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Soil organic matter stocks and spatial distribution in the Río Grande de Arecibo watershed[1,2]

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ABSTRACT

This research evaluated the influence of land use and soil classification, as stratified by taxonomic soil order, on the spatial distribution of soil organic carbon (SOC) and soil organic nitrogen (SON) of the Río Grande de Arecibo (RGA) watershed, Puerto Rico. The objectives were to quantify the present state of SOC and of SON stocks and potential C sequestration capability of the watershed to 1-m depth. Samples were taken from representative soils of the watershed occupying 39,361 ha (or 87.3% of the total watershed area) under secondary forest, pasture, or agricultural land use. Soils of the watershed store 5.02 × 10^6 Mg of SOC and 0.48 × 10^6 Mg of SON at a depth of

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100 cm. The weighted mean SOC and SON contents of the 0- to 15-cm layer of the watershed were 4.33 kg C/m² and 0.390 kg N/m², respectively, whereas at 0 to 100 cm it was 11.13 kg C/m² and 1.08 kg N/m², respectively. The soil mapping unit × land use interaction represented the best area-wide estimates of soil organic matter because there was improved resolution on a spatial scale. Forest and pasture soils contained higher amounts of SOC (12.8 and 9.79 kg C/m², respectively) ($P < 0.05$) than soils under cropland (7.90 kg C/m²) for the 0- to 100-cm depth. The 0- to 15-cm SOC was ranked as Oxisols = Ultisols > Inceptisols, with values of 5.85, 4.77, and 3.18 kg C/m², respectively ($P < 0.05$); and for the 0 to 100 cm, were ranked as Oxisols > Ultisols > Inceptisols, with values of 18.3, 13.3, and 6.71 kg C/m², respectively. We estimate that an additional amount of 46,627 Mg C could be sequestered within the watershed if 50% of the agricultural or pasture land were reverted to forest. This estimate represents a modest 1.0% increase above the current watershed C level.

Key words: soil organic matter, soil organic carbon and nitrogen, carbon sequestration, land use, tropical watershed

RESUMEN

Reservas de materia orgánica en suelos y distribución espacial en la cuenca del Río Grande de Arecibo

Se estudió la influencia de los factores orden de suelo, fase y uso de terreno sobre la distribución espacial del carbono orgánico (SOC) y nitrógeno total del suelo (SON) en la cuenca del Río Grande de Arecibo, Puerto Rico. Los objetivos eran cuantificar las reservas de C y N en suelos y el potencial de secuestro de C de la cuenca. Se tomaron muestras de suelos representativos de la cuenca de un área de 39,361 ha (o 87.3% de la totalidad del área de la cuenca) bajo bosque secundario, pastura y uso agrícola. Los suelos de la cuenca almacenan 5.02×10^6 Mg de SOC y 0.48×10^6 Mg de SON a una profundidad de 100 cm. Las medias ponderadas de SOC y SON a 15 cm de profundidad fueron 4.33 kg C/m² y 0.390 kg N/m², respectivamente, y a una profundidad de 100 cm fueron de 11.13 kg C/m² y 1.08 kg N/m², respectivamente. La interacción entre unidad de mapa y uso de terreno representó el mejor estimado de SOC por la mayor resolución espacial. Suelos bajo bosque secundario y pasturas tuvieron mayor SOC (12.8 y 9.79 kg C/m², respectivamente) ($P < 0.05$) que suelos bajo uso agrícola (7.90 kg C/m²) a una profundidad de 100 cm. El SOC a una profundidad de 15 cm fue similar entre Oxisoles y Ultisoles, los que juntos fueron mayores que los Inceptisoles con valores de 5.85, 4.77, y 3.18 kg C/m², respectivamente. Estimamos que la cuenca puede secuestrar 46,627 Mg C adicionales, lo cual representa un aumento de 1.0% sobre el nivel actual de C.

Palabras clave: materia orgánica en suelo, secuestro de carbono, uso de terreno, cuenca hidrográfica

INTRODUCTION

Organic carbon (C) in world soils to 1-m depth hold nearly 3.3% of the global C stocks, estimated at 4.606×10^{13} Mg (Lal, 2004; Lal, 2006). Most of the carbon stored in soil organic matter is considered stable with long residence time (Buyanovsky et al., 1994; Hsieh, 1996), and world soils store more organic and inorganic C than that present in the atmosphere and vegetation combined (Lal, 2004). The depletion of organic matter via oxidation because of intensive soil cultivation leads to

C loss as CO_2 production leading to increased atmospheric C loading. Lal et al. (2007) estimated that on a global basis, between 26 to 43% of the original total soil organic C (SOC) pool has been lost, and most cultivated soils have lost 50 to 75% of their antecedent C pool. Cultivated soils are a net source of C to the atmosphere when the amounts of C output (erosion, gaseous, leaching, vegetative removal) exceed the magnitude of input (brought on by litterfall, plant residue, root biomass). However, soils under proper management can mitigate atmospheric C increase and ameliorate global warming.

Storage of SOC is especially important in the tropics because this region holds more than one-third of the world's soil area. There is a need for increased agricultural production, and many soils are subjected to degradation (Eswaran et al., 1993; Lal et al., 2007). This aspect is especially important for the Caribbean because by the end of the nineteenth century most land areas had been deforested and were under some form of management or cultivation. In Puerto Rico in particular, much of the agricultural land has been abandoned because of population migration to cities. Since the 1950s, agricultural land of the mountainous interior has reverted to secondary forests and unmanaged pasture (Aide and Grau, 2004; Grau et al., 2004).

