

Soil landscape evolution due to soil redistribution by tillage: a new conceptual model of soil catena evolution in agricultural landscapes

S. De Alba , M. Lindstrom , T.E. Schumacher , D.D. Malo

Abstract

This paper focuses on analysing tillage as a mechanism for the transformation of soil spatial variability, soil morphology, superficial soil properties and development of soil–landscape relationships in agricultural lands. A new theoretical two-dimensional model of soil catena evolution due to soil redistribution by tillage is presented. Soil profile truncation occurs through loss of soil mass on convexities and in the upper areas of the cultivated hillslopes; while the opposite effect takes place in concavities and the lower areas of the field where the original soil profile becomes buried. At sectors of rectilinear morphology in the hillslope (backslope positions), a null balance of soil translocation takes place, independent of the slope gradient and of the rate of downslope soil translocation. As a result, in those backslope areas, a substitution of soil material in the surface horizon with material coming from upslope areas takes place. This substituted material can produce an inversion of soil horizons in the original soil profile and sometimes, the formation of “false truncated soil”. In the Skogstad agricultural field (Cyrus, MN) spatial patterns of soil properties (soil calcium carbonate content) in the surface soil horizons and soil morphology along several slope transects were analyzed. These spatial patterns are compared with those estimated for soil redistribution (areas of erosion and deposition) due to tillage using the *Soil Redistribution by Tillage* (SORET) model and water erosion using the models Water Erosion Prediction Project (WEPP) and Universal Soil Loss Equation (Usle2D). Results show that tillage was the predominant process of soil redistribution in the studied agricultural field. Finally, some practical implications of the proposed model of soil landscape modification by tillage are discussed. Nomographs to

calculated the intensity of the expansion process of the eroded soil units by tillage are proposed for three different patterns of tillage.

Keywords: Soil redistribution; Tillage erosion; Water erosion; Soil catena; Soil spatial variability; Pedoturbation; Pedology; Mollisols

1. Introduction

Unquestionably, soil redistribution by tillage plays a key role in building and modifying the geomorphology and pedology of sloping agricultural landscapes (Papendick and Miller, 1977; Govers et al., 1999). In recent years, high tillage erosion rates have been reported in agricultural fields under different technological and environmental conditions. In many cases, for specific landscape positions, tillage erosion rates reached higher values than soil loss tolerance levels (Lindstrom et al., 1992; Govers et al., 1996). First Lindstrom et al. (1992) and later several authors including Govers et al. (1994), Lobb et al. (1995), and De Alba (2003) have documented how tillage tends to produce a progressive denudation of rolling landscapes. Fig. 1 shows a widely accepted model of long-term evolution of a complex slope profile as predicted by a simple simulation using a fixed soil transport rate by tillage operation. The rates of tillage soil translocation are proportional to the slope gradient, while the net rates of soil loss or gain are related to the morphology and curvature of the slope (Lindstrom et al., 1992; Govers et al., 1994), i.e., soil loss occurs on convex areas and deposition takes place on concave areas.

On the other hand, tillage contributes to the creation of distinctive landforms, such as, lynchets that form along field boundaries. Soil accumulates on the upslope side of field

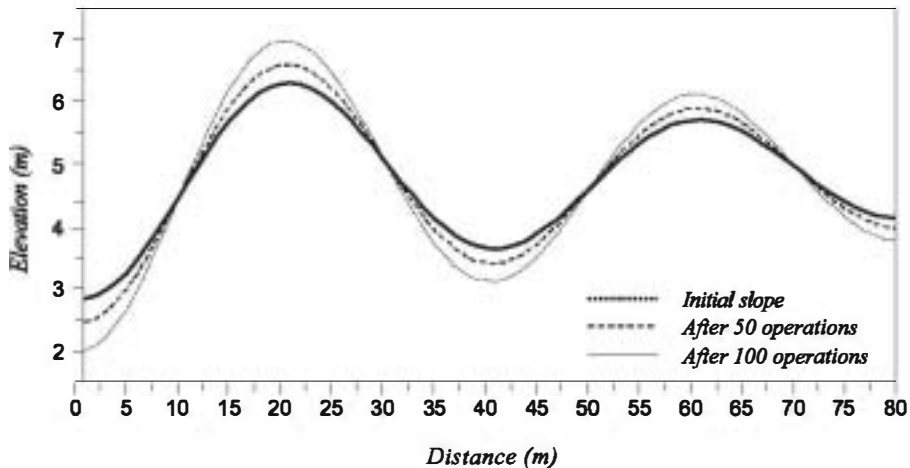


Fig. 1. Simulated long-term effects of soil redistribution by tillage on a theoretical slope profile.

boundaries and soil is translocated away from the downslope side of field boundaries (Papendick and Miller, 1977). As a result, landscape benching takes place when boundaries between adjacent fields are located at backslope positions (e.g., De Alba, 2002) or if tillage is conducted between grass hedges (Dabney et al., 1999).

During the last decade, an increasing number of studies have been conducted to quantify soil translocation rates produced by different tillage implements and identifying controlling factors Lindstrom et al. (1990,1992), Revel et al. (1993), Govers et al. (1994), Lobb et al. (1995), Poesen et al. (1997), Van Muysen et al. (1999), De Alba (2001), and Torri and Borselli (2002). High soil translocation rates have not only been documented for modern tillage equipment using mechanical power, but as well for tillage practices using animal power (e.g., in Thapa et al., 1999). Quine et al. (1999) found that because tillage by animal power necessitates downslope turning of the soil on every occasion, the resultant net downslope translocation may exceed the levels associated with tillage by mechanized power, in which the soil is turned in opposing directions on successive occasions. Intense translocation rates and erosive effects due to manual tillage have been reported by Turkelboom et al. (1999) in Thailand.

Regarding on-site effects of tillage erosion on soil quality and productivity, Schumacher et al. (1999) gave an example of how tillage erosion increases soil variability and degradation of surface soil quality in convex slope positions, as well as increasing spatial variability of crop production. Torri et al. (2002) discusses how soil redistribution may cause modification of soil hydrology resulting in a complex series of interactions and synergies between tillage and water erosion processes, as well as, with other geomorphic processes. Modification of soil slope stability due to soil accumulation over a possible surface of rupture can increase the risk of surface mass movement. There are few studies documenting the effects of soil redistribution by tillage on soil variability at field and landscape scales (e.g., Schumacher et al., 1999; Kosmas et al., 2001).

In this paper, we discuss the effects of soil redistribution on the spatial variability of soil properties, soil profiles, and soil landscapes. A new conceptual model of modification by tillage of the soil profile morphologies and soil catenas is proposed. In order to identify field evidence of this model of soil modification, the spatial pattern of soil variability is analyzed over an agricultural field that shows evidence of prior intense erosion. This soil pattern is compared with those predicted for tillage and water erosion to identify those erosion processes that had the predominant role in producing the current soil pattern. Finally, some practical implications of soil landscape modification by tillage are discussed.

2. Modification of the soil profile morphology due to soil redistribution by tillage

2.1. Mixing and inversion of the upper soil horizons by tillage using a moldboard plow

At landscape positions where the thickness of the surface soil horizon is less than the depth of tillage, the plow layer comprises material from both the surface and the subsurface soil horizons (e.g., shoulder positions). As a consequence of this, moldboard

plow tillage operations may invert and mix the two soil horizons (e.g., McKyes, 1985). Fig. 2a shows an idealized sketch of the inversion process of soil horizons. At early stages after a few tillage operations, the plow layer presents contrasted components from two original genetic horizons (e.g., A and Bk horizons in Fig. 2a). After repeated

