Effects of Soil Redistribution on Landscape Patterns of Organic Carbon

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Abstract

Soil organic carbon (SOC) is important to soil productivity and is an important part of the global carbon cycle. Soil redistribution within hummocky landscapes has also resulted in SOC redistribution. Soil loss estimates using ^{137}Cs techniques and SOC levels were measured on a 7x7 grid with a 100m sampling interval on a quarter section approximately 30 km east of Saskatoon. The quarter section has been under crop-fallow management for at least 50 years. ^{137}Cs and SOC were also measured on a 5x6 grid (25m sampling interval) at a nearby native site as a reference for soil loss calculations. At the cultivated site, 34 out of the 49 sampling points had experience net erosion since ^{137}Cs fallout (1960), 13 out of the 49 points were depositional, while ^{137}Cs levels at the remaining two points were close to reference levels. A net soil loss of 7 Mg ha^{-1} yr“ was calculated based on the mean ^{137}Cs concentration of the entire quarter section. Soil loss displayed a landscape pattern with footslope elements being areas of deposition and shoulder, backslope and level elements being eroded. SOC patterns followed soil loss patterns with depositional areas (footslopes) having higher levels of SOC than eroded areas. SOC that is not mineralized is redistributed within the landscape and concentrated into a relatively small area. As as a result, SOC levels over most of the quarter have been decreased substantially, indicating that there may be potential to sequester carbon over a larger area if management practices are changed.

Introduction

Soil erosion and redistribution have a significant impact on the distribution of soil organic carbon (SOC) in prairie landscapes (Gregorich and Anderson, 1985; de Jong and Kachanoski, 1988; Pennock et al., 1994). Soil organic carbon (SOC) is intimately related to soil fertility and productivity. Therefore, the distribution of SOC within the landscape will affect yield potential within a given field, and is important for developing management units for precision agriculture (Beckie et al., 1997). Also, SOC is a major component in the global carbon cycle (Pennock and van Kessel, 1997). Recent interest in the potential for SOC to act as a carbon sink for reducing the effects of CO_2 emissions (Janzen et al., 1998) also require information on the distribution of SOC in the landscape and the controls on landscape scale SOC distribution.

Methods

The research site is located approximately 30 km east of Saskatoon (SE 12-37-2 W3) near St. Denis, and has been under a crop-fallow rotation for at least 50 years (air-photo analysis; Ted Deptuck, landowner, personal communication). The site is mapped as a Weyburn association consisting predominantly of Orthic Dark Brown Chernozems developed on loamy glacial till with significant occurences of Calcareous Dark Brown Chemozems, Regosolic and Gleysolic soils (Acton and Ellis, 1978). Slopes range from 6 to 15% (slope classes 3 and 4), and the surface form is mapped as knob and kettle moraine indicating a hummocky landscape.

While the majority of landscape studies have covered areas of one to four hectares (e.g. Pennock et al., 1991; 1999), sampling was carried out at this site to capture the variability of an entire quarter section. As such, a 7 x 7 sampling grid with a sampling interval of 100 m was established (see Figure 1). At each sampling point, three depth increments (O-15, 15-30, and 30-45cm) were sampled and bulked in triplicate and taken back to the lab for analysis. In addition to the above depth increments, one core of 1 to 1.5 meters was extracted for profile description and subsequent classification at the subgroup level (Canadian System of Soil Classification). Sampling points and the surrounding topography were surveyed using a laser theodolite (Sokia total station). The topographic data was then used to generate a digital elevation model and classify sampling points into the landform elements of Pennock et al. (1987): 1) divergent shoulder (DSH); 2) convergent shoulder (CSH); 3) divergent backslope (DBS); 4) convergent backslope (CBS); 5) divergent footslope (DFS); 6) convergent footslope (CFS); 7) upper level (UL); and 8) high catchment level (HCL).

A native site approximately 3 km away from the cultivated site was sampled as well. Here, 30 samples were taken from a 6 x 5 grid with a 25 meter sampling interval. Samples were taken to establish reference ^{137}Cs concentrations for soil loss calculations.

Soil samples from both sites were air-dried, weighed (without stones) and ground to pass through a 2 mm seive. Analysis for ^{137}Cs was carried out according to the method of de Jong et al. (1982). Soil organic carbon (SOC) was determined with a Leco CR-12 carbon analyzer set at 880 ^{o}C. Cesium-137 and SOC concentrations were converted to volumetric concentrations (i.e. Bq m^{-2}, and Mg m^{-2}) with bulk density and sampling depth.

