SOIL ORGANIC CARBON AND NITROGEN DISTRIBUTION IN A TROPICAL WATERSHED

By

Lionel Cruz-Rodríguez

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Soils

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2004

Approved by:

________________________ ____________

Fred H. Beinroth, Ph.D. Date
Member, Graduate Committee

________________________ ____________

Luis R. Pérez-Alegría, Ph.D. Date
Member, Graduate Committee

________________________ ____________

David Sotomayor-Ramírez, Ph.D. Date
President, Graduate Committee

________________________ ____________

Dimaris Acosta-Mercado, Ph.D.
Representative of Graduate Studies Date

________________________ ____________

Winston de la Torre, Ph.D. Date
Department Director

Abstract

The role of soils in sequestering atmospheric carbon (C) and nitrogen (N) can best be understood from a watershed perspective because the multiple influences of factors influencing the process can be assessed simultaneously, within a hydrologic unit. It is important to identify land uses and management practices that maximize soil carbon sequestration and help a meliorate the effects of CO_2 emissions to the atmosphere. The spatial distribution and the effects of soil order, land use and soil phase on the total soil organic carbon (SOC) and soil organic nitrogen (SON) content were assessed in the Río Grande de Arecibo watershed in Puerto Rico (RGA). A Geographical Information System (GIS) was used to develop the sampling strategy. Soil samples were taken at five depth increments (0-15, 15-30, 30-50, 50-75, 75-100 cm) from 21 soil series under diverse land use types within the watershed. Spatial distribution maps of SOC and SON according to mapping units, soil orders and land use types were generated. The mapping unit area-weighted mean SOC content was 4.15 kg C m^{-2} and 10.9 kg C m^{-2} in the 0-15 cm and 0-100 cm depths, respectively. In general, the soils sampled in the watershed (33,322 ha or 84% of the total land area) contain 3.98 x 10^6 Mg of organic C and 0.38 x 10^6 Mg of organic N to depth from 0 to 100 cm. The area-weighted mean SON content was 0.372 kg N m^{-2} and 1.05 kg N m^{-2} for the 0-15 and 0-100 cm, depths respectively. Forest and pasture soils contained higher amounts of SOC (12.8 and 9.79 kg C m^2, respectively) ($P<0.05$) than soils under cultivation (7.90 kg C m^{-2}) for the 0-100 cm depths. The SOC was significantly different ($P<0.05$) among soil orders in the 0-15cm depth (Oxisols and Ultisols > Inceptisols) and in the 0-100 cm depth (Oxisols > Ultisols > Inceptisols). These results allow a better understanding of the impacts of land use on soil C and N stocks at the watershed level.

Resumen

Es importante identificar los usos de terreno y las prácticas de manejo que maximizan la fijación del carbono orgánico del suelo que a su vez ayudan a minimizar el efecto de emisiones de CO_2 a la atmósfera. En este estudio se determinó la distribución espacial y el contenido carbono orgánico del suelo (COS) y nitrógeno orgánico del suelo (NOS) en la cuenca del Río Grande de Arecibo en la parte norte-central de Puerto Rico. Como estrategia para el muestreo del COS y NOS se desarrolló un Sistema de Información Geográfico (SIG) utilizando varias capas de información relevante. Se muestrearon 21 unidades de mapeo bajo diferentes usos de terreno y a cinco profundidades: 0-15, 15-30, 30-50, 50-75, 75-100 cm. El promedio del COS ponderado por el área de mapeo para toda la cuenca fue 4.15 kg C m^{-2} y 10.9 kg C m^{-2} en 0-15 cm y 0-100 cm de profundidad, respectivamente. El promedio del SON ponderado para toda la cuenca fue 0.372 kg N m^{-2} y 1.05 kg N m^{-2} en 0-15 y 0-100 cm de profundidad, respectivamente. Los suelos bajo cobertura de bosque y pastos tienen un contenido de COS significativamente más alto ($P<0.05$) (12.8 y 9.79 kg C m^{-2}, respectivamente) que los suelos agrícolas (7.90 kg C m^{-2}) a 0-100 cm de profundidad. El COS fue significativamente diferente ($P<0.05$) entre los ordenes de suelo (Oxisoles y Ultisoles > Inceptisoles) a 0-15 cm de profundidad, y entre Oxisol > Ultisol > Inceptisol a 1 m de profundidad. Como resultado se obtuvo que el 84% de los suelos de la cuenca tiene 3.98 x 10^6 Mg de C orgánico y 0.38 x 10^6 Mg de N orgánico a la profundidad de 0 a 100 cm. Estos resultados ayudan a entender el impacto del uso del terreno en la cantidad de C y N a nivel de una cuenca hidrográfica.

Dedication

Dedicated to my parents, Rafael Cruz Santiago and Elena Rodriguez Muñiz, my brother Rolando, my sister Damarys, my girlfriend Leslie Santiago and to my nephew Sebastián.

Acknowledgements

I would like to thank the professors of my committee, Dr. David Sotomayor, Dr. Fred Beinroth and Dr. Luis Pérez-Alegría for their support and guidance on this project. Thanks to the NASA–URC, Tropical Center for Earth and Space Studies (TCESS) for providing financial graduate assistantship within the project "Atmospheric Carbon Sequestration in Tropical Watershed."

I would also like to thank all personnel in the Agriculture and Biosystem Engeneering Department, Yesennia Gonzalez, Jessica Alcover, Willian Lozada and Ramón Ortíz for their help and support throughout my studies. I would also like to thank all undergraduate students that helped in the field sampling, particularly Edwin Martinez, Dewell Páez, Omar Acevedo, Kevin Torres, Jacqueline Vega and Angélica Alvarado. I also like to thank María del Rocío Suárez and project colleagues for their help and good times through our work in the field and the office.

In addition, I appreciate and thank Dr. Verónica Acosta-Martínez and Dr. Ted Zobeck for their support in particle size analysis and the opportunity given to me to conduct research in the USDA-ARS laboratory in Lubbock, Texas.

Table of Contents

List of Tables

List of Figures

Appendices

1. Introduction

Recent environmental concerns have stimulated interest in world-wide estimates of soil organic carbon (SOC) and soil organic nitrogen (SON) sequestration. Although these estimates have been generally derived from national resource inventory, there is little knowledge about soil carbon pools in tropical watershed. This information can improve our knowledge about carbon dynamics and their spatial distribution. The objective of estimating carbon and nitrogen pools at a watershed level is to gain a better understanding of how the SON and SOC is distributed across the watershed area according to land use and soil type, and how we can use the results to develop management practices that are conducive to improve the watershed conditions as a carbon sink. In addition, the spatial distribution of the SOC and SON are important requirements for understanding the role of soils in the global C cycle. Our capacity to predict and ameliorate the consequences of climate and land use changes depends, in part, on baseline description of SOC and SON distributions and the management practices that control the SOC and SON inputs and outputs (Jobbagy and Jackson 2000).

The Río Grande de Arecibo (RGA) watershed is one of the most ecologically important watersheds in Puerto Rico, since it continuously supplies potable water to the capital city, San Juan. Little is known about the soil properties, environment moderation capacity (water, air and soil quality), and the potential for soil carbon (C) and nitrogen (N) storage in the RGA watershed. This information is important because adequate soil organic matter levels can help improve soil water and nutrient-retention capacity, structural stability, infiltration rates, and also can decrease runoff and soil erosion (Lal, 2002). Adequate land use and management plans that include soil C and N conservation within the RGA watershed can help to maintain the quality of water production system as well as to increase soil C sequestration in tropical areas. The first approach to accomplish this objective is to quantify soil C and N stocks and their distribution at the watershed level.

Carbon sequestration implies transferring atmospheric CO_2 into stable terrestrial or marine pools and storing it securely so it is not immediately re-emitted (Lal, 2004). Soil C sequestration typically involves increasing soil organic carbon (SOC) and soil inorganic carbon (SIC) stocks through judicious land use and recommended best management practices (BMPs) (Lal, 2004). Net losses of SOC and soil organic nitrogen (SON) due to land use changes may occur as the result of decreased organic residue inputs and changes in plant litter composition and increased rates of soil organic decomposition and soil erosion (Lugo and Brown, 1993). Depletion of SOC degrades soil quality, reduces biomass productivity, and adversely impacts water quality. Moreover, it is hypothesized the C depletion may be exacerbated by global warning (Lal, 2004).

The main focus of this research was assess the effects of land use, soil order and soil phase on to SOC and SON stocks and their distribution within the RGA watershed. This information can provide a base-line level understanding about the role that a tropical watershed can play in sequestering atmospheric CO_2.

2. Objectives

The general objective of this project is to develop a base-line knowledge on the status of soil carbon and nitrogen in a tropical watershed that could be later used for the development of appropriate watershed management plans. The specific objectives of this thesis are to:

1. Quantify SOC and SON stocks in the Río Grande de Arecibo watershed.
2. Assess the distribution of the SOC and SON as stratified by soil type and land use.
3. Determine if and how soil organic carbon and soil organic nitrogen are affected by soil type, soil phase and land use in the watershed.

3. Literature Review

3.1 Overview of the global carbon and nitrogen cycles

Atmospheric CO_2 concentrations have seen increasing since the 1870 (Burke and Lashof, 1990). This has occurred primarily by burning of fossil fuels in industrialized countries and reduces C storage in soil and vegetation. The Kyoto protocol of 1997 and its later international commitments such as the Rio Declaration on Environment and Development proposed that C reduction could take place by decreasing fossil fuel emissions, or by accumulating C in vegetation and in soils of terrestrial ecosystems (United Nations, 1992). Soils of terrestrial ecosystems are valuable C reservoirs, since the capacity of soils to store and maintain the C pool in the long run is generally thought to be greater than that of the vegetation (Silver et al., 2000a). Atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) can be lowered by reducing emissions or by transferring CO_2 from the atmosphere via photosynthesis and sequestering it in different components of terrestrial, oceanic, and freshwater aquatic ecosystems (Kimble et al., 2001).

Soil C storage is an important pool of the global C cycle (Lal, 2002). The global C cycle is presented in Figure 1 which describes the different C reservoirs and the C flows or fluxes between them. In the context of global warming and C sequestration, the primary interests are C reservoirs in the atmosphere, land plants and soil, and in the mass flows of C between these reservoirs.

In this cycle, a global C pool of 25000 gigaton (Gt) includes about 1580 Gt of SOC and 950 Gt SIC (Lal, 2004). The SOC pool is the largest terrestrial C pool and important in the long term sustainability of soil and life on earth. It is double the size of the atmospheric pool (750 Gt) and 3 times the size of the C storage in plants (610 Gt) (Lal. 2004). Small changes in such a large C pool would have a significant impact on the global climate system. The SOC pool to 1-m depth rages from 30 x Mg/ha in arid climates to 800 Mg/ha in organic soils in cold regions, and a predominant range of 50 to 150 x Mg/ha (Lal, 2004).

Nitrogen is essential for all living cells and is the major component of the earth's atmosphere (78 % N_2). It is an essential nutrient for both, plant growth and development and usually the limiting nutrient for plant production. More than 90% of the total N in most soils is in the organic form. Organic N in soils occurs as proteins, amino acids, amino sugars and others complex N compounds. Organic soil N is not available to plants until it is mineralized into inorganic forms such as NH_4^+ and NO_3^- for plant uptake (Halvin et al., 1999). Global estimates of N in soils are 63-67 Gt and 133-140 Gt for the first 30 cm and 100 cm depths, respectively (Batjes and Dijkshoorn, 1999). It enters the food chain (Figure 2) by means of nitrogen-fixing bacteria, algae, atmospheric deposition (lightning, rainfall) and fertilization in the soil.

The C and N cycles are linked in such a way that soil C storage requires inputs of N. The rate and magnitude of stable N retention may also have implications for stable C sequestration in soils (Kaye et al., 2002). Most mechanisms that promote stable N formation also stabilize soil C. For example, organic N, NH_4^+, and NO_2^- can react directly with soil organic C to form complex molecules (humus) (Kaye et al., 2002). In addition the NH_4^+ fixation by clay minerals, NH_3 and NO_2^- react chemically with organic matter to form stable organic N complexes.

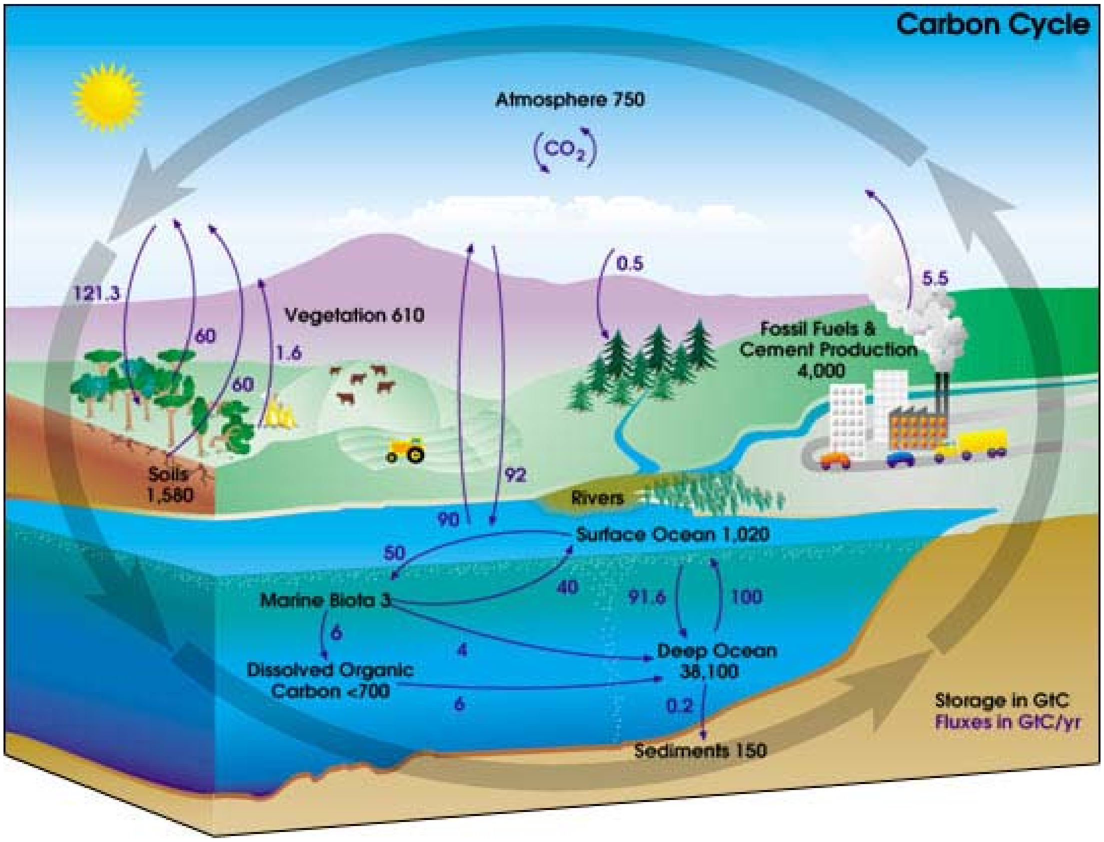


Figure 1. Conceptual diagram of the global carbon cycle (reproduced from NASA Earth Observatory, 2004).

When the C in organic materials is used for energy by microorganisms, N is released in a molecular form that is no longer associated with C. This process of transformation from organic to inorganic N is called mineralization. Ammonification is the first step in mineralization that produces ammonium (NH_4). Nitrification is the second step that converts NH_4 to nitrate (NO_3). The opposite of mineralization is immobilization; the process of inorganic N uptake by microorganisms. Both of these processes occur simultaneously and provide continuous movement between the organic and inorganic pools of N in the environment.

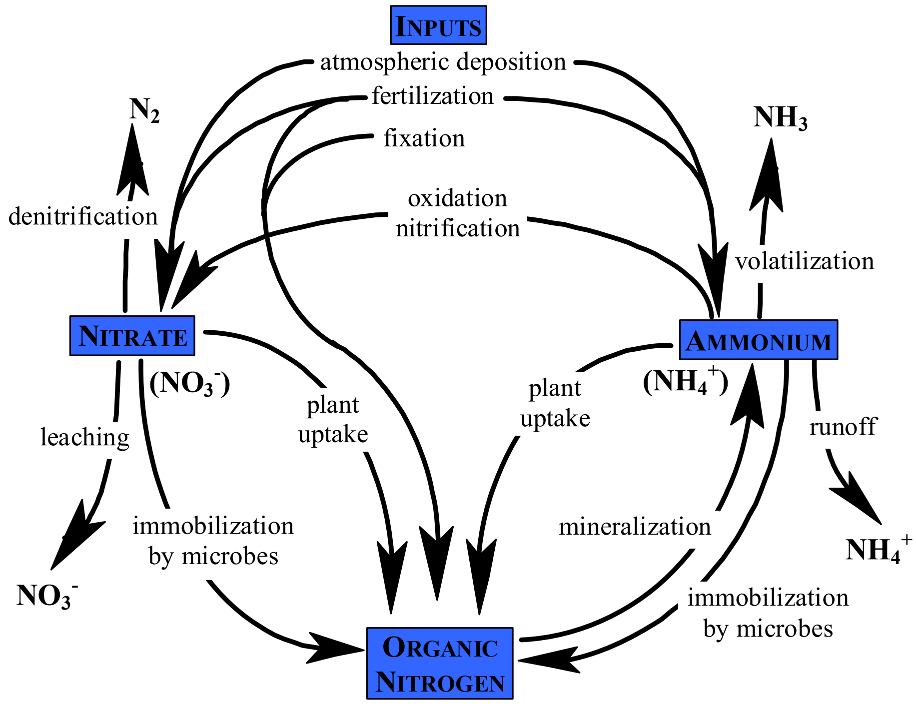


Figure 2. Conceptual diagram of the nitrogen cycle (taken from The National Park Service, 2004).

3.2 Dynamics of organic carbon in soils

The SOC pool represents a dynamic balance between the inputs of dead plant and animal material and losses from decomposition (Figure 3). The different C pools existing in the soil has been described in terms of the different mean residence times, ranging from years (active fraction), decade to hundreds of years (passive), to thousands of year (stable) (Carter el al., 2002). For the stable carbon fraction, a distinction is made between physical and chemical protection. Organic material is physically protected via an encapsulation of OM fragments by clay particles within soil macro- or microaggregates and chemically protected due to specific bonds of OM with other soil constituents (colloids or clays)(Balesdent et al., 2000). The long-term stabilization of C and N in temperate and tropical soils is mediated by soil biota (e.g. fungi, bacteria, roots and earthworms), soil structure (e.g. aggregation) and their interactions, and is influenced by agricultural management (Six et al., 2002).

The different organic carbon and nitrogen pools in soils are influenced by different factors. Free organic matter particles and microbial biomass in soils are controlled by residue inputs (management of crop residues or mulching) and climate. For example, the microbial populations and activities in pasture tends to be higher compared to the corresponding agricultural soils due to the positive impacts of the surface cover, vegetation, belowground C allocation via roots, and lack of tillage of pasture (Acosta-Martínez et al. 2004). Soil aggregation, texture and mineralogy control organic matter in macro-aggregates. The other pools are less influenced by agronomic factors but mainly by pedological factors (micro-aggregation, clay composition) (Feller and Beare, 1997).

Decreases in the SOC pools may be caused by three often simultaneous processes: mineralization, transport by soil-erosion processes, and leaching into the ground water or subsoil (Lal, 2000a). The mineralization process increases with a rise in temperature. Soil erosion contributes to a depletion of SOC pools when the natural ecosystem is converted to agricultural use with inadequate soil management practices (Lugo and Brown, 1993). Soil erosion can be described as a three-stage process: detachment or breakdown of aggregates, transport of detached particles and other light fractions, and deposition of the material whenever the velocity of runoff slows sufficiently (Lal, 2000b). Leaching of the SOC occurs when the soluble fraction of the SOC pool (dissolved organic carbon) moves vertically with the percolating water through the soil profile (Lal, 2000a). Some of the eroded soil carbon is redistributed across the landscape, and some is transported and deposited to waterlogged environments, such as reservoirs, lakes, wetlands or lost from the watershed and ultimately deposited in the ocean. (Lal, 2000b; Smith et al., 2001). Lal (2000b) estimated that a significant portion of the missing sink of atmospheric CO_2 (1.2–2.0 Pg C yr^{-1}) could be explained by the SOC eroded and redeposited annually if the redeposited SOC is replaced by sequestering new SOC from the atmosphere at the eroding sites.

