Sediment Dynamics in Changing Environments (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publ. 325, 2008.

Redistribution of soil and soil organic carbon on agricultural landscapes

J. C. RITCHIE & G. W. MCCARTY
USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, Maryland 20705, USA
jerry.ritchie@ars.usda.gov

Abstract Patterns of soil organic carbon (SOC) vary widely across the landscape leading to large uncertainties in the SOC budgets for agricultural systems, especially for landscapes where water, tillage, and wind erosion redistributes soil and SOC across the landscape. It is often assumed that soil erosion results in a loss of SOC from agricultural ecosystems, but recent studies indicate that soil erosion on agricultural landscapes is not a source of carbon dioxide to the atmosphere, but that soil erosion and its subsequent redistribution within agricultural fields and watersheds can lead to limited carbon sequestration on agricultural landscapes. This study investigates the relationship between SOC and soil redistribution patterns on agricultural landscapes using fallout ^{137}caesium (^{137}Cs) to determine patterns of soil redistribution. SOC and ^{137}Cs concentrations of soils were significantly correlated in our study areas. Soils in eroding areas have significantly less SOC than soils in depositional areas. SOC decreased as gradient slope increases and soils on concave slopes had higher SOC than soils on convex slopes. These data suggest that soil redistribution and topographic patterns may be used to help understand SOC dynamics on the landscape. The strong significant relationships between soil redistribution and SOC concentrations in the soils suggest that soil and soil organic matter are transported along similar physical pathways in agricultural systems. These transport processes move soils and SOC to sites of deposition within agricultural fields, riparian zones, and water bodies in the watershed, where SOC is buried, leading to more carbon being removed from the atmosphere than is emitted, creating a sink of atmospheric carbon. Our study indicates the importance of understanding soil movement and redistribution patterns within a field or watershed for understanding soil carbon cycles in agricultural ecosystems

Key words soil organic carbon; caesium-137; soil erosion; soil redistribution; soil organic carbon redistribution

INTRODUCTION

Redistribution of soil organic carbon (SOC) has been related to erosion, landscape properties, vegetation and landscape management (Gregorich *et al.*, 1998; Van Oost *et al.*, 2007). Soil erosion by water, tillage, and wind significantly redistributes soil and SOC, leading to redeposition within the field and movement off the field (Harden *et al.*, 1999; Smith *et al.*, 2001; Ritchie & McCarty, 2003; van Oost *et al.*, 2007). Understanding the processes involved in soil and SOC redistribution are key to understanding the potential of agricultural systems to sequester SOC and to the development of models to predict SOC distribution patterns in agricultural ecosystems. Field-scale sampling and spatial mapping techniques have been used to study the relationship between soil redistribution and SOC spatial patterns on the landscape (VandenBygaart, 2001; Ritchie & McCarty, 2003). The purpose of this study was to use the redistribution of fallout ^{137}caesium (^{137}Cs) to evaluate the spatial redistribution patterns of soil and SOC in agricultural landscapes.

METHODS

Tilled agricultural fields in Maryland and Iowa, USA, were sampled. The Maryland field is located in the Northern Coastal Plains physiographic province near Beltsville, Maryland, USA, on a research farm. Soils are Hapludults, Paleudults, and Fragiudults with fine sandy loam to loamy sands textures (USDA, 1975). The field has been planted in corn (*Zea mays* L.) since 1998. Prior to 1998, the field was used as a pasture for swine research.

Two Iowa fields located on operational farms were sampled in the Des Moines Lobe Till Plain near Ames, Iowa, USA. The soils are Hapludolls, Endoaquolls, and Calciaquolls with loams to clay loams textures (USDA, 1975). The fields are planted in a corn (*Zea mays* L.) and soybean (*Glycime max* (L.) Merr.) rotation (Jaynes *et al.*, 2003).

Soil samples were collected of the 0–30 cm layer on 25-m grid patterns in the 5 ha fields. Selected soil profiles were also collected in 5-cm increments to a depth of 50-cm to measure the depth distribution patterns of ^{137}Cs and SOC. Reference soil samples to determine baseline levels of ^{137}Cs were collected at non eroding sites within 2 km of the study fields.