Stocks of SOC and potential sequestration have been estimated on a world-wide scale (Eswaran et al., 2000; Lal, 2004) and for soils in Latin America (Liegel, 1992; Bernoux and Volkoff, 2006) with an estimated 90.3 $\times 10^6$ Mg C and a mean C density of 10.2 kg C/m^2 at 0 to 100 cm. There have been some reports on the status of SOC in the Caribbean (Barreteau et al., 2004; Feller et al., 2006) and for the island of Puerto Rico (Weaver et al., 1987; Beinroth et al., 1992; Lugo-López, 1992; Beinroth et al., 2003; Johnson and Kern, 2003). For example, Beinroth et al. (1992) used soil survey information to produce estimates of 14.0 kg C/m^2, 12.8 kg C/m^2 and 12.2 kg C/m^2 in Oxisols, Ultisols, and Inceptisols, respectively. In a study conducted in a secondary forest in the central part of Puerto Rico, Weaver et al. (1987) partitioned the area into four broad geologic associations based on geologic origin. They found that SOC content in the top 23 cm was 9.93 kg C/m^2, 7.83 kg C/m^2, and 9.06 kg C/m^2 in shallow volcanic clays, sandy granitic soils, and limestone soils, respectively, in subtropical moist forests. Beinroth et al. (2003) used soil survey information at the soil series level to estimate the amount of SOC stored in the Río Grande de Arecibo (RGA) watershed to a depth of 1 m. Their SOC watershed estimate was 4.8 $\times 10^6$ Mg of SOC, about 62% of which was contained in the top 30 cm of the soil (Beinroth et al., 2003). Some of the drawbacks associated with the above cited publications are attributed to the lack of site-specific data, and to not using the US Soil Taxonomy as a reference base, as occurs for Weaver et al. (1987).

Evaluation of soil C stocks and sequestration is usually done by using ecoregion, soil type or land management units. Because of the strong influence of climate on SOC levels, greater precision may be achieved if monitoring is conducted within regions containing similar climatic conditions as occurs at the watershed scale. We are unaware of any published study using the watershed as the study unit for site-specific evaluation of SON or SOC stocks and sequestration. Understanding how soil organic matter is affected by land use, management, and soil types is important for assessing the degree of soil C sequestration (Lal et al., 1998; Silver et al., 2000a; Lal, 2004). The objectives of this study were to assess the present state of SOC and SON distribution as influenced by discrete variables (soil classification according to Soil Taxonomy, land use, soil phase) and to provide an estimate of potential C sequestration at the watershed scale.

MATERIALS AND METHODS

Site Description

The RGA watershed has an area of 45,067 ha, with 36,500 ha having greater than 40% slopes. The watershed is located in the north central part of the island of Puerto Rico bordered by latitudes 18°11'N and 18°20'N, and longitudes 66°32'W and 66°46'W. Before the 1950s, the majority of the land area had been farmed with crops such as coffee (*Coffea* spp.), plantains (*Musa* spp.), sugarcane (*Saccharum officinarum*) and citrus (*Citrus* spp.). The areas classified as agricultural have crops such as coffee, plantains, and citrus. Currently much of the land area formerly under sugarcane has been abandoned to give place to secondary forests (Aide and Grau, 2004). The dominant species in the forest areas are *Guarea guidonia, Cecropia scherebertiana, Inga vera, Prestoea montana, Deondropanax arboreus, Didymopanax morototoni,* and *Syzigium jambos,* and had been as such for periods ranging from 15 to 40 years at the time of sampling in 2004 (Suárez-Rozo, 2005). Within the RGA watershed, there are 35 soil series within eight soil orders, which are subdivided into 79 mapping units based on slope and level of erosion (Gierbolini et al., 1979; Acevedo, 1982). The major soil orders (series in parentheses) are Ultisols (Consumo, Humatas, Lirios, Maricao), Oxisols (Los Guineos), and Inceptisols (Alonso, Múcara, Caguabo, Pellejas, Maraguez, Viví) comprising 96% of the total land area of the watershed. Most upland pedons are Oxisols and Ultisols having high clay content and acid conditions, whereas Inceptisols tend to be coarser textured.

Soil sampling strategy

Land use information was obtained from a digital version of a land use map developed in 2000 (CSA group, unpublished, 2000) using the USGS classification system (Anderson, 1976). About 5,706 ha (12.7% of the watershed) is considered non-soil (rocky outcrops, residential, commercial, streams, and lakes); 32,006 ha (71.0%) is secondary forest land; 3,776 ha (8.4%) is pasture land; and 3,579 ha (7.9%) is agricultural land. A GIS database map was created by delineating the RGA watershed, which includes all of the area south of the dam at Lago Dos Bocas reservoir. A digital version of the soil mapping units as assessed by U.S. Soil Taxonomy (Soil Survey Staff, 2004) was obtained from the Soil Survey Geographic Database (USDA-NRCS, 2001), whose boundaries were delineated as polygons within the GIS base map. The main and secondary roads were obtained from the TIGER/Line data file published by the U.S. Bureau of the Census for the United States (ESRI, 2000), and a satellite image from IKONOS (Space Imaging, LLC, 2001)[6]. The most representative soil mapping units of the watershed were identified by using the GIS-based map. A map with 18 soil mapping units (each mapping unit with a minimum area greater than 453 ha) was developed, including three units with an area of less than 453 ha (CuF2, MuF2 and PeF2) for the purpose of comparing eroded and uneroded phases. Twenty-one mapping units were sampled, representing 33,362 ha (or 74.0% of the total land area) and 39,361 ha (or 87.3% of the land area) when data were grouped by land use. This layer of information was overlapped with the layer containing the main roads.