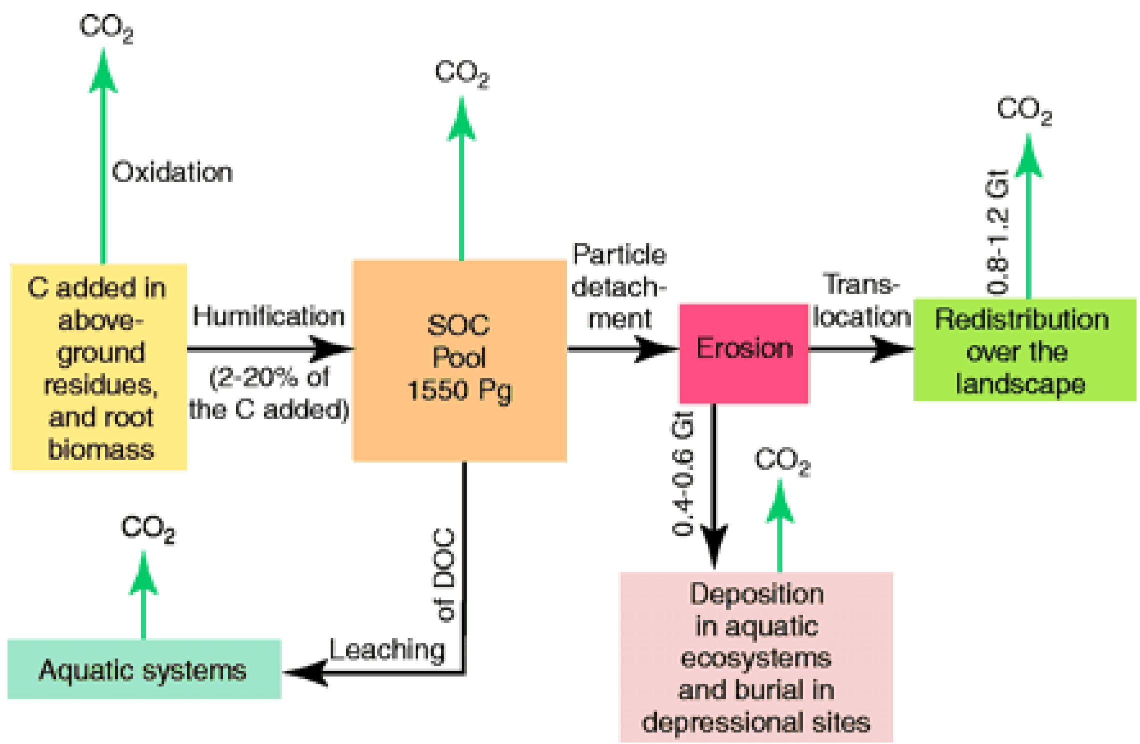


Figure 3. Processes affecting soil organic carbon dynamics (Lal, 2004).

3.3 Soil carbon and nitrogen stocks in the tropics

There have been few reports on the status of soil organic C in the island of Puerto Rico. For example, Beinroth et al, (1992) reported estimates values for the whole island that amount to 14.0 kg C m^{-2} in Oxisols, 12.8 kg C m^{-2} in Ultisols and 12.2 kg C m^{-2} in Inceptisols. 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 SOM content in the top 23 cm was 8.34 for volcanic clays, 9.93 in shallow volcanic clays, 7.83 in granitic sandier soils, and 9.06 kg C m^{-2} in limestone soils in subtropical moist forests.

At watershed level (Beinroth et al., 2003) using soil series-specific values and estimated bulk density values, reported the amount of soil organic carbon stored in the RGA watershed to a depth of 1 m. They estimated approximately 4.8 x 10^6 Mg of organic carbon in this watershed, of which about 62% is contained in the top 30 cm of the soil profile (Beinroth et al., 2003). However, this study did not compare different land uses.

Another study that provided C and N estimates in tropical soils of the Brazilian Amazon basin reported values that ranged from 4.0 kg C m^{-2} to a depth of 100 cm for coarse textured Arenosols (Psamments) to 72.4 kg C m^{-2} for the poorly drained Histosols (Batjes and Dijkshoorn, 1999). The mean carbon density for mineral soils, excluding Arenosols and Andosols (Andisols) was 9.8 kg C m^{-2}. Mean nitrogen densities to a depth of 1m ranged from 0.46 kg N m^{-2} for Arenosols to 3.13 kg N m^{-2} for Histosols. On other hand, Morales et al. (1995) found in the Brazilian Amazon basin, mean soil SOC values was 10.3 kg C m^{-2} in the top 1 m of soil (Morales et al., 1995). Furthermore, in terms of spatial variability Batjes and Dijkshoorn, (1999) found high variation in soil C and N.

Li and Zhao (2001) used data from the national soil survey to estimate that about 28.7 ± 8.2 Pg of SOC are stored in the upper 1 m of soils in the 215 × 10^6 ha of tropical and subtropical China. These broad-scale analyses show that estimates of SOC at national and global scales are often accompanied by a large range of SOC due to soil spatial variability and lack of reliable field measurement (Batjes, 2000).

Estimates of the global mean of SOC content in soils of the tropics are 8.3 for Ultisols, 9.7 for Oxisols, and 10.4 kg m^{-2} for Inceptisols (Table 16) (Lal, 2002). The data presented in the Table 1 illustrate the great variation of soil organic carbon stocks in relation with soil order. These differences between soil orders in the tropics are mainly in relations to temperature, rainfall, soil texture and land use (Batjes, 2000). About 52% of this carbon pool is held in the top 30 cm of the soil profile, the layer most susceptible to land use changes and responsive to management practices (Lal, 2002).

Table 16. Estimates of soil organic C pool in soils of the tropics.*

Order	**Mean SOC content (kg m^{-2})**	**All tropical Soils (Pg)**	**Tropical forest soils (Pg)**
Alfisols	5.2	30	4
Andisols	18.4	47	25
Aridisols	2.7	29	ND
Entisols	10.2	19	1
Histosols	ND	100	100
Inceptisols	10.4	60	2
Mollisols	8.8	2	ND
Ultisols	8.3	85	30
Spodosols	23.6	2	ND
Oxisols	9.7	119	43
Vetisols	6.2	11	1
Miscellaneous	ND	2	ND
Total		**506**	**206**

* Kimble et al. (1990); Adapted by Lal. 2002

3.4 Soil carbon and nitrogen sequestration

Given that the 1997 Kyoto Protocol requires a major reduction in CO_2 emissions by participating countries by the next decade, more attention has been given to understand the role of soils in carbon sequestration and storage, and their effect on C fluxes in the global atmospheric C budget (Kimble et al., 2001). Atmospheric CO_2 can be sequestered and stored in soils as soil organic matter (SOM), which in turn mitigates the increasing atmospheric CO_2 concentrations.

In most soils, C is organic in nature and constitutes approximately 57% of the SOM. That includes a wide spectrum of organic compounds, from labile components, such as relative fresh plants material and microbial biomass, to refractory components such as charcoal, which accumulate slowly over thousands of years (Trumbore, 1993). SOM is an important factor that affects soil fertility (Lal, 2002). For example, reduced-tillage can improve the macro-aggregate structure of soils and increase the capacity of the soil to sequester organic matter relative to conventional tillage (Cambardella and Elliot, 1994). In addition, the sequestering and long term storage of C within SOM improves soil structure in terms of both size and stability of soil aggregates, leading to a decrease in soil erodability.

Improvement of soil structure depends on soil management practices. For example, when tropical forests are cultivated, SOC losses to a 1 m depth range from 15 to 40% within 2–3 years (Ingram and Fernandes, 2001), reducing soil fertility and crop productivity. Other factors that have been classified as immediate causes of a decline in SOC include residue removal, soil erosion, intensive tillage, and bare fallowing (Lal and Kimble, 2000, Paustian et al., 2000). In addition in tropical and temperate soils, a general increase in C levels (≈ 325 ± 113 kg C ha^{-1} yr^{-1}) was observed under no-tillage compared with conventional tillage (Six et al., 2002).

The turnover and cycling of SOC is more rapid in the tropics than in temperate regions (Trumbore et al., 1995). Six et al., (2002) found on average that the soil C turnover was twice as fast in tropical compared with temperate regions, but no major differences were observed in SOM quality between the two regions. One possible reason is the continuous inputs of fresh organic matter in tropical soil. However, for natural ecosystems and similar soil and moisture regimes, the quantity and quality of SOC is similar in temperate and tropical ecosystems (Greenland et al., 1992). The efficiency with which soils in a watershed can sequester and store carbon depends on land use and management practices over time (Lal, 2002). Thus, soils under agricultural crops or forest cover conserve carbon in greater magnitude than eroded areas (Lal, 2002).

Physical fractionation of the soil according to aggregate size has been used to study the partitioning of organic carbon in the soil (Buyanovsky et al., 1994). A greater proportion of the SOC pool in large macroaggregates implies greater C losses to the atmosphere if macroaggregates are broken by soil management practices. Different soils in similar land uses and management practices within a watershed may contain different amounts of SOC and SON as a result of changes in the proportion of aggregates sizes, nutrient availability and texture. Other factors that influence the SOC and SON pools may be the magnitude and quality of C inputs, disruption of aggregates, or microclimatic changes within a relatively small area (Six et al., 1999). Also, because SOM is composed of a series of fractions (varying from very active to passive) of varying degrees of decomposability, land use changes will influence the distribution of organic C and N among the SOM pools.

As reported by Cambardella and Elliot (1993, 1994), changes in land use and management practices can alter the distribution of organic C and N among labile and stable pools with kinetically different turnover rates. For example, conversions of secondary forest to continuous cultivation can decrease the SOM carbon by 44% within 5 years after conversion (Motavalli, 2000). Also, intensive cultivation of grassland reduces the SOC and SON because the destruction of soil macroaggregates by different levels of tillage (Cambardella and Elliot 1993). The losses of SOC are in turn associated with losses in the particulate organic matter (POM) fraction and therefore the amount of aggregation and aggregate turnover (Six et al., 1999).

4. Materials and Methods

4.1 Site description

The watershed approach given to this study appropriately allows the integration of different areas of knowledge into a given management unit (Dwiprabowo and Wulan., 2003). A watershed can be viewed as an ecosystem of its own, and all its components (hydrology, soils, geology, land use, and socioeconomic factors) can be described as a function of this management unit. An understanding of the relationships among these components can serve as solid basis to formulate management plans and programs conducive to the preservation of the area as a whole.

The RGA watershed, to the point of interest at Lago Dos Bocas, encompasses an area of 45,067 ha of which 36,500 ha have slopes greater than 40%. The watershed is located in the north central part of the island of Puerto Rico and includes five municipalities: Adjuntas, Arecibo, Ciales, Jayuya and Utuado with an estimated population of 173,721 (U.S. Bureau of the Census, 2000). The watershed is bordered by latitudes 18°11’N and 18°20’N to the north and south, respectively, and longitudes 66°32’W and 66°46’W to the east and west, respectively (Figure 4). Before the 1950, the majority of the land area within the watershed has been farmed with crops such as coffee, plantains, sugarcane and citrus. Currently much of the land has been abandoned to give place to secondary rapid growing forests. The watershed has an area of exceptional natural value like Caño Tiburones and Reserva Natural Cueva del Indio (both near Arecibo), Bosque Estatal Río Abajo (Arecibo/Utuado), Bosque Tres Picachos (Jayuya) and Terrenos Forestales de la Zona Minera (Utuado and Adjuntas). The municipality of Arecibo and some parts of the Ciales and Utuado municipalities overlay a limestone aquifer that is part of the North Coast Limestone Aquifer System, which is one of the most productive sources of ground water in Puerto Rico. The landscape of the watershed is characterized by floodplains, terraces, and strongly dissected uplands. According to the land use map developed in 2000 (CSA Group – unpubl data, 2000), about 5,706 ha (12.6 %) in the watershed is described as "non-soil", 32,006 ha (71.2 %) are forest lands, 3,776 ha (8.3 %) are pasture lands and 3,579 ha (7.9 %) are agricultural lands (Table 17).

Table 17. Land use description on the RGA watershed

Land Uses	Description	Area (ha)
Forest	Mixed Forest Land	28236
	Mixed Rangeland	3770
Pasture	Herbaceous Rangeland	3680
	Shrub and Brush Rangeland	96
Agriculture	Confined Feeding Operations	293
	Orchards, Groves, Vineyards, Nurseries	2323
	Cropland	962
non soil	Bare Exposed Rock	1017
	Bare Soils	28
	Commercial	13
	Industrial	79
	Lakes and Reservoirs	520
	Nonforested Wetlands	49
	Recreational and Public Uses	169
	Residential High	448
	Residential Low Density	2578
	Sandy Areas Other than Beaches	5
	Streams and Canals	503
	Strip mines, Quarries, and Gravel Pit	41
	Transitional Land	186
	Transportation, Communications	69

Table 18. Taxonomic classification of the soil series of the RGA watershed

Soil Series	Mapping Units	Taxonomic Classification
Alonso	AoF2	Very-fine, parasesquic, isohyperthermic Oxic dystrudepts
Caguabo	CbF2	Loamy, mixed, active, isohyperthermic, shallow Typic Eutrudepts
Consumo	CpF, CuF2	Fine, mixed, semiactive, isohyperthermic Typic Haplohumults
Humatas	HmF, HmF2, HmE, HmE2	Very-fine, parasesquic, isohyperthermic Typic Haplohumults
Lirios	LcF2	Fine, mixed, subactive, isohyperthermic Typic Hapludults
Los Guineos	LgF, LgE, LuF,LME, LyFx	Very-fine , Kaolinitic, isothermic Humic Haplodox
Maraguez	MaF2	Fine-loamy, Mixed, superative, isohyperthermic Typic Eutrudepts
Maricao	MkF2	Fine, mixed, subactive, isohyperthermic Inceptic Hapludults
Mucara	MuF, MuF2	Fine-loamy, mixed, superactive, isohyperthermic Dystric Eutrudepts
Pellejas	PeF, PeF2	Fine-loamy over sandy or sandy-skeletal, mixed, subactive, isohyperthermic Typic Dystrudepts
Viví	Vm	Coarse-loamy over sandy or sandy-skeletal, mixed, subactive, isohyperthermic Fluventic Dystrudepts

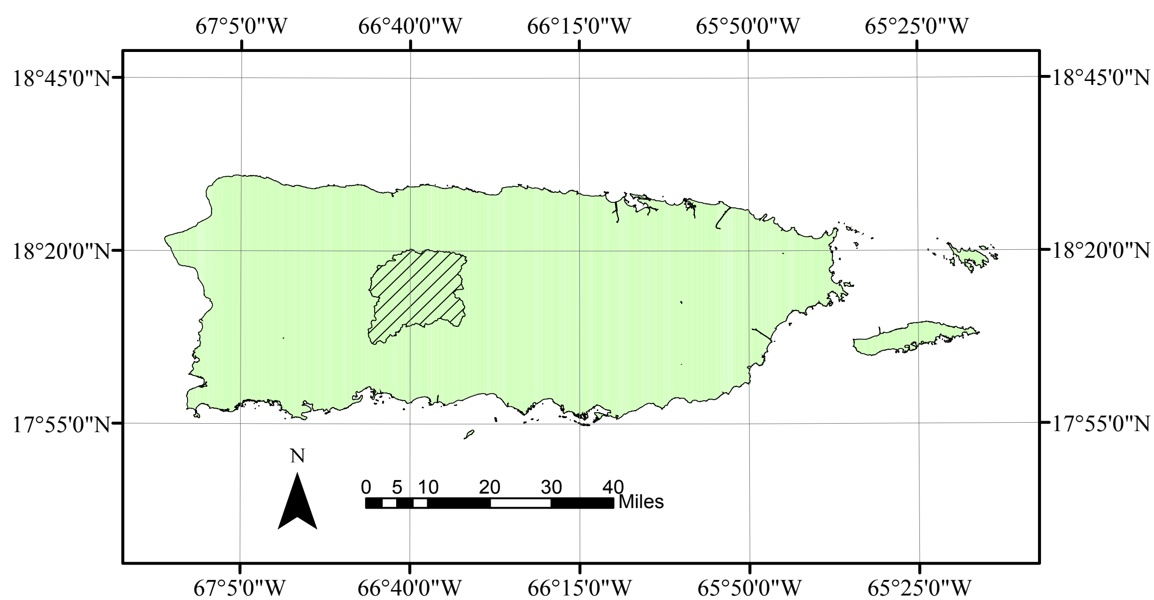


Figure 4. Delineation and location of the Rio Grande de Arecibo watershed.

The geology is dominated by Cretaceous volcanic rocks and plutonic rocks, Tertiary limestones and Quaternary alluvial deposits (Beinroth et al., 2003). Within the RGA watershed there are 35 soil series which are subdivided into 79 mapping units based on slope and level of erosion (Figure 5) (Acevedo, 1982; Gierbolini et al., 1979). There are 18 mapping units of eleven soil series that represent the most extensive soils of the watershed, each with an area greater than 453 ha, and with a total combined area of 32,787 ha (81.4% of the land area). There are five soil series that have both eroded and non-eroded map units with the same slope (Consumo, Humatas, Pellejas and Mucara). The major soil orders (series in parenthesis) are Ultisols (Humatas,) Oxisols (Los Guineos) and four Inceptisols (Múcara, Caguabo, Pellejas and Maraguez). The taxonomic classification of the soil series according to Soil Taxonomy (Soil Survey Staff, 1999) is presented in Table 18. Most upland pedons are Oxisols and Ultisols. Common features of the upland soil series in the watershed include high clay content and acid conditions. The Inceptisols tend to be coarser textured on eroded landscapes, than their contiguous upland counterparts.

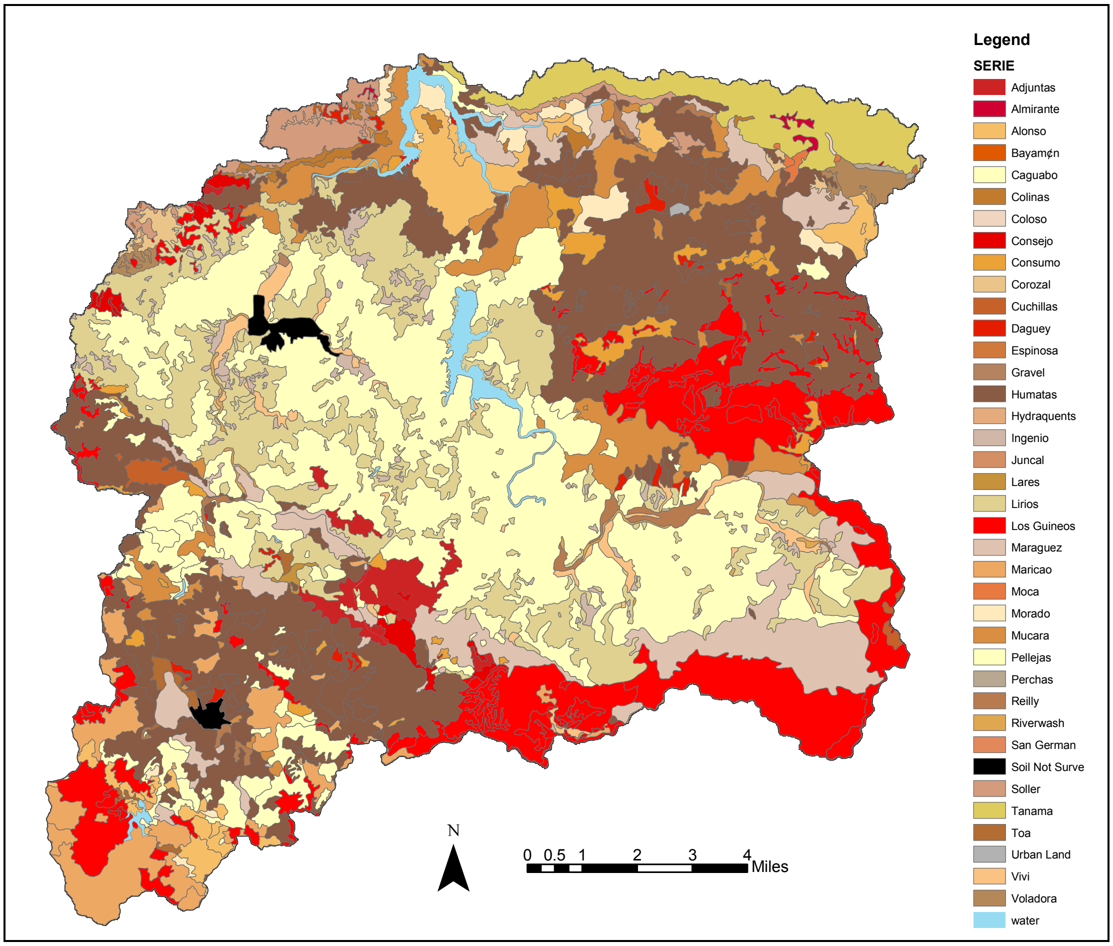


Figure 5. Spatial distribution of the thirty-five soil series within the Rio Grande de Arecibo watershed (USDA-NRCS, 2001).

4.2 Soil sampling strategy

A GIS database map was created (Figure 6) by delineating the RGA watershed, with the point of interest at Lago Dos Bocas. A digital version of the soil mapping units was obtained from the Soil Survey Geographic Database (USDA-NRCS, 2001), whose boundaries have been 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, 1 meter resolution (Space Imaging, LLC, 2001). The soil mapping units most representative of the watershed were identified using the GIS base map developed. A map with 18 soil mapping units (each map unit an area > 453 ha) was developed and represented 82.8% of the total watershed area. In addition, three different mapping units less than 453 ha (CuF2, MuF2 and PeF2) were selected to compare eroded and uneroded phases of the same soil series. A total of 21 mapping units were sampled and they represent 33,322 ha, or 84.6% of the total land area. This layer of information was overlapped with the layer containing the main roads.