The soil samples were dried and screened through a 2-mm sieve. Total carbon (%) and nitrogen (%) were measured by dry combustion using a Leco CNS 2000 elemental analyser on a sub-sample of the dried composited soil sample that had been ground to a very fine powder with a roller grinder. Calcium carbonate ($CaCO_3$) was measured by ashing the soil samples in a furnace (420°C for 16 h) and re-analysing the ashed sample for the carbon in $CaCO_3$. SOC was calculated from the difference between total carbon and $CaCO_3$ carbon (Nelson & Sommers, 1996).

Analysis for ^{137}Cs was made by gamma-ray analysis using a Canberra Genie-2000 Spectroscopy System that receives input from three Canberra high purity coaxial germanium crystals (HpC >30% efficiency) into 8192-channel analysers. The system is calibrated and efficiency determined using an Analytic mixed radionuclide standard (10 nuclides) whose calibration can be traced to US National Institute of Standards and Technology. Measurement precision for ^{137}Cs is ± 4 to 6 % and concentration is expressed in Becquerels per kilogram (Bq kg^{-1}) and Becquerels per square metre (Bq m^{-2}).

Soil redistribution (erosion or deposition) rates and patterns were calculated for each soil sample site based on the ^{137}Cs concentrations in the soil using models that convert ^{137}Cs measurements to estimates of soil redistribution rates (Walling & He, 1999). The Mass Balance Model 2 (Walling & He, 1999) was used to calculate soil redistribution rates. A plough depth of 25 cm was used to convert ^{137}Cs activity to erosion/deposition rates.

The elevation and location data for each sample site, measured using differential Global Positioning Systems (GPS), were used with Surfer (Golden Software, 2002) to produce a DEM of each field by kriging. Terrain attributes of each grid cell in this DEM (i.e. slope (the maximum rate of gradient change in elevation), plan curvature (curvature surface perpendicular to the gradient slope, values are negative for curvatures that are convex and positive for curvatures that are concave), profile curvatures (curvature of the surface in direction of the gradient slope, values are negative for curvatures that are convex and positive for curvatures that are concave)) were calculated using Surfer software algorithms. Surfer was also used with field measurements and location data to create spatial maps for erosion/deposition rate (t ha^{-1} year^{-1}), SOC (%), and ^{137}Cs (Bq m^{-2}) and then to calculate values of each for each grid cell for comparison with the terrain attributes. Statistical analyses of the calculated grid cell values for erosion/deposition rate, SOC, ^{137}Cs and terrain attributes were made using Statistix software (Analytical Software, 2003). One-way ANOVA and Tukey's pair wise comparison were used to examine differences between means between grid cells for erosion/deposition rate, SOC, ^{137}Cs and terrain attributes.

RESULTS AND DISCUSSION

Tillage operations in our fields uniformly mixed ^{137}Cs in the tilled layer of the profiles (Ritchie & McCarty, 2003). ^{137}Cs distribution was slightly deeper in depositional areas indicating the redistribution and subsequent deposition of eroded material within the field. However, ^{137}Cs was not found below 30-cm in any soil profile. At the reference sites, ^{137}Cs showed the typical decrease with depth found in undisturbed sites (Ritchie & McHenry, 1990). SOC was highest in the surface layers and decreased slowly through the tilled layer with greater decreases with depth below the tilled layer.

The mean and standard deviation for the field measurements of SOC (%), ^{137}Cs (Bq m^{-2}), and soil redistribution (t ha^{-1} year^{-1}) are given in Table 1. SOC was higher in the Iowa soils and statistically different from SOC in the Coastal Plains soils of Maryland. Soil redistribution rates and SOC were highly correlated in Iowa and Maryland. SOC were significantly different between Iowa and Maryland; however, the soil redistribution rates were not significantly different for the three fields based on the field measurements. The ^{137}Cs (Bq m^{-2}) and soil redistribution (t ha^{-1} year^{-1}) data had high coefficients of variation so that significant differences were less evident.