Rates of soil loss were calculated for the cultivated site by comparing the measured ^{137}Cs concentration to the reference ^{137}Cs concentration. The average reference ^{13} Cs concentration was calculated as 1638 Bq m^{-2} with a coefficient of variation of 14%. This coefficient of variation is comparable to the 18% of Sutherland and de Jong (1990), and the 23%, 24%, and 14% of Pennock et al., (1994b; 1999).

Sampling points were classified as eroded, depositional, or having no erosion or deposition by calculating the fractional loss of ^{137}Cs (de Jong et al., 1983):

$$FL = (^{137}Cs_{ref} - ^{137}Cs_{n}) / ^{137}Cs_{ref} \quad [1]$$

where FL = the fractional loss of ^{137}Cs

$^{137}Cs_{ref}$ = the concentration of ^{137}Cs at the reference site
$^{137}Cs_n$ = the concentration of cesium at an individual sampling point.

A positive fractional loss indicates erosion, whereas a negative fractional loss indicates deposition. If the $^{137}Cs_n$ concentration was within the 95% confidence interval of the $^{137}Cs_{ref}$ concentration, the sampling was considered to have experienced no erosion or deposition (i.e. no soil loss). For eroded sites, soil loss (SL) was calculated using the power method of Kachanoski (1993):

$$SL = M\,(1 - (^{137}Cs_n/^{137}Cs_{ref}))^{1/n} \qquad [2]$$

where SL = soil loss in Mg $ha^{-1}\,yr^{-1}$
M = specific mass of the plough layer (top 10cm) in Mg ha^{-1}.
n = the number of years between sampling and original cesium fallout (1960).

For depositional sites, soil loss was calculated using the proportional method of de Jong et al. (1983):

$$SL = -\,(d_e \times BD / n)*10 \qquad [3]$$

Where SL = soil loss in Mg $ha^{-1}\,yr^{-1}$
d_e = effective depth of deposition (m)
BD = bulk density (kg m^{-3}).

Equation 3 gives a negative number. For the sake of convention, a negative soil loss means deposition or soil gain.

Results and Discussion

Table 1 summarizes the soil loss classification, and mean ^{137}Cs and soil loss levels for the sampling points. Although mean erosion rates are slightly lower than deposition rates, there was a larger proportion of eroded sites resulting in a net soil loss from the quarter amounting to 7 Mg $ha^{-1}\,yr^{-1}$ (based on using the mean ^{137}Cs concentration in Equation [3]).

For the sake of better resolution, eroded points were further classified as severely eroded if the fractional loss (Equation [1]) of ^{137}Cs was greater than 0.50. Similarly, depositional sites were further classified as heavy depositional if fractional loss of ^{137}Cs was less than -0.50; that is, 137Cs gain was 50% greater than the background levels. Table 2 summarizes the results of this soil loss classification. Figure 2 illustrates the spatial distribution of the sampling points classified according to soil loss. Depositional points appear to be restricted to concave portions of the landscape.

Relationship between soil loss, soil organic carbon and landform element

Landscape patterns in soil loss and SOC were readily apparent. Figure 3 shows box plots of soil loss according to landform element. Convergent and divergent footslope elements were areas of soil deposition, while all other landform elements experienced net erosion. Further inspection reveals that shoulder and backslope elements experienced the highest rates of erosion where as the level elements experienced intermediate rates of erosion. These results are consistent with other studies of erosion on hummocky landscapes in Saskatchewan (e.g. Pennock and de Jong, 1991; Pennock et al., 1994).

The box plots in Figure 4 also indicate a distinct landscape pattern in SOC (O-45cm). The most obvious features are the high levels of SOC in the convergent footslope landform elements well above the area1 mean SOC for the quarter section. The divergent backslopes had the lowest SOC levels. SOC levels of the other landform elements straddled the area1 mean SOC. Distribution of the SOC levels in the different landscape elements is consistent with the catena concept of soil genesis in hummocky terrains. Footslopes are usually wetter areas in the landscape and are therefore more productive and acquire higher levels of organic carbon. However, comparison of Figure 4 with Figure 3 suggests a relationship between soil loss and organic carbon. The depositional landscape elements (convergent footslopes) have higher levels of organic carbon than the rest of the landscape elements. A stronger relationship between soil loss and organic carbon is apparent in Figure 5 that plots soil loss classification against SOC.