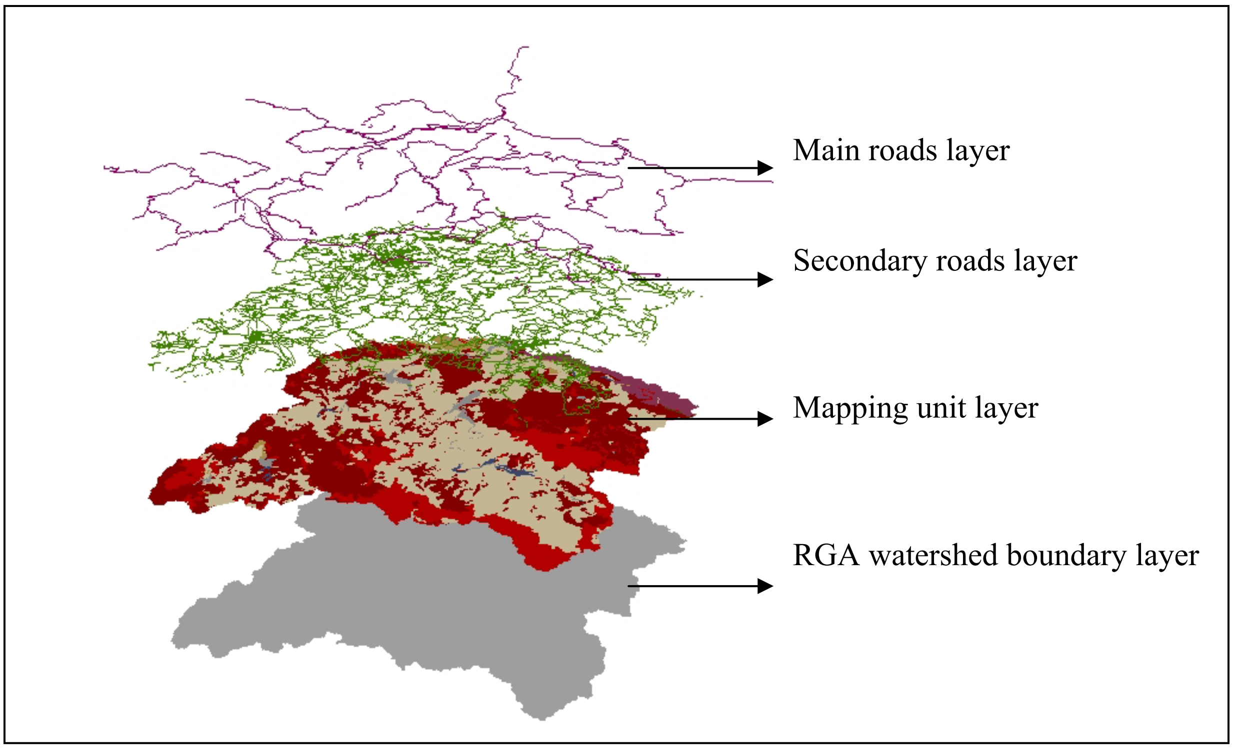


Figure 6. Conceptual diagram of the geographic information system of the Rio Grande de Arecibo watershed.

There are several polygons for each soil mapping unit. Based on area distribution of soil mapping units it was decided to sample one pedon for approximately every 500 ha. For example, the Pellejas series (PeF) has a total area of 8,674 ha distributed among 28 soil polygons. A total of 23 samples were collected for this soil unit. The sampling point for each polygon was selected at random where each number corresponds to the kilometer marking of the road that intersects the polygon. For example, for mapping units in which more than one pedon was sampled, the sample points were selected by choosing random numbers corresponding to the kilometer number of the road that coincides with the soil polygon. For soils in which one pedon was evaluated, sampling was performed at any point near the road that geographically coincides with the polygon. To avoid the disturbance effect of previous or current construction project and to make sure the intended soil polygon was sampled, a buffer zone between 25 m and no more that 100 m from trafficable main roads was made.

The geographic coordinates of each sampling site were taken with a GPS (Model Trimble Pro XR, Trimble Inc. Sunnyvale, CA.) with sub-metric resolution. A data sheet was developed to record the characteristics of each sampling site (Appendix A). The record describes the site elevation, slope, aspect, geology, vegetation, relief and land use. Soil samples were collected using an auger at 0-15, 15-30, 30-50, 50-75, and 75-100 cm depths or to a lithic or paralithic contact if it is shallower. A total of 524 soil samples were collected for analysis. Samples were distributed proportionally to the area of the 21 mapping units (Table 19, Figure 7).

Table 19. Number of samples taken by soil series and mapping units within the Rio 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
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
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
Maraguez	Inceptisol	MaF2	2283	4	20
Maricao	Ultisol	MkF2	770	3	14
Los Guineos	Oxisol	LyFx	560	2	10
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	233	1	5
		Total	**33,322**	**107**	**524**

4.3 Soil handling and sample preparation

Samples were air-dried or put into an oven at 50°C for 48 hours, then gently sieved to pass through a 4-mm sieve to remove rock fragments. Subsequently, the sample was divided into two equal parts and stored at 22°C in plastic bags, labeled and stored for future analysis; the second part was sieved to pass a 2-mm sieve and placed in two separate plastic bags. One portion was used for the analysis of total organic carbon and the second for storage. The sample bags were stored at room temperature in the dark until analysis.

4.4 Chemical assessment

4.4.1 Total C and N analysis

Total organic C and N content of the bulk soil (< 2 mm size class) were quantified by automated dry combustion using a LECO C and N analyzer at the Soil, Plant and Water Laboratory of the College of Agricultural and Environmental Science, University of Georgia.

4.4.2 Soil pH analysis

Soil pH was measured on the soil fraction samples <2mm using 1:2 soil:water mixtures. The mixtures were shaken for one hour, and centrifuged for 1 minute at 1000 rpm for pH measurement. The pH was measure in the supernatant.

4.5 Physical assessment

4.5.1 Bulk density

The mean bulk density was obtained from soil characterization data by the Soil Survey Laboratory of the USDA Natural Resources and Conservation Service (Soil Survey Staff 2004) (Table 20). If bulk density data were not available for a particular soil series, it was inferred from the data for a similar soil series. Bulk density was used to calculate SOC and SON on an area basis.

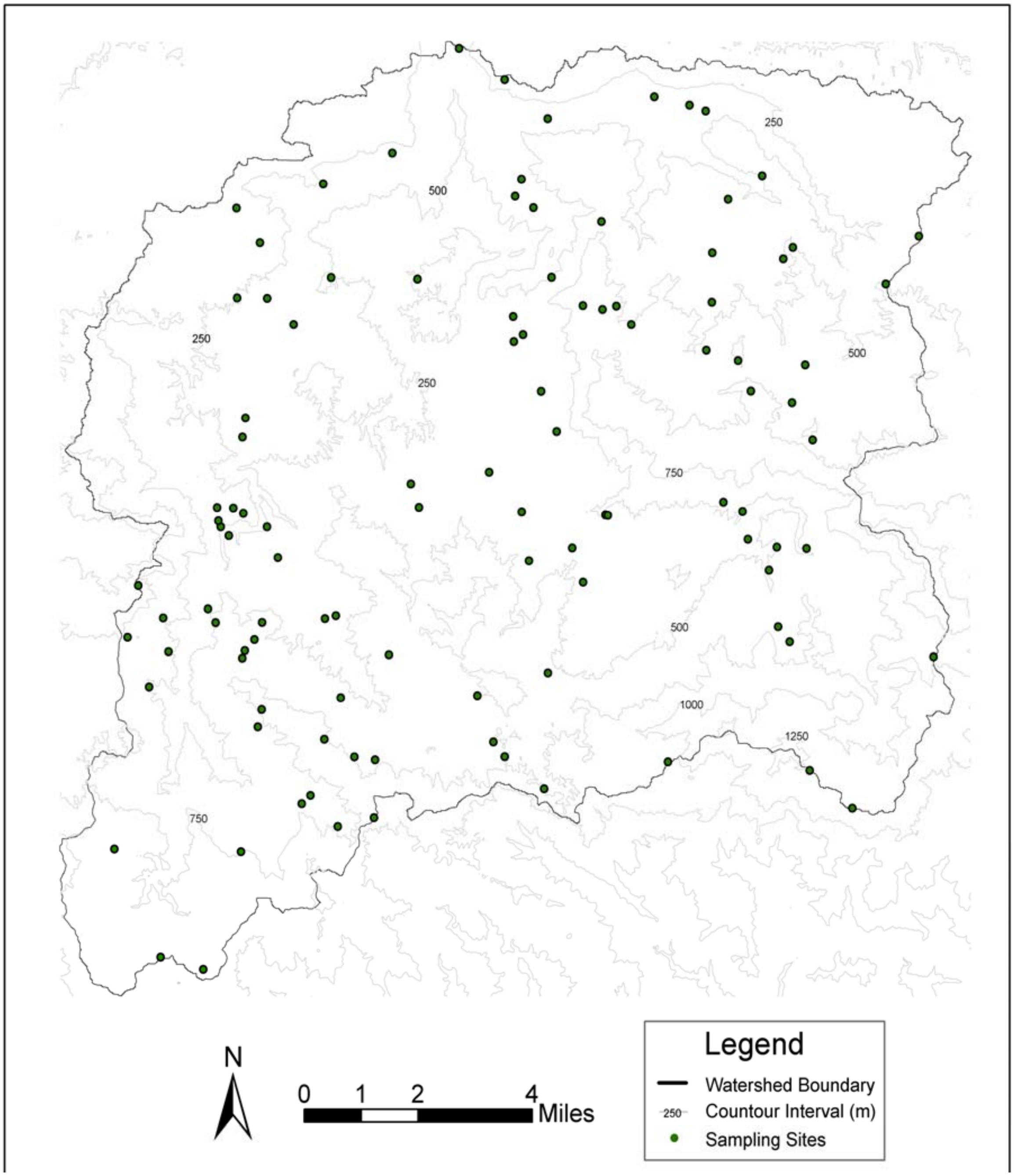


Figure 7. Map of soil sampling sites within the RGA watershed.

Table 20. Bulk density (g/cm^3) in RGA soils (Soil Survey Staff 2004).

Series	Depth (cm)				
	0-15	15-30	30-50	50-75	75-100
Vivi	1.51	1.65	1.48	1.51	1.50
Maricao	1.31	1.35	1.44	1.38	1.38
Pellejas	1.32	1.43	1.51	1.49	1.54
Mucara	1.25	1.14	1.27	1.43	1.38
Los Guineos	1.09	1.31	1.32	1.44	1.48
Alonso	1.40	1.43	1.47	1.29	1.46
Humatas	1.12	1.40	1.48	1.48	1.49
Maraguez	1.25	1.14	1.27	1.43	1.38
Caguabo	1.25	1.14	1.27	1.43	1.38
Consumo	1.39	1.45	1.21	1.15	1.15

4.5.2 Particle size analysis

Soil texture was determined for 0-15 cm depth using a laser diffraction particle size analyzer (Model LS-230, Beckman-Coulter Inc, Fullerton CA) at the USDA-ARS Wind Erosion and Water Conservation unit (WEWCU), Lubbock, Texas. This method requires estimates of the refractive index of the liquid and solid used in the analysis. The instrument was controlled with an IBM - compatible PC (Windows 95 operating system) using Coulter LS series software (v. 3.01). In order to validate and compare the laser diffraction method with the pipette method, 18 soil samples were analyzed using the pipette method at the Ward Laboratories, Inc, Kearney, Nebraska, according to the procedure outlined by the Soil Survey (1996). The data were facilitated by USDA-ARS-WEWCU staff and correlation analysis was performed.

4.6 Soil organic carbon and nitrogen calculation

The organic carbon and nitrogen contents were calculated by multiplying gravimetric organic carbon content, bulk density and depth of sampling of the different soils layers, using the following equation:

$$C = \%C / 100 \text{ g soil} * BD * SD \qquad (1)$$

where,

%C = percentage of C given by lab results

BD = bulk density expressed in g/cm^3

SD = soil depth expressed in cm

The results obtained from this equation were then expressed in kg m^{-2} by using the appropriate conversion factors. Each layer was calculated separately and later integrated over depth of 0-15 and 0-100 cm.

4.7 Statistical analyses

The statistical design was a completely randomized design with soil order and land uses as main effects. The number of replicates for each order/land use varied proportionally to the land area of each of the effects. To determine significant effects of soil order and land uses on C and N stocks, analysis of variance (ANOVA) was performed. To compare eroded and uneroded soil phases a Student's t-test was used. All statistical analyses were performed using InfoStat V3.0.2. Statistical significance at level of $P \leq 0.05$ was considered.

4.8 Hypothesis Testing

- H_{o1}: The soil organic C and N contents are similar between land uses, soil orders and soil phases.
- H_{o2}: The soil organic C and N content are similar between soil phases (eroded and uneroded) of the same series.

5. Results and Discussion

5.1 Soil organic carbon distribution within the RGA watershed

The mapping unit weighted SOC mean for the depths of 0-15 and 0-100 cm was 4.12 and 10.8 kg C m^{-2}, respectively. The values measured for the 0-100 cm depth are similar to those reported by Beinroth et al., (2003) which amounts to 10.9 kg C m^{-2} in the RGA watershed. The island-wide mean C content was estimated at 10.72 kg C m^{-2} (Beinroth et al.,1992). Morales et al. (1995) estimated 10.3 kg C m^{-2} for Amazon Basin, and Brown and Lugo (1982) estimated 8.60 kg C m^{-2} for tropical wet forest soils in Puerto Rico.

From the soils evaluated, approximately 42 to 63 % of the SOC content is stored in the depths of 0-15 and 0-30 cm of the pedon, respectively. The SOC content of the 21 mapping units at 0-100 cm varied from 1.63 kg C m^{-2} in the Inceptisols under agricultural land to 34.6 kg C m^{-2} in Ultisols under forest cover. These low and high values can be explained by the geology of the parent material and management practices. For example, Plutonic rocks are dominant rock formations that weather to Inceptisols such as the Pellejas series and volcanic rock weather to Ultisols, such as the Los Guineos and Humatas series. These soils tend to accumulate carbon over time if the soil aggregates are maintained or created, and if the through sound management practices, the soil is capable of forming new aggregates.

In order to prepare a spatial distribution map of soil C for the 0-15 and 0-100 cm depths of the RGA watershed, different methodologies were considered. First, the mean of the mapping units was calculated using mean C data of each mapping unit (Figure 8 and Figure 9).

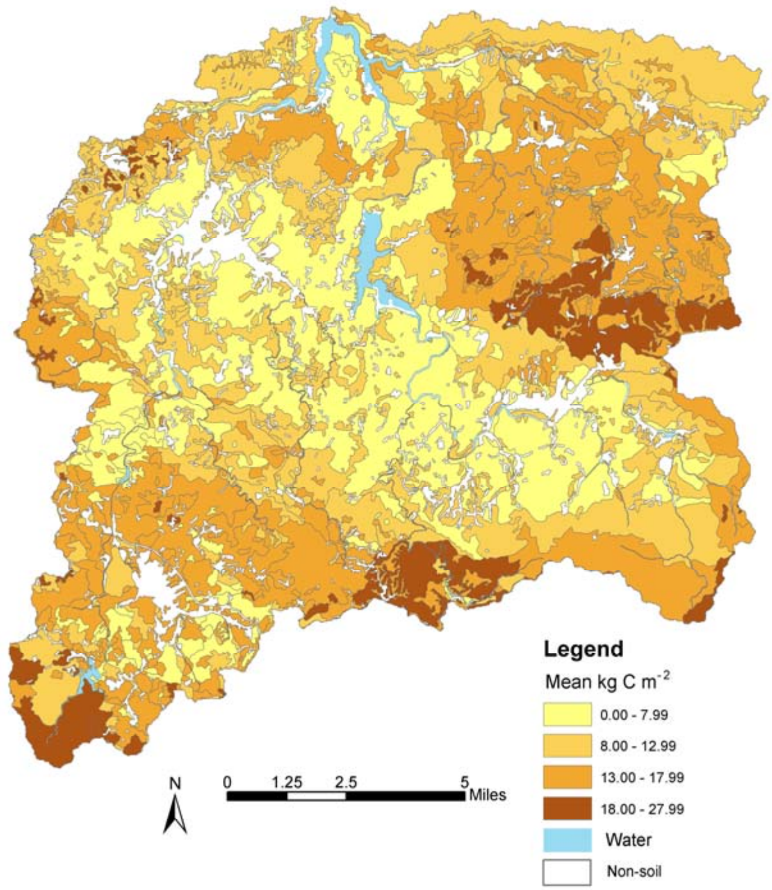


Figure 8. Soil organic carbon content of the soils of the RGA watershed (kg C m^{-2}, 0-15 cm).

The mean organic C content of the soils of the watershed was 4.65 at 0-15 and 11.9 kg C m^{-2} at 0-100 cm, which are slightly higher than the weighed C average values. The SOC stock was calculated as the product of the C content of each mapping unit and corresponding total area, expressed as megagrams (Mg). The 21 mapping units represent an area of 33,322 ha (84.7%). A mapping unit consists of one or more major soils and some minor soils and it is named for the major soils (Acevedo, 1982). To complete SOC data for the remaining 15.4 % of the total watershed area (6,038 ha), we used the data provided by the National Soil Survey Laboratory of the NRCS, calculated by Beinroth et al. (2003) in his RGA watershed study.

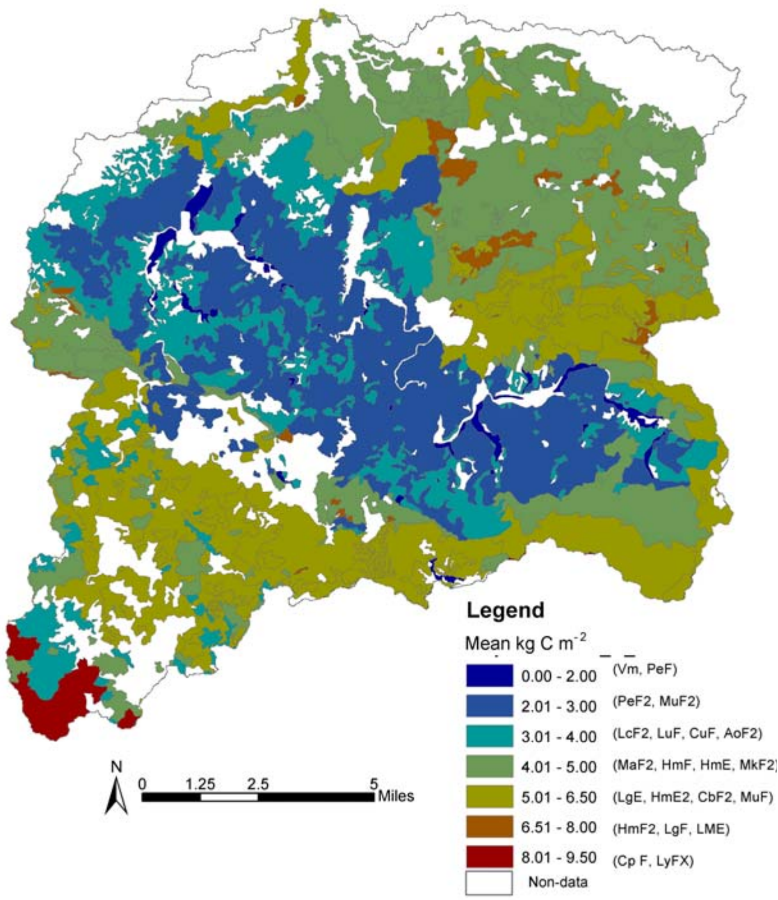


Figure 9. Soil organic carbon content by mapping unit in the RGA watershed (kg C m^{-2}, 0-100 cm). See table 4 for descriptions of abbreviations.

The soils sampled in the watershed (84.7% of the total land area) currently store 3.61 x 10^6 Mg of C to a depth of 100 cm. Using the data of all mapping units, the watershed currently sequesters 4.76 x 10^6 Mg of C to a depth of 100 cm (24.1% greater when including 15.3 of the area) which is close to the value of 4.80 x 10^6 Mg of C for the 78 mapping units reported by Beinroth et al. (2003). Their results represent carbon content for the total area of the RGA watershed for the same soil depths. The differences may be due to differences in total soil area sampled for both studies. In addition this report presents the field-measured status and not the estimated SOC from the Soil Survey (Soil Survey Staff, 2004) presented by Beinroth et al. (2003).

Another SOC distribution map was developed using ArcMap (v. 8.2) by using the intersection of the mapping unit and land use layers, and calculating the mean C values for each mapping unit in a particular land use type (forest, pasture and agriculture) (Figure 10, Figure 11) (Table 21).

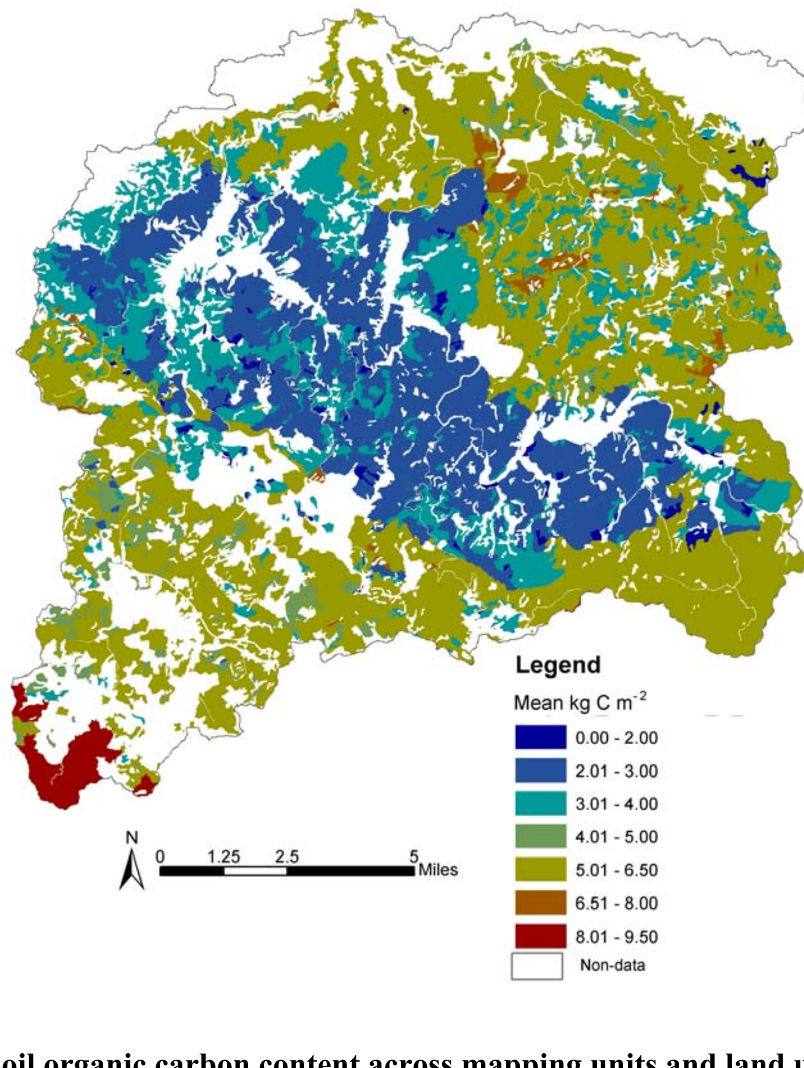


Figure 10. Soil organic carbon content across mapping units and land use in the RGA watershed (kg C m^{-2}, 0-15 cm).