^{137}Cs (Bq m^{-2} or Bq kg^{-1}) and SOC (%) were significantly related in the three study areas. SOC and ^{137}Cs concentrations increased or decreased together indicating that they are probably moving along similar physical pathways. ^{137}Cs is strongly adsorbed to the fine soil fraction and any movement is associated with the physical movement of these fines (Ritchie & McHenry, 1990). SOC also moves with the fines (Gregorich *et al.*, 1998; Harden *et al.*, 1999).

The spatial distribution patterns of SOC and ^{137}Cs follow elevation patterns for the Iowa fields showing deposition in the depressions and erosion on the ridges that are associated with glacial stagnation and melting during the last deglaciation. Both Iowa fields are nearly-closed basins with most of the runoff being collected in the low areas (depressions) in the fields. Areas of high SOC are present in the depressions where water collects and soil deposition occurs. The ridges and hill slopes have lower SOC and represent areas where soil loss is occurring. The relationship between SOC and elevation is especially strong in the Iowa fields. In the Maryland field, the field slopes toward a riparian area and patterns of SOC and erosion are related to the drainage patterns and to depressions in the field where water movement slows and soil collects.

Using Surfer's algorithms, SOC (%), ^{137}Cs (Bq m^{-2}), soil redistribution (t ha^{-1} year^{-1}) and slope (% in direction of steepest gradient descent) were calculated for each grid cell. The three fields were significantly different from each other for these four calculated grid cell attributes. In general the means and standard deviations for these grid cell estimates follow the same patterns and are similar in absolute value to the field measurements (Table 1). Erosion was greatest on the field area (Iowa Field 2) with the steepest average slope. SOC was lower in the field area with the greater erosion and steeper slopes.

Combining the data from the three fields and comparing eroding and depositing grid cells (Table 2) shows that the average SOC concentration at the depositing sites was significantly greater than the SOC at the eroding sites. The average slope was greater for grid cells with soil loss than for the grid cell with soil deposition. The grid cells with higher slopes tended to be on the ridges. Comparing slopes for the grid cell shows that SOC decreases and soil loss increases as slope increases. In the depression (slopes <1%) soil deposition and higher SOC values were found.

Table 1 Mean and standard deviation for the field measurements for soil organic carbon, soil redistribution and ^{137}Cs. Note that negative values of soil redistribution are erosion sites while positive values are deposition sites. Means in a column with different letters are significantly different at the 0.05 level of probability.

Site	Number of samples	Soil Organic Carbon (%)	Soil Redistribution (t ha^{-1} year^{-1})	^{137}Cs (Bq m^{-2})
Iowa (Field 1)	230	2.42 ± 1.04a	0.1 ± 32.4a	2624 ±1462a
Iowa (Field 2)	229	2.34 ± 0.88a	–3.5 ± 21.6a	2354 ± 1054b
Maryland	273	1.50 ± 0.35b	–1.8 ± 8.0a	2583 ± 478a
All	732	2.11 ± 1.08	1.8 ± 22.4	2524 ± 1056

Table 2 Mean and standard deviation for the calculated grid-cell values compared by soil redistribution. Note that sites losing soil are listed as erosion grid cells while sites gaining soil are listed as deposition grid cells. Note that the three fields have been combined. Means in a column with different letters are significantly different at the 0.05 level of probability.

Soil Redistribution	Soil organic Carbon (%)	Soil redistribution (t ha^{-1} year^{-1})	^{137}Cs (Bq m^{-2})	Slope (%)
Erosion	1.90 ± 0.94a	–13.2 ± 11.3a	2070 ± 675a	1.52 ± 0.94a
Deposition	2.53 ± 0.92b	14.4 ± 19.9b	3041 ± 1243b	1.22 ± 1.08b
All	2.15 ± 0.87	–2.3 ± 20.4	2453 ± 1054	1.41 ± 1.01

Comparing slope shape, concave slopes have higher SOC and less soil loss than the convex slopes. These patterns are the same as has been shown in other studies (Pennock & Frick, 2001;

Mueller & Pierce, 2003). The gradient slopes were less on the concave slope indicating a convergence and potential slowing of run off which would allow water to slow and eroded soil particles and SOC to be deposited.

