plowing from 70 kg m^{-1} for a grass fallow consolidated soil to 254 kg m^{-1} on a pre-tilled unconsolidated soil condition, suggesting the increase in soil erosivity that will occur with secondary tillage. Under these conditions local maximum erosion rates increased from approximately 8 to 35 Mg ha^{-1} from the consolidated to unconsolidated soil condition.

Tillage equipment should be designed with consideration for tillage translocation and tillage erosion. Tool geometry, arrangement, and combination should not only create a suitable seedbed, incorporate residue, etc., they should also minimize the amount of soil translocated and minimize the potential for variation in translocation. The size of tillage implements in relation to landscape size may be an important consideration. Tillage implements that are very long and/or very wide have the potential to increase tillage erosion through a planing effect over variable topography. Variability in soil translocation has the potential to increase with tillage implements equipped with multiple ranks over a single ranked design. Systematic research will be required to assess these relationships.

Simulation models can identify lands that are sensitive to tillage erosion that may require changes in land management or, in serious cases, changes in land use. Presently the models that have been developed only consider soil translocation in one direction, forward or lateral. De Alba (2001) has developed a two dimensional model for the moldboard plow representing a more accurate presentation on how soil truly moves with tillage. Fully integrated soil erosion models must be developed to understand the synergy between erosion processes. Govers *et al.* (1996), Quine *et al.* (1999), and Schumacher *et al.* (1999) have used water and tillage erosion models in tandem. To fully understand and predict soil erosion potentials, wind, water, and tillage erosion processes should be integrated into a single model.

Soil translocation downslope due to tillage action has the potential to alter soil profile characteristics. As subsoil is exposed to the surface with tillage erosion, subsoil material will be dispersed over the landscape. De Alba (1999) in his Ph.D. thesis presents a hypothesis on changes in soil horizon sequences that would occur due to tillage erosion (Fig. 3). Ellis (1938) proposed a similar sequence of change while observing differences in horizon sequence of short-term cultivated and non-cultivated soils in the Canadian Province of Manitoba. These changes in profile characteristics will undoubtedly alter soil productivity potentials and vulnerability to wind and water erosion, but will also have an effect on other soil physical, chemical, and biological properties and processes. This is a relatively unexplored area of research that merits much attention in the future.

The recognition of tillage translocation and tillage erosion, and their significance, present considerable challenges and opportunities for tillage researchers and practitioners. Soil conservation strategies must be broadened to include tillage erosion and they must be fully integrated. To undertake this approach in soil conservation requires research on many aspects of tillage. These challenges and opportunities are equal in magnitude to those placed on wind and water erosion.

Conclusions

Tillage erosion, the progressive downslope movement of soil through the action of tillage operations, is a serious problem that needs to be considered during the development of conservation management plans. Tillage erosion is directly proportional to the degree and scale of topographic complexity. The magnitude of soil translocation from upslope positions, either convex slopes or upper terrace borders, can result in soil loss, which can greatly exceed levels that would be considered sustainable. Although soil is not directly lost from fields by tillage erosion, it is moved from upslope or convex slope positions and deposited at field or terrace borders and