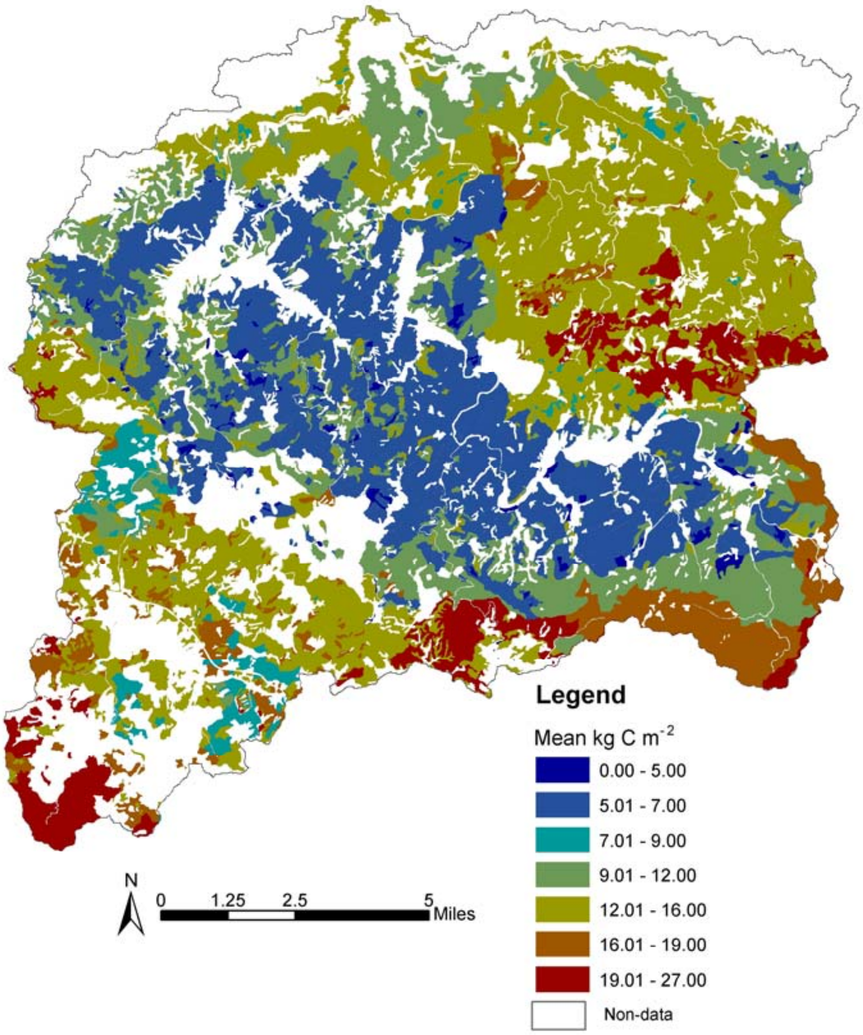


Figure 11. Soil organic carbon content across mapping unit and land use in the RGA watershed (kg C m^{-2}, 0-100 cm).

Table 21. Soil carbon content across map unit and land use in the RGA watershed.

Land use	Mapping Unit	Mean kg C m^{-2} 0-15 cm	Mean kg C m^{-2} 0-100 cm
agriculture	AoF2	1.48	5.11
	CpF	6.07	15.76
	HmE2	4.64	18.09
	HmF	3.55	12.16
	HmF2	4.03	13.63
	LcF2	3.05	5.39
	LgF	4.00	12.35
	LuF	3.15	12.59
	MaF2	1.50	3.95
	MuF2	2.87	8.67
	PeF	1.98	3.84
	PeF2	0.88	3.74
	Vm	0.73	1.63
forest	AoF2	5.53	10.80
	CbF2	5.20	7.22
	CpF	7.75	17.47
	CuF2	3.91	14.26
	HmE	4.73	12.29
	HmF	5.04	14.47
	HmF2	6.27	14.39
	LcF2	4.00	9.72
	LgE	5.19	13.96
	LgF	6.02	19.25
	LME	5.65	17.94
	LyFX	9.49	26.94
	MaF2	5.13	11.55
	MkF2	6.35	17.21
	MuF	5.92	12.37
	MuF2	4.09	11.08
	PeF	2.37	5.08
	PeF2	3.76	6.58
pasture	CuF2	4.70	7.45
	HmE	4.41	8.67
	HmE2	5.46	15.86
	HmF	3.39	13.96
	HmF2	5.21	16.86
	LcF2	3.83	13.60
	LuF	4.50	19.01
	MkF2	4.27	14.43
	MuF	3.81	8.60
	PeF	2.53	5.06

These maps have greater resolution than the ones presented only for mapping units, indicating that when taking into account land use, we can observe the distribution of C in greater detail. Thus for example, at the upper eastern part of the watershed, shown in figure 8 the C content varied mostly between 4.01 and 5.40 kg C m^{-2}, but the second map (Figure 10) shows that this variation ranges from 2.76 to 6.80 kg C m^{-2} when incorporating land use information. The mean C content for depths of 0-15 and 0-100 cm was 4.30 and 11.8 kg C m^{-2}, respectively. This intersection of layers (for mapping unit and land use) represents an area of 31,307 ha or 73% of the total watershed area, which is 5,049 ha less than the maps represented only by mapping units. When the intersection of mapping unit and land use layers is performed, areas of the some mapping units are eliminated, producing greater detail in the SOC spatial distribution. The estimated SOC stock for this intersection was 3.55 x 10^6 Mg to a depth from 0 to 100 cm.

A third representation of the C content was depicted by the mean C of the soil orders sampled within the watershed (Ultisols, Inceptisols, and Oxisols). The SOC values were paired with all polygons of the corresponding order. The results of these analyses show that the mean C content for soil order was 4.60 and 12.1 kg C m^{-2} for depths of 0-15 and 0-100 cm, respectively (Figures 12 and 13).

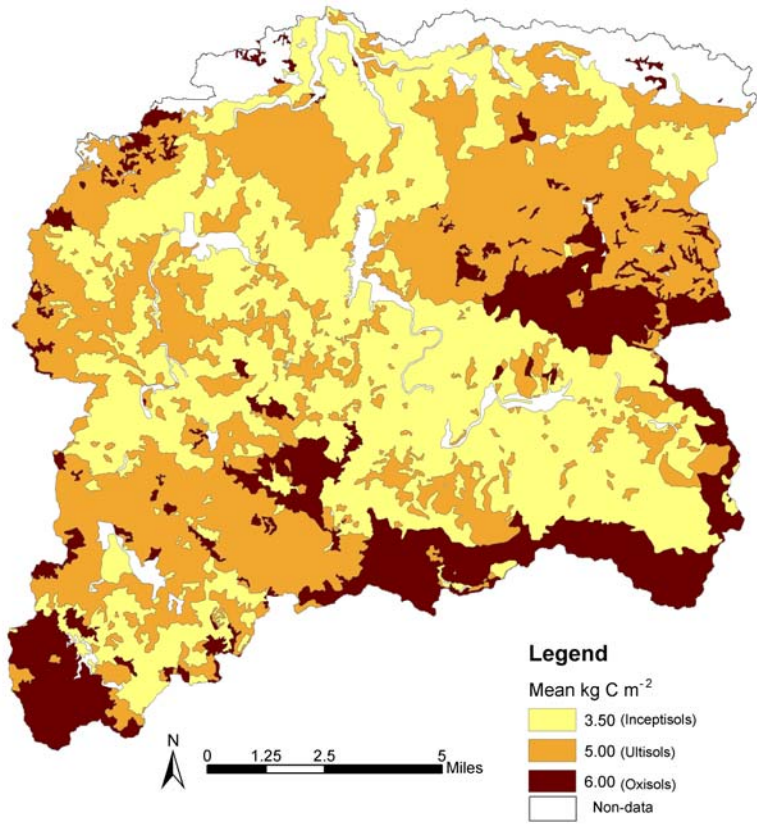


Figure 12. Soil organic carbon content by soil order in the RGA watershed ($kg\ C\ m^{-2}$, 0-15 cm).

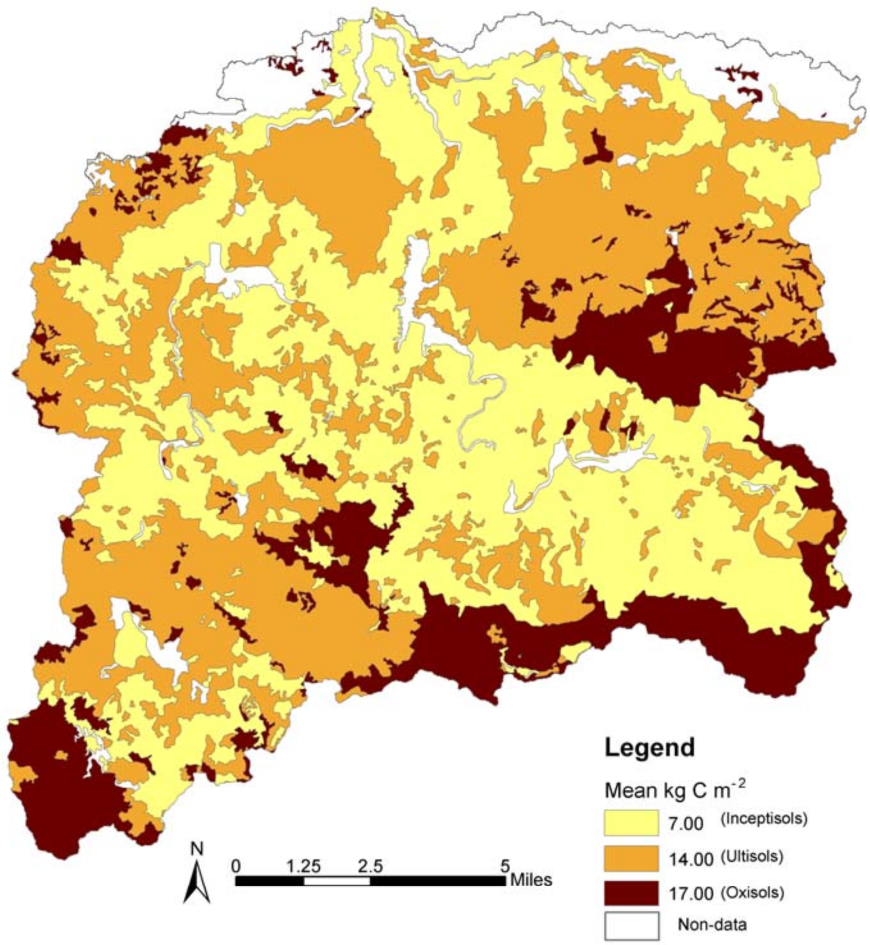


Figure 13. Soil organic carbon content by soil order in the RGA watershed (kg C m^{-2}, 0-100 cm).

The estimate of SOC stock for this map representation was 4.06 x 10^6 Mg to a depth from 0 to 100cm. The area consider in this estimation is 41,494 ha. When the mapping units are generalized by soil order, some mapping units that were not sampled are represented in this estimation.

A final representation of mean soil C content was developed using the land use layer and the mean C content for each land use type (forest, pasture, and agriculture). The results shown in Figure 14 and Figure 15 indicate that the mean C content for land use was 3.9 and 10.7 kg C m^{-2}, for depths from 0-15, and 0-100 cm, respectively. This map represents an area of 44,994 ha. The estimated SOC for this watershed is 4.88 x 10^{6} Mg to a depth from 0 to 100cm.

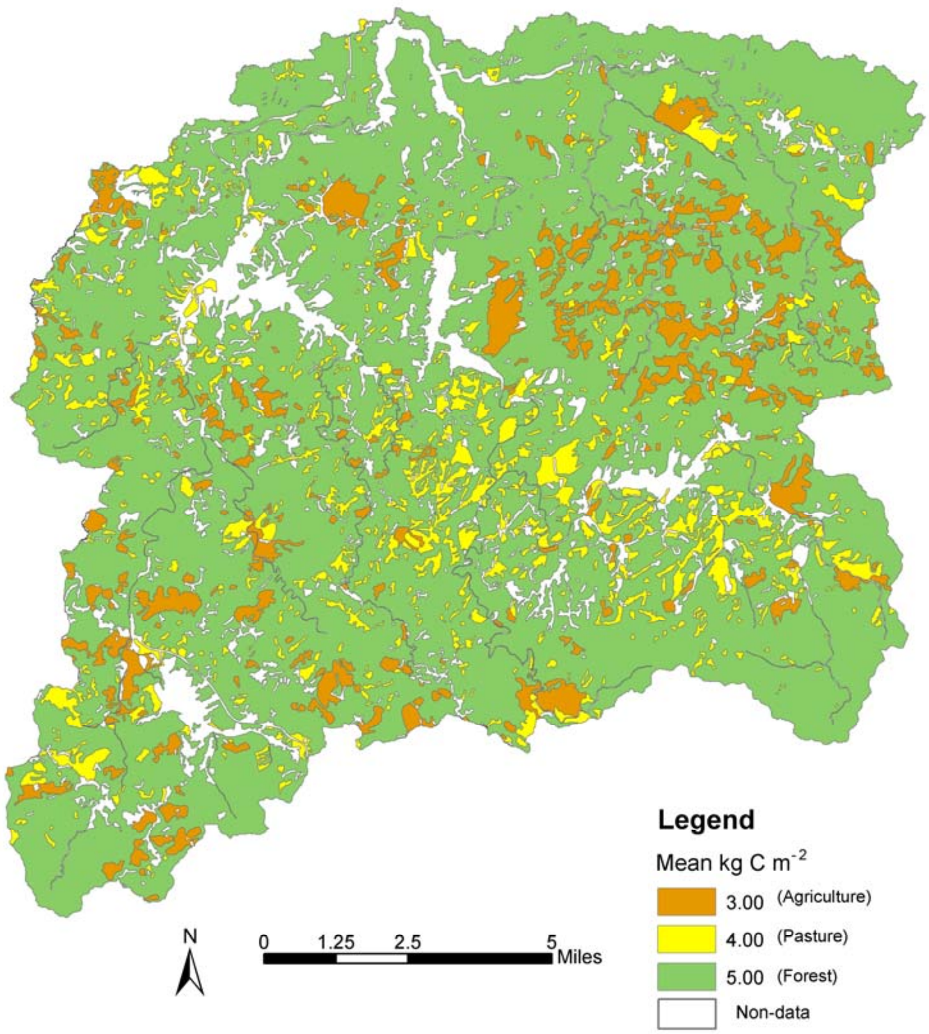


Figure 14. Soil organic carbon content by land uses in the RGA watershed (kg C m^{-2}, 0-15 cm).

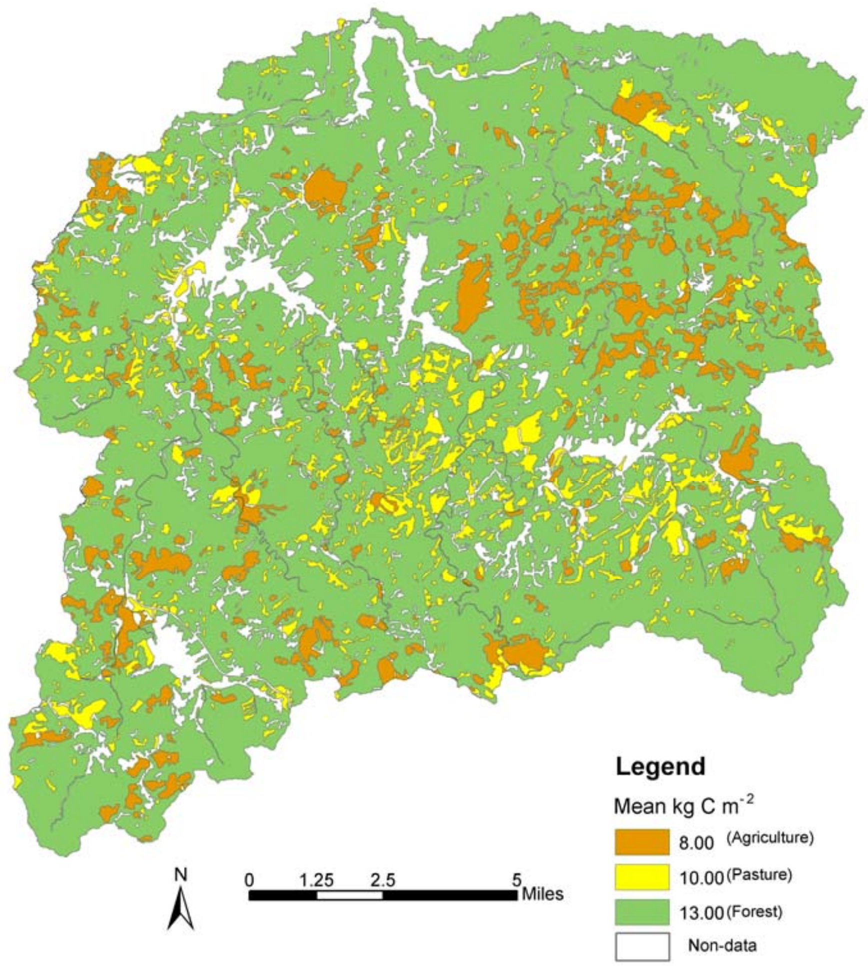


Figure 15. Soil organic carbon content by land uses in the RGA watershed (kg C m^{-2}, 0-100 cm).

A summary of the mean C contents for 0-15, 0-30, 0-100 cm depth is shown in Table 22. As expected the highest SOC stocks were obtained with the land use layer (4.88 x 10^6 Mg) and the lowest with the combination intersection of map unit and land use layers (3.55 x 10^6 Mg). When the mapping unit is generalized to order or land use, the represented areas increase.

Table 22. Soil organic carbon in the RGA watershed at different GIS layers.

Layers	SOC content kg C m^{-2} — Depth (cm) —			Area represented (ha)	Carbon stocks (10^6 Mg)	n*
	0-15	0-30	0-100			
Map unit	4.13	6.49	10.84	33,322	3.61	22
Map unit & Land use	4.33	6.80	11.13	31,261	3.48	40
Order	4.21	6.58	10.99	41,494	4.15	3
Land use	4.63	7.19	12.45	44,994	5.02	3

* n is the number of experimental units associated with the analyses.

5.2 Soil organic nitrogen distribution within the RGA watershed

The spatial distribution maps were done in similar form as those developed for the SOC spatial distribution using ArcMap (v. 8.2) for depths 0-15 and 0-100 cm. First, the mean of the mapping units was calculated using mean N data of each mapping unit (Figure 16 and Figure 17). The mean N content for depths 0-15 and 0-100 cm were 0.41 and 1.12 kg C m^{-2}, respectively, which are slightly higher than the weighed N average values. The SON estimate to a depth of 0-100 cm for the soils sampled in the watershed (84% of the total land area) is 0.38 x 10^6 Mg of organic nitrogen.

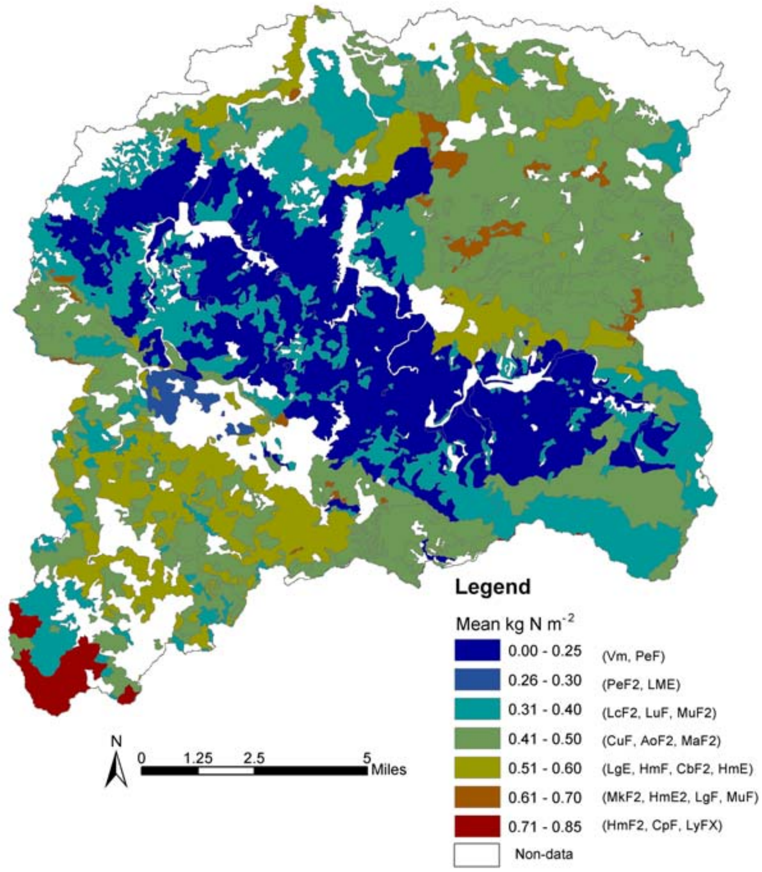


Figure 16. Soil organic nitrogen content by mapping unit in the RGA watershed (kg N m^{-2}, 0-15 cm). See table 4 for descriptions of abbreviations.