Each soil mapping unit had several contiguous and non-contiguous polygons. On the basis of total areal extent of the soil mapping units, one pedon was sampled for approximately every 400 to 500 ha irrespective of the number of polygons (Figure 1). For example, the Pellejas series (PeF) had a total area of 7,867 ha distributed among 28 soil polygons; 23 samples were collected. Three additional samples were collected from the eroded counterpart (Table 1). Within the potential polygon to be sampled, there were state and municipal roads that intersected. Each segment of the road that coincided with the polygon to be sampled had kilometer markings. The specific sampling point within the polygon was selected at random from the pool of numbers that corresponded to the kilometer markings of the roads. To avoid the disturbance effect of near-road activities and to make sure the intended

[6]Company and trade names in this publication are used only to provide specific information. Mention of a company or trade name does not constitute a warranty of equipment or materials by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials.

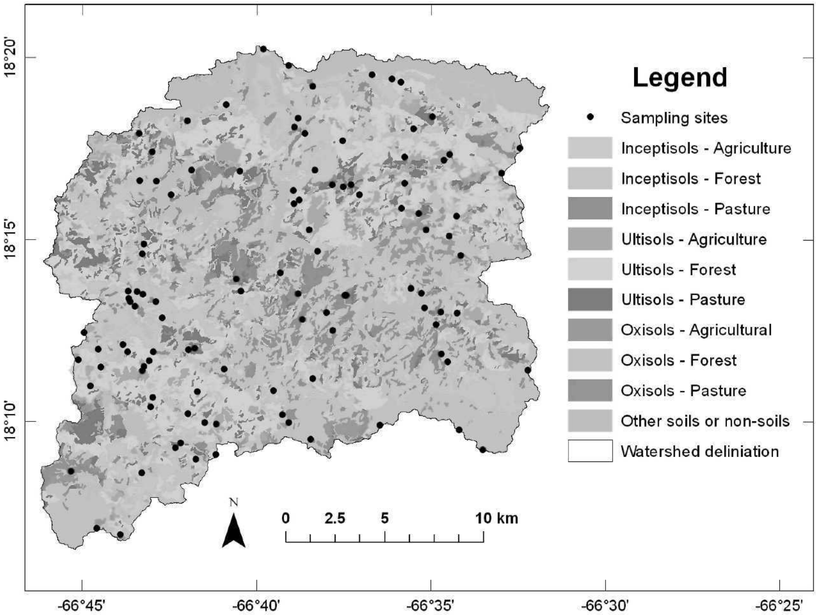

FIGURE 1. Spatial distribution of sampling sites including soil order and land use polygons.

soil polygon was sampled, the sampling area was from 25 m and 100 m from trafficable roads. The geographic coordinates of each sampling site were taken with a Global Positioning System (GPS) (Model Trimble Pro XR, Trimble Inc. Sunnyvale, CA) with sub-metric resolution. Soil samples were collected by using an auger at 0- to 15-, 15- to 30-, 30- to 50-, 50- to 75-, and 75- to 100-cm depths, or to a lithic or paralithic contact if it was shallower. A total of 107 pedons and 524 soil samples were collected for analysis with the number of samples distributed proportionally to the area of the 21 mapping units (Table 1).

Soil chemical and physical analyses

Soil samples were air-dried and gently sieved to pass through a 2-mm sieve to remove rock fragments and coarse roots. Soil total C and N concentration in ground soil subsamples (<0.05 mm fraction) were quantified by automated dry combustion by using a LECO C and N analyzer (Leco Corp., St. Joseph, MI) at the Soil, Plant and Water Laboratory of the College of Agricultural and Environmental Sciences, University of Georgia. Carbon concentrations were converted to total

TABLE 1. *Number of samples taken by soil series and mapping units within the Río Grande de Arecibo watershed.*

Soil Series	Soil Order	Soil mapping unit	Area (ha)	Number of pedons	Number of samples
Alonso	Inceptisol	AoF2	766	3	14
Caguabo	Inceptisol	CbF2	756	3	14
Maraguez	Inceptisol	MaF2	2283	4	20
Mucara	Inceptisol	MuF	1658	4	20
Mucara	Inceptisol	MuF2	207	3	15
Pellejas	Inceptisol	PeF	7867	23	111
Pellejas	Inceptisol	PeF2	262	3	15
Viví	Inceptisol	Vm	533	1	5
Los Guineos	Oxisol	LgF	2034	4	20
Los Guineos	Oxisol	LgE	713	2	10
Los Guineos	Oxisol	LuF	657	2	10
Los Guineos	Oxisol	LME	1301	3	15
Los Guineos	Oxisol	LyFx	560	2	10
Consumo	Ultisol	CpF	518	3	15
Consumo	Ultisol	CuF2	66	3	15
Humatas	Ultisol	HmF	5203	16	79
Humatas	Ultisol	HmF2	2498	10	48
Humatas	Ultisol	HmE	495	3	14
Humatas	Ultisol	HmE2	470	3	15
Lirios	Ultisol	LcF2	4005	9	45
Maricao	Ultisol	MkF2	770	3	14
		Total	33,622	107	524

content per square meter based on sampling interval depth and soil bulk density as reported by the Soil Survey Staff (2004). Each layer was calculated separately and integrated over depths of 0 to 15, 0 to 30 and 0 to 100 cm. Soil pH was measured on the supernatant of the <2 mm soil fraction using 1:2 soil:water mixtures, after shaking for one hour and separating the soil-water mixture by centrifugation. The mean pH of the soils ranged from 3.8 to 6.9. No evidence of calcium carbonate was found; thus the totality of the quantified carbon was organic in nature. Soil particle distribution was determined for 0- to 15-cm depth intervals by using a laser diffraction particle size analyzer (x-values) (Model LS-230, Beckman-Coulter Inc., Fullerton, CA) and converted to values quantified by using the pipette method (y-values) (Soil Survey Staff, 1996) with the regressions:

$$y(\text{clay}) = 0.688x + 13.5;\ r^2 = 0.92 \qquad [1]$$

$$y(\text{sand}) = 0.851x + 0.788;\ r^2 = 0.94 \qquad [2]$$

which were determined empirically from selected samples.

