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Using soil redistribution to understand soil organic carbon redistribution and budgets

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Abstract Patterns of soil organic carbon (SOC) vary across the landscape leading to uncertainties in SOC budgets, especially for agricultural areas where water, wind, and tillage erosion redistribute soil and SOC. This study determined SOC patterns related to soil redistribution in small agricultural fields. Soil redistribution patterns were determined using the fallout caesium-137 technique in agricultural fields in Maryland and Iowa, USA. In two Iowa fields, SOC ranged from 0.5 to 5% whereas in the Maryland field the SOC ranged from 0.4 to 2.9%. Soil organic carbon was statistically significantly correlated with soil ^{137}Cs inventories and soil erosion/deposition rates. Sites of soil erosion in Iowa and Maryland had significantly lower average concentrations of SOC (2.4% and 1.3%, respectively) than sites of soil deposition (3.4% and 1.6%, respectively). These studies show the impact of soil redistribution patterns, within a field or catchment, and aid in understanding SOC patterns and budgets.

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

INTRODUCTION

Increasing atmospheric carbon dioxide (CO_2), and concern about potential global warming has raised interest in using agricultural soils as carbon sinks (Gregorich *et al.*, 1998; Harden *et al.*, 1999; Lal, 2004). Soil organic carbon (SOC) is related to vegetative productivity, mineralization of SOC, landscape characteristics, management practices, and soil redistribution (Gregorich *et al.*, 1998). Water, tillage, and wind erosion significantly contribute to the redistribution of soil and SOC across the landscape, with both soil and SOC often being redeposited within the same field, as well as being moved off the field (Harden *et al.*, 1999; Smith *et al.*, 2001; Ritchie & McCarty, 2003). Understanding SOC redistribution patterns and processes across agricultural landscapes is key to understanding and managing agricultural ecosystems as carbon sinks, and developing models to predict SOC distribution patterns in agricultural areas. The purpose of this study was to determine the redistribution patterns of soil and SOC in tilled agricultural ecosystems using fallout caesium-137 (^{137}Cs) distribution patterns on the landscape.

MATERIALS AND METHODS

Sample sites

Tilled agricultural fields were sampled in Maryland and Iowa, USA. The Maryland site is located on the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE^3) research watershed (Gish *et al.*, 2003) in the Northern Coastal Plain physiographic province at the USDA Agriculture Research Service (ARS), Beltsville Agriculture Research Center near Beltsville, Maryland, USA. The study area is approximately 25 ha, approximately 40 m above sea level, and separated into four small watersheds for monitoring runoff from different research treatments. Mean annual rainfall is 1035 mm with a range from 547 to 1584 mm for the period 1871–2000. Mean annual temperature is 13°C with monthly averages ranging from 4°C in February to 27°C in July. The soils on the study area are Hapludults, Paleudults, and Fragiudults. The native vegetation is pine (*Pinus* ssp.) and hardwood (*Quercus* spp., *Acer* spp.) forests. The study area has been tilled and planted in corn (*Zea mays* L.) since 1998. Bulk soil samples were collected from the 0–30 cm layer, in a 30-m grid pattern, across the study area. Additional soil profile samples were collected by 5-cm depth increments down to 40-cm along four transects, to determine depth distribution patterns of ^{137}Cs and SOC.

Two fields on different operational farms in Iowa, with areas of approximately 15 ha each, were sampled in the Des Moines Lobe Till Plain in Central Iowa near Ames, Iowa, USA. The elevation of the fields is approximately 300 m. Mean annual rainfall is 835 mm. Mean annual temperature is 8°C with monthly averages ranging from –6°C in January to 22°C in July. The soils are Udolls and Udalfs. The native vegetation is grass. The fields were in a corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) rotation. Bulk soil samples were collected for the 0–30 cm layer on a 25-m grid. Deeper soil samples were collected for the 30–50 cm layer at sites of deposition. At selected sites, soil samples were taken to a depth of 100 cm, and divided into 5-cm increments, to study depth distributions of ^{137}Cs and SOC.

Sample collection and analysis

Three bulk soil samples were collected to a depth of 30-cm at each point on a grid pattern across the three fields using a 3.2-cm (1.25-inch) diameter push probe. The three samples for each point were combined for analyses. Soils in areas of apparent deposition were collected to 30–50 cm to insure that the total depth of soil with ^{137}Cs was collected. At selected sites, samples were collected in 5-cm depth increments to a depth of 50–100 cm to study the vertical distribution patterns of ^{137}Cs and SOC (Ritchie & McCarty, 2003; Ritchie *et al.*, 2004). All soil samples were dried, sieved to pass a 2-mm screen, placed into Marinelli beakers, and sealed for ^{137}Cs analyses.

Reference soil samples were collected in areas where no apparent soil redistribution had occurred since the mid 1950s, and were used to determine baseline ^{137}Cs input to the areas. At least six reference sites were collected near the study fields in both Maryland and Iowa.