Using the intersection of the mapping unit and land use layers another map was developed using ArcMap (v 8.2) (Figures 18 and 19) (Table 8). Greater resolution can be observed in this map compared to the one presented only for mapping unit. The results for SON follow the same pattern as those presented in the SOC maps. The mean N content for depths of 0-15 and 0-100 cm were 0.39 and 1.15 kg N m^{-2}, respectively. The SON estimate to a depth of 0-100 cm for the soils sampled in the watershed (84% of the total land area) is 0.34 x 10^{6} Mg of organic nitrogen.

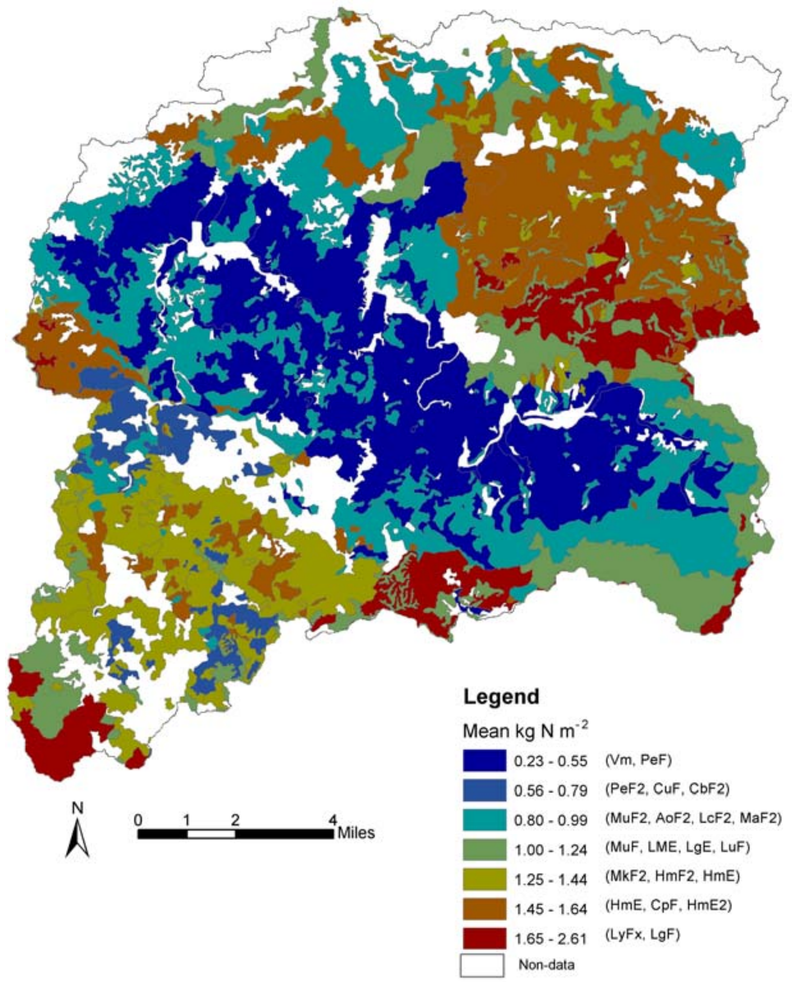


Figure 17. Soil organic nitrogen content by mapping unit in the RGA watershed ($kg\ N\ m^{-2}$, 0-100 cm). See table 4 for descriptions of abbreviations.

A third representation of the N content was made by using the mean N of the soil orders (Ultisols, Inceptisols, and Oxisols). The results of these analyses show that the mean N content for soil order was 0.40 and 1.09 kg N m^{-2} for depths of 0-15 and 0-100 cm, respectively (Figure 20 and Figure 21). The SON estimate to a depth of 0-100 cm for the soils sampled in the watershed (84% of the total land area) is 0.39×10^6 Mg of organic nitrogen.

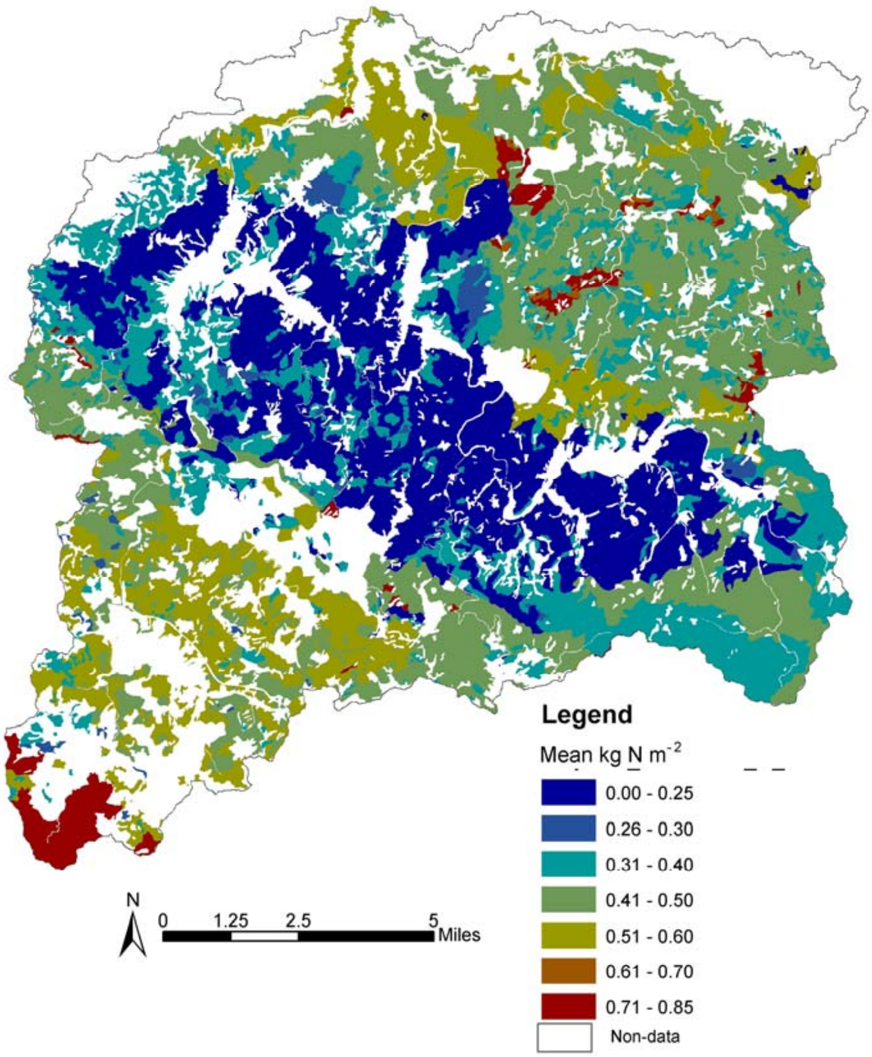


Figure 18. Soil organic nitrogen content across mapping unit and land use in the RGA watershed (kg N m^{-2}, 0-15 cm).

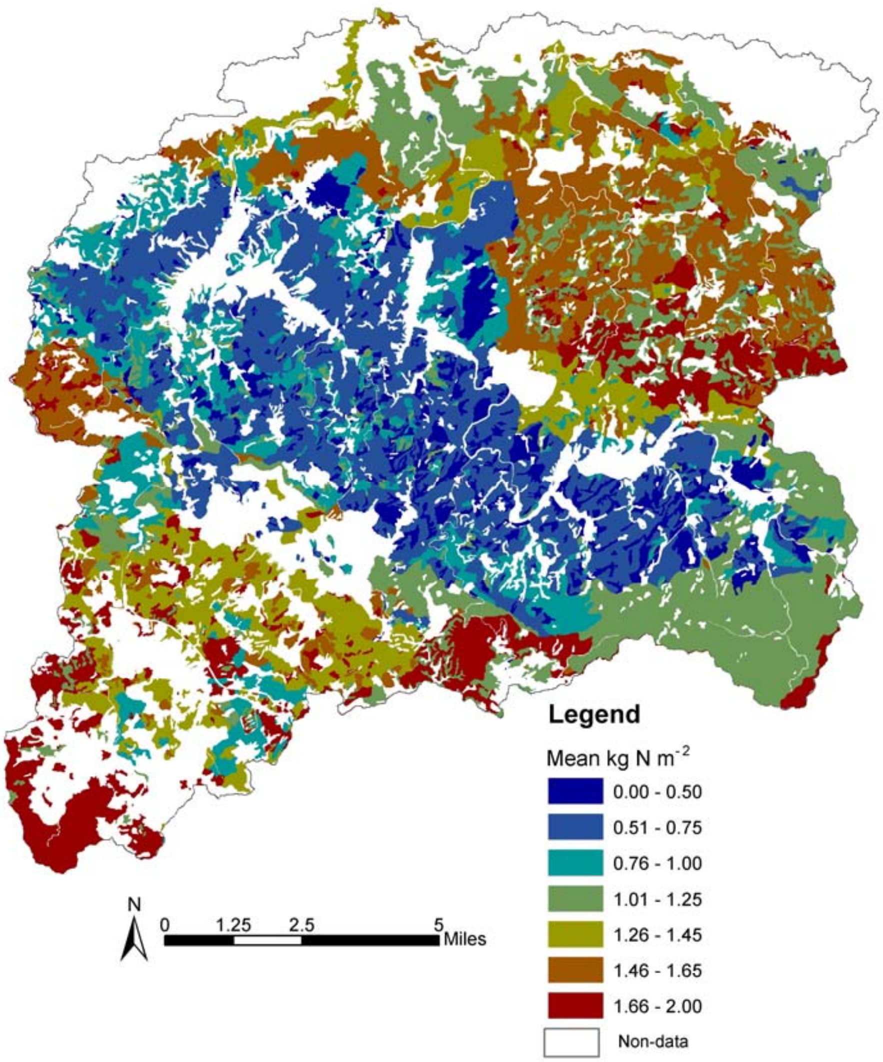


Figure 19. Soil organic nitrogen content across mapping unit and land use in the RGA watershed (kg C m^{-2}, 0-100 cm).

Table 23. Soil nitrogen content across map unit and land use in the RGA watershed.

Land use	Mapping Unit	Mean kg N m^{-2} 0-15 cm	Mean kg N m^{-2} 0-100 cm
agriculture	AoF2	0.15	0.60
	CpF	0.62	1.78
	HmE2	0.49	1.93
	HmF	0.33	1.21
	HmF2	0.43	1.54
	LcF2	0.28	0.49
	LgF	0.38	1.16
	LuF	0.27	1.17
	MaF2	0.16	0.41
	MuF2	0.29	1.02
	PeF	0.20	0.41
	PeF2	0.10	0.44
	Vm	0.08	0.23
forest	AoF2	0.52	1.18
	CbF2	0.43	0.78
	CpF	0.73	1.53
	CuF2	0.39	1.51
	HmE	0.43	1.33
	HmF	0.46	1.54
	HmF2	0.59	1.42
	LcF2	0.36	0.87
	LgE	0.43	1.10
	LgF	0.49	1.66
	LME	0.31	1.03
	LyFX	0.85	2.61
	MaF2	0.49	1.10
	MkF2	0.57	1.66
	MuF	0.58	1.29
	MuF2	0.41	1.16
	PeF	0.23	0.55
	PeF2	0.37	0.73
pasture	CuF2	0.30	0.54
	HmE	0.50	0.44
	HmE2	0.51	1.64
	HmF	0.39	1.68
	HmF2	0.50	1.73
	LcF2	0.36	1.21
	LuF	0.39	1.78
	MkF2	0.40	1.20
	MuF	0.34	0.87
	PeF	0.24	0.50

The last representation of mean soil N content was developed using the land use layer and the mean N content for each land use type (forests, pasture, and agriculture). The results shown in Figure 22 and Figure 23 indicate that the mean N content for land use was 0.36 and 0.98 kg N m^{-2} for depths from 0-15, and 0-100 cm, respectively. The SON estimate to a depth of 0-100 cm for the soils sampled in the watershed (84% of the total land area) is 0.46 x 10^6 Mg of organic nitrogen. Table 24 shows a summary of the N means values for different layers.

Table 24. Soil organic nitrogen in the RGA watershed at different GIS layers.

Layers	SON content kg N m^{-2} Depth (cm)			Area represented (ha)	Nitrogen stocks (10^6 Mg)	n*
	0-15	0-30	0-100			
Map unit	0.38	0.61	1.05	33,322	0.35	22
Map unit & Land use	0.39	0.63	1.08	31,261	0.34	40
Order	0.38	0.61	1.05	41,494	0.40	3
Land use	0.42	0.67	1.18	44,994	0.48	3

* n is the number of experimental units associated with the analyses.

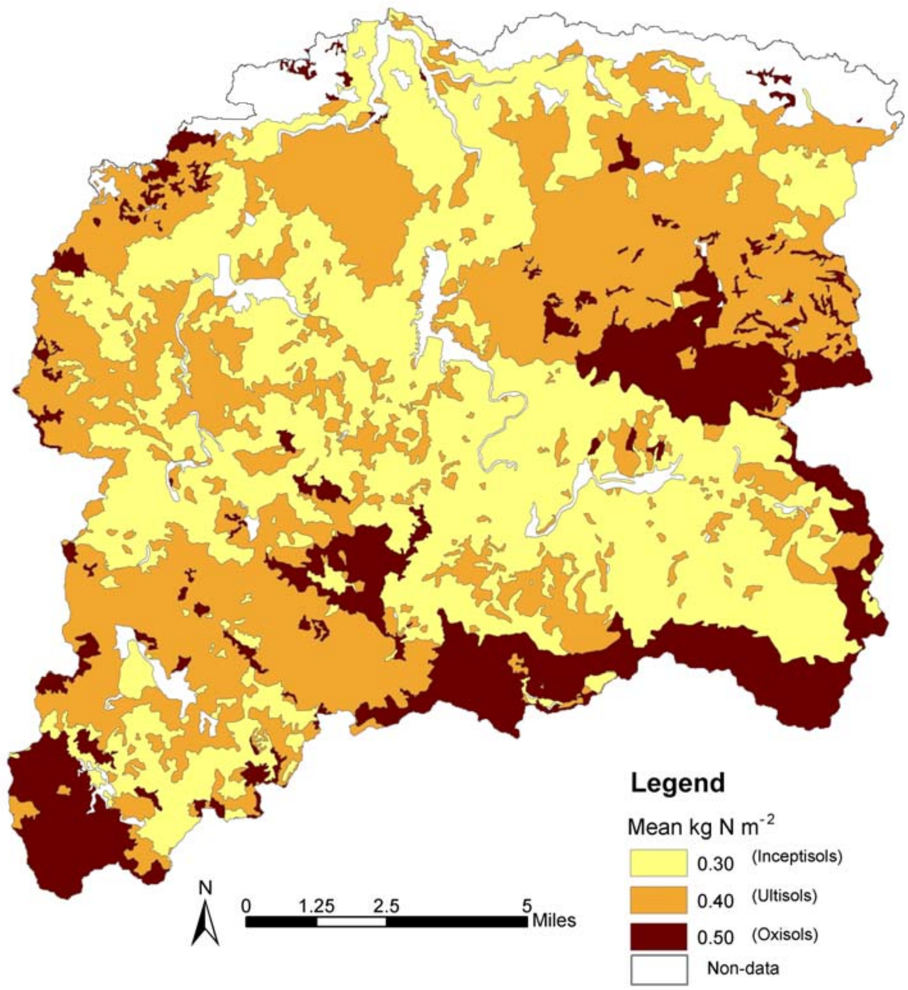


Figure 20. Soil organic nitrogen content by soil order in the RGA watershed (kg N m^{-2}, 0-15cm).

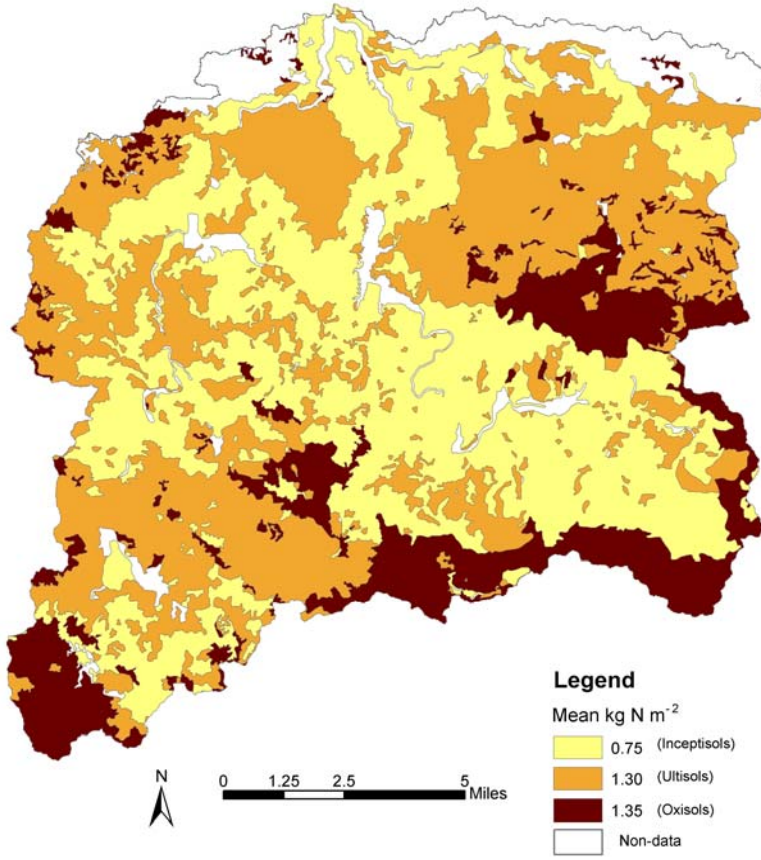


Figure 21. Soil organic nitrogen content by soil order in the RGA watershed ($kg\ N\ m^{-2}$, 0-100cm).

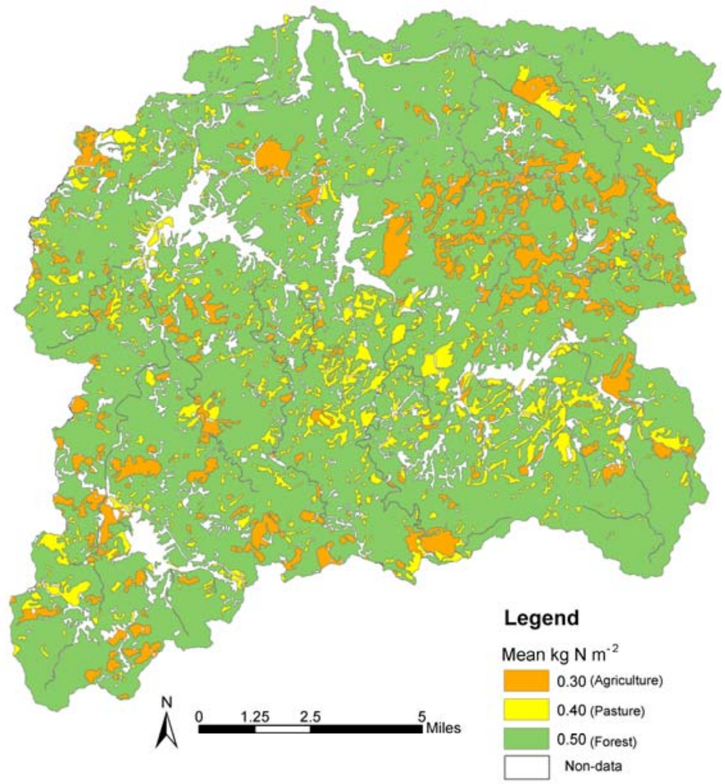


Figure 22. Soil organic nitrogen content by land use in the RGA watershed (kg N m^{-2}, 0-15cm).