Spatial variability and statistical analysis

Spatial distribution maps of the SOC and SON content were prepared by using ArcMap v. 8.2 (ESRI, Redlands, CA). The intersection of mapping unit, land use and soil order and their combinations was delineated. Each of the polygons (mapping unit, soil order or land use) received the same SOC and SON value that corresponded to mean values for each factor. We used the data from Suárez-Rozo (2005) to evaluate the effect of soil order on C associated with above-ground biomass of forest vegetation of the RGA watershed. The above-ground biomass C data was grouped a posteriori, because it had been classified on the basis of life-zones and geological units. An analysis of variance (ANOVA) on the effects of soil order on above-ground biomass C was performed by using a completely randomized design.

An ANOVA was performed to determine the effects of soil classification on C and N stocks as stratified by soil order and land use. The statistical design was a completely randomized design with soil order and land use as main effects. The effect of depth was included when evaluating C and N concentration variation in the soil profile. The number of replicates for each order/land use varied proportionally with the land area of each of the effects. To compare eroded and uneroded soil phases we used Student's t-test. All statistical analyses were performed with InfoStat V3.0.2. (Universidad Nacional de Córdova, Argentina) using a significance level of $P \leq 0.05$. A multiple regression model was constructed to examine the effects of categorical variables (land use, soil order, soil moisture regime, and mineralogy) and continuous variables (elevation, soil pH, and silt+clay proportion) on SOC using proc mixed of SAS (SAS Institute, Cary, NC). The model was constructed by selecting variables using stepwise procedure adapted for mixed type variables (categorical and continuous).

RESULTS

Soil organic carbon and nitrogen concentrations

Soil organic C and SON concentrations were affected ($P < 0.05$) by land use x depth and soil order × depth interactions. Greater SOC and SON concentrations were generally observed at the top of the soil profile, and values generally decreased with depth (Figure 2). The SOC concentrations were generally in the order of Oxisol > Ultisol > Inceptisol (Figure 2a), and SON concentrations were Oxisol = Ultisol > Inceptisol (Figure 2b). When evaluating the effects of land use on SOC and SON, concentrations at 0- to

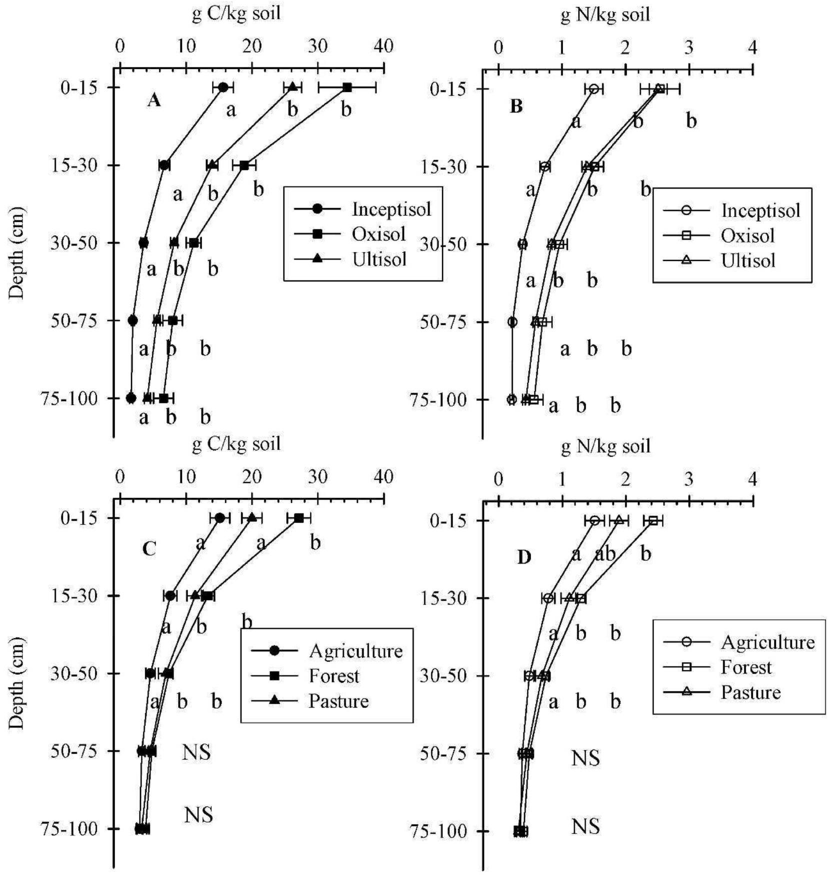

FIGURE 2. Concentration depth profiles of soil organic carbon as affected by soil order (A) and land use (C); and of soil organic nitrogen as affected by soil order (B), and land use (D). Horizontal error bars represent standard errors. Soil order or land use within a depth with different letters are significantly different at $P < 0.01$. NS denotes non-significance.

15- and 15- to 30-cm depths were greater in forest than in pasture, with similar values among pasture and agriculture. Land use did not affect SOC and SON concentrations at greater depths (Figures 2c and 2d).