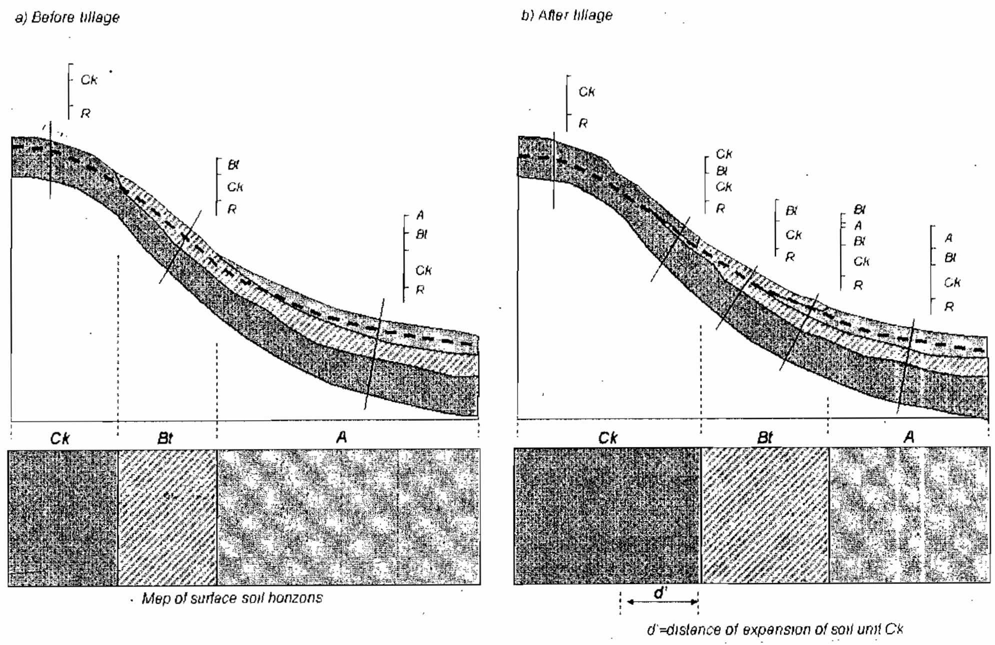

Fig. 3. Effects of soil redistribution by tillage on soil profile morphology and soil landscape variability, showing catena transformation due to tillage erosion.

concave slope positions. The interactions between tillage and water erosion require that both processes be considered. The net effect of soil erosion, either tillage or water erosion, is an increase in field variability and a reduction in crop production potential.

References

De Alba, S. 1999. Soil degradation processes by erosion in agricultural systems under Mediterranean environmental conditions in central Spain. *Ph.D. Thesis.* Universidad Autonoma de Madrid, 590 pp. (in Spanish).

De Alba, S. 2001. Modelling the effects of complex topography and patterns of tillage on soil translocation by tillage with mouldboard plough. *Journal of Soil and Water Conservation* (in press).

Ellis, J.H. 1938. *Soils of Manitoba.* Province of Manitoba. 112 p.

Flanagan, D.C. and Nearing, M.A. 1995. *USDA-water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation*, NSERL Report No. 10, USDA-ARS National Soil Erosion Laboratory, West Lafayette, IN.

Govers, G., Quine, T.A., Desmet, P.J.J., Poesen, J. and Bunte, K. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* 45: 469-478.

Govers, G., Quine, T.A., Desmet, P.J.J. and Walling, D.E. 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. *Earth Surface Processes and Landforms* 21: 929-946.

Lal, R. 1988. Monitoring soil erosion's impact on crop productivity. In *Soil Erosion Research Methods* (Ed. R. Lal), pp. 187-200. Soil and Water Conservation Society, Ankeny, IA, USA.

Lewis, L.A. 1992. Terracing and accelerated soil loss on Rwandan steeplands: A preliminary investigation on the implications of human activities affecting soil loss. *Land Degradation and Rehabilitation* 3: 241-246.

Li, Y. and Lindstrom, M.J. 2001. Evaluating soil quality-soil redistribution relationship on terraces and steep hillslopes. *Soil Science Society of America Journal* 65: 1500-1508.

Lindstrom, M.J., Nelson, W.W. and Schumacher, T.E. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil and Tillage Research* 24: 243-255.

Lobb, D.A. and Kachanoski, R.G. 1999. Modelling tillage translocation using step, linear-plateau and exponential functions. *Soil and Tillage Research* 51: 317-330.

Lobb, D.A., Kachanoski, R.G. and Miller, M.H. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. *Canadian Journal of Soil Science* 75: 211-218.

Lobb, D.A., Lindstrom, M.J., Quine, T.A. and Govers, G. 2000. Tillage at the threshold of the 21st Century: New directions in response to tillage translocation and tillage erosion. In *Proceedings, 15th Conference of the International Soil Tillage Research Organization*, July 2000, Fort Worth, TX.

