Using fallout Cesium-137 to understand soil redistribution on agricultural landscapes

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1. Abstract

While it is recognized that soil erosion is highly variable in space and time, studies of the redistribution of soil and soil organic carbon (SOC) within a field or watershed are limited. Our studies focus on the use of fallout Cesium-137 to understand pattern of soil and SOC movement on the landscape. It is often assumed that eroding soils results in soil losses from agricultural fields; however, our studies indicate that most of the eroding soils are redeposited within same field. These studies also investigated the relationship between soil redistribution and SOC patterns in agricultural fields. Cesium-137, soil, and SOC redistribution in agricultural fields were significantly correlated. Hillslope areas lost significantly more soil and SOC than soils in toe slope positions (deposition). Soil erosion increased as the slope increases and soils on concave slopes had higher SOC than soils on convex slopes. These data suggest that soil and SOC redistribution patterns and topographic patterns can be used to help understand soil erosion and SOC redistribution patterns on agricultural landscapes. The strong significant relationships between soil and SOC redistribution patterns in agricultural soils suggest that they are moving along similar physical pathways in these systems. Our study also indicates that geomorphic position is important for understanding soil and SOC movement and redistribution patterns within a field or watershed. Such information can help develop and implement management systems to increase SOC and reduce soil loss in agricultural ecosystems.

2. Introduction

Spatial patterns of soil redistribution and soil organic carbon (SOC) have been shown to be a function of soil erosion and redeposition, vegetative productivity, mineralization of SOC, landscape position, and management (Gregorich et al., 1998; West and Marland, 2003). Water, tillage, and wind erosion contribute significantly to the redistribution of soil and SOC across agricultural landscapes, with both soil and SOC being redeposited within the field as well as being moved off the field (Harden et al., 1999; Smith et al., 2001; Ritchie and McCarty, 2003). Understanding the patterns and processes involved in soil and SOC redistribution are keys to understanding SOC sequestration in agricultural ecosystems as well as the development models that can predict soil and SOC distribution patterns in agricultural ecosystems. Studies have used field scale sampling and spatial mapping techniques to study the relationship between soil redistribution and SOC (VandenBygaart, 2001; Ritchie and McCarty 2003). This study used fallout ^{137}Cesium (^{137}Cs) distribution on the landscape as a tool to evaluate the spatial redistribution patterns of soil and SOC in tilled agricultural ecosystems.

3. Materials and Methods

Conventional tilled fields in Maryland and Iowa USA were sampled. Sample sites (Venteris et al., 2004) were surveyed with a Geographic Positioning System (GPS) (Trimble Geoexplorer XT[1]). The Maryland field is located in the Northern Coastal Plains physiographic province near Beltsville, Maryland, USA. The fine sandy loam to loamy sands soils are Hapludults, Paleudults, and Fragiudults (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 farm fields were sampled in the Des Moines Lobe Till Plain in Central Iowa near Ames, Iowa USA with an area of approximately 15 ha each. The loams to clay loams soils are Hapludolls, Endoaquolls, and Calciaquolls (USDA, 1975). Both fields have tile drains. The fields are in a corn [*Zea mays* L.] and soybean [*Glycime max* (L.) Merr.] rotation (Jaynes et al., 2003).

In the Maryland and Iowa fields, three soil samples were collected of the 0-30 cm layer at each sample site. The three samples at each site were combined into a single sample for analyses. Selected soil profile samples were also collected in 5-cm increments to a depth of 50-cm to measure the depth distribution of ^{137}Cs and SOC. Six reference soil samples were collected within 2 km of the study fields where soil erosion had not occurred since the mid 1950s and used to determine baseline ^{137}Cs input to the each area.

[1] Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U. S. Department of Agriculture

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 hours) and reanalysing the ashed sample for the remaining C in $CaCO_3$. SOC was calculated from the difference between total carbon and $CaCO_3$ carbon (Nelson and Sommers, 1996).

Analyses for ^{137}Cs were 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 U.S. National Institute of Standards and Technology. Measurement precision for ^{137}Cs is ± 4 to 6 % and is expressed in Becquerels per kilogram (Bq kg^{-1}) or Becquerels per square meter (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 and He, 1999). The Mass Balance Model 2 (Walling and He, 1999) that uses time-variant ^{137}Cs fallout input and consideration of the fate of freshly deposited fallout 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 were used with Surfer (Golden Software, 2002) to produce a DEM of the elevation in 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 (t ha^{-1} yr^{-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 field measurements and calculated grid cell values 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 sites for each variable.

4. Results and Discussion

^{137}Cesium was uniformly distributed with depth in the 15-20 cm tilled layers which is typical of agricultural soils where tillage operations mix ^{137}Cs in the tilled layer of the profile (Ritchie and McCarty, 2003). In depositional areas on the fields, ^{137}Cs distribution was slightly deeper than the tilled depth indicating the redistribution and subsequent redeposition 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 an exponential decrease with depth typical of undisturbed sites (Ritchie and McHenry, 1990). SOC was highest in the surface layers and decreased slowly through the tilled layer with greater decreases with depth below this tilled layer.