Soil organic carbon and nitrogen content as influenced by soil order and land use

The SOC and SON contents were significantly influenced by the main effects of soil order and land use ($P < 0.05$), but not by their interaction (Table 2). At 0- to 15- and 0- to 30-cm depths, SOC and SON contents were greater in Oxisols and Ultisols, and both orders had higher values than Inceptisols. At 0- to 100-cm depth, Oxisols had higher SOC levels than Ultisols, with values of 18.3 and 13.3 kg C/m^2, respectively, values which in turn were higher than those of Inceptisols (6.71 kg C/m^2). At 0- to 100-cm depth, SON was highest in Oxisols and Ultisols, with lowest values in Inceptisols.

Soils under agricultural land use had significantly lower mean SOC contents (7.90 kg C/m^2) than pasture (9.79 kg/C m^2) and forest (12.8 kg C/m^2) soils, with no significant difference between the latter two land uses at 0- to 100-cm depth. Similar trends were observed with SON contents. Soils under pasture and agriculture at 0- to 15-cm depth had similar SOC and SON contents, but lower values than those of soils under forest. The SOC quantified by us in eroded and uneroded phases (as mapped by USDA-NRCS Soil Survey) were not significantly different ($P > 0.05$), except in the Consumo soil series (15.4 vs. 9.8 kg C/m^2) ($P < 0.05$). Alvarado (2006) has developed quantitative relationships between SOC in surface soil and that at greater depths as classified by soil order or life zones, for the purpose of improving C accounting in soils. When data at greater depths are not available in the RGA watershed, quantification of SOC and SON to a depth of 0 to 15 cm within any land use or soil order can be used to estimate SOC and SON to a depth of 100 cm based on the following equations:

$$SOC_{1m} = 0.290 \times SOC_{15cm} + 0.975; r^2 = 0.659 \qquad [3]$$

$$SON_{1m} = 0.275 \times SON_{15cm} + 1.10; r^2 = 0.610 \qquad [4]$$

Soil organic carbon and nitrogen distribution within the RGA watershed

The GIS layers of soil order and land use each had three experimental units associated with the analysis, whereas mapping unit and mapping unit x land use had 22 and 40, respectively (Table 3). The area represented in the analysis decreased in the order of land use, soil order, mapping unit and mapping unit × land use, with area-wide SOC and SON stocks concomitantly following these trends. The intersection of the mapping unit and land use layers represented an area of 31,307 ha

TABLE 2. *Soil organic carbon and soil organic nitrogen among different soil orders and land uses within the RGA watershed. Values within a main effect with different letters are significantly different ($P < 0.05$). Standard deviations are in parenthesis.*

	SOC (kg C/m^2)			SON (kg N/m^2)		
Main effect	0-15 cm	0-30 cm	0-100 cm	0-15 cm	0-30 cm	0-100 cm
			Soil Order			
Oxisol	5.85 (2.4) a	9.8 (3.5) a	18.29 (5.9) a	0.46 (0.2) a	0.78 (0.3) a	1.51 (0.6) a
Ultisol	4.77 (1.6) a	7.64 (2.5) a	13.30 (4.5) b	0.45 (0.1) a	0.74 (0.2) a	1.32 (0.4) a
Inceptisol	3.18 (1.9) b	4.51 (2.5) b	6.71(3.7) c	0.31 (0.1) b	0.45 (0.2) b	0.7 (0.3) b
			Land Use			
Forest	5.02 (2.2) a	7.72 (3.4) a	12.80 (2.3) a	0.45 (0.2) a	0.71 (0.3) a	1.21 (0.5) a
Pasture	3.78 (1.2) b	6.16 (2.6) a	9.79 (1.2) a	0.36 (0.1) b	0.59 (0.2) a	1.04 (0.5) a
Agriculture	2.81 (1.3) b	4.4 (2.4) b	7.90 (4.9) b	0.28 (0.1) b	0.44 (0.2) b	0.83 (0.5) b

TABLE 3. *Watershed based cumulative and mean values of soil organic carbon (SOC) and soil organic nitrogen (SON) contents in the Río Grande de Arecibo watershed.*

Layers	Area represented	n	Stocks		SOC content mean values		SON content mean values	
			C	N	0-15 cm	0-100 cm	0-15 cm	0-100 cm
	ha		- - - - - x10^6 Mg - - - - -		- - - - -kg C/m^2 - - - - -		- - - - - kg N/m^2 - - - - -	
Map unit	33,622	21	3.61	0.35	4.13	10.84	0.38	1.05
Map unit*land use	31,307	40	3.48	0.34	4.33	11.13	0.39	1.08
Soil Order	37,779	3	4.15	0.40	4.21	10.99	0.38	1.05
Land use	39,361	3	5.02	0.48	4.63	12.45	0.42	1.18

or 69.5% of the total land area, which is less than the area represented only by mapping units, soil order, or land use. When the intersection of mapping unit and land use layers was performed, areas corresponding to mapping units not sampled were not included, but there is greater detail in the SOC spatial distribution. The latter will lead to a greater variation in the range of values and improved accuracy in the geographic estimate. For example, at the upper eastern part of the watershed, the SOC content varied between 3.50 and 6.00 kg C/m^2 when considering only mapping unit, and from 2.76 to 6.80 kg C/m^2 when incorporating land use information with mapping unit. Since the map with the greatest resolution will undoubtedly leave some areas out of the analysis, watershed-based cumulative estimates of SOC and SON stocks should use the layering which will include the greatest land area (land use effect), but will result in the lowest accurate estimate (Figure 3). In contrast, if the user is interested in obtaining spatially based watershed SOC and SON estimates, the mapping unit × land use intersecting layering should be used (Figure 4).