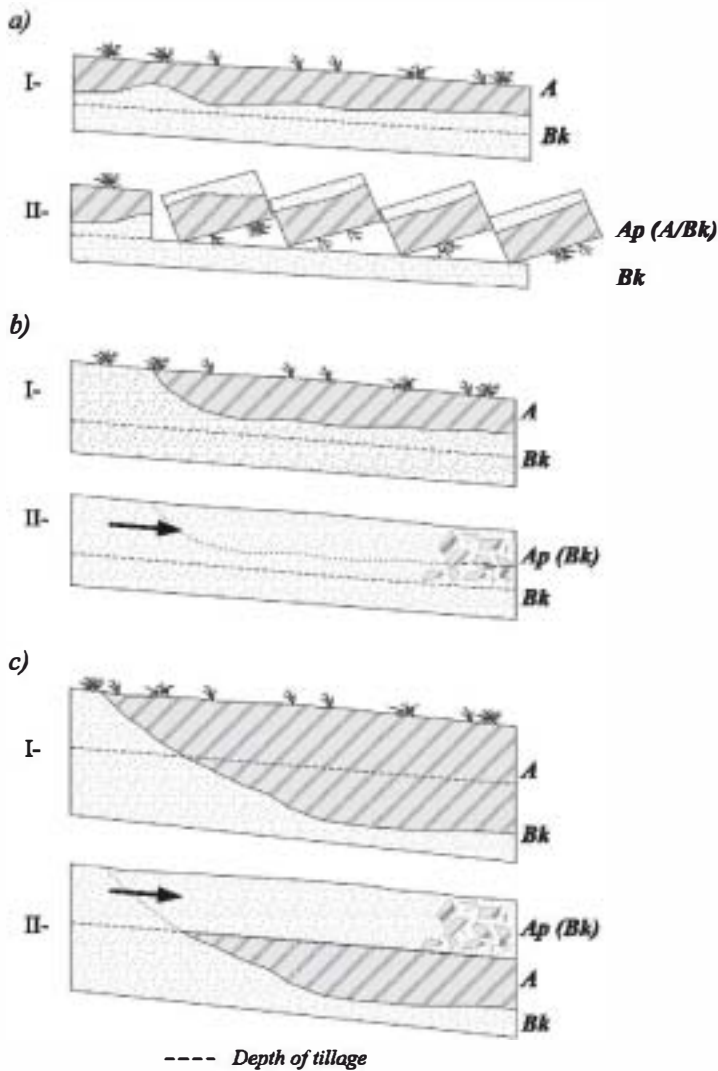


Fig. 2. Modifications of soil profile morphologies due to soil redistribution by tillage. Scheme of processes on three theoretical cases of soil profile: (a) mixing and inversion of the upper soil horizons; (b) substitution of surface soil horizon; (c) partial substitution of the surface soil horizon and formation of a "false truncate soil profile". The genetic horizon material composing the plow layer is shown in parentheses following the Ap symbol (I—before tillage; II—after tillage).

tillage operations, the original differentiated components are mixed creating a homogeneous plow layer (Ap horizon). At this point, the properties of the final homogeneous soil horizon reflect the proportions of the material from the two original horizons. Sibbensen and Andersen (1985) demonstrated the significance of the mixing of soil constituents and developed a model to predict the mixing for long-term small-plot research. A more recent modeling approach is that of Van Oost et al., 2000.

2.2. Soil profile truncation resulting from the loss of the upper soil horizon

In general terms, soil redistribution by tillage produces a net soil loss on convexities and the upper part of the hillslopes. The medium- and long-term effects of such soil erosion will result in the complete truncation of the soil profile by removing the surface soil horizon or horizons (A, AB, Bw or Bt). At that point, material from an original subsurface genetic horizon (e.g., a Bk horizon in Fig. 2b) becomes directly exposed at the surface and constitutes the plow layer (Ap horizon). In order to reveal the nature of the material that composes the new Ap horizon, this horizon is designed as Ap(Bk) denoting within the parentheses the genetic horizon source of materials that constitute the plow layer.

2.3. Soil profile truncation due to the substitution of surface soil horizons

In backslope positions, where there may not be a net balance of soil loss or gain, the dominant soil transport process is tillage. The plow layer is transported downslope similar to the action of a conveyor belt from the top to the bottom of the slope. In backslope positions, when the soil profile presents a surface horizon shallower than the depth of tillage, a substitution of soil material in the surface horizon with soil material transported from upslope positions takes place. The sketch in Fig. 2b shows that soil material from the original surface Ap horizon, comprised of A and Bk horizons, is removed and transported downslope and replaced by subsurface horizon material (horizon Bk) located upslope. The final soil profile is similar to that derived from soil truncation due to the loss by erosion of the upper soil horizon. Nevertheless, there is a difference in that the soil truncation by substituting surface soil material is not related to a net loss of soil mass or lowering of the surface level.

2.4. Formation of soil profiles with an inverted sequence of soil horizons: false truncated soils

The partial substitution of the superficial soil horizons with soil being translocated from upslope positions due to tillage can produce the formation of soil profiles, in which the original sequence of soil horizons becomes partially inverted. This is the case of soil profiles where the thickness of the surface horizon is greater than the depth of tillage. As represented in Fig. 2c, after repeated tilling, the upper part of the soil surface horizon is substituted with material from a genetically different surface horizon located upslope; while below the plow layer, a portion of the original surface horizon remains unaltered by tillage. In the case represented in Fig. 2c, the soil profile at the

bottom of the slope that initially has a sequence of genetic horizons of the type A-Bk is transformed to Ap(Bk)-A-Bk, by partially substituting the original A horizon with soil material from Bk horizon located upslope. This type of inverted soil profile can be called a “false truncated soil” because of its similarity at the surface level to an actual truncated soil formed by losing the surface horizons. In both cases, the upper surface horizon after tillage corresponds to the original subsurface soil horizon (e.g., Bk in Fig 2c). Similar to what happens with the truncated type soils described in Section 2.3, the key mechanism to form this type of “false truncated soils” is soil transport by tillage and not a net balance of soil gain or loss.

2.5. Soil profile buried due to the accumulation of material over the surface horizon

Tillage causes a net soil gain on concavities and at the bottom of hillslopes, giving place to the infilling of depressions and the formation of slope banks at the lower boundary of the fields. In the long-term, the original soil profile becomes buried under a deposit of material coming from upslope. In this case, the accumulated soil constitutes the new plow layer and its properties are related to those of the soil located upslope.

3. Modification of the soil catena by tillage

In addition to pedogenic processes and the action of soil degradation by water and aeolian erosion, soil redistribution by tillage represents another substantial mechanism that increases soil variability in sloping agricultural landscapes. A new conceptual model of soil catena evolution in sloping agricultural landscapes can be drawn based on the above-described mechanisms of soil profile modification by tillage.

An idealized transformation of a hypothetical soil catena due to soil redistribution by tillage is presented in Fig. 3. Before tillage, the initial hillslope presents a typical eroded soil catena (Fig. 3a) showing soil profiles with contrasting sequences of soil horizons. Three sequences of soil profiles are observed: (1) at the top of the slope (shoulder), a truncated soil profile composed of a sequence of genetic horizons of the type Ap(Bk)-Bk-C; 2) at backslope positions, a partially truncated soil profile with the horizon sequence of Ap(Bt)-Bt-Bk-C; and (3) at the bottom of the slope (footslope), the most complete soil profile composed of Ap(A)-A-Bt-Bk-C. As stated before, the Ap horizons are designed denoting between parentheses the genetic horizon source of materials that constitute the plow layer [(e.g., Ap(Bk)], to reveal the nature of the material which composes these surface horizons.

The accumulated long-term effects of soil redistribution by tillage are represented in Fig. 3b. The model shows that soil of the plow layer is gradually transported from the top to the bottom of the slope, and consequently the surface genetic horizons are expanded downslope along the plow layer. At the top and bottom of the hillslope, opposite surface level changes take place corresponding to different net balances of soil loss and gain, respectively. As a result, a progressive soil truncation occurs in the summit and shoulder, while soil is buried in the footslope and toeslope. At backslope positions in Fig. 3b where the surface Ap(Bt) horizon is not as thick as the plow layer,