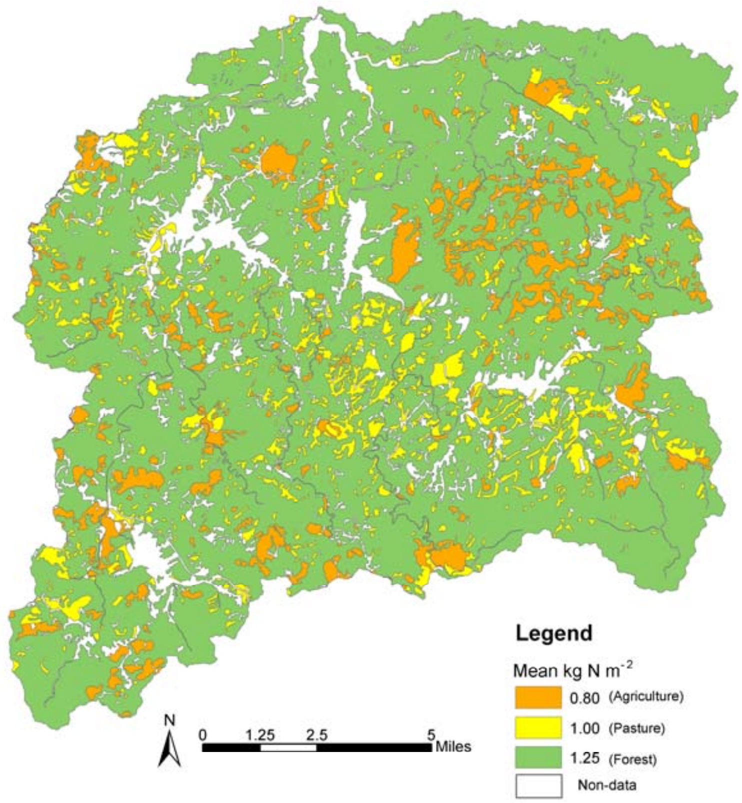


Figure 23. Soil organic nitrogen content by land use in the RGA watershed (kg N m^{-2}, 0-100 cm).

5.3 Soil organic carbon and nitrogen concentrations

SOC and SON concentration were stratified in the soil profiled by soil order (Figures 24 and 26) and by land use (Figures 25 and 27). As expected, higher organic C and N are observed levels noted in the top of the profile compared to the deeper soil depths. The area of greatest variations was in the top three soil depths (0-15, 15-30 and 30-50 cm), with highest changes observed in both SOC and SON concentration. Below 50 cm, few differences were observed within soil depths among different land uses. In contrast, large differences were observed for SOC and SON concentration by soil order. This suggests that Oxisols and Ultisols have greater SOC and SON concentration than the Inceptisols in this watershed.

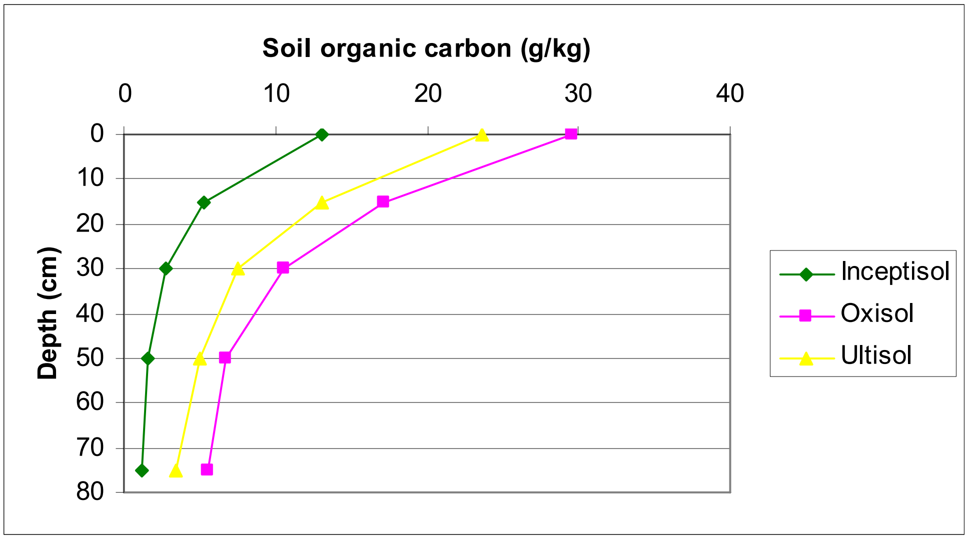


Figure 24. Soil organic carbon concentration by soil orders in the RGA watershed

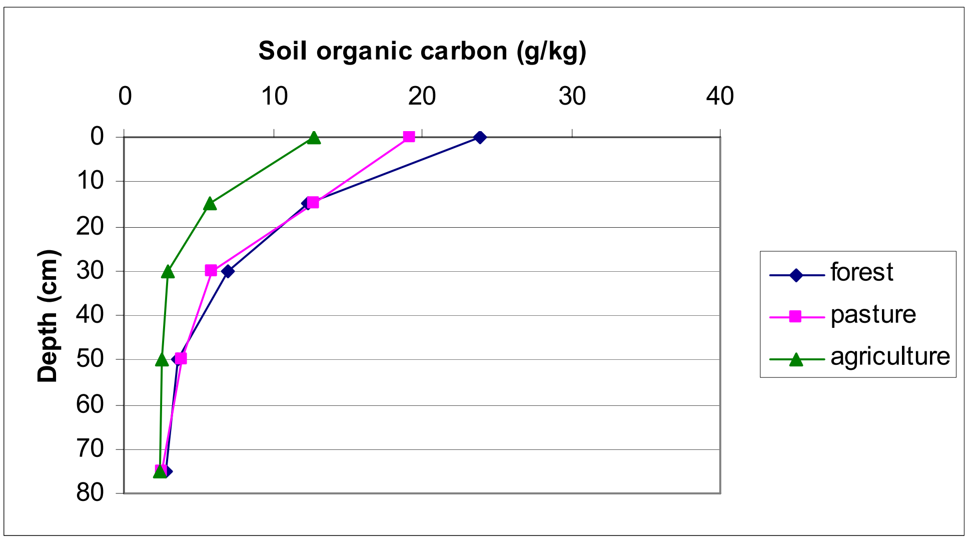


Figure 25. Soil organic carbon concentration by land use in the RGA watershed

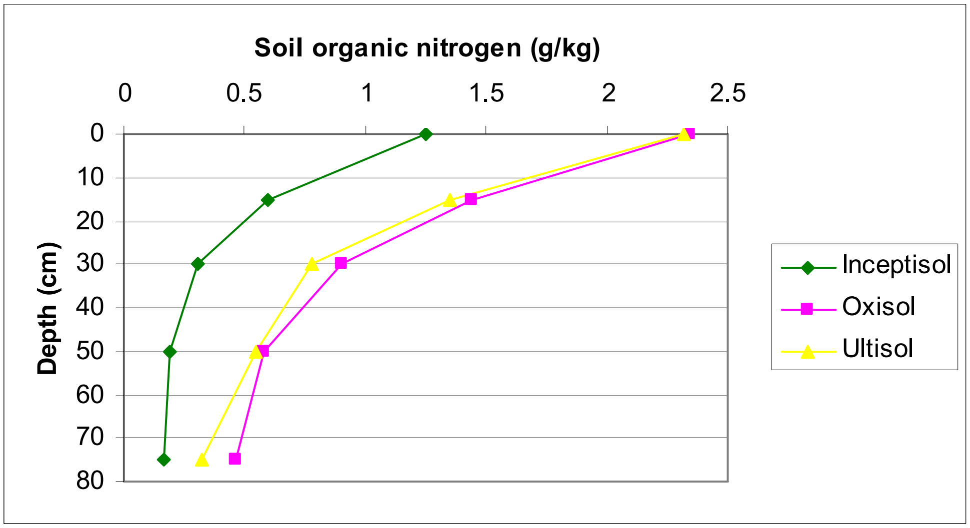


Figure 26. Soil organic nitrogen by soil order in the RGA watershed

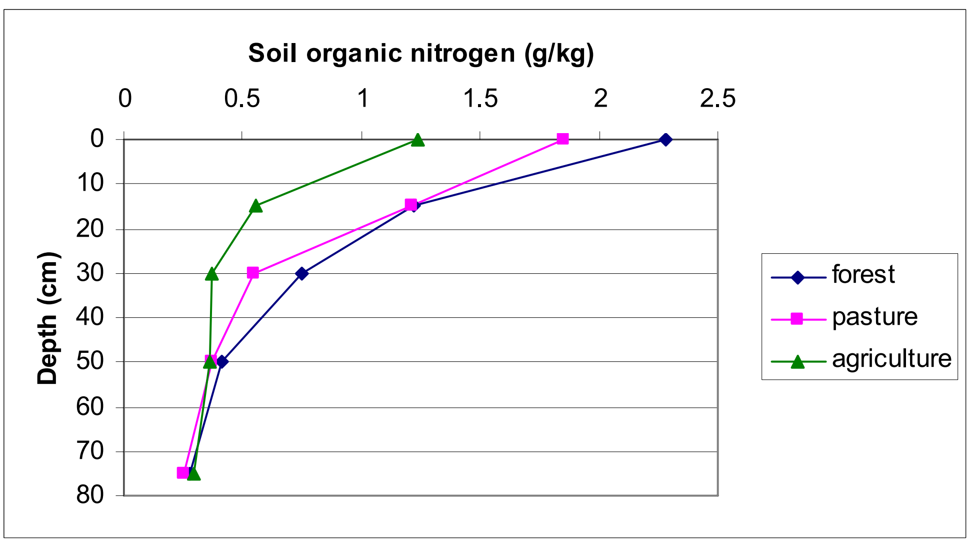


Figure 27. Soil organic nitrogen by land use in the RGA watershed

5.4 Soil organic carbon and soil order

The soil organic carbon was affected significantly by soil order ($P<0.05$) (Table 25). None of the interactions were significant. Oxisols showed higher levels of SOC than Ultisols (16.93 and 13.03 kg C m^{-2}, respectively), which were in turn higher than Inceptisols (6.21 kg C m^{-2}) at a depth of 0-100 cm (Figure 28). At the depth of 0-15 and 0-30 cm, the Oxisols and Ultisols showed similar values and both orders had higher values of SOC than the Inceptisols. For Oxisols (Udox and Ustox) of the Amazon region Morales et al., (1995), reported values between 8.9 and 10.51 kg C m^{-2} at a depth of 0-100 cm in undisturbed tropical forest vegetation. Beinroth (1992) reported values for the whole island that amount to 14.0 kg C m^{-2} in Oxisols, 12.8 kg C m^{-2} in Ultisols and 12.2 kg C m^{-2} in Inceptisols. These results are similar to those presented in this study, except that for Inceptisols which is approximately half of the island-wide estimate. The Oxisols from the RGA watershed are classified as Humic Haplodox according to the Soil Taxonomy (Soil Survey Staff, 1999), which defines for this soil, levels of 16 kg m^{-2} or more of organic carbon between the mineral soil surface and the depth of 100cm.

Table 25. Summary of analysis of variance for soil organic carbon.*

Source	0-15 cm	0-30 cm	0-100 cm
Land use (LU)	<0.0001	<0.0001	<0.0001
Phase (P)	0.2026	0.4957	0.8896
Order (O)	<0.0001	<0.0001	<0.0001
LU x P	0.7391	0.7198	0.9153
LU x O	0.7698	0.7094	0.6806
P x O	0.1232	0.1389	0.0789
LU x P x O	0.5575	0.6268	0.9686

* = significant at the 0.05 level

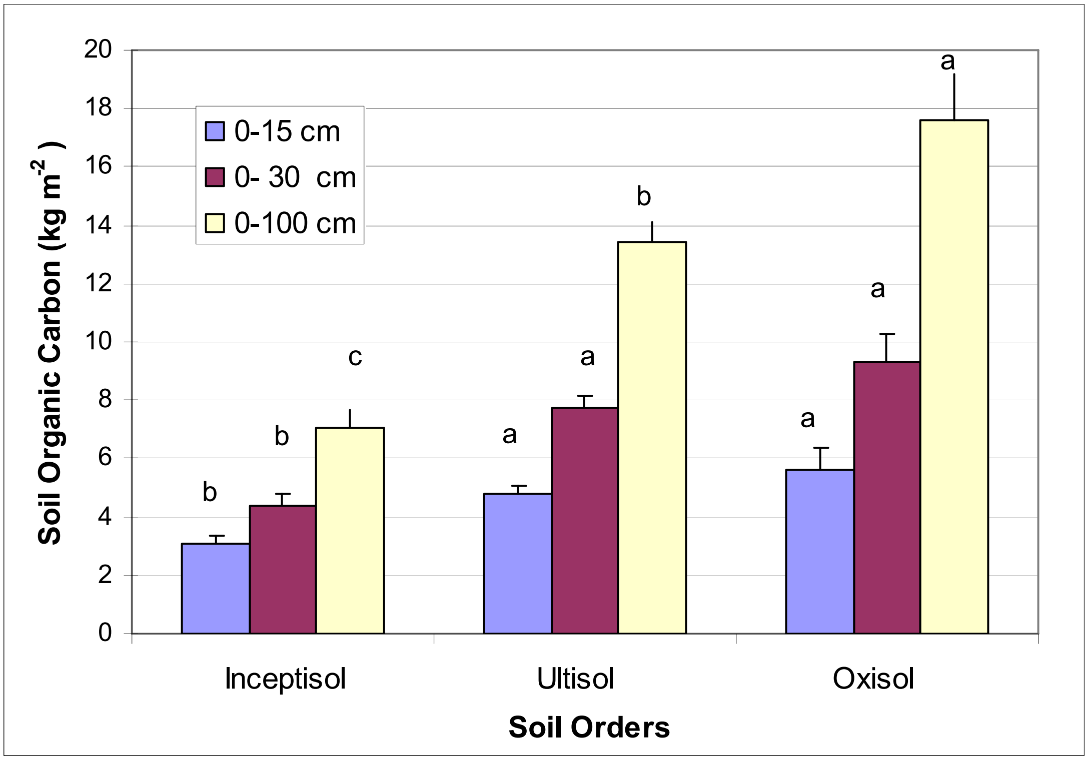


Figure 28. Soil organic carbon among different soil orders within the RGA watershed. Columns of the same color with different letters are significantly different (p<0.05).

5.5 Soil organic carbon and land use

The SOC to a depth of 0-100 cm ranged from 1.63 kg C m^{-2} in agricultural lands to 31.8 kg C m^{-2} in forest lands. The SOC was significantly affected ($P<0.05$) by land use (Table 25). For example, the SOC was significantly lower in agricultural land (7.90 kg C m^{-2}) than in pasture lands (9.79 kg C m^{-2}) and forest lands (12.8 kg C m^{-2}) (Figure 29). Although, the SOC was affected by land use, it was not affected by soil phase (erodable and not erodable). The same pattern was observed in a depth of 0-15 and 0-30 cm. In agreement with these results, Torberts et al. (2004) observer similar values of SOC between forested soil and permanent pasture in clay loam soil to 1m depth. In contrast

Cerri et al. (2003) in Brazil, modeled the impact of converting forest area to pasture on SOC content, and found initial fall in the SOC stock followed by a slow rise. After 88 yr, pasture soil contained 53% more C than the forest soil. Several factors may be responsible for these results such as: the geographical localization and the soil type, the cultural practices and the soil management. These results confirm previous studies (Lal, 2002) in that changes in land use cause losses of SOC due to changes in vegetation and soil management practices. However, some forest sites do not present significant disturbances while others were abandoned agricultural areas that reverted to secondary forest. During and after the conversion from natural to agricultural ecosystems, SOC losses are accentuated; especially when soil erosion and nutrient losses occur (Lal, 2002). However, agricultural land if properly managed can also have great potential for SOC and SON accumulation and storage. Accelerated soil erosion causes the removal and displacement of fine top soil particles and the light fraction of the SOM from the soil surfaces. This material is redistributed over the landscape where it may be easily mineralized. When soil aggregates are broken down, the protected C is exposed to microbial activities. The net effect is a loss of SOC in the soil.

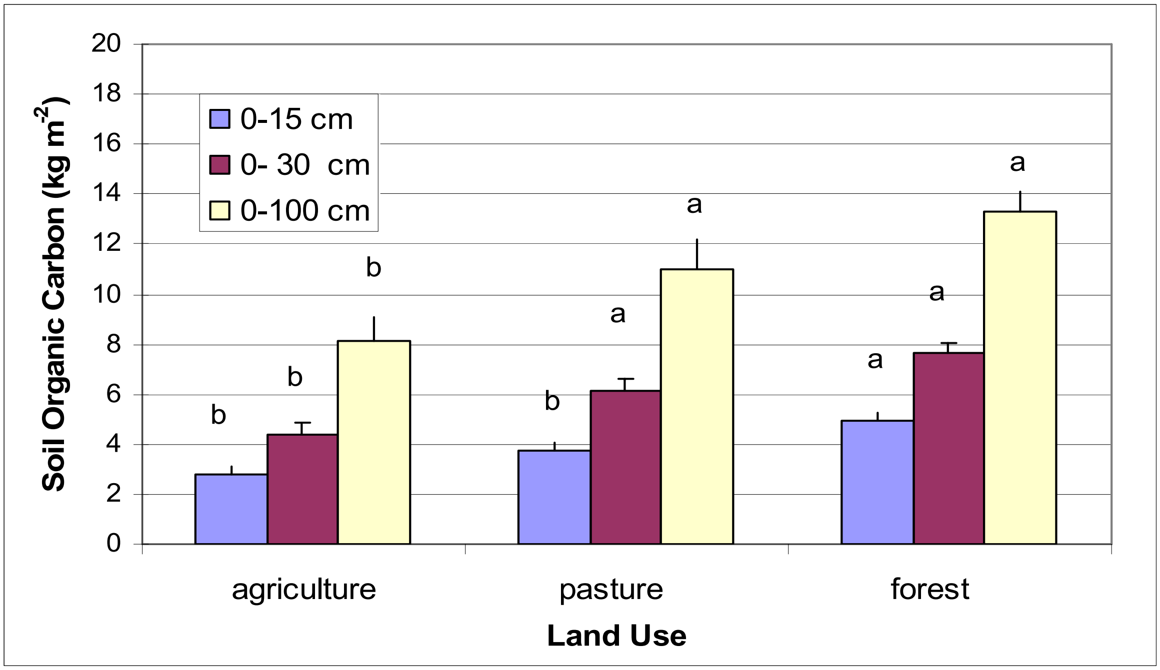


Figure 29. Soil organic carbon among different land uses within the RGA watershed. Columns of the same color with different letters are significantly different (p<0.05).

5.6 Soil organic nitrogen and soil order

The soil organic nitrogen was affected significantly by soil order (P<0.05) (Table 26) but none one of the interactions (land use, phase and soil order) were significant. The SON to a depth of 0-100 cm ranged from 0.23 kg N m^{-2} in agricultural lands to 2.61 kg N m^{-2} in forest lands. The SON was significantly higher in Oxisols than Ultisols to depths of 0-15, 0-30 and 0-100 cm. The SON values in Oxisols and Ultisols were higher than the N values in Inceptisols (Figure 30). The greatest variation by soil order, indicated by the greatest standard error, corresponds to Oxisols (1.34), followed by Inceptisols (0.66) and Ultisols (0.07).

Table 26. Summary of analysis of variance for soil organic nitrogen.*

Source	0-15 cm	0-30 cm	0-100 cm
Land use (LU)	<0.0001	<0.0001	<0.0022
Phase (P)	0.1045	0.2194	0.6220
Order (O)	<0.0002	<0.0001	<0.0001
LU x P	0.6393	0.3637	0.8469
LU x O	0.9001	0.8205	0.8007
P x O	0.2000	0.1401	0.1008
LU x P x O	0.6111	0.6175	0.9672

* = significant at the 0.05 level

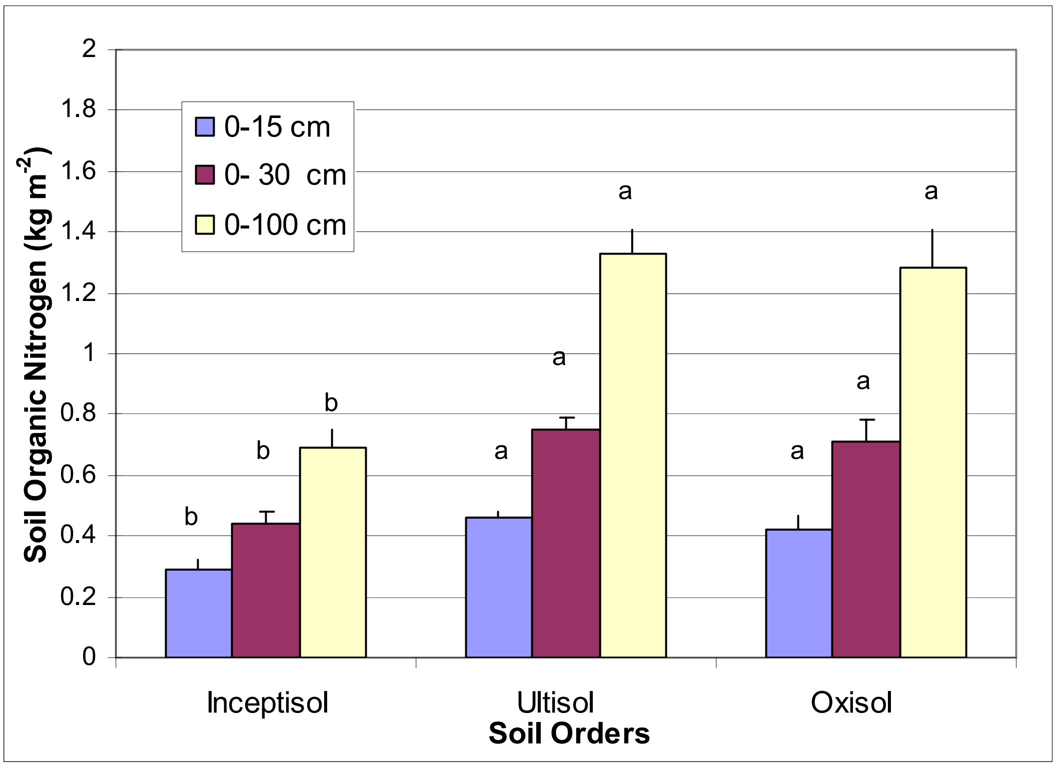


Figure 30. Soil organic nitrogen among different soil orders within the RGA watershed. Columns of the same color with different letters are significantly different (p<0.05).