Thus it would seem that soil redistribution may be responsible for the landscape distribution of SOC, but it could be from landscape variations in SOC as a result of soil genesis. Figure 6 shows the relationship between SOC and landform elements at the native site about 3 km away from the cultivated site. At the native site, SOC distribution is almost the opposite of the cultivated site. SOC levels in the convergent footslopes are well below the area1 mean SOC, while the rest of the landform elements straddle the mean. Closer inspection of the soils associated with the landform elements at the native and cultivated sites revealed a similar soil distribution. Eluviated chernozems are the dominant soils in the convergent footslopes. For these sites, the footslopes have high catchment areas and deep water tables, resulting in eluviated profiles (Miller, 1985). Low SOC eluviated Ae horizons occur in the upper 45 cm of the soil profile explaining the low SOC levels in the convergent footslopes at the native site. On the other hand, the shoulder and level elements have quite initial SOC levels at the native site. These landscape positions are occupied by Calcareous and Orthic Chernozems which have thick organically enriched Ah horizons, and Bm horizons with moderate amounts of SOC.

Therefore, the distribution of SOC at the cultivated site can be interpreted as follows. Cultivation has resulted in carbon losses from the quarter section via mineralization. Soil redistribution has dramatically altered the landscape patterns of SOC. Shoulder, level, and backslope elements that had high amounts of SOC under native grassland, have lost high amounts of SOC to the footslope elements as a result of soil redistribution. In fact, the mean SOC of the convergent footslope elements under cultivation is almost identical to the mean SOC of the convergent footslope elements under native grassland. Considering that mineralization has been occuring in the footslope areas since cultivation, the amount of SOC deposition required to maintain the mean SOC levels of the footslopes to those under native grassland is significant.

Conclusions

Despite low SOC loss as a result of erosion from the quarter section, the redistribution of soil and SOC has significant implications. Figure 7 shows the area occupied by each of the landform elements. The majority of the site is occupied by level elements that experience intermediate amounts of erosion. In essence, SOC has been concentrated into a relatively small area of the landscape. Therefore, even though there was little net loss of soil from the landscape, the potential productivity of the quarter section has been reduced dramatically. SOC has been redistributed to inherently productive areas of the landscape at the expense of the level and shoulder elements.

The redistribution of SOC as a result of soil redistribution has many important applications to agricultural management. The dramatic redistribution of SOC observed is likely due to many years of conventional tillage management. Summerfallow every other growing season increases the probability of wind, water, and tillage erosion. Gregorich and Anderson (1985) and Pennock et al., (1994) suggest that mineralization contributes significantly to SOC loss during the first 20 years of cultivation, and erosion is primarily responsible of SOC loss over longer periods of cultivation. Unfortunately, there is a lack of data about different management regimes and the redistribution of SOC as a result of erosion. Long term studies have indicated that zero-till management systems have higher amounts of SOC (Janzen et al., 1998), but these did not include soil loss measurements. Gregorich et al. (1998), recently ran century model simulations with the data of Greer (1989) to predict SOC changes under different management regimes. Rotations with hay experienced the least erosion, and had consistently higher levels of SOC. Conventional fallow-wheat rotations experienced the greatest amount of erosion and had the lowest levels of SOC. Continuous wheat had soil loss rates between hay and conventional tillage rotations. Therefore, although SOC levels have been depleted over a relatively large area of this quarter, a change in management practices may do much to increase SOC levels. However, More research on management practices, soil and SOC redistribution in hummocky landscapes is required.

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References

Acton, D. F., and J. G. Ellis. 1978. The Soils of the Saskatoon Map Area 73-B Saskatchewan. Saskatchewan Institute of Pedology Publication S4. Extension Division, University of Saskatchewan, Saskatoon.

Beckie, H. J., A. P. Moulin, and D. J. Pennock. 1997. Strategies for Variable Rate Nitrogen Fertilization in Hummocky Terrain. Canadian Journal of Soil Science, 77: 589 - 595.

de Jong, E., H. Villar, and J. R. Bettany. 1982. Preliminary Investigations on the use of Cs-137 to Estimate Erosion in Saskatchewan. Canadian Journal of Soil Science, 62: 673 - 683.

de Jong, E., C. B. M. Begg, and R. G. Kachonoski. 1983. Estimates of Soil Erosion and Deposition for Some Saskatchewan Soils. Canadian Journal of Soil Science, 63: 607 - 617.

de Jong, E. and R. G. Kachonoski. 1988. The Importance of Erosion in the Carbon Balance of Prairie Soils. Canadian Journal of Soil Science, 68: 111 - 119.