^{137}Caesium, soil redistributions and SOC concentrations of agricultural soils were significantly related in Iowa and Maryland fields. Eroding soils determined by the ^{137}Cs technique have significantly less SOC than soils in deposition areas. Our data suggest that soil redistribution patterns may be used to help understand SOC dynamics on agricultural landscapes. Different productivity and oxidation rates of SOC of eroded *vs* deposited soil would also contribute different patterns of SOC on the landscape. However, the strong, significant relationships between soil redistribution and SOC concentrations in these agricultural soils suggest that they are moving along similar physical pathways in these agricultural ecosystems. A strong relationship was also found between terrain attributes (slopes shapes and types) and SOC, suggesting that models can be developed to predict patterns of soil redistribution and SOC on agricultural landscapes, so providing potential insights into management systems that will enhance sequestration of carbon in agricultural ecosystems.

REFERENCES

Analytical Software (2003) *Statistix 8*. Analytical Software, Tallahassee, Florida, USA.

Golden Software (2002) *Surfer 8*. Golden Software, Inc., Golden, Colorado, USA.

Gregorich, E. G., Greer, K. J., Anderson, D. W. & Liang, B. D. (1998) Carbon distribution and losses: erosion and deposition effects. *Soil Till. Res*. **47**, 291–302.

Harden, J. W., Sharpe, J. M., Parton, W. J., Ojima, D. S., Fries, T. L., Huntington, T. G. & Dabney, S. M. (1999) Dynamic replacement and loss of soil carbon on eroding cropland. *Global Biogeochem. Cycles* **13,** 885–901.

Jaynes, D. B., Kaspar, T. C., Colvin, T. S. & James, D. E. (2003) Cluster analysis of spatiotemporal corn yield patterns in an Iowa field. *Agron. J.* **95,** 574–586.

Mueller, T. G. & Pierce, F. J. (2003) Soil carbon maps: Enhancing spatial estimates with simple terrain attributes at multiple scales. *Soil Sci. Soc. Am. J.* **67,** 258–267.

Nelson, D. W. & Sommers, L. E. (1996) Total carbon, organic carbon, and organic matter, In*: Methods of Soil Analysis*, Part 3: *Chemical Methods* (ed. by J. M. Bartels & J. M. Bigham), 961–1010. Soil Science Society of America, Madison, Wisconsin, USA.

Pennock, D. J. & Frick, A. H. (2001) The role of field studies in landscape-scale applications of process models: an example of soil redistribution and soil organic carbon modelling using CENTURY. *Soil Till. Res.* **58,** 183–191.

Ritchie, J. C. & McCarty, G. W. (2003) Using ^{137}Cesium to understand soil carbon redistribution on agricultural watersheds. *Soil Till. Res.* **69,** 45-51.

Ritchie, J. C. & McHenry, J. R. (1990) Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *J. Environ. Qual.* **19,** 215–233.

Smith, S. V., Renwick, W. H., Buddemeier, R. W. & Crossland, C. J. (2001) Budgets of soil erosion and deposition of sediment and sedimentary organic matter across the conterminous United States. *Global Biogeochem. Cycles* **15,** 697–707.

United States Department of Agriculture (USDA) (1975) *Soil Taxonomy. Agriculture Handbook no. 436*. United States Department of Agriculture–Soil Conservation Service, Washington, DC, USA.

VandenBygaart, A. J. (2001) Erosion and deposition history derived by depth-stratigraphy of Cs-137 and soil organic carbon. *Soil Till. Res*. **61,** 187–192.

Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, K., Giraldez, J. V., Marques da Silva, J. R. & Merckx, R. (2007) The impact of agricultural soil erosion on the global carbon cycle. *Science* **318,** 626–629.

Walling, D. E. & He, Q. (1999) Improved models for estimating soil erosion rates from cesium-137 measurements. *J. Environ. Qual.* **28,** 611–622.