5.7 Soil organic nitrogen and land use

The SON to a depth of 0-100 cm ranged from 0.23 kg N m^{-2} in agricultural lands to 2.61 kg N m^{-2} in forest lands. At the depth 0-15 cm the SON was significantly higher in forest lands (0.45 kg N m^{-2}), than pasture and agricultural lands (0.36 and 0.28 kg N m^{-2}, respectively). At the 0-30 and 0-100 cm depths, SON was significantly lower in agricultural lands (0.81 kg N m^{-2}), followed by pasture (1.01 kg N m^{-2}) and forest (1.21 kg N m^{-2}) (Figure 31). The depth of 0-15 cm is more susceptible to the losses of SON due changes in land use and management practices.

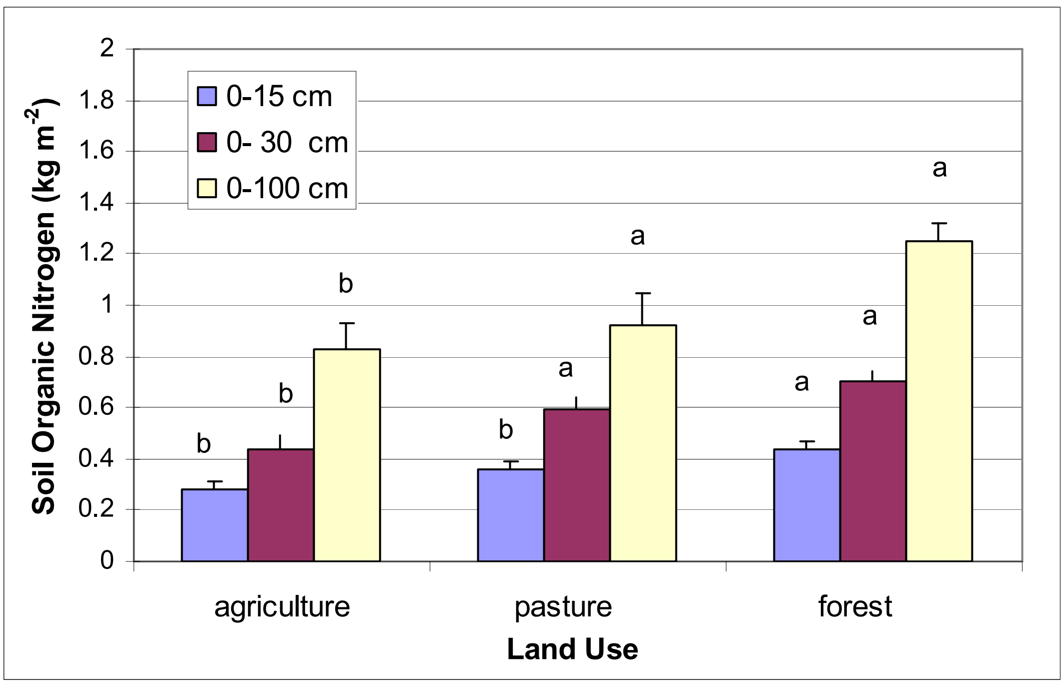


Figure 31. Soil organic nitrogen among different land uses within the RGA watershed. Columns of the same color with different letters are significantly different (p<0.05).

5.8 Eroded and uneroded soil phases

Soil organic carbon was significantly affected ($P<0.05$) by soil phase of the Consumo soil series (Table 27) (Figure 32). The mean SOC content was 7.19 and 15.3 kg C m^{-2} for Consumo uneroded phase (CpF), and 4.17 and 6.09 kg C m^{-2} for Consumo eroded phase (CuF2) at 0-15 and 0-100 cm depth, respectively. The SOC in the others soil mapping units (Humatas, Mucara, and Pellejas) were not affected by soil erosion status.

Table 27. Organic carbon in eroded and uneroded phases in the RGA watershed.

Serie	Map unit uneroded	Order	Map unit eroded	0-15 cm	0-30 cm	0-100 cm
Consumo	CpF	Ultisol	CuF2	*	*	ns
Humatas	HmE	Ultisol	HmE2	ns	ns	ns
Humatas	HmF	Ultisol	HmF2	ns	ns	ns
Mucara	MuF	Inceptisol	MuF2	ns	ns	ns
Pellejas	PeF	Inceptisol	PeF2	ns	ns	ns

* = significant different at the 0.05 level

A priori, one should expect more SOC in uneroded phases than in the eroded ones. The analysis by soil phase in the same mapping unit indicated that only Consumo series has higher amounts of SOC in the uneroded phase. Other series show similar or trend for higher values of SOC in eroded phase. This can be explained because a mapping unit consists of one or more major soils (more dominant soil serie) and some minor soils, and it is named for the major soils (Acevedo, 1982). This characterization of a mapping unit means that a given soil mapping unit comprises several soil series, and that when a sample is taken from a particular site, it can represent one series or other. The same condition applies for eroded vs. non-eroded series: a sample taken from a place within the polygon classified as eroded might not actually be an eroded site. In addition, eroded and uneroded phases within a mapping unit were identified about 30 years ago, which may not reflect what the conditions are today, especially when abandoned agricultural lands are being reverted to secondary forests, and a successional pattern for vegetation development is taking place. Because of these reasons, an update of the soil survey is needed to properly identify eroded and uneroded areas in the present context of the new land use that prevails in the RGA watershed.

The soil organic nitrogen was not significantly affected ($P>0.05$) by soil phase within each mapping unit (Table 28). The Consumo series had significantly more organic nitrogen at a depth of 0-15 and 0-30 in uneroded than in the eroded phase (Figure 33). The mean of SON to uneroded phase (CpF) was 0.69, 1.10 and 1.60 kg C m^{-2} to a depth of 0-15, 0-30 and 0-100 cm, respectively. The eroded phase (CuF2) was 0.36, 0.57 and 0.98 to a depth of 0-15, 0-30 and 0-100 cm, respectively.

Table 28. Organic nitrogen in eroded and uneroded phases in the RGA watershed.

Serie	Map unit uneroded	Map unit eroded	0-15 cm	0-30 cm	0-100 cm
Cunsumo	CpF	CuF2	*	*	ns
Humatas	HmE	HmE2	ns	ns	ns
Humatas	HmF	HmF2	ns	ns	ns
Mucara	MuF	MuF2	ns	ns	ns
Pellejas	PeF	PeF2	ns	ns	ns

* = significant different at the 0.05 level

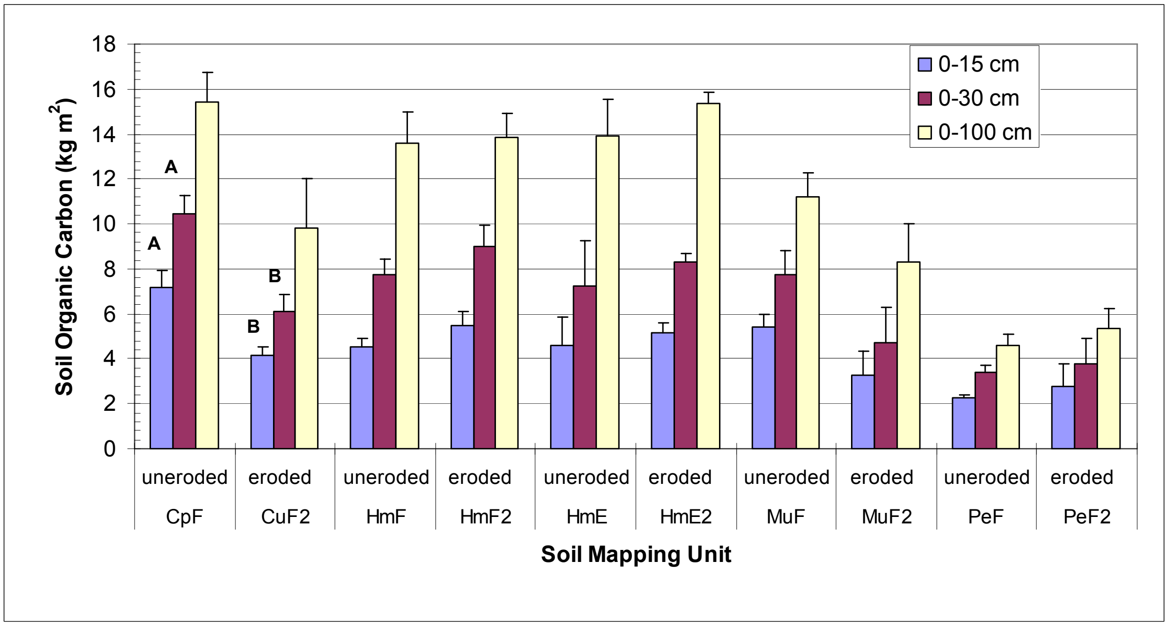


Figure 32. Soil organic carbon by soil mapping unit in different soil phases in the RGA watershed. Columns with the same color and different letters are significantly different ($p<0.05$).

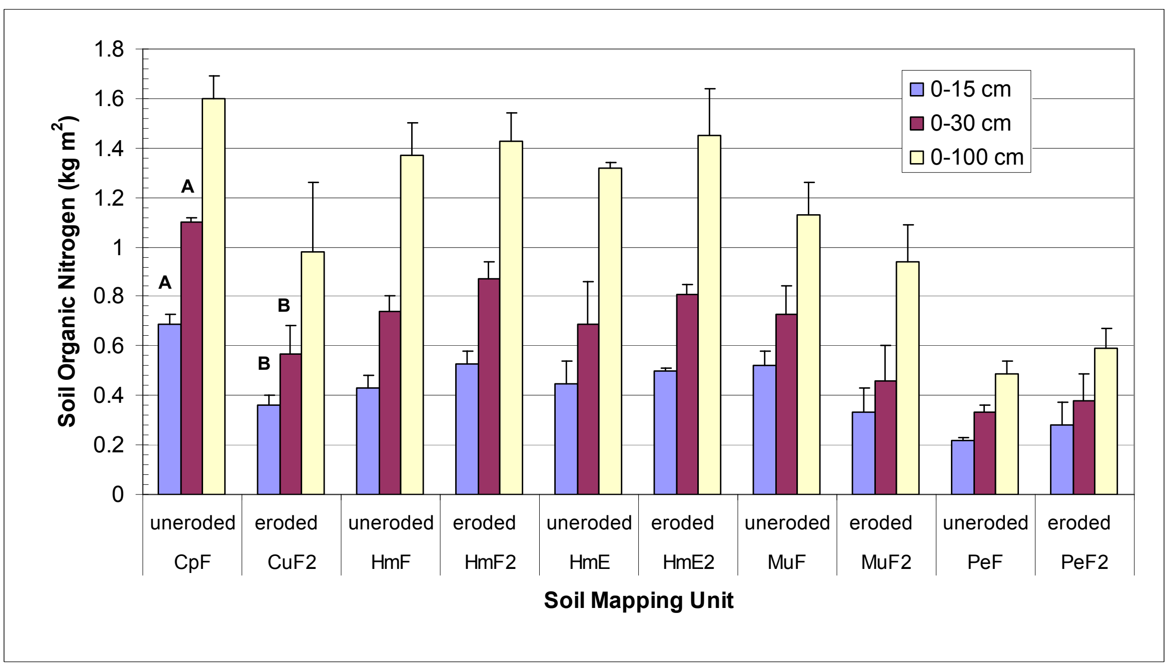


Figure 33. Soil organic nitrogen by mapping unit in different soil phases of the RGA watershed. Columns with the same color and different letters are significantly different ($p<0.05$).

5.9 Soil pH, C:N ratio

The mean pH values to depths of 0-15 cm and 0-100 cm were 5.06 and 4.90, respectively. These estimates and the variability in pH observed are similar to other estimates for tropical soils. For example, Cerri et al. (2003) reported values of 5.59 for forest soils in the Brazilian Amazon Basin .

In terms of C:N ratio, the RGA watershed shows values of 10:1 which falls within the typical values reported for Brazilian soils. For example, Batjes and Dijkshoorn (1999) reported values of C:N that range from 9:1-12:1 ratio in the Brazilian Amazon basin. The general trend of the values (Table 29) suggests a decrease in C:N ratio with depth, which reflects the older age of humus material in the lower parts of the soil profile. The C:N ratio was generally higher and with small variability in the soil profile of the Oxisols than those in Ultisols and Inceptisols, where this ratio tends to be lower at the lower depths of the soil profile. This behavior can be explained because 77% of the Oxisols in the watershed are under forest cover and high values of precipitation, which favors the conditions for leaching of carbon to lower depths in the soil profile (Lugo and Brown, 1993).

Table 29. Distribution of C:N ratio as a function of depth by soil orders.

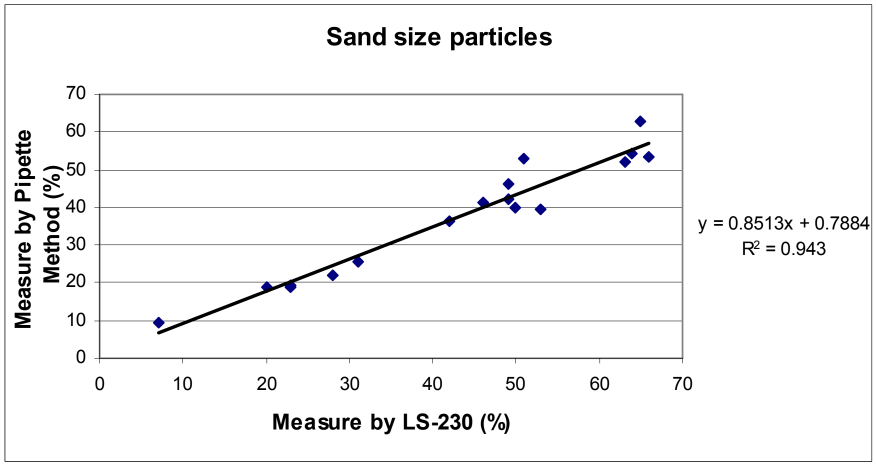
Order	Depth (cm)	Mean	S.E.	Min	Max
Inceptisols	0-15	10.18	0.16	8.42	13.9
	15-30	9.28	0.26	1.24	12.05
	30-50	8.96	0.29	3.48	16.34
	50-75	8.73	0.31	5.4	14.25
	75-100	7.86	0.31	1.04	12.25
Oxisols	0-15	13.41	0.94	8.11	19.86
	15-30	12.75	0.76	9.71	17.39
	30-50	12.24	0.76	9.04	16.98
	50-75	12.61	0.82	9.61	18.29
	75-100	12.21	0.85	8.43	17.9
Ultisols	0-15	10.41	0.19	8.23	15.58
	15-30	10.1	0.19	8.13	14.26
	30-50	9.8	0.22	6.6	13.08
	50-75	9.64	0.26	5.68	13.59
	75-100	9.83	0.39	5.42	17.57

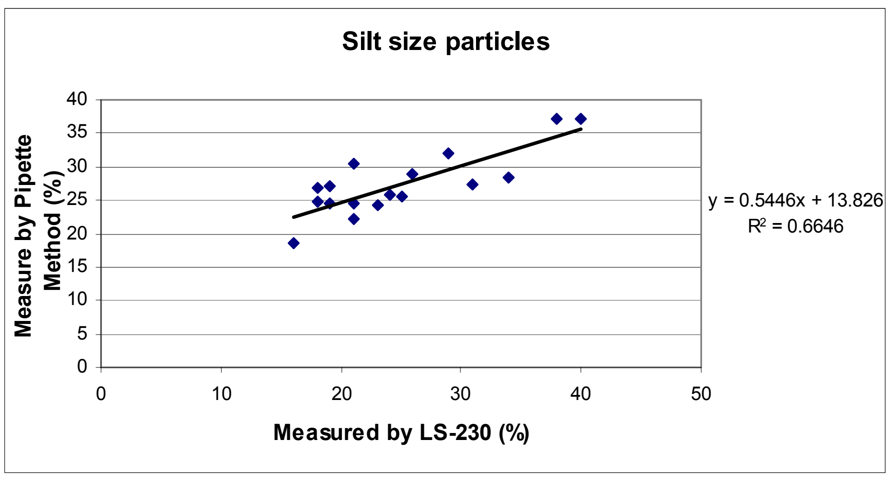
5.10 Soil texture

The determination of soil texture using the LS-230 has been positively and significantly correlated to the pipette method as shown in Figure 34. In general, the Oxisols and Ultisols have a clay texture and Inceptisols have a clay loam texture (Table 30). The Pearson correlation coefficient between SOC and clay content was 0.36 for Ultisols, 0.49 for Oxisols and 0.72 for Inceptisols. The SON Pearson correlation coefficient was 0.33 for Ultisols, 0.39 Oxisols and 0.78 for Inceptisol (Figure 35). The figure generally showed a positive correlation with total SOC and SON contents, suggesting that clay soils facilitate the formation of passive C and N pools with slow turnover due to the physical protection of SOM by clay minerals (Silver et al., 2000b). In the study by Beinroth et al., (1996), the strongest correlation between SOC and quantitative soil variables was obtained when grouping the soils according to clay content. As shown in Figure 31, the majority of the Inceptisols present in the RGA watershed have lower clay content than Oxisols and Ultisols, indicating that the lower the clay content, the lower the SON and SOC contents, and vice versa. This indicated that soil with high clay content had higher potential to sequester C and N than soil with low clay content and confirm that the soil organic carbon and nitrogen content are strongly influenced by the clay content.

Table 30. Particle size distribution among soil orders (0-15 cm).

Order	Particle size	Mean	S.E.	Min	Max	Textural Classification
Inceptisols	Sand	39.15	2.34	9.76	68.37	Clay loam
	Silt	28.40	1.01	18.56	45.31	
	Clay	32.45	1.83	13.07	63.46	
Oxisols	Sand	16.63	0.92	12.11	20.53	Clay
	Silt	32.31	1.97	20.87	41.98	
	Clay	51.07	2.08	38.04	59.05	
Ultisols	Sand	21.73	1.38	8.17	45.14	Clay
	Silt	31.96	0.82	21.85	47.41	
	Clay	46.31	1.30	30.50	66.33	





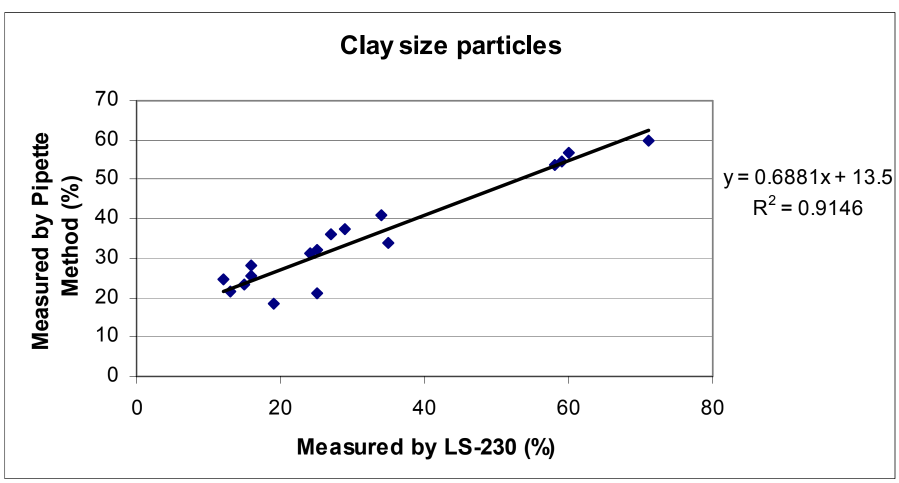
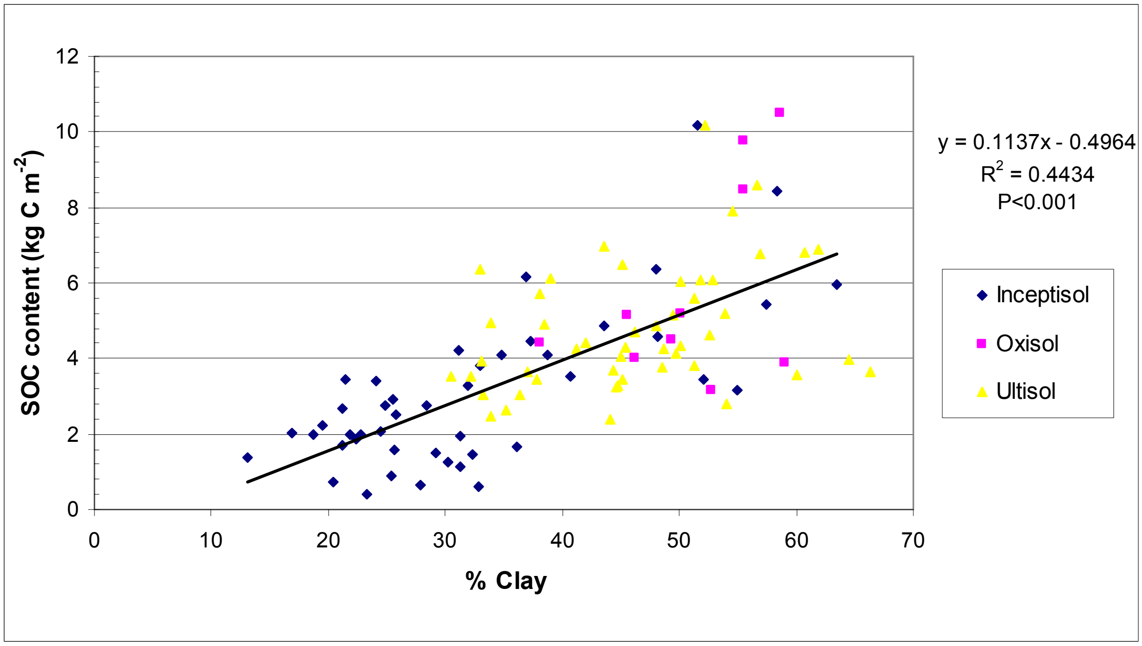


Figure 34. Soil texture correlation between pipette and LS 230 method.