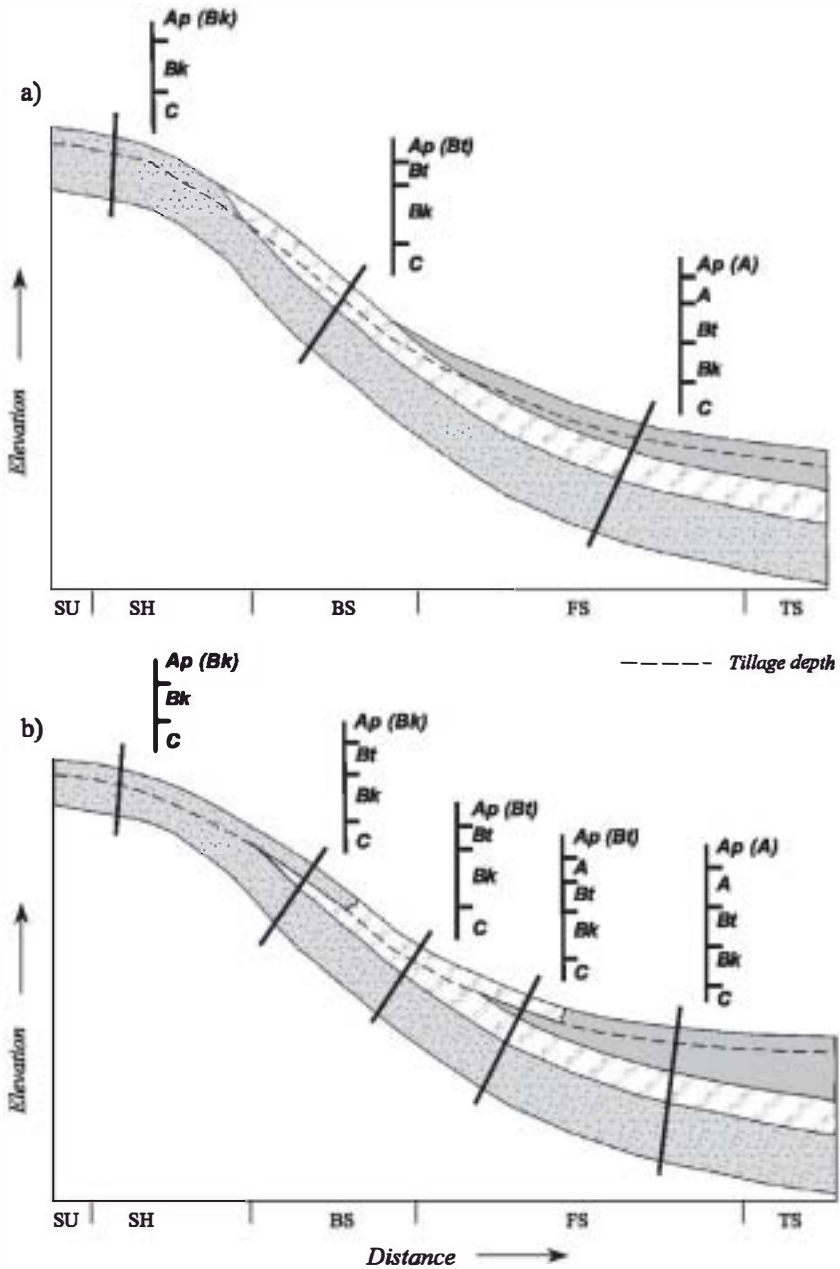
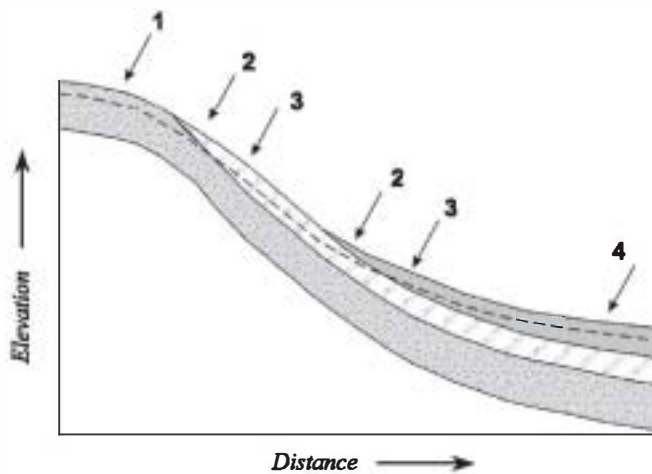


Fig. 3. Idealized model of soil catena modification by tillage. (a) Initial theoretical soil catena; (b) soil catena modified by soil redistribution due to repeated tillage. The genetic horizon material composing the plow layer is shown in parentheses following the Ap symbol. Slope profile elements: SU=summit, SH=shoulder, BS=backslope, FS=footslope, TS=toeslope.



- 1.- Soil truncation due to net soil loss
- 2.- Soil truncation by substitution of surface horizons
- 3.- Formation of soil profiles with a inverted sequence of genetic horizons: false truncated soils.
- 4.- Buried soils due to net soil accumulation

Fig. 4. Variability of mechanisms of soil profile modification by tillage along the slope.

the surface horizon is replaced with soil coming from upslope, resulting in the formation of truncated soil profiles of the types Ap(Bk)-Bk-C. At backslope positions, where the originally surface horizon Bt is deeper than the plow layer, this horizon becomes only partially substituted causing the soil profiles to have an inverted sequences of horizons. This is the case of profiles Ap(Bk)-Bt-Bk-C or Ap(Bt)-A-Bt-Bk-C in Fig. 3b. Fig. 4 shows the distribution of the different processes of soil profile modifications produced by tillage along the original soil catena in Fig. 3a.

4. Field evidence of soil catena modification by tillage: a case study

An agricultural field with features of intense soil degradation by erosion was studied in order to identify patterns of soil variability. The expected patterns of soil redistribution by tillage and water erosion were determined. Then agreement in observed field variability between the two soil redistribution processes was determined. In this approach, we used spatial variability of calcium carbonate as an indicator of prior soil redistribution. The proposed model of soil profile modification due to tillage is evaluated using a case study that examined the current soil variability over an agricultural landscape.

4.1. Materials and methods

4.1.1. Study area: the Skogstad field

The study area was a 4-ha portion of a larger 16-ha field located north of Cyrus, MN in west central Minnesota (45° N 41', 95° W 45'). This area was selected because of its past management history of intensively based moldboard plow tillage and evidence of prior erosion (Lindstrom et al., 2000a). Prior erosion was identified by the exposure of calcareous subsoil material in the upper shoulder landscape positions. The landscape is characterized by a rolling topography with slopes up to 10%. The climate is subhumid with approximately 600 mm of annual precipitation. The dominant soil catena in the study area was Svea (fine-loamy, mixed, superative, frigid Pachic Hapludolls)–Barnes (fine-loamy, mixed, superactive, frigid Calcic Hapludolls)–Buse (fine-loamy, mixed, superactive, frigid, Typic Calcicudolls) was formed in Wisconsin-aged glacial till. A topographic survey of the 4-ha portion of the field was conducted on a 10- by 10-m grid using a survey-grade Differential Global Positioning System (DGPS) to develop a digital terrain model (DTM).

4.1.2. Spatial variability of soil calcium carbonate content

Spatial variability of soil calcium carbonate content was characterized along three transects in the study area. Fig. 5 shows the location of the three transects in the study area DTM. Along each transect, 1.4-m depth soil profiles were described and sampled at 10-m intervals. A separate transect was described and sampled in an adjacent non-cultivated field. For this study, we analyzed the soil inorganic carbon content determined by the method of Wagner et al. (1998) and reported as calcium carbonate (CaCO₃) equivalent.

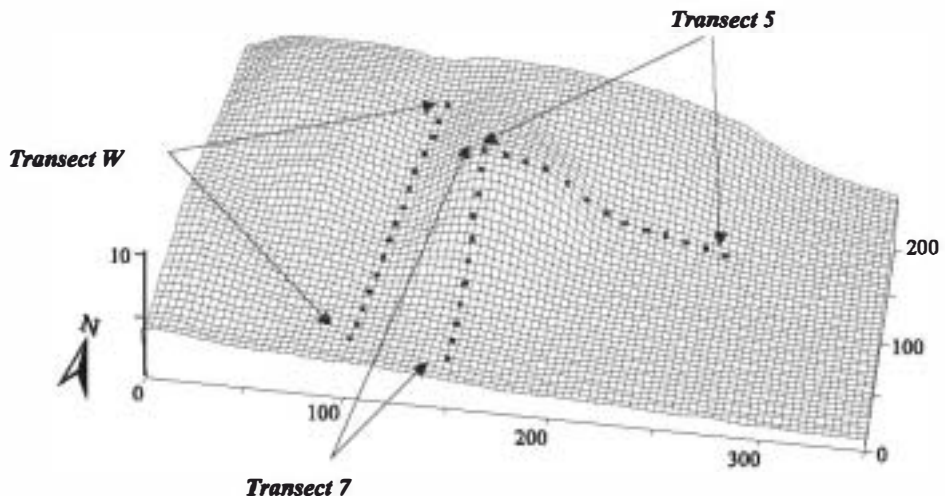


Fig. 5. DTM (Digital Terrain Model) of the study site and localization of soil sampling transects (Axis units in meters).

4.1.3. Modeling spatial pattern of soil redistribution by tillage

In order to simulate the accumulated effects of soil translocation by tillage on soil redistribution within the study area, the Soil Redistribution by Tillage (SORET) model was applied. The SORET model is a spatially distributed model performing 3-D simulations of soil redistribution by tillage on DTMs at field scale (De Alba, 1999). A general flowchart of the model is presented in Fig. 6. The inputs of the simulation process include, besides the DTM of the field, the single or multiple tillage patterns simulated including direction(s), depth, and frequency of tillage. The simulation model produces a final DTM of the area showing the topographical variations produced by the soil redistribution, a raster map of variations of the elevations of soil surface, and depth (m) of soil loss and/or accumulation. A map of spatial variability of average soil erosion-accumulation rates per tillage operation ($\text{tons ha}^{-1} \text{ year}^{-1}$) for each individual grid cell is also produced. The simulation process involves a calculation step corresponding to a single tillage operation, after which a modified DTM is produced. The model can predict soil redistribution effects of a single operation, as well as the long-term effects of repeated tillage operations. The simulation process is built around deterministic relationships between tillage translocation intensity and the characteristics of terrain (e.g., slope gradients), tillage, and soil (e.g., dry soil bulk density). The soil translocation equations are of the type:

$$d = f(\text{ST}; \text{SP}) \quad (1)$$

in which the actual soil displacement distances (i.e., forward d_{DT} and lateral d_{DP} translocations) are calculated as functions of the slope gradients simultaneously in two directions, parallel (ST) and perpendicular to the direction of tillage (SP). Preliminary