Greet-, K. J. 1989. Evaluating Soil Quality of Longterm Crop Rotations at Indian Head. M. Sc. Thesis. University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Gregorich, E. G., and D. W. Anderson. 1985. Effects of Cultivation and Erosion of Soils of Four Toposequences in the Canadian Prairies. Geoderma 36: 343-354.

Gregorich, E. G., K. J. Greet-, D. W. Anderson, and B. C. Liang. 1998. Carbon Distribution and Losses: Erosion and Deposition Effects. Soil and Tillage Research, 47: 291 – 302.

Janzen, H. H., C. A. Campbel, R. C. Izaurralde, B. H. Ellert, N. Juma, W. B. McGill, and R. P. Zentner. 1998. Management Effects of Soil C Storage on the Canadian Prairies. Soil and Tillage Research, 47: 181 – 195.

Kachanoski, R. G. 1993. Estimating Soil Loss from Changes in Soil Cesium-137. Canadian Journal of Soil Science, 73: 629 – 632.

Pennock, D. J., B. J. Zebarth, and E. de Jong. 1987. Landform Classification and Soil Distribution in Hummocky Terrain, Saskatchewan, Canada. Geoderma, 40: 297 - 315.

Pennock, D. J. and E. de Jong. 1991. Spatial Pattern of Soil Redistribution in Boroll Landscapes, Southern Saskathcewan, Canada. Soil Science, 150: 867 - 873.

Pennock, D. J., D. W. Anderson, and E. de Jong. 1994. Landscape-scale Changes in Indicators of Soil Quality due to Cultivation in Saskatchewan, Canada. Geoderma, 64: 1- 19.

Pennock, D. J., D. W. Anderson, and E. de Jong. 1994b. Distribution of Cesium-137 in Uncultivated Black Chernozemic Landscapes. Canadian Journal of Soil Science, 74: 115 – 117.

Pennock, D. J. and C. van Kessel. 1997. Effect of Agriculture and of Clear-cut Forest Harvest on Landscape-scale Soil Organic Carbon Storage in Saskatchewan. Canadian Journal of Soil Science, 77: 211 – 218.

Pennock, D. J., B. L. McCann, E. de Jong, and D. S. Lemmen. 1999. Effects of Soil Redistribution in a Cultivated Solonetzic-Chernozemic Landscape of Southwestern Saskatchewan. Canadian Journal of Soil Science, 79: 593 – 601.

Sutherland, R. A. and E. de Jong. 1990. Estimation of Sediment Redistribution within Agricultural Fields using Caesium-137, Crystal Springs, Sk. Applied Geography, 10: 205 -221.

Table 1: Soil Loss Classification, Mean ^{137}Cs and Calculated Soil Loss for Sampling Points

Soil loss classification	Number of points	^{137}Cs Bq m^{-2}	Soil loss Mg ha^{-1} yr^{-1}
Eroded	34	1005 (405)"	22 (20)"
Depositional	13	2312 (564)	-24 (8.5)
No Erosion/Deposition	2	1680 (N/A)	0 (N/A)
All Points	49	1379 (729)	7 (N/A)

*mean values with standard deviation in parenthesis

Table 2: Additional Soil Loss Classification

Soil loss classification	Classification Criteria	Number of points	^{137}Cs Bq m^{-2}	Soil loss Mg ha^{-1} yr^{-1}
Severely Eroded	FL > 0.50	10	483 (185)"	47 (18)"
Eroded	0.05 < FL < 0.50	24	1222 (233)	11 (7)
No Erosion/Deposition	-0.05 <FL < 0.05	2	1681 (NA)	0 (N/A)
Depositional	-0.05 > FL > -0.50	9	2017 (195)	-20 (3)
Heavy Depositional	FL < -0.50	4	2973 (573)	-32 (11)