All soil sampling points were surveyed with a code based Geographic Positioning System (GPS) (Trimble Geoexplorer XT) and are accurate to approximately 1 m. In the three fields, a RTK (Real-Time Kinematic) GPS unit installed on an ATV (All Terrain Vehicle) was used to measure transects at approximately 5-m spacing across the sampled area. Measurement accuracy was approximately 5 cm for location and elevation. These data were used to develop Digital Elevation Models (DEM) for the three fields to help understand redistribution patterns.

Analyses for ^{137}Cs were made by gamma-ray analyses using a Canberra Genie-2000 Spectroscopy System that receives input from three Canberra high purity coaxial germanium crystals into 8192-channel analysers. The system is calibrated, and efficiency determined, using a mixed radionuclide standard (10 nuclides) whose calibration can be traced to the US National Institute of Standards and Technology. Measurement precision for ^{137}Cs is ±4–6% based on repetitive measurements of the same sample.

Carbon and nitrogen were measured on the soil samples by dry combustion, after screening through a 2-mm sieve and grinding to a very fine powder with a roller grinder. A Leco CNS 2000 elemental analyser was used to determine total carbon (%) and nitrogen (%) (Nelson & Sommers, 1996). Carbonate carbon was determined by ashing the soil samples at 400°C for 16 h, and determining weight loss. Soil organic carbon was calculated as the difference between total carbon and carbonate carbon.

Soil redistribution

Soil redistribution (erosion or deposition) rates were calculated for each soil sample point using a model that converts ^{137}Cs inventory at a point, into estimates of soil redistribution rates (Ritchie & McHenry, 1990; Walling & He, 1999, 2001). The Mass Balance Model 2 of Walling & He (2001), 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 standard plough depth of 25 cm was used in the model. Sample sites with less ^{137}Cs inventory than the ^{137}Cs inventory at the reference sites are assumed to be eroding, whereas sites with more ^{137}Cs inventory than the ^{137}Cs inventory at the reference sites are assumed to be deposition zones.

RESULTS AND DISCUSSION

Caesium-137 was uniformly distributed in the upper 20–25 cm tilled layer in all three agricultural fields. This is typical of soils where tillage operations mix ^{137}Cs in the tilled layer of the profile (Walling & He, 1999; Ritchie, *et al*., 2004). In depositional areas on the fields, ^{137}Cs distribution was slightly deeper than the tilled depth, indicating deposition of eroded material within the field. However, ^{137}Cs was not found below 30-cm in any of the soil profiles sampled in these three agricultural fields. At the reference sites, ^{137}Cs showed an exponential decrease with depth, typical of undisturbed sites (Ritchie *et al*., 1972; Basher *et al*., 1995; Owens & Walling, 1996). Soil organic carbon was highest in the surface layers and decreased slowly through the

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

Location	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

tilled layer, with greater decreases with depth below the tilled layers at the Maryland and Iowa fields (Ritchie *et al.*, 2004).

The means and standard deviations for SOC (%), ^{137}Cs (Bq m^{-2}), and soil redistribution (t ha^{-1} year^{-1}) are given in Table 1. Soil organic carbon was almost 1% higher in the soils in Iowa, and statistically greater than the SOC in the Maryland fields, as was expected because of the naturally higher SOC concentrations in prairie soils (Follett, 2001). Soil organic carbon concentrations were related to soil redistribution patterns in all fields. Sites of soil erosion had significantly lower concentrations of SOC (2.4% and 1.3%, respectively) than sites of soil deposition (3.4% and 1.6% SOC, respectively). Average soil redistribution rates were similar for the three fields but patterns of redistribution differed.

The Iowa fields had large standard deviations for SOC and soil redistribution, indicating a large variation in the patterns within the fields. The Iowa fields have hummocky surfaces with depressions (pot holes) and ridges that are associated with glacial stagnation and melting during the last deglaciation. Both fields are nearly closed basins with most of the runoff being collected in the low areas (pot holes) in the fields. High SOC is found in these depressions where water collects and soil deposition is occurring. Tile drains are used as a standard management practice to remove excess water from the low areas in the fields. The ridges and side slopes have lower SOC, and represent areas where soil loss is occurring; the eroded material appears to be moving to the depressions.

At the Maryland site, the field slopes toward a riparian area and patterns of SOC distribution are related to the drainage patterns and depressions in the field where water movement slows and the eroding soil collects. Soil and SOC can also move off the field into the riparian zone (Ritchie & McCarty, 2003).

Statistically significant relationships between ^{137}Cs (Bq m^{-2}) and SOC (%) were found for the three fields (Figs 1–3), although the r^2 values are not high (0.55, 0.68 and 0.21 for Iowa Field 1, Iowa Field 2 and the Maryland field, respectively). The positive correlation between SOC and ^{137}Cs suggests that both constituents probably are transported along similar physical pathways in these agricultural systems. It is known that ^{137}Cs is strongly adsorbed to the fine soil fraction and any movement (relocation) is associated with the physical movement of these fines (Ritchie & McHenry, 1990; Walling & He, 1999). Soil organic carbon also moves with these fines (Gregorich *et al.*, 1998; Harden, 1999; Lal, 2004). Using ^{137}Cs inventories to determine patterns of soil redistribution within agricultural fields will allow the development of models that can be used to predict SOC budgets in these fields.