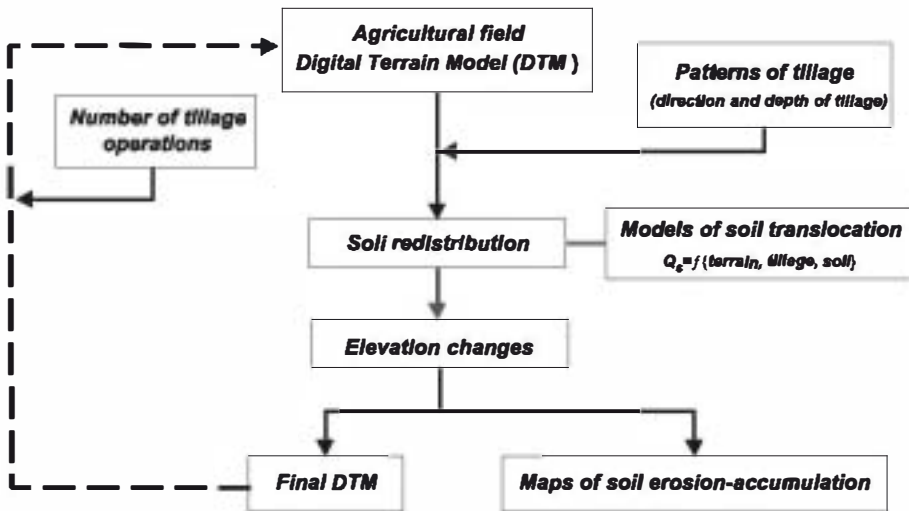


Fig. 6. Flowchart of the SORET (Soil Redistribution by Tillage) simulation model (after De Alba, 2003).

results of the SÖRET model were recently presented by De Alba (1999, 2003) and De Alba and Lindstrom (2000).

In the present analysis, the study area DTM was recalculated to have a cell size of 4 m² (2×2) using a Kriging method of interpolation (Cressie, 1991). The SÖRET model uses differences in elevation between adjacent cells for calculating gradient slopes and soil movement over the individual grid cells. The simulation performed 40 operations of tillage alternating in the North–South direction using a right-hand moldboard plow as that described by De Alba (2001) at a tillage depth of 0.24 m. Parameters describing soil translocation models used in the SÖRET model for the moldboard plow are shown in Table 1.

4.1.4. Spatial pattern of water erosion along the hillslopes profiles

For two of the selected slope transects, Nos. 5 and 7 in Fig. 5, the expected water erosion response was evaluated along the transects using the Water Erosion Prediction Project (WEPP) Hillslope model—Beta 4 version, 2001—(Flanagan and Nearing, 1995). As a management system, a continuous corn rotation was used with fall moldboard plow using management and dates of operations from the WEPP database. Climatic data from the West Central Research and Outreach Center, University of Minnesota, meteorological station was used as an input into WEPP to develop average annual rates of soil detachment and deposition. Over a 40-year simulated period, the average annual precipitation was 614 mm. Since, here we were interested in determining the spatial pattern of net soil loss or gain areas along the slope profiles and not the accurate erosion rates, we considered only the WEPP outputs in terms of relative erosion and not the absolute rates. Therefore, a static hillslope model was used over the 40 years of water erosion simulation.

The hillslopes were idealized by assuming that the whole hillslope length had a single soil series. For our analysis, the Barnes soil series (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) was selected. The Barnes soil has a surface soil horizon free of calcium carbonate and is the dominant soil in the studied unplowed field of semi-natural vegetation (Fig. 7). This is a necessary simplification because the landscape exhibited a high degree of variability in soil properties due to the long-term accumulated effect of the tillage, water and wind erosion processes and soil developmental processes. Since we were interested in exploring the relationships between the current soil variability and tillage and water erosion, idealized hillslopes showing a simplified undisturbed soil was built.

Table 1

Soil translocation equations used in the SÖRET model to simulating long-term patterns of soil redistribution by tillage, as defined by De Alba (2001) for a right-hand moldboard plow

Soil displacement	Soil translocation models
Forward direction d_{DT} (cm)	$d_{DT}=38.03-0.62*ST+0.40*SP$
Lateral direction d_{DP} (cm)	$d_{DP}=41.10-0.50*SP$
Actual direction d (cm)	$d=(d_{DT}^2+d_{DP}^2)^{1/2}$

ST=slope gradient in the direction of tillage; SP=slope gradient in the direction perpendicular to tillage.

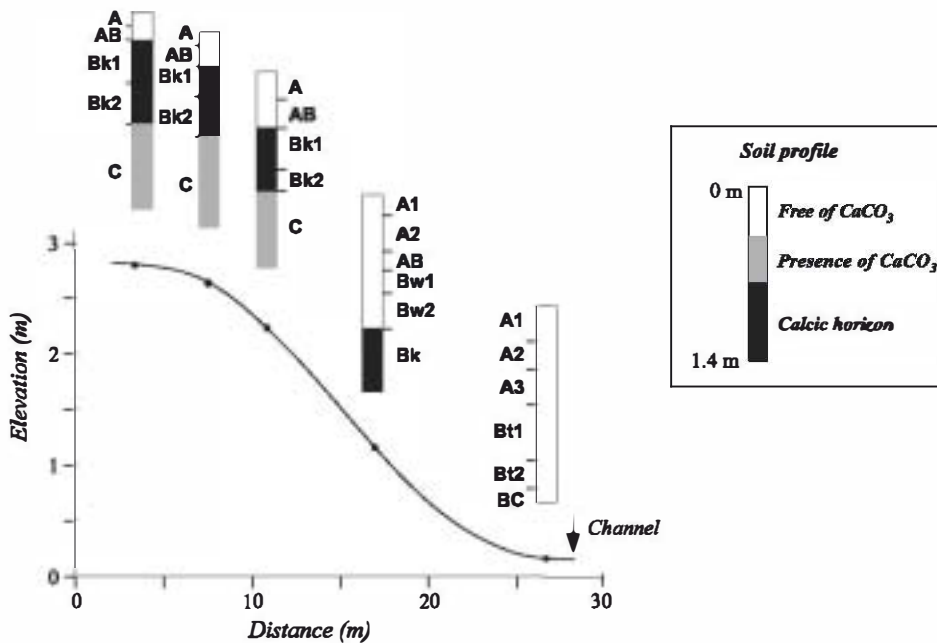


Fig. 7. Spatial variability of soil calcium carbonate in the non-cultivated field.

4.1.5. Spatial pattern of water erosion: 2-D simulation of the Universal Soil Loss Equation (USLE) topographic LS-factor (slope length and slope gradient factor)

In order to evaluate the variability of the potential intensity of water erosion regarding the topography on the DTM of the study area, we used the Usle2D model (Van Oost and Govers, 2001). In the calculation of the Universal Soil Loss Equation (USLE) topographic LS factor (slope length and slope gradient factor Foster and Wischmeier, 1974), the Usle2D model replaces the slope length by the unit contributing area (Desmet and Govers, 1996). The unit contributing area is defined as the upslope drainage area per unit of contour length (Kirkby and Chorley, 1967). The Usle2D model, different than the WEPP hillslope model, can perform two-dimensional analysis on DTMs of topographically complex landscapes (Van Oost and Govers, 2001). Again, in this case, the output of the model will not be a map showing accurate erosion or deposition rates, but a map presenting the expected variability of erosion intensity as influenced by a static topography.

4.2. Soil variability in CaCO_3 content in the Skogstad field vs. patterns of water and tillage erosion

4.2.1. Simulated soil redistribution by tillage in the study site

The map of soil redistribution after 40 tillage operations simulated using the SORET model is shown in Fig. 8. In general terms, the simulated pattern of soil redistribution is in

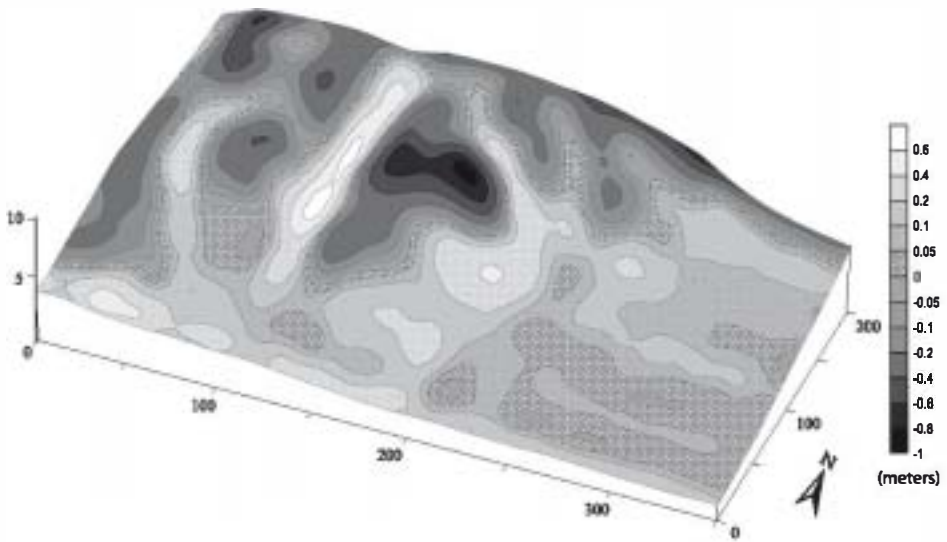


Fig. 8. Simulated soil redistribution by tillage in the study site using the SORET model. Surface elevation changes are given in meters (Axis units in meters).

agreement with those described by others (Quine et al., 1994; Govers et al., 1996; Lobb et al., 1995; De Alba, 2003). Net rates of soil loss or gain are related to the morphology and curvature of the hillslope. An intense net soil loss takes place at convex positions, while a net soil gain occurs in concavities. An area equivalent to 35.5% of the total DTM shows a net lowering of the soil surface, with maximum and average depths of 0.87 and 0.02 m, respectively, that correspond to equivalent erosion rates of 29.3 and 0.7 kg m⁻² year⁻¹. On the other hand, the area of net soil deposition is 64.5% of the total DTM with maximum and average deposit depths of 0.73 and 0.02 m, respectively, that correspond to equivalent deposition rates of 24.7 and 0.7 kg m⁻² year⁻¹.