*mean with standard deviation in parenthesis

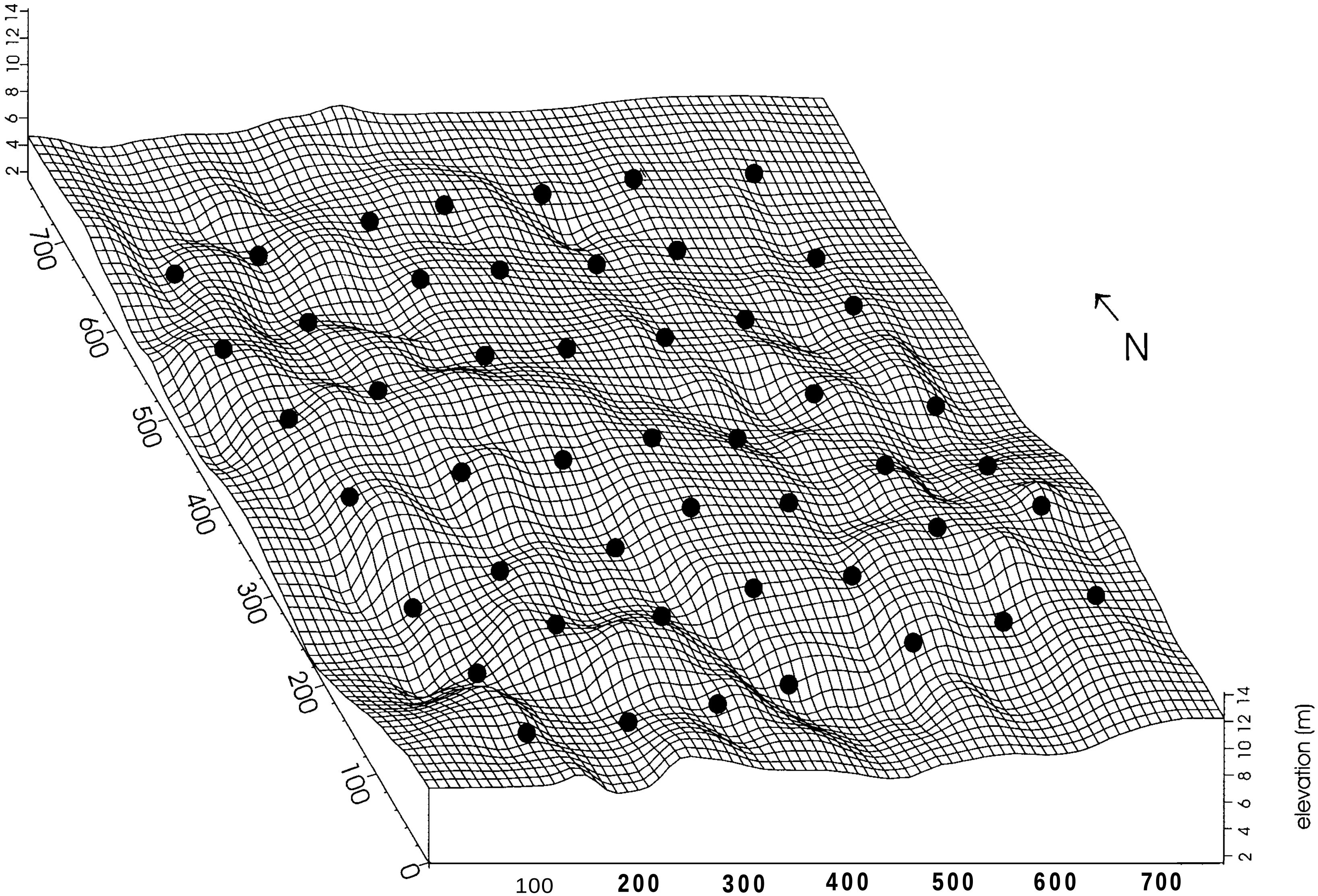

Figure 1: Topography and Distributio of Sampling Points at the Cultivated Site (SE 12-37-2 W3).