The mapping unit x land use area-weighted mean SOC and SON content was 4.33 kg C/m^2 and 0.390 kg N/m^2 for 0- to 15-cm depth, respectively, whereas for 0 to 100 cm it was 11.13 kg C/m^2 and 1.08 kg N/m^2, respectively, and represents the best area-wide mean estimate. The land area of 39,361 ha (or 87.4% of the total watershed area) contains 5.02×10^6 Mg of SOC and 0.48×10^6 Mg of SON to a depth of 0 to 100 cm. Bernoux and Volkoff (2006) estimated soil carbon stocks for Puerto Rico at 93×10^6 Mg. Although the RGA watershed accounts for 4.4% of the total land area of Puerto Rico, its soils hold 5.6% of the C content of Puerto Rico.

DISCUSSION

Beinroth et al. (1992) reported that SOC to 100-cm depth in Oxisols of Puerto Rico was 14.0 kg C/m^2, 12.8 kg C/m^2 in Ultisols, and 12.2 kg C/m^2 in Inceptisols, without considering the effects of land use. Our SOC measurements in the RGA watershed are greater for Oxisols, lower than those for Inceptisols, but similar to those of Ultisols estimated by Beinroth (1992), who used data from 167 pedons collected throughout Puerto Rico. Furthermore, our site-specific values are generally higher than the overall mean values of 10.9 kg C/m^2 reported by Beinroth et al. (2003). The higher SOC and SON contents at 0- to 15-cm depth of highly weathered Ultisols and Oxisols, as compared to less weathered Inceptisols, are in accordance with previous trends of enzyme activities which have been linked to improved soil quality in the RGA watershed (Acosta-Martínez et al., 2007).

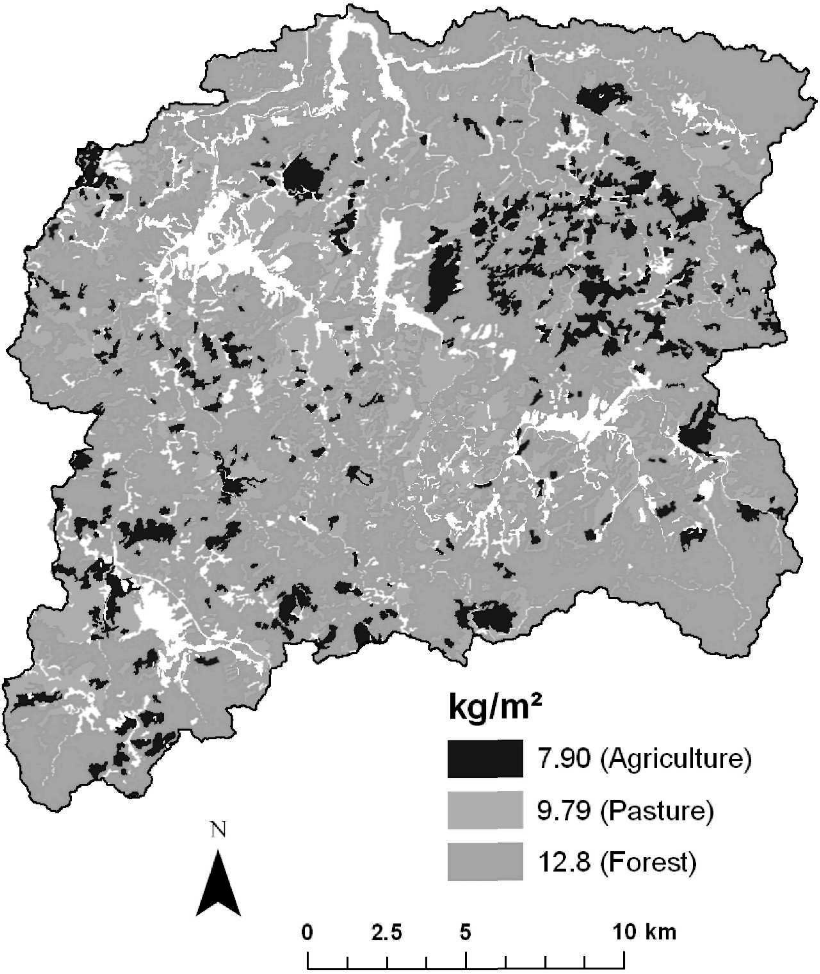

FIGURE 3. Soil organic carbon content (kg C/m^2, 0 to100 cm) by land use layering in the Río Grande de Arecibo watershed.

One of the classification factors used to evaluate the spatial variation in SOC and SON was the soil order level using US Soil Taxonomy. Our results do not imply that soil order is the major driving factor influencing SOC and SON. Soil order has been found to be useful as a classification factor for policy considerations in C accounting and in global estimates, since soil boundaries delineated by soil order are widely available (USDA-NRCS, 2001; Alvarado, 2006). Soil order, land use and