In a previous study, Lindström et al. (2000b) simulated the long-term effects of soil redistribution by tillage in the same field using a modified version of the Tillage Erosion Prediction (TEP) model (Lindström et al., 2000b). A comparison between the soil redistribution map in Fig. 8 and that (data not presented) obtained by Lindström et al. (2000a) highlights that in both cases, the spatial pattern of soil redistribution is nearly identical. However, regarding the absolute rates of soil loss and gain some differences were noted between both approaches. The differences seem to be explained by: (1) the calculation algorithms in the TEP model are calibrated to the particular agronomic conditions in west-central Minnesota when compared to the algorithms in the SORET model, and (2) differences on the basic calculation procedures and algorithms between the two models (see Lindström et al., 2000a,b; De Alba, 2003).

4.2.2. Variability of soil content in calcium carbonate in a non-cultivated grass field

The depth of dissolved calcium carbonate precipitation from high calcium carbonate parent material in the soil profile is strongly dependent on soil water flow and

increases with increasing precipitation in a well drained soil. Jenny and Leonard (1934) were the first to quantify this relationship and established a direct regression between the average annual precipitation and depth to the top of the carbonate horizon (Bk). Applying the model of Jenny and Leonard using the average annual precipitation from west central Minnesota of 610 mm, the model predicts an average depth to the top of the calcic horizon of 76.3 cm. Consistent values are predicted by modern regression models as those established by Retallack (1994) and Royer (1999), which lead to average depths of 90 and 108 cm, respectively. Hence, all the models indicate that for the climate in Central Minnesota, surface soil horizons should be expected to be free of calcium carbonate. In actual fact, this is the pattern observed over the soil catena described on the non-cultivated field. Fig. 7 shows the spatial variability of calcium carbonate content in the soil profiles along the catena. In this figure, the soil profiles illustrate the calcium carbonate content, and classify the soil horizons in three groups: (1) absence of calcium carbonate, (2) presence of calcium carbonate (i.e., effervescence with 1.0 N HCl), and (3) horizon that meet the requirements to be classified as calcic as defined by the Soil Survey Staff (1998). The five soil profiles of the catena presented in Fig. 7 show the upper part of the profile to be free of calcium carbonate until a depth, which increases downslope and varies between 11 cm on the shoulder and more than 140 cm on the footslope.

4.2.3. Spatial patterns of calcium carbonate distribution vs. patterns of erosion in the study area

The patterns of soil variability in calcium carbonate content in the soil profiles along transects 5 and 7 are shown in Figs. 9 and 10, respectively. They are compared to the patterns of soil redistribution predicted by tillage using the SORET model and for water erosion using the WEPP model. In both transects, all the soil profiles in the catena, except the lowest positions, exhibit surface horizons that have presence of calcium carbonate. Moreover, the profiles located in the upper half of the hillslope, at the shoulder and upper backslope positions, effervesce throughout the entire profile and a subsurface calcic horizon (Bk) with an upper depth limit varying between 0.2 and 0.3 m from the soil surface is presented. According to the model of Jenny and Leonard (1934), the presence of calcium carbonate in the topsoil and the shallow identification of the calcic horizon could be interpreted as the result of the loss by erosion of the upper soil horizons free of calcium carbonate. Consequently, these soil profiles can be classified as truncated soils.

The profiles located at distances greater than 60 m from the top of the hillslope in Transect 5, and 132 m in transect 7, show a discontinuity in the distribution of calcium carbonate throughout the profile. This discontinuity is the presence of a soil layer free of calcium carbonate under the calcareous topsoil and, in most cases, above a deep calcic (Bk) or a less calcareous horizon (e.g., C). Since this pattern of calcium carbonate distribution is not consistent with the expected pedogenic calcium carbonate pattern along the profile (e.g., in Chadwick and Graham, 2000), a reasonable interpretation is that the calcareous topsoil corresponds to soil material transported along the plow layer from upslope positions. Moreover, this is consistent with the observed trends in thickness of the calcareous horizon that decreases as we move downslope while the intermediate horizons

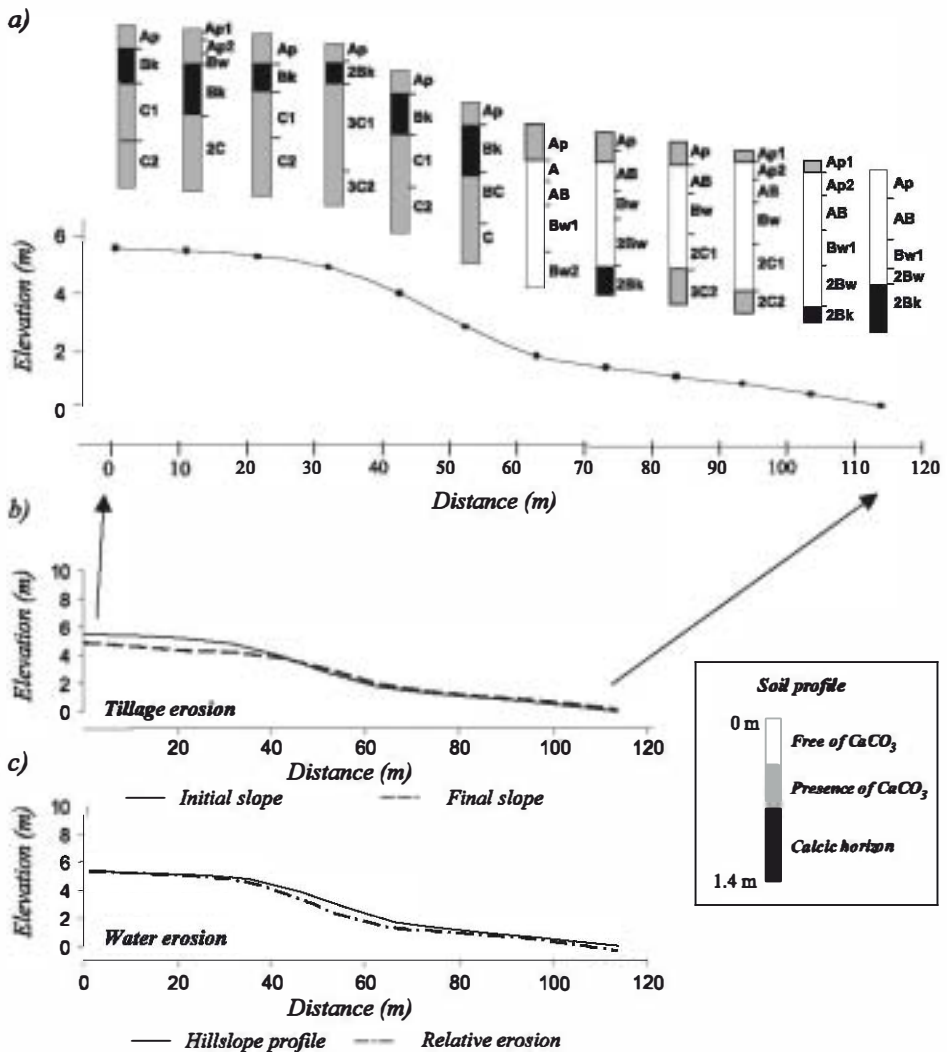


Fig. 9. Spatial variability of soil calcium carbonate (a), predicted soil redistribution by tillage (b), and by water erosion (c) along the Transect 5 (Fig. 5).

free of calcium carbonate become larger. The calcareous horizon was completely absent in the lower soil profiles (lower footslope positions).