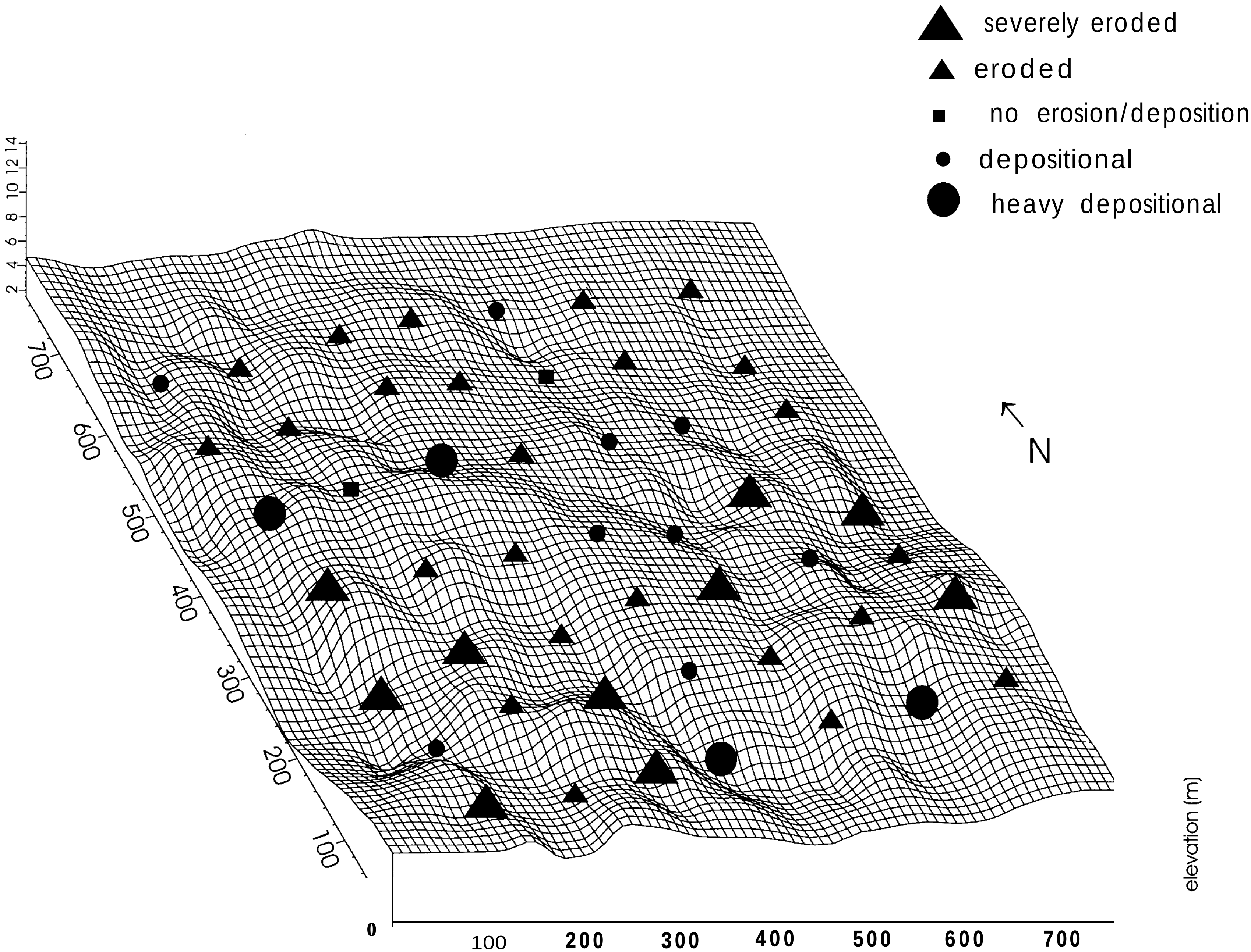

Figure 2: Soil Loss Classification of Each Sampling Point for the Cultivated Site (SE 12-37-2 W3)