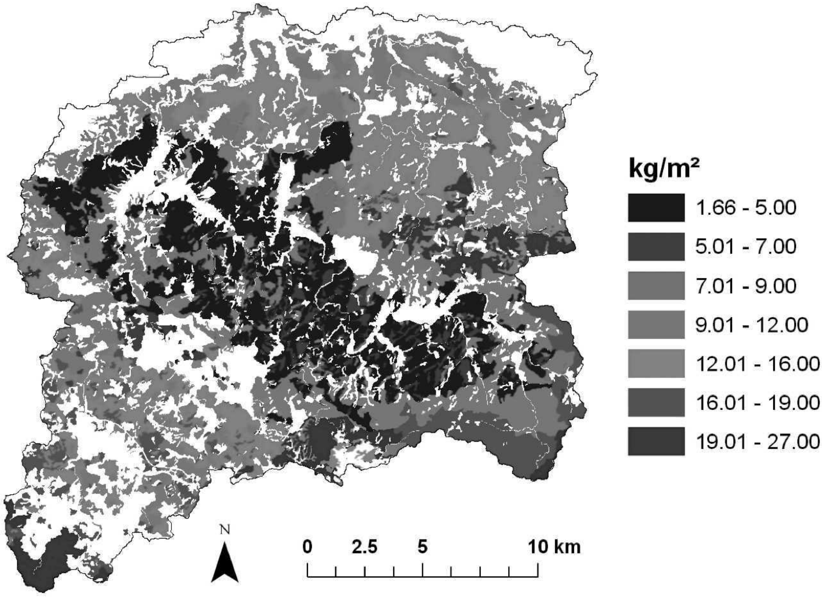

FIGURE 4. Soil organic carbon content (kg C/m^2, 0 to100 cm) by mapping unit*land use layering in the Río Grande de Arecibo watershed.

soil moisture regime have been found to account for 50% of the variability in whole-profile SOC (Beinroth et al., 1996). The general conditions that enhance the formation of soils lead to the presence or absence of major diagnostic horizons which are often used as classification criteria. The diagnostic properties at the order level are probably not what controls soil organic matter in the watershed, but rather geomorphology, mineralogy, and particle size distribution, which in turn influence the diagnostic horizons. Although we did not evaluate geomorphology as a factor, Cruz (2004) found that north-facing slopes and soils within the toe-slope position of the landscape of the RGA watershed tended to have higher SOC and SON at 0- to 15- and 0- to 100-cm depths than other parts of the landscape.

In the RGA watershed, about 63% of the soils originate from volcaniclastic rocks of andesitic and basaltic composition giving rise to Ultisols and Oxisols; 31% of the soils are plutonic of quartzdiorite and granodiorite composition, giving rise primarily to Inceptisols (Beinroth et al., 2003; Suárez-Rozo, 2005). The subtropical wet forest ecological life zone (Holdrige, 1967) covers about 77% of the RGA land area whereas subtropical moist forest covers about 15% of the area. Suárez-Rozo

(2005) did not find above-ground forest biomass to be influenced by rock formation type or ecological life zone. Our further analysis of the data gathered by Suarez-Rozo (2005) reveals that all soil orders have similar forested biomass C with mean values (standard deviation in parenthesis) of 3.44 (± 2.39), 3.48 (± 0.941), and 3.62 (± 1.69) kg C/m^2 for Oxisols, Ultisols and Inceptisols, respectively. If we assume that there are similar C inputs among forested areas (based on above-ground biomass), then the variation in soil C among soil orders was due to soil properties influencing decomposition, properties which include moisture and temperature, soil texture, aggregate size distribution, and soil mineralogy.

Precipitation and temperature are two properties that reflect soil development, causing in most instances diagnostic horizons and other major characteristics which can be used as a basis for soil order classification. Since we did not have site-specific data of precipitation and temperature, elevation could serve as a proxy. We tested a multiple regression model controlling for land use and soil order that included the combination of soil moisture regime, mineralogy, elevation, soil pH, and silt+clay. The interactions of the variables were not found to be significant ($P < 0.05$). Soil moisture regime and mineralogy were not significant when these were included in the model in combination with soil order. Elevation and soil pH were important predictors of SOC if the effect of silt+clay was not included in the model, but not if silt+clay was present. Elevation was always an important factor in the model. Because SOC to 1-m depth was similar in forest and pasture soils and in Ultisols and Oxisols, these were combined as separate groups. Our data demonstrates that with prior knowledge of soil order and land use combinations, elevation and soil silt+clay proportion can be used as predictors of SOC to depths of 15 and 100 cm in the RGA watershed (Table 4). For example, a 100-m change in altitude with a fixed clay content will result in a SOC change of 0.811 kg C/m^2 at a constant silt+ clay content; and a unit change of 1% in soil silt+clay at a constant elevation will result in a SOC change of 0.268 kg C/m^2 to a depth of 100 cm.

Ultisols and Oxisols had similar silt+clay contents (mean of 78.0%), which were higher than that for Inceptisols within their corresponding land use ($P < 0.05$). Land use did not influence soil silt+clay content. Over 60% of the area covered by Inceptisols in the watershed corresponds to Pellejas series, which have a fine-loamy over sandy texture. In contrast, Ultisols and Oxisols tend to have clayey or clay-loam texture, and are primarily dominated by kaolinite clay, goethite and gibbsite (Beinroth, 1971; USDA-NRCS, 2007) which in combination are known to influence soils to have a high degree of aggregate stability (Schwertmann and Herbillon, 1992). Ultisols were found to have increased large macro-aggregate stability, and higher SOC concentra-

TABLE 4. *Regression equations from the multiple regression model predicting SOC to a depth of 1 m in the Río Grande de Arecibo watershed.*

Dependent variable	Soil	Landuse	Equation[1]
SOC_{1m}[2]	Inceptisol	Agriculture	0.811 x ele + 0.268 × silclay - 15.98
	Inceptisol	Forest and pasture	0.811 x ele + 0.268 × silclay - 13.02
	Ultisol and Oxisol	Agriculture	0.811 x ele + 0.268 × silclay - 13.24
	Ultisol and Oxisol	Forest and pasture	0.811 x ele + 0.268 × silclay - 10.28
SOC_{15cm}[2]	NS[3]	Agriculture	0.335 x ele + 0.100 × silclay - 5.79
	NS	Forest	0.335 x ele + 0.100 × silclay - 5.45
	NS	Pasture	0.335 x ele + 0.100 × silclay - 4.78

[1]ele is elevation x 100 m; silclay is the soil silt+clay content.
[2]The r^2 for SOC_{1m} was 0.672 and for SOC_{15cm} it was 0.60.
[3]NS, the term was not significant ($P < 0.05$).

tions than Inceptisols (Sotomayor-Ramírez et al., 2010). We hypothesize that the increased aggregate stability of Oxisols and Ultisols may account for enhanced C protection within aggregates and increased SOC (Feller and Beare, 1997; Six et al., 2000; Denef et al., 2004).