Regarding erosion patterns, Figs. 9 and 10 show contrasted spatial patterns for soil redistribution by tillage and water erosion. For both transects, the WEPP model predicts a net soil loss along the entire slope due to water erosion. The soil losses are very low in the summit and shoulder, increase downslope until the maximum values are reached in the upper footslope and decrease again in the lower footslope. In contrast, the SÖRET model predicts a different response to soil redistribution in each transect. The SÖRET model

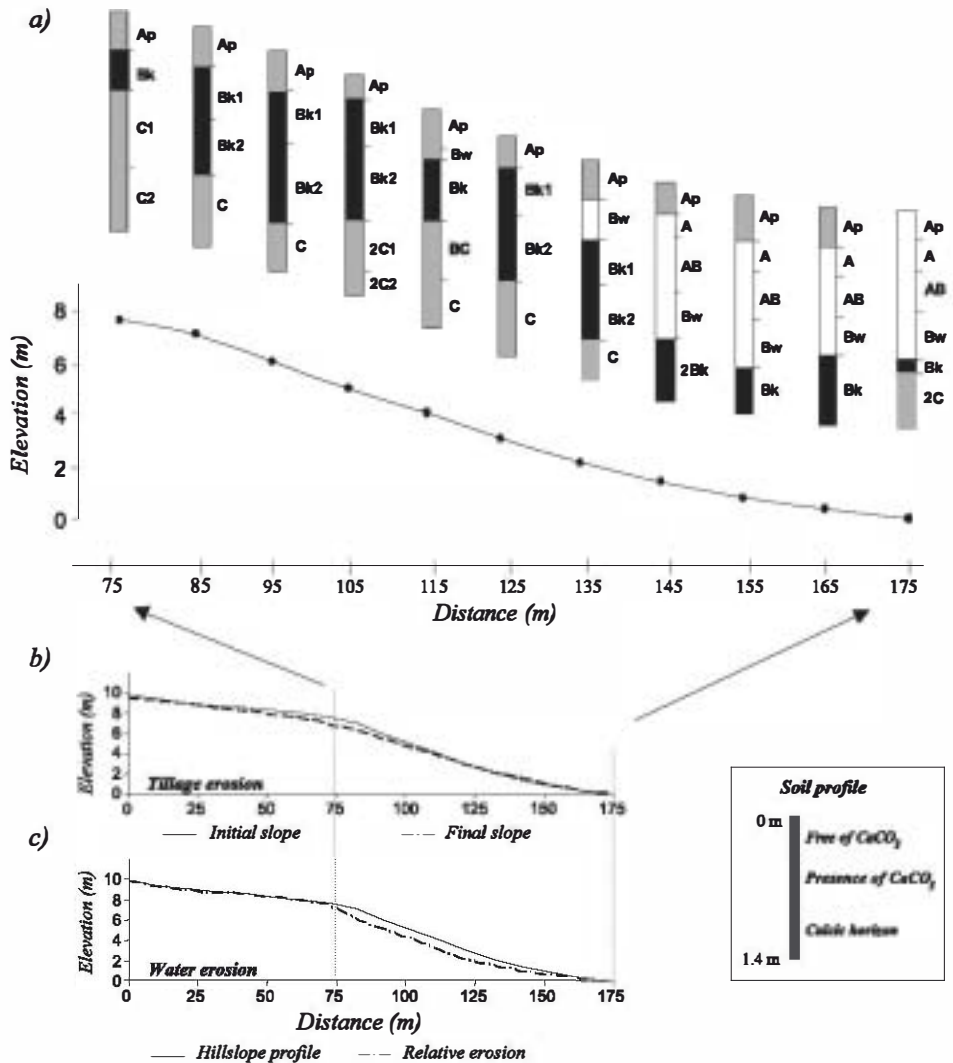


Fig. 10. Spatial variability of soil calcium carbonate (a), predicted soil redistribution by tillage (b), and by water erosion (c) along the Transect 7 (Fig. 5).

shows a section of net soil loss in the upper part of the slope (i.e., summit and shoulder) and a section of net soil gain in the concave and lowest portions of the slope (i.e., lower footslope). Hence, tillage and water erosion show contrasting patterns of soil loss or gain in these concave and lower slope sectors. Consequently, only the predicted pattern of soil redistribution by tillage can explain the spread of calcareous material downslope along the plow layer over an intermediate horizon that is free of calcium carbonate. Mechanisms of soil profile modification are shown in Figs 2–4. Furthermore, for the two transects analyzed, the point predicted by the SORET model to be the starting area of net soil

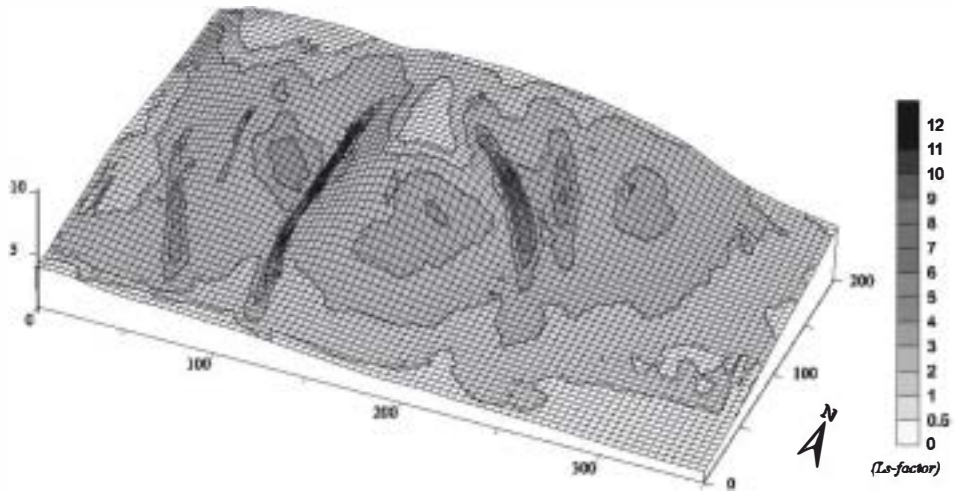


Fig. 12. Spatial variability of the USLE (Universal Soil Loss Equation) topographic LS-factor (slope length and slope gradient factor, dimensionless) in the study site (Axis units in meters).

patterns of calcium carbonate distribution can only be properly explained as the result of the predominant effect of the soil redistribution by tillage. This pattern of soil redistribution is comparable with the idealized model of soil catena modification presented in Fig. 3, causing the formation of soil profiles showing an inverse sequence of genetic soil horizons. In the case studied, the discontinuous distribution of calcium carbonate in the profile reproduces such an inverted sequence of horizons. Of course, here we are using only the distribution of a single soil property, the calcium carbonate content, as an indicator of soil redistribution and not the genetic soil horizons. This points to the need for further field research to prove the proposed model of catena modification by tillage. Furthermore, as it has already been established by several authors including, Govers et al. (1994), Schumacher et al. (1999) and Torri et al. (2002), the actual pattern of soil redistribution exhibits the combined effects and synergies between water and tillage erosion processes. Hence, a more realistic approach requires the use of simulation models that integrate both erosion processes.

5. Implications of increasing soil landscape variability due to soil redistribution by tillage

As a direct consequence of soil redistribution along the plow layer, an increase in spatial variability of surface soil properties occurs, which could be monitored in a sequence of detailed soil maps. In order to explore the implications of such an increase of spatial variability on soil mapping and further interpretations of soil surveys, let us analyze some of the cartographic consequences of the soil catena modification model presented above.

Fig. 13 shows the expected soil map changes derived from the accumulated effects of the soil catena modification as represented in Fig. 3. The most evident change is that the boundaries between surface soil map units have been transposed downslope. Hence, map units of eroded soils located in the upper part of the hillslope become enlarged and expand downslope. On the other hand, Fig. 13 reveals that a simple approach based on surface soil units does not allow the identification of the different soil profile modification occurring from tillage erosion, and consequently, actual soil variability is masked. In the example in Fig. 13, the Ap(Bk) horizon overlies soils of contrasting profile morphologies which have formed differently depending on landscape position interacting with the tillage erosion process. These are truncated soils with a decapitated profile of the type Ap(Bk)-Bk-C, and false truncated soils represented by an inverted sequence of horizons of the type Ap(Bk)-Bt-Bk-C or Ap(Bt)-A-Bt-Bk-C.