The mean and standard deviation for the field measurements of SOC (%), ^{137}Cs (Bq m^{-2}), and soil redistribution (t ha^{-1} yr^{-1}) are given in Table 1. A morphological study of the soil profile at each sample site in Iowa found similar pattern of erosion and deposition as found with ^{137}Cs (Fenton, personal communication). SOC was higher in the soils in Iowa and statistically different from SOC in the Coastal Plains soils of Maryland. SOC concentrations were related to soil redistribution rates in both areas. Field 2 in Iowa had higher erosion rates and lower SOC that Field 1 in Iowa. While the SOC rates were significantly different, 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} yr^{-1}) data had high coefficient of variation so that significant differences were less evident.

A statistically significant relationship between ^{137}Cs (Bq m^{-2}) and SOC (%) was found for the three fields (Fig. 2). SOC increases as ^{137}Cs increases indicating that they are probably moving along similar physical pathways. It is known that ^{137}Cs is strongly adsorbed to the fine soil fraction and any movement is associated with the physical movement of these fines (Ritchie and McHenry, 1990). SOC moves with these fines also (Gregorich et al., 1998; Harden et al., 1999).

The spatial distribution patterns of SOC and elevation for Iowa Field 2 (Fig. 1) show hummocky surfaces with small depressions and ridges that are associated with glacial stagnation and melting during the last deglaciation. The depressions generally have tile drainage at these sites as is common throughout the area. Both Iowa fields are nearly closed basins with most of runoff being collected in the low areas (pot holes) in the fields. Areas of high SOC are in the depressions where water collects and soil deposition is occurring. The ridges and hill slopes have lower SOC and represent area where soil loss is occurring. The relationship between SOC and elevation is especially strong in the Iowa fields. SOC was lower in Field 2 where soil erosion was higher (Table 1). At the Maryland field, the field slopes toward a riparian area and patterns of SOC are related to the drainage patterns and depression 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} yr^{-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 (Iowa Field 2) with the steepest average slope. Also SOC was lower in the field with the greater erosion and steeper slopes.

Combining the data from the three fields and comparing eroding and deposition grid cells (Table 2) show that the average SOC concentration at the depositing sites was significantly greater than the SOC at the eroding sites (Table 2). The average slope was greater for the eroding grid cells 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.

Whether comparing slope shape in the gradient direction of the slope or perpendicular to the gradient direction of the slope, 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 (Gregorich et al., 1998; Pennock and Frick, 2001; Mueller and Pierce, 2003). The gradient slopes were less in 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}Cesium, 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 versus 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 providing potential insights into management system that will enhance sequestration of carbon in agricultural ecosystems.

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} yr^{-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	Number of samples	Soil Organic Carbon (%)	Soil Redistribution (t ha^{-1} yr^{-1})	^{137}Cs (Bq m^{-2})	Slope (%)
Erosion	14772	1.90 ± 0.94a	-13.2 ± 11.3a	2070 ± 675a	1.52 ± 0.94a
Deposition	9630	2.53 ± 0.92b	14.4 ± 19.9b	3041 ± 1243b	1.22 ± 1.08b
All	24402	2.15 ± 0.87	-2.3 ± 20.4	2453 ± 1054	1.41 ± 1.01

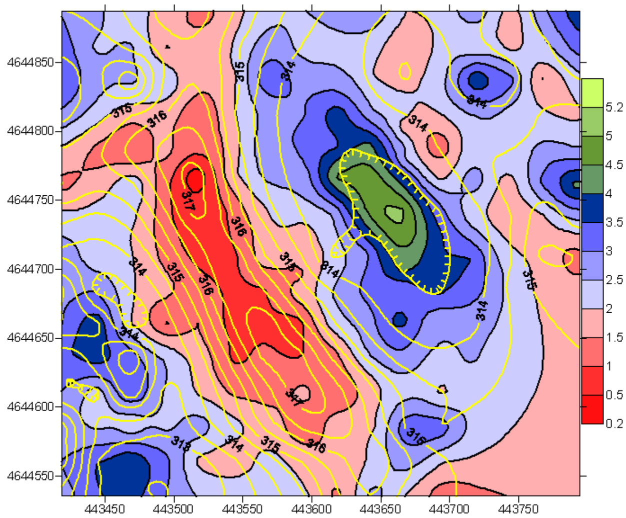

Figure 2 Spatial distribution of soil organic carbon and surface elevation for Iowa Field 2. Color scale is soil organic carbon (%) and yellow lines are elevations (m).

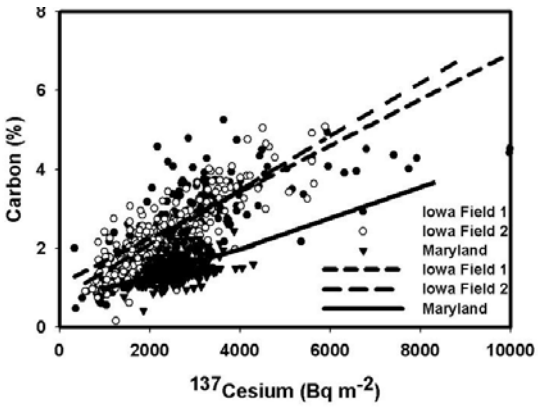

Figure 1 Plot of the relationship between 137Cs (Bq m-2) and soil organic carbon (%) for Maryland and Fields 1 and 2 in Iowa.

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