Montgomery, J.A., McCool, D.K., Busacca, A.J. and Frazier, B.E. 1999. Quantifying tillage translocation and deposition rates due to moldboard plowing in the Palouse Region of the Pacific Northwest, USA. *Soil and Tillage Research* 51: 175-187.

Papendick, R.I. and Miller, D.E. 1977. Conservation tillage in the Pacific Northwest. *Journal of Soil and Water Conservation* 32: 40-56.

Piece, F.J., Larson, W.E., Dowdy, R.H. and Graham, W.A.P. 1983. Productivity of soils: Assessing long-term changes due to erosion. *Journal of Soil and Water Conservation* 38: 39-44.

Posen, J., van Wesemael, B., Govers, G., Martinez-Fernadez, J., Desmet, P., Vandaele, K., Quine, T. and Degraer, G. 1997. Patterns of rock fragement cover generated by tillage erosion. *Geomorphology* 18: 183-197.

Quine, T.A., Desmet, P.J.J., Govers, G., Vandaele, K. and Walling, D.E. 1994. A comparison of the roles of tillage and water erosion in landform development and sediment export on agricultural land near Leuven, Belgium. In *Variability in Stream Erosion and Sediment Transport* (Eds. L.J. Olive, R.J. Loughran and J.A. Kesby), IAHS Publ. 224: 77-86.

Quine, T.A. and Walling, D.E. 1993. Use of caesium-137 measurements to investigate relationships between erosion rates and topography. In *Landscape Sensitivity* (Eds. D.S.G. Thomas and R.J. Allison), pp. 31-48. John Wiley, Chichester.

Quine, T.A., Walling, D.E., Chakela, Q.K., Mandiringana, O.T. and Zhan, X. 1999. Rates and patterns of tillage and water erosion on terraces and contour strips: Evidence from casium-137 measurements. *Catena* 36: 115-142.

Revel, J.C. and Guiresse, M. 1995. Erosion due to cultivation of calcareous clay soils on hillslopes of south west France. I. Effect of former farming practices. *Soil and Tillage Research* 35: 147-155.

Sibbesen, E., Andersen, C.E., Andersen, S. and Flensted-Jensen, M. 1985. Soil Movement in long-term field experiments as a result of cultivation. I. A model for approximating soil movement in one horizontal dimension by repeated tillage. *Experimental Agriculture* 21: 101-107.

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

Thapa, B.B., Cassel, D.K. and Garrity, D.P. 1999. Ridge tillage and contour natural grass barrier strips reduce tillage erosion. *Soil and Tillage Research* 51: 341-356.

Thapa, B.B., Cassel, D.K. and Garrity, D.P. 2001. Animal powered tillage translocated soil affects nutrient dynamics and soil properties at Claveria, Philippines. *Journal of Soil and Water Conservation* 56: 14-21.

Thomas, A.W. and Welch, R. 1988. Measurement of ephemeral gully erosion. *Transactions of ASAE* 31: 1723-1728.

Turkelbloom, F., Poesen, J., Ohler, I. and Ongprasert, S. 1999. Reassessment of tillage erosion rates in northern Thailand. *Soil and Tillage Research* 51: 245-259.

Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M. and Poesen, J. 1999. Measurement and modeling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. *Soil and Tillage Research* 51: 303-316.

Van Muysen, W., Govers, G., Van Oost, K. and Van Rompaey, A. 2000. The effect of tillage depth, tillage speed, and soil condition on chisel tillage erosivity. *Journal of Soil and Water Conservation* 55: 355-364.

Van Oost, K., Govers, G., Van Muysen, W. and Quine, T.A. 2000. Modeling translocation and dispersion of soil constituents by tillage on sloping land. *Soil Science Society of America Journal* 64: 1733-1739.

Vandaele, K., Vanommeslaeghe, J., Muylaert, R. and Govers, G. 1995. Monitoring soil redistribution patterns using sequential aerial photographs. *Earth Surface Processes and Landforms* 21: 353-364.