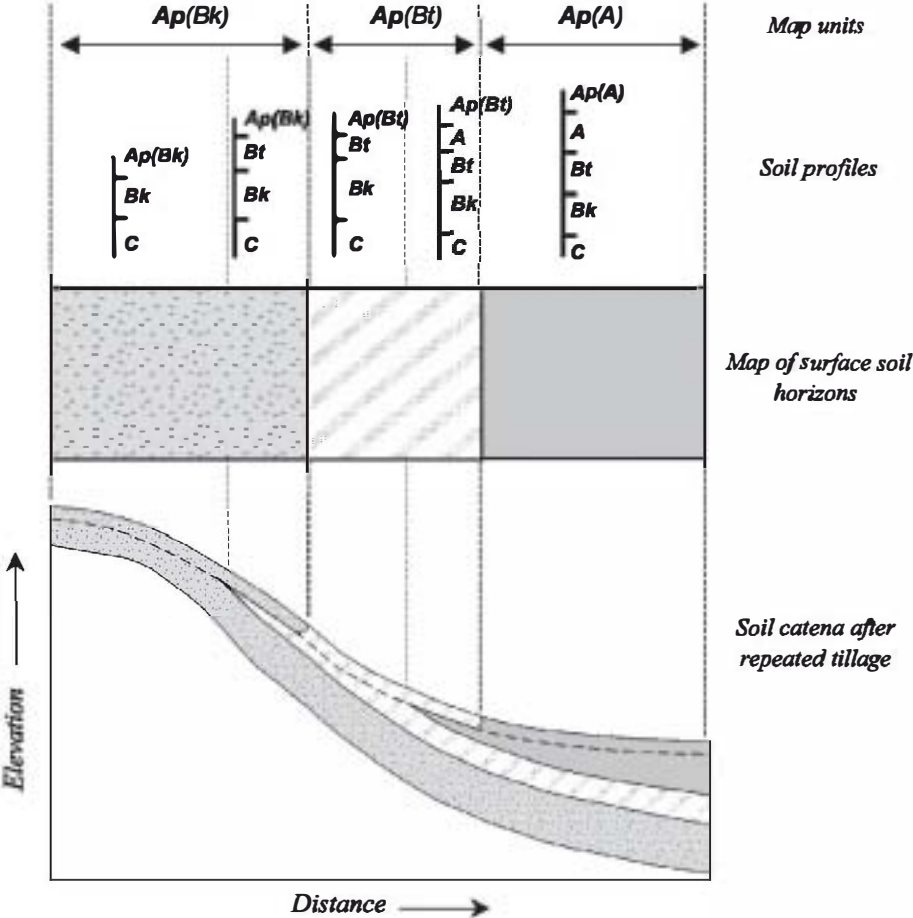


Fig. 13. Increasing variability of soil profiles within map units of surface soil horizons due to soil redistribution by tillage. The genetic horizon material composing the plow layer is shown in parentheses following the Ap symbol.

The implication of not taking into account the soil profile variability within map units can result in an overestimation on soil erosion rates when those rates are calculated by analyzing a sequence of detailed soil maps. For example, when measuring the total area of the surface presenting truncated soils and assuming those truncated surface soil material correspond to soil profiles, which have been eroded and decapitated with a loss of material equivalent to the average thickness of the missed upper horizons. Therefore, the points in which the soil profile has been modified due to the partial substitution of the surface horizon by tillage (i.e., false truncated soils), the estimated soil loss using the former assessment method has to be rather high, even when the surface elevation does not change.

Another aspect of importance is the understanding of how these soil profile modifications could alter the whole system of complex flows of material and energy in the soil profile. As an example, consider the possible implications on the surface and subsurface hydrology of the hillslope. Soil redistribution by tillage explains the partial or total substitution of the surface horizon with material that presents contrasting physical (e.g., texture, soil structure, porosity...) and hydraulic properties (e.g., hydraulic conductivity, water retention). As represented in Fig. 13, consider a partial substitution of a Bt horizon of clay loam texture with strong prismatic structure with material coming from a Bk horizon of sandy texture with weak prismatic to massive structure. The new soil profile Ap(Bk)-Bt-C would show a quite different hydrological response from that expected of the initial profile Ap(Bt)-Bt-C, as well as of that located upslope and showing a profile of the type Ap(Bk)-Bk-C. Our aim of using such as a simplified example is to illustrate the possible physical implications derived of the soil profile modifications due to the soil redistribution by tillage. Torri et al. (2002) discuss other examples.

This analysis suggests a need to evaluate the change in spatial distribution of surface soil properties and that of the soil profile morphology as a result of tillage. This will allow us to make a more accurate representation of the spatial variability of soil properties (e.g., nutrients availability, water retention capacity, drainage class...) that can be used to make proper soil management decisions (e.g., precision agriculture).

6. Intensity of the expansion process of the eroded soil units

In order to evaluate the magnitude of the intensity of the expansion process of soil units, a series of nomographs were constructed, that allow us to predict the distance of downslope expansion as a function of the pattern of tillage, frequency of tillage, and slope gradient. Fig. 14 shows the nomographs obtained for three different patterns of tillage: (1) contouring tillage (tuning the soil alternately up- and downslope), (2) up- and downslope tillage, and (3) repeated tillage downslope.

For a given pattern of tillage, the average distance of displacement downslope of a boundary between two soil units can be calculated using the nomographs as a function of the slope gradient and the number of tillage operations. Obviously, the model is a simplification of the actual process using the assumption that the transition between

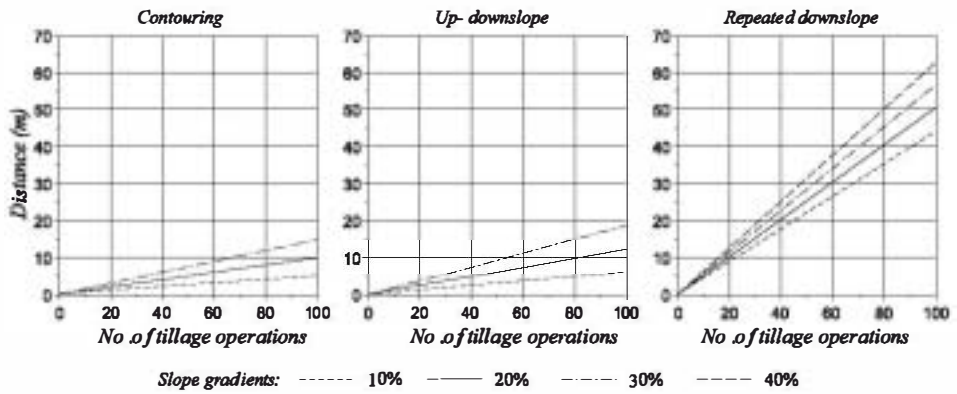


Fig. 14. Nomographs to calculate the distance of expansion of the eroded soil units due to three different patterns of tillage. Tillage downslope is generally the only one possible when the absolute slope gradient is higher than 30%.

surface soil units is displaced a distance equal to the average soil displacement. This assumption does not take into account any additional process of soil dispersion or mixing of contiguous soil horizons. The main equation describing the process will be as follows:

$$Ex = d \cdot n \quad (2)$$

where, Ex is the distance (m) of the soil unit expansion downslope, d is the average distance (m) of soil translocation by a tillage operation, and n is the total number of operations.

The distance d of soil translocation can be calculate using the empirical algorithms of the type $d=f(S)$ (e.g., see Lindstrom et al., 1992), in which d is calculated as a function of the slope gradient (S) as follows:

$$d = a + b \cdot S \quad (3)$$

where a and b are constants.

The combination of Eqs. (2) and (3) using the number N of tillage operations simulated to be applied per year, an annual expansion rate T_x , expressed as $m \text{ year}^{-1}$ is obtained, as follows:

$$T_x = (a + b \cdot S) \cdot n/N \quad (4)$$

for patterns of tillage along a single direction of tilling. When the pattern of tillage include opposing directions on successive operations, T_x is calculated as follows:

$$T_x = (b \cdot S) \cdot n/N \quad (5)$$

Nomographs in Fig. 14 were developed using the soil translocation models and coefficients defined empirically by De Alba (2001) for tillage operations using a right-

hand moldboard plow. As an example, the results in Fig. 14 show that after 100 operations on a 20% slope, the upper soil unit would be expanded downslope in distances of 10 m with contouring tillage, 13 m with up- and downslope tillage and more than 50 m with repeated tillage downslope. If the frequency of tillage is between one to three tillage operations a year (common frequency in southern Europe), the equivalent expansion rates T_x vary between 0.10 and 0.30 m year⁻¹ for contour tillage, 0.12 and 0.37 m year⁻¹ for up- and downslope tillage, and 0.51 and 1.52 m year⁻¹ for repeated downslope tillage. These results point to the extreme values of expansion for repeated tillage downslope that is generally the only one possible when the absolute slope gradient is higher than 30%. The above examples indicate that soil redistribution by tillage is a mechanism of high intensity soil-landscape transformation.

7. Conclusions

Soil redistribution by tillage is an anthropogenic process of soil formation and intense transformation of the soil-landscapes in agricultural lands. The accumulated long-term tillage effects result in a modification of the soil profile and spatial patterns of soil variability. Moreover, soil redistribution by tillage results in a severe modification of the landscape topography as well as of the surface and subsurface hydrology (e.g., variability of infiltration and overland flow paths), causing substantial modification of geomorphic processes (e.g., slope stability and water erosion).

The conceptual model of soil catena modification by tillage and the field conditions presented in this paper document the alteration and formation of soil profiles due to tillage which can present an inverted sequence of genetic horizons, as well as those called false truncated soil profiles. At backslope positions, the formation of truncated soil profiles can take place without any significant net balance of soil loss or gain, as a consequence of the substitution of soil material in the surface horizon with material coming from upslope areas along the plow layer.