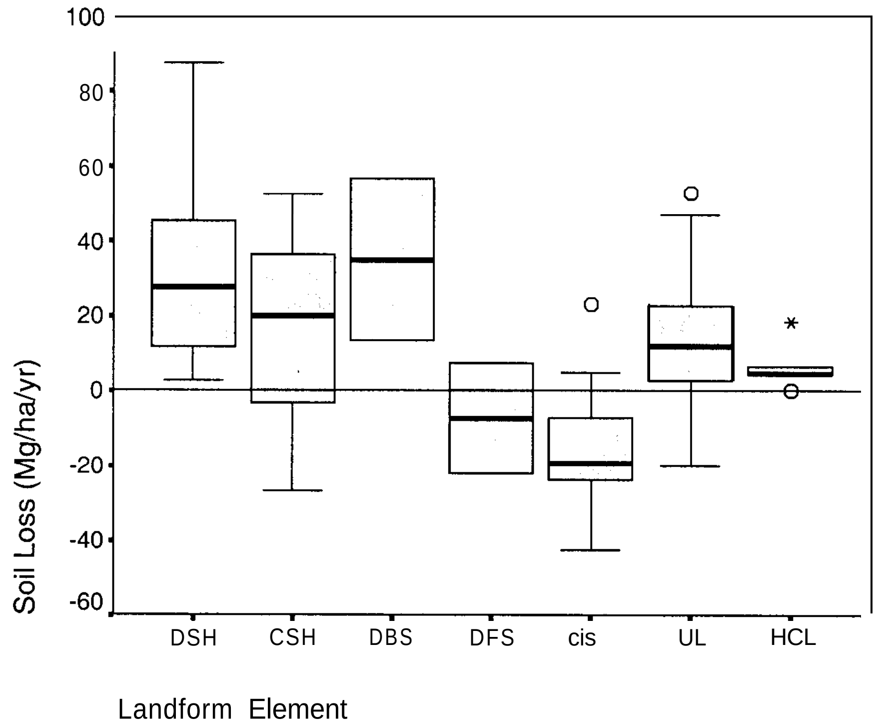

Figure 3: Soil Loss for Each Landform Element

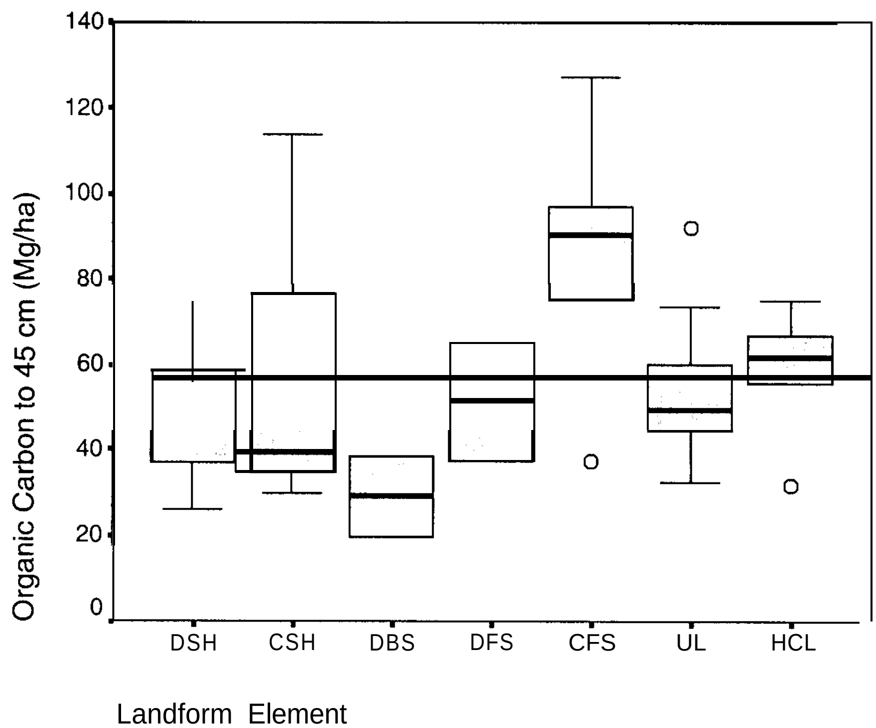

Figure 4: SOC for each Landform Element; the Reference Line is the Area1 Mean SOC (57 Mg ha^{-1})