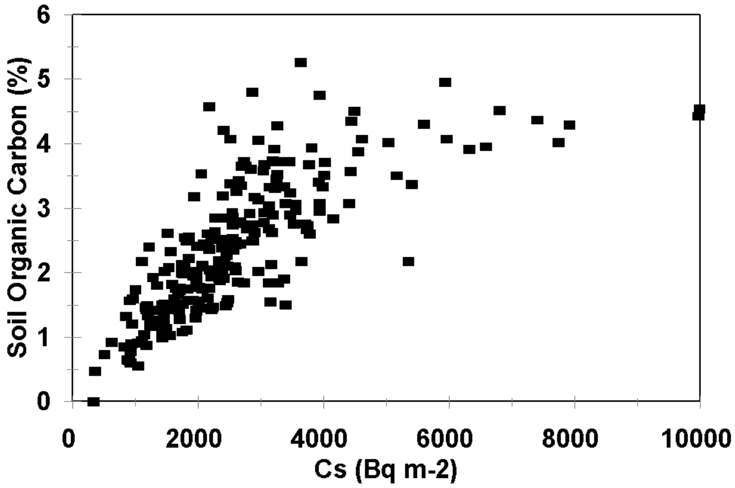

Fig. 1 Plot of the relationship between ^{137}Cs inventory (Bq m^{-2}) and soil organic carbon (%) for Field 1 in Iowa.

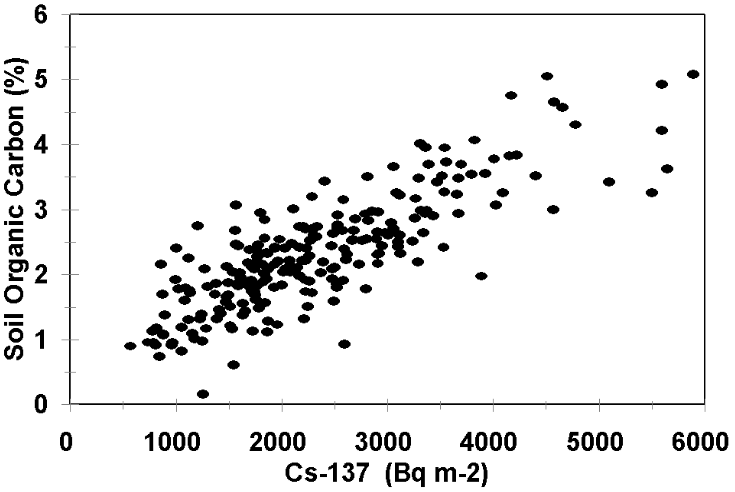

Fig. 2 Plot of the relationship between ^{137}Cs inventory (Bq m^{-2}) and soil organic carbon (%) for Field 2 in Iowa.

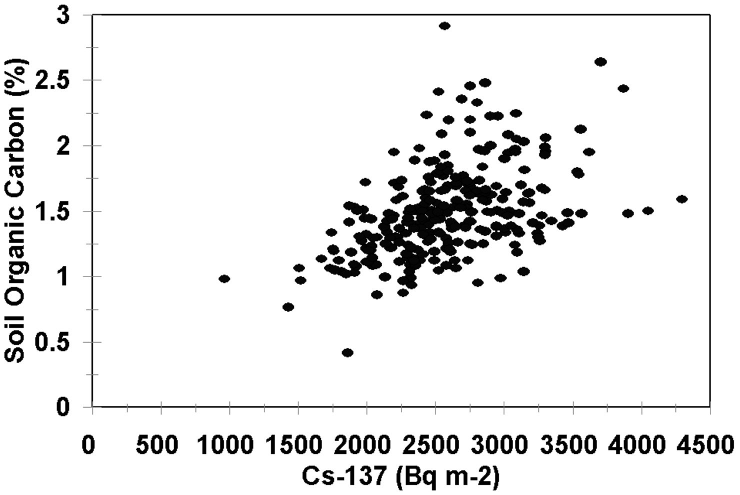

Fig. 3 Plot of the relationship between ^{137}Cs inventory (Bq m^{-2}) and soil organic carbon (%) for the field in Maryland.

CONCLUSIONS

Caesium-137 inventories and SOC concentrations of upland soils are significantly correlated in three study fields. In the upland areas, eroding soils, identified using ^{137}Cs inventories, were sites of SOC loss whereas sites identified as deposition areas had increased SOC. These data suggest that patterns of ^{137}Cs inventories may be used to help understand and model SOC dynamics and budgets on the landscape. Other factors, such as different productivity and oxidation rates of SOC of eroded *vs* deposited soils, would also contribute different patterns of SOC on the landscape. However, the strong significant relationships between ^{137}Cs inventories and SOC concentrations in the soils suggest that they are moving along similar physical pathways in these systems and that models can be developed to predict patterns of soil and SOC redistribution on the landscape providing potential insights into management systems to enhance carbon sequestration, and provide a better understanding of carbon budgets, in agricultural ecosystems.

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