Further research programs should be established to identify soil mapping units modified by tillage and evaluate and monitor those soil-landscapes modifications as well as to document the implications of such an anthropogenic soil formation process on the biophysical dynamics of the soil and landscape.

Results from this study reveal the importance of incorporating the process of soil redistribution by tillage into comprehensive models of soil erosion and hydrological process, soil genesis, soil survey, and the need to explore subsequent interactions and synergies.

Acknowledgements

Research was carried under a Marie Curie Fellowship of the European Community programme "Improving Human Research Potential" under contract No. HPMFCT-2000-00706, and a contract of the "Ramon y Cajal" Program (Spanish Ministry of Sciences and Technology MCyT).

References

- Chadwick, O.A., Graham, R.C., 2000. Pedogenic processes. In: Summer, M.E. (Ed.), *Handbook of Soil Science*. CRC Press, Boca Raton, FL, pp. E41–E72.
- Cressie, N.A.C., 1991. *Statistics for Spatial Data*. Wiley, New York, p. 900.
- Dabney, S.M., Liu, Z., Lane, M., Douglas, J., Zhu, J., Flanagan, D.C., 1999. Landscape benching from tillage erosion between grass hedges. *Soil and Tillage Research* 51, 219–231.
- De Alba, S., 1999. A computer model for simulating soil redistribution and erosion by tillage operations using digital terrain models of arable fields. Abstracts of 2nd International Symposium on Tillage Erosion and Tillage Translocation. Katholieke Universiteit Leuven, Belgium, pp. 20–21.
- De Alba, S., 2001. Modelling the effects of complex topography and patterns of tillage on soil translocation by tillage with mouldboard plough. *Journal Water and Soil Conservation* 56 (4), 335–345.
- De Alba, S., 2002. Implications of soil redistribution by tillage on geomorphologic landscapes. In: Pérez-González, A., Vegas, J., Machado, M.J. (Eds.), *Aportaciones a la Geomorfología de España en el inicio del Tercer Milenio*. IGME-SEG, Madrid, Spanish, pp. 219–225.
- De Alba, S., 2003. Simulating long-term soil redistribution generated by different patterns of mouldboard ploughing in landscapes of complex topography. *Soil and Tillage Research* 71, 71–86.
- De Alba, S., Lindstrom, M., 2000. Tillage erosion due to mouldboard ploughing: a computer model of simulation at field scale using DTMs. Abstracts of the Annual Meeting of the American Society of Agronomy, Soil Science Society of America and Crop Science Society of America. MN, USA.
- Desmet, P.J.J., Govers, G., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *Journal Water and Soil Conservation* 51 (5), 427–433.
- Flanagan, D.C., Nearing, M.A., 1995. USDA-Water erosion prediction project hillslope profile and watershed model documentation. NSERL Report. No.10 USDA-ARS National Soil Erosion Research Laboratory. West Lafayette, Indiana.
- Foster, G.R., Wischmeier, W.H., 1974. Evaluating irregular slopes for soil loss prediction. *Transactions of the ASAE* 17, 305–309.
- Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, J., 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., 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.
- Govers, G., Lobb, D., Quine, T.A., 1999. Tillage erosion and translocation: emergence of a new paradigm in soil erosion research. *Soil and Tillage Research* 51, 167–174.
- Jenny, H., Leonard, C.D., 1934. Functional relationships between soil properties and rainfall. *Soil Science* 38, 363–381.
- Kirkby, M.J., Chorley, R.J., 1967. Throughflow, overland flow and erosion. *Bulletin International Association of Hydrological Science* 12, 5–21.
- Kosmas, C., Gerontidis, St., Marathianou, M., Detsis, B., Zafiriou, Th., Van Muysen, W., Govers, G., Quine, T.A., Van Oost, K., 2001. The effect of tillage displaced soil on soil properties and wheat biomass. *Soil and Tillage Research* 58, 31–44.
- Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., Lemme, G.D., 1990. Soil movement by tillage as affected by slope. *Soil and Tillage Research* 17, 255–264.
- Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to mouldboard plowing. *Soil and Tillage Research* 24, 243–255.
- Lindstrom, M.J., Schumacher, T.E., Malo, D.D., 2000a. Soil Quality alterations across a complex prairie landscape due to tillage erosion. 15th Conf. of the Intl. Soil Tillage Research Organization. July 2000. Fort Worth, TX. Texas Agricultural Experiment Station, Temple, TX, p. 9.
- Lindstrom, M.J., Schumacher, J.A., Schumacher, T.E., 2000b. TEP: a tillage erosion prediction model to calculate soil translocation rates from tillage. *J. Soil and Water Conservation* 55, 105–108.
- Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using Cs-137 as a tracer. *Canadian Journal of Soil Science* 75, 211–218.
- McKyes, E., 1985. *Soil Cutting and Tillage*. Elsevier, Amsterdam. 217 pp.

- Papendick, R.I., Miller, D.E., 1977. Conservation tillage in the Pacific Northwest. *Journal of Soil and Water Conservation* 32, 49–56.
- Poesen, J.W., Van Wesemael, B., Govers, G., Martínez-Fernández, J., Desmet, P., Vandaele, K., Quine, T.A., Degraer, G., 1997. Patterns of rock fragment cover generated by tillage erosion. *Geomorphology* 18, 183–197.
- Quine, T.A., Desmet, P.J.J., Govers, G., Vandaele, K., Walling, E., 1994. A comparison of the roles of tillage and water erosion in landform development and sediment export on agricultural land near Leuven, Belgium. *Variability in Stream Erosion and Sediment Transport*. IAHS Publication, vol. 224, pp. 77–86.
- Quine, T.A., Walling, D.E., Chakela, Q.K., Mandiringa, O.T., Zhang, X., 1999. Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from caesium-137 measurements. *Catena* 36, 115–142.
- Retallack, G.J., 1994. The environmental factor approach to the interpretation of paleosols. In: Admuntson, R. (Ed.), *Factors of Soil Formation*. Soil Sci. Soc. of America Special Publication, vol. 33, pp. 31–64.
- Revel, J.C., Guireesse, M., Coste, N., Cavalie, J., Costes, J.L., 1993. Erosion hydrique et entraînement mécanique des terres par les outils dans les côtes de sud-ouest de la France. La nécessité d'établir un bilan avant toute mesure anti-érosive. In: Wicherek, S. (Ed.), *Farm Land Erosion in Temperate Plains Environments and Hills*. Elsevier, Amsterdam, pp. 551–562. French.
- Royer, D.L., 1999. Depth to pedogenic carbonate horizon as a paleoprecipitation indicator? *Geology* 27, 1123–1126.
- 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 and Tillage Research* 51, 331–339.
- Sibbensen, E., Andersen, C.E., 1985. Soil movement in long-term field experiments as a result of cultivation: II. How to estimate the two-dimensional movement of substances accumulating in the soil. *Experimental Agriculture* 21, 109–117.
- Soil Survey Staff, 1998. *Keys to Soil Taxonomy*. USDA, US Gov. Print. Office, Washington D.C. 328 pp.
- Thapa, B.B., Casel, D.K., Garrity, D.P., 1999. Assessment of tillage erosion rates on steepland Oxisols in the humid tropics using granite rocks. *Soil and Tillage Research* 51, 233–243.
- Torri, D., Borselli, L., 2002. Clod movement and tillage tool characteristics for modelling tillage erosion. *Journal of Water and Soil Conservation* 57 (1), 24–28.
- Torri, D., Borselli, L., Calzolari, C., Yañez, M., Salvador-Sanchis, M.P., 2002. Soil erosion, land use, soil quality and soil functions: effects of erosion. In: Rubio, J.L., Morgan, R.P.C., Asins, S., Andreu, V. (Eds.), *Man and soil at the third millennium*. Geofoma Ediciones—CIDE, Logroño, Spain, pp. 131–148.
- Turkelboom, F., Poesen, J., Ohler, I., Ongprasert, S., 1999. Reassessment of tillage erosion rates by manual tillage on steep slopes in northern Thailand. *Soil and Tillage Research* 51, 245–259.
- Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M., Poesen, J., 1999. Measurement and modelling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. *Soil and Tillage Research* 51, 303–316.
- Van Oost, K., Govers, G., 2001. *Usle2D Model*, on Line Manual Katholieke Universiteit Leuven <http://www.kuleuven.ac.be/geography/fig/leg/modelling/usle2d/index.htm>.
- Van Oost, K., Govers, G., Van uysen, W., Quine, T.A., 2000. Modelling translocation and dispersion of soil constituents by tillage on sloping land. *Soil Science Society of America Journal* 64, 1733–1739.
- Wagner, S.W., Hanson, J.D., Olness, A., Voorhees, W.B., 1998. A volumetric inorganic carbon analysis system. *Soil Science Society of America Journal* 62, 690–693.