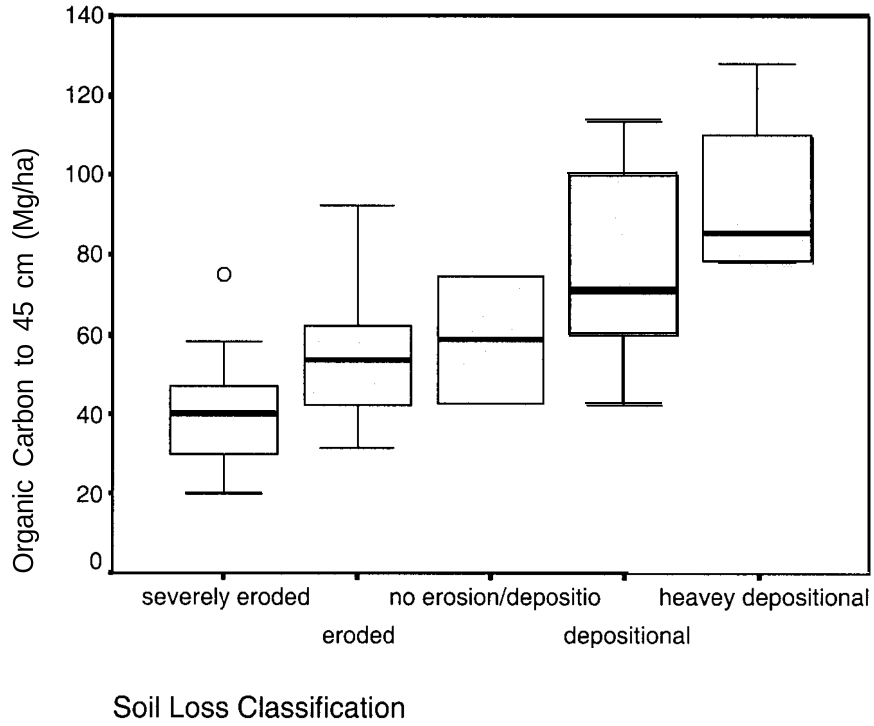

Figure 5: SOC versus Soil Loss Classification

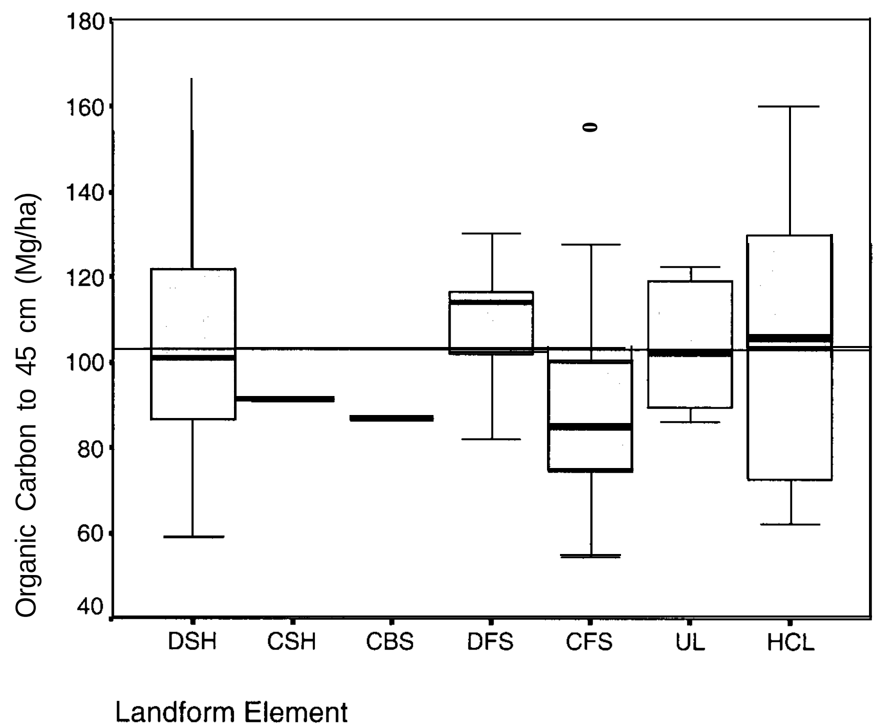

Figure 6: SOC for Each Landform Element at the Native Reference Site; the Reference line is the Areal Mean SOC (103 Mg ha^{-1})

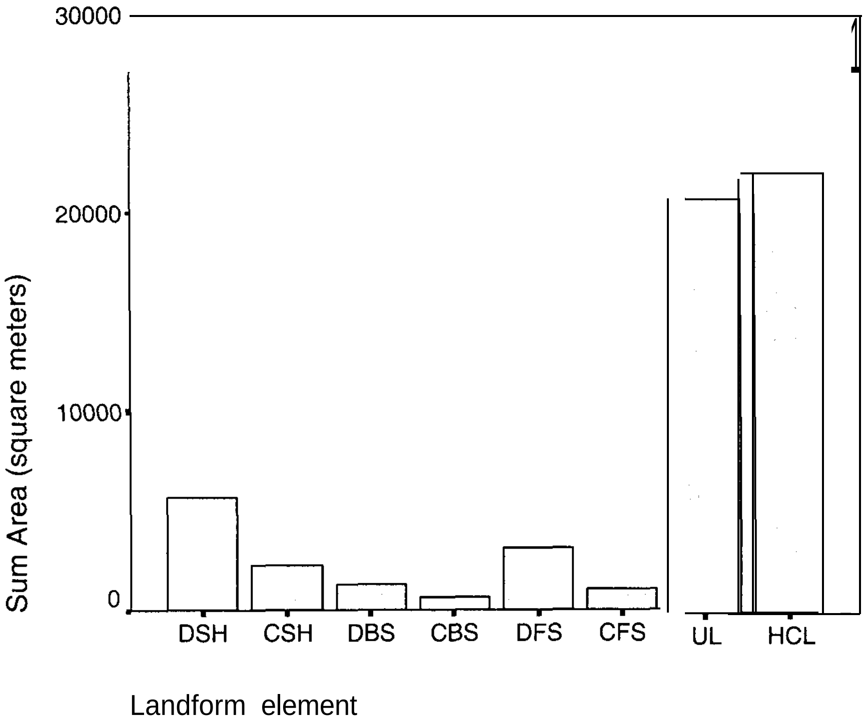

Figure 7: Area Occupied by Each Landform Element