The Oxisols from the RGA watershed are classified as Humic Hapludox according to the Soil Taxonomy (Soil Survey Staff, 1999), all of which implies that they should have SOC levels of 16 kg/m^2 to 100-cm depth. Our SOC measurements to 100 cm for Oxisols are higher than those reported by Beinroth et al. (1992) (mean of 14.0 kg C/m^2) using soil survey data, and also for Udic and Ustic Oxisols of the Amazon region under undisturbed forest vegetation (range of 8.9 to 10.51 kg C/m^2) (Morales et al., 1995). The higher values found for Udic Oxisols in our study suggest that other properties not diagnostic at the order level of Soil Taxonomy, possibly texture and mineralogy (although not detected in the multiple regression model), are an important influence in SOC storage. About 60% of the soil area classified as Oxisols in the RGA watershed is under secondary forest vegetation, and our results are in accordance with SOC estimates by Johnson and Kern (2003) for Oxisols dominated by forest vegetation in Puerto Rico.

Soils under pasture and agriculture at 0- to 15-cm depth had similar SOC and SON contents but had significantly lower ($P < 0.05$) values than those under forest. In contrast, SOC and SON were similar under pasture and forest to a depth of 100 cm ($P > 0.05$). In the RGA watershed, soils under pasture had previously been under agricultural land use and are in the process of reverting to a more stable ecosystem such as forest if kept unmanaged. Puerto Rico has one of the highest rates of forest regeneration in the world (Aide and Grau, 2004), and pasture soils could potentially be accumulating additional C as succession to forest-land occurs. Torbert et al. (2004) observed similar values of SOC between forested soil and permanent pasture in clay loam soil to 1-m depth. In contrast, Cerri et al. (2003) modeled the impact of converting a Brazilian forest area to pasture on SOC content, and found an initial decrease in the SOC stock followed by a slow rise. After 88 years, pasture soil contained 53% more C than the forest soil. The observed reduction in the SOC content of agricultural soils could be related to aggregate disruption during cultivation, and increased erosion as cultivated soils tend to have less vegetative cover. Sotomayor-Ramírez et al. (2010) reported that the macroaggregate (>2,000 µm-size class) proportion decreased whereas small macroaggregates and large microaggregates increased (250- to 2,000- and 50- to 250-µm aggregate size classes) in soils under agriculture; SOC concentrations within aggregates were similar among aggregate size classes but were lower than those under forest. These results support studies summarized by Lal

(2004), that changes in land use cause losses of SOC because of changes in vegetation and soil management practices.

The potential SOC levels for a given geographic location and climate are reached when "reducing" factors are minimized and are controlled by the silt + clay content and aggregate formation (Ingram and Fernandes, 2001; Chevallier et al., 2004; Denef et al., 2004; Plante et al., 2006). Macroaggregate-associated C is most susceptible to losses due to reducing factors such as cultivation, residue removal, and tillage. Silt+clay-associated C is the most susceptible to losses due to erosion (Ingram and Fernandes, 2001). If the factors limiting the actual capacity of soils to sequester C are alleviated by some sort of practice, then the soils can increase their C content to an "attainable" C level, which in turn will be limited by climate and primary productivity. Beinroth et al. (2003) based their estimate of the potential SOC sequestration of the watershed on the premise of restoration of eroded phases to their original level of organic matter. Although eroded soils account for 39% of the watershed, we did not find significantly lower SOC and SON contents in eroded phases, except in Consumo soil series, for which the eroded phase is less than 100 ha.

We hypothesize that soils under forested vegetation are near the current maximum C sequestration potential for each of their corresponding soil mapping units. Forest soils cover about 81.3% of the surveyed area and account for 84.3% of the total C of the watershed. Within each soil order, the maximum C potential could be reached solely by reverting pasture and agricultural lands to forested land use or planting high biomass-yielding crops such as environmental cane (*Saccharum spontaneum*). Assuming that only about 50% of the land area under pasture and agriculture, or about 3,523 ha, is converted to forested land, an additional amount of 46,627 Mg of C could be sequestered. This amount represents a modest 1.0% increase above the current level. We estimate that at soil C accumulation rates ranging from 210 to 1,300 kg C/ha/yr (Silver et al., 2000a), it would take from 10 to 32 years for the managed lands reverted to forest to reach maximum C levels.

CONCLUSIONS

The spatial distribution maps of SOC and SON in the RGA watershed describe the spatial variation in present-state soil C and N storage and serve as a baseline for the future evaluation of the effects of land-use changes on SOC sequestration. Soils under forest and pasture, and soils classified as Oxisols and Ultisols, store the majority of soil organic matter. Elevation and soil texture (using the silt+clay proportion) were important predictors of SOC within specific soil order and landuse combinations. The maintenance of present state SOC in unmanaged forested areas or improving soil C storage in managed sites such as agriculture can be achieved through formation and preservation of soil macroaggregates. However, coarser-textured Inceptisols will be limited in their capacity to form macroagregates and hence store SOC because of reduced soil specific surface area. As a management option, it is important to continue the implementation of best management practices on erodible soils, especially on agricultural lands. The extent of C storage in the RGA watershed should be similar to that of other watersheds of comparable geology, ecological life zones and land use in the Caribbean.

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