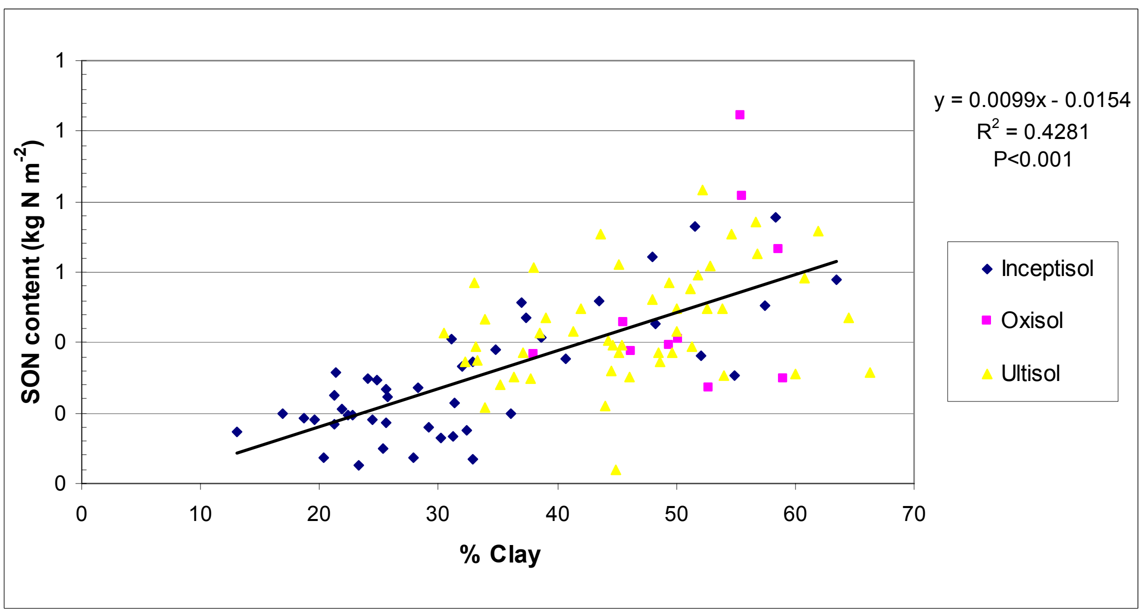


Figure 35. Correlation between clay content and SOC and SON.

6. Conclusions and Recommendations

In general, SOC and SON in the RGA watershed is in accord with values reported by Beinroth et al (2003). The spatial distribution of the SOC and SON in the RGA watershed, serves as a baseline for the evaluation of the effects of land use and land use changes and the potential for soil carbon and nitrogen sequestration at the watershed level. The use of the Geographic Information System proved useful in terms of sampling strategy, field sample location and spatial analysis of the soil characteristics. With this tool, sampling points can be re-sampled in the future to determine SOC and SON changes.

The separation of soil mapping units in their respective land use improves the SOC and SON estimates and the resolution of the spatial distribution. The greater the resolution on the spatial distribution, the better the SOC and SON estimates. The spatial distribution map represented by soil order and land use type showed a more generalized map of the spatial distribution of soil C and N, because several mapping units are integrated within the same soil order and/or land use type when the layers are combined. This causes changes in total land area of analysis and in the estimation of carbon and nitrogen stocks in the RGA watershed.

The soils sampled in the watershed (84% of the total land area) contain 3.61×10^6 Mg of organic carbon and 0.38×10^6 Mg of organic nitrogen to a depth from 0 to 100 cm, or to a lithic or paralithic contact if it was shallower. These estimates increase with a decrease of the map resolution, because in the processes of generalization by soil order or by land use type, the total land area of analysis is increased. The effects of land use on soil carbon and nitrogen sequestration suggest that forest and pasture lands hold the majority of soil organic carbon and nitrogen. This suggest that in order to increase soil C sequestration it is necessary to establish management practices that are conducive to maintain the soil aggregates and maintain the SOC and SON stable and protected from microorganism decomposition (Sotomayor et al., 2004).

To improve the results, it is recommended that an update of the soil survey be performed to properly identify eroded and uneroded areas in the present context of the new land use that prevails in the RGA watershed.

The development and adoption of conservation and sound management practices for these areas with low SOM will be needed in order to maintain an increase in the soil organic carbon levels. The SOC and SON pools can be increased only if inputs into the soil, such as plant biomass, crop residue, manure or compost exceed outputs which are in the form of oxidation, erosion or leaching. Because the SOC and SON are concentrated in the soil surface, it is important to adopt corrective management practices for the eroded soils, especially in agricultural lands. The conservation and accretion of forest area in the RGA watershed will help increase the SOC and SON in soils. Additional information may be of assistance to landowners and land use planners to facilitate the adoption of sustainable land use practices that will lead to an increase of organic C and N levels in the soil.

7. Literature cited

Acosta-Martínez V, Zobeck TM, Allen V (2004) Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci Soc Am J (in press)

Acevedo, G. 1982. Soil Survey of Arecibo Area Northern Puerto Rico. USDA Soil Conservation Service in coop. with Univ. Puerto Rico College of Agric. Sciences, U.S. Gov. Printing Office, 268-941/29. Washington, DC, 81pp., 41maps.

Balesdent, J., Chenu, C., Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil and Tillage Research 53: 215-220.

Batjes, H. N. 2000. Effects of mapped variation in soil conditions on estimates of soil carbon and nitrogen stocks for South America. Geoderma 97:135-144

Batjes, H. N., and Dijkshoorn, J.A. 1999. Carbon and nitrogen stocks in the soils of the Amazon region. Geoderma 89:273-286

Beinroth, F.H., G. Acevedo, B.C. Dubee, A.M Esnard, P.J. Hernandez, L.H. Liegel, M.A.Lugo-Lopez, 1992. Organic carbon sequestration in the soil of Puerto Rico-A case study of a tropical environment. University if Puerto Rico, Mayagüez Campus, and USDA Soil Conservation Services, Dept. of Agronomy and Soil, UPR, Mayagüez, P.R. 00681-9030, 68pp

Beinroth, F.H., M.A. Vázquez, V.A. Snyder, P.F.Reich and L.R.Pérez Alegría, 1996. Factors controlling carbon sequestration in tropical soils – A case study of Puerto Rico.University if Puerto Rico, Mayagüez Campus, and USDA Soil Conservation Services, Dept. of Agronomy and Soil, UPR, Mayagüez, P.R. 00681-9030, 63pp

Beinroth, F.H., M.A. Vázquez, and L.J. Olivieri 2003. Carbon Sequestration in Soils of the Rio Grande de Arecibo Watershed, West-Central Puerto Rico. J. Agri. Univ. P.R. 87:51-57.

Brown, S., and A. E. Lugo. 1982. The storage and production of organic matter in tropical forest and their role in the global carbon cycle. Biotropica 14: 161-187.

Burke M. Lauretta and D. A. Lashof. 1990. Greenhouse gas emissions related to agriculture and land use practices. In: Impact of carbon dioxide, trace gases, and climate change on global agriculture. American Society of Agronomy, Madison Wisconsin. ASA Special Publication 53: 27-30

Buyanovsky, G.A., Aslam, A., and Wagner, G.H. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58:1167-1173.

Cambardella, C.A., and E.T. Elliot. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grasslands soils. Soil Sci. Am. J. 57: 1071-1076.

Cambardella, C.A., and E.T. Elliot. 1994. Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grasslands soils. Soil Sci. Soc. Am.J.58:123-130.

Carter M. R., D.A. Angers, E.G. Gregorich, and M.A. Bolinder. 2002. Characterizing organic matter retention for surface soil in eastern Canada using density and particle size fractions. Can. J. Soil Sci. 77:205-210

Cerri C.E.P., K.Coleman, D.S. Jenkinson, M.Bernoux, R.Victoria and C.C. Cerri. 2003. Modeling soil carbon from forest and pasture ecosystems of Amazon, Brazil. Soil Sci. Am. J. 67: 1879-1887.

CSA Group. 2000. Land use map of the Rio Grande de Arecibo Watershed. Unpubl. Data.

Dwiprabowo Hariyatno and Y C. Wulan. 2003. A description of the Citanduy watershed, west java and preliminary analysis of carbon sequestration potential by smallholders. Working paper CC09, ACIAR project ASEM 1999/093, http://www.une.edu.au/febl/Econ/carbon/.

ESRI - Environmental System Research Institute. 2000. TIGER/Line Data file published by U.S. Bureau of the Census for the United States.

Franzluebbers, A.J., F.M Hons, and D.A. Zuberer. 1995. Soil organic carbon, microbial biomass, and mineralizable carbon and nitrogen in sorghum. Soil Sci. Soc. Am. J. 59:460-466.

Feller C. and Beare, M.H. 1997, Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69-116

Gierbolini, R.E., G.Acevedo, J.Torres Mas, E. Ortiz Torres, and L.H. Rivera, 1979. Soil survey of Ponce area of southern Puerto Rico. USDA Soil Conservation Service in coop. with Univ. Puerto Rico College of Agric. Sciences, U.S. Gov. Printing Office, 268-941/29. Washington, DC, 81pp., 41maps.

Greenland, D.J., Wild, A., and Adams, D. 1992. Organic matter dynamics in soil of the tropics: From myths to complex reality. In "Myths and Science of Soils of the Tropics". R. Lal and P.A. Sanchez, Eds. SSSA Special Publication No 29:17-33

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil fertility and fertilizers: an introduction to nutrient management. Sixth Ed. Prentice-Hall Inc. Upper Saddle River. New Jersey 07458.

Ingram, J.S.I., Fernandes, E.C.M., 2001. Managing carbon sequestration in soils: concepts and terminology. Agric. Ecosyst. Environ. 87, 111–117.

Jobbagy G. Esteban and R.B. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate vegetation. Ecological Applications.10:423– 436

Kaye J.P., J. Barret., and I Burke. 2002. Stable nitrogen and carbon pools in grassland soils of variable texture and carbon content. Ecosystems 5:461-471.

Kimble J.M., R. Lal., and R.F. Follett. 2001. Methods for assessing soil C pools. P. 3-12. In R. lal, J.M Kimble, R.F Follett, and B.A Stewart (ed). Assessment methods for soil carbon. CRC Press, Boca Raton, FL.

Lal, R. 2002. The potential of soil of the tropics to sequester carbon and mitigate the greenhouse effect. Adv. Agron. 76: 1-30.

Lal, R. 2000a. Mitigation of climatic change by soil carbon sequestration: Issues of science, monitoring, and degraded lands. Adv. Agron. 70:2-62.

Lal, R. 2000b. World cropland soils as a source or sink for atmospheric carbon. Adv. Agron. 71:145-174

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science magazine. Vol. 30: 1623-1627.

Lal, R., Kimble, J.M., 2000. Tropical ecosystems and the global carbon cycle. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.), Global Climate Change and Tropical Ecosystems. CRC–Lewis Publishers, Boca Raton, FL, pp. 3–32.

Li, Z. and Zhao, Q. 2001. Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. Plant and Soil 231, 175–185.

Lugo, A. E. and S. Brown, 1993. Management of tropical soil as sinks or sources of atmospheric carbon. Plant and soil 149:27-41.

Morales J.L., C.C Cerri,, J.M. Mellilo, D. Kichlighter, C. Neill, D.L Skole, , P.A. Steudler. 1995. Soil Carbon stocks of the Brazilian Amazon Basin. Soil Sci. Soc. of Am. J. 59:244-247.

Motavalli P.P.., H. Discekici, and J. Kuhn. 2000. The impact of land clearing and agricultural practices on soil organic C fractions and CO_2 efflux in the Northern Guam aquifer. Agriculture, Ecosystems and Environment 79:17-27.

National Park Service. 2004. Using biosolids for reclamation and remediation of disturbed soils. http://www.nps.gov/plants/restore/pubs/biosolids/design.htm

NASA earth observatory. 2004. The carbon cycle. http://earthobservatory.nasa.gov/Library/CarbonCycle/carbon_cycle4.html

Paustian, K., Six, J., Elliott, E.T. and Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147–163

Silver , W.L. , R. Ostertag, and A.E. Lugo. 2000a. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restoration Ecology: 8:394-407.

Silver W.L., Neff. J., McGroddy M., Veldkamp E., Keller M., and Cosme R. 2000b. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. Ecosystems 3:193-209.

Six, J., E.T. Elliot and K.Paustian.1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J 63:1350-1358.

Six Johan., Feller C., Denef K., Ogle S.M., Morales C.J. ans Albrecht A. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils – Effects of no-tillage. Agronomie 22:755-775.

Smith, S. V., W. H. Renwick, R. W. Buddenmeier, and C. J. Crossland. 2001. Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States, Global Biogeochem. Cycles, 15:697– 707

Soil Survey Staff 1996. Soil survey laboratory manual. USDA-SCS National Soil Survey Center Soil Survey Investigations Report 42, Version 3. U.S. Government Printing Office, 732 N. Capitol Street, NW, Washington DC 20401.

Soil Survey Staff, 1999. Soil Taxonomy – A basic system of soil classification for making and interpreting soil survey, 2nd ed. USDA Natural Resources Conservation Service, Agric. Handbook no. 436, U.S. Gov. Printing Office, Washington, DC, 81pp., 41 maps.

Soil Survey Staff. 2004. National Soil Survey Characterization Data Soil Survey Laboratory National Soil Survey Center USDA-NRCS - Lincoln, NE. http://ssldata.nrcs.usda.gov/

Sotomayor-Ramirez. David., L. R. Perez., Y. Espinosa., L Cruz., F.H Beinroth. 2004. Organic carbon pools and active fractions in soils from diverse land uses in a tropical watershed. Abstract, Soil Sci. Soc Am. 68th Annual Meeting, Oct 31-Nov 4, Seattle Washington.

Space Imaging, LLC, 2001. Satellite Images from IKONOS 1 meter resolution for the Island of Puerto Rico.

Trumbore, S.E. 1993. Comparison of carbon dynamics in tropical and temperate soil using radiocarbon measurements. Global Biogeochemical Cycles. vol. 7:275-290.

Trumbore, S.E., E.A. Davidson, P. Barbosa de Camargo, D.D. Nepstad,. L.A Martinelli,. 1995.Belowground cycling of carbon in forests and pastures of eastern Amazonia. Global Biogeochemical Cycles 9: 515-528.

United Nations, 1992. The Río Declaration on Environment and Development Conference on Environment and Development. Río de Janeiro. 3 to 14, June 1992. http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

U.S. Bureau of the Census for the United States. 2000. Census 2000 Data for Puerto Rico. http://www.census.gov/census2000/states/pr.html

USDA Natural Resources Conservation Service. 2001. Detailed Soil Survey Data for GIS (SSURGO). United States Department of Agriculture. http://www.ftw.nrcs.usda.gov/ssur_data.html.

Weaver, P. L., R. A. Bindsey, and A. E. Lugo, 1987. Soil organic matter in secondary forest of Puerto Rico. Biotropica 19:17-23.

8. Appendices

Appendix A. Field data sheet

Rio Grande de Arecibo Watershed
Soil Sampling Protocol

- Sample Site Identification:____

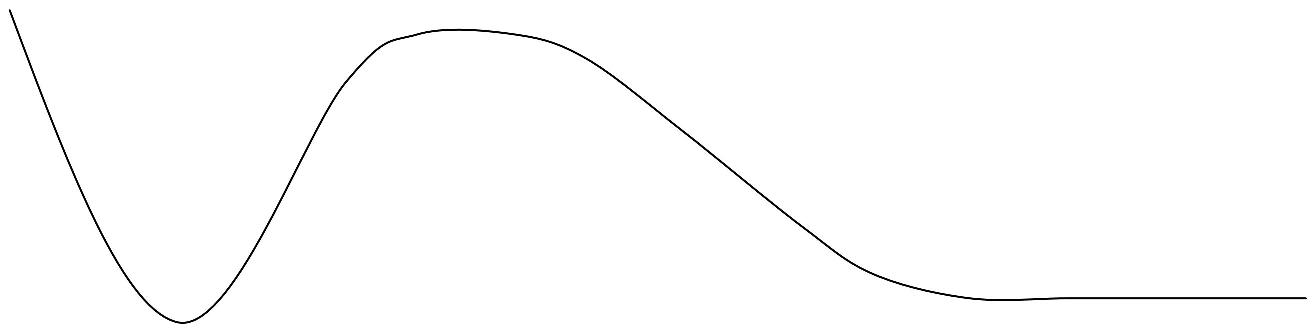
- Sample Sie Data:

Longitude	Latitude	Elevation	Slope	Geology	Slope aspect	Vegetation	Land use

- Sample Identification

0-15 cm	Site-id + a	
15-30cm	Site-id + b	
30-50cm	Site-id + c	
50-75cm	Site-id + d	
75-100cm	Site-id + e	

- Sample Site Geomorphology:



- Land Use Description

Vegetation	
Relief	
Land Use	

Appendix B. Mean carbon and nitrogen concentration by soil order, land use and soil mapping unit

Order	g/kg of carbon				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
Inceptisol	13.11	5.2165	2.79	1.634	1.171
Oxisol	29.56	17.185	10.54	6.7495	5.5735
Ultisol	23.68	13.1	7.474	4.98	3.385

Land Use	g/kg of carbon				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
forest	23.875	12.305	6.969	3.597	2.806
pasture	19.16	12.755	5.8945	3.9395	2.558
agriculture	12.7	5.805	3.01	2.518	2.371

Mapping unit	g/kg of carbon				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
AoF2	19.36	9.41	6.96	3.07	1.7
CbF2	25.26	6.69	7.57	3.88	1.42
CpF	34.48	18.1	10.11	5.5	2.94
CuF2	20	10.57	6.51	4.53	1.79
HmE	26.08	12.03	8.67	8.37	3.93
HmE2	28.79	13.94	9.71	6.44	7.42
HmF	26.93	14.58	8.75	6.03	4.57
HmF2	29.71	15.98	7.96	5	2.66
LcF2	17.79	9.75	5.93	3.58	2.5
LgE	31.72	15.07	9.89	8.56	2.85
LgF	33.75	18.83	12.89	10.24	9.89
LME	34.58	20.62	9.97	6.07	6.09
LuF	23.42	18.49	11.68	8.22	4.87
LyFX	58.03	28.55	12.21	7.16	9.02
MaF2	23.47	10.93	5.51	2.72	2.22
MkF2	25.25	12.14	9.11	7.69	8.93
MuF	28.76	12.48	4.97	2.82	3.75
MuF2	17.47	7.57	4.65	3.17	4.13
PeF	10.16	4.82	2.11	1.15	0.78
PeF2	14.16	4.2	1.61	0.87	2.88
Vm	3.24	0.91	0.79	0.69	0.55

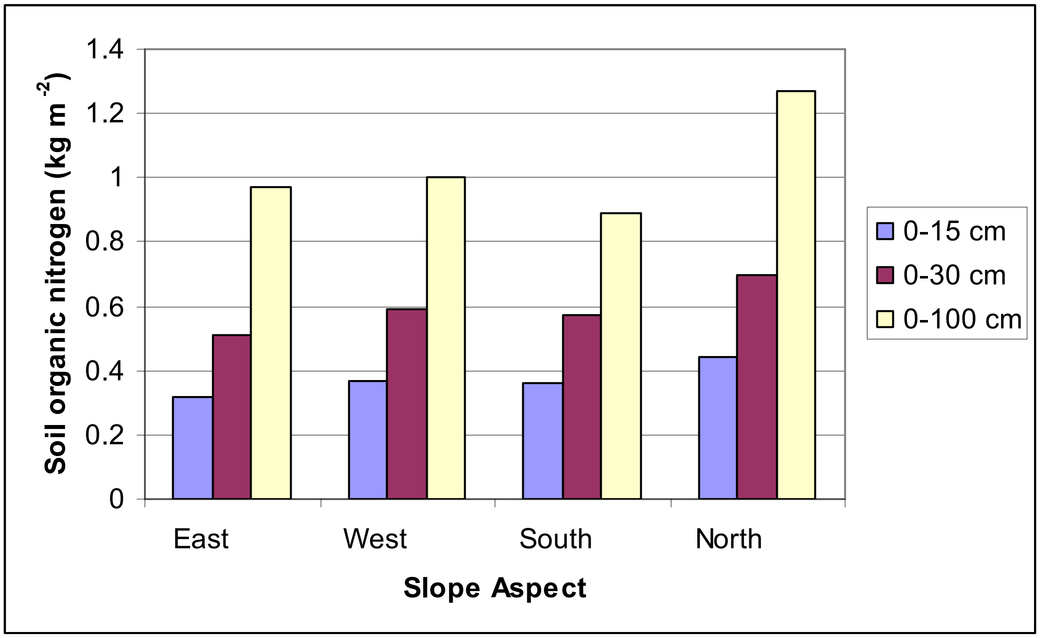
Appendix B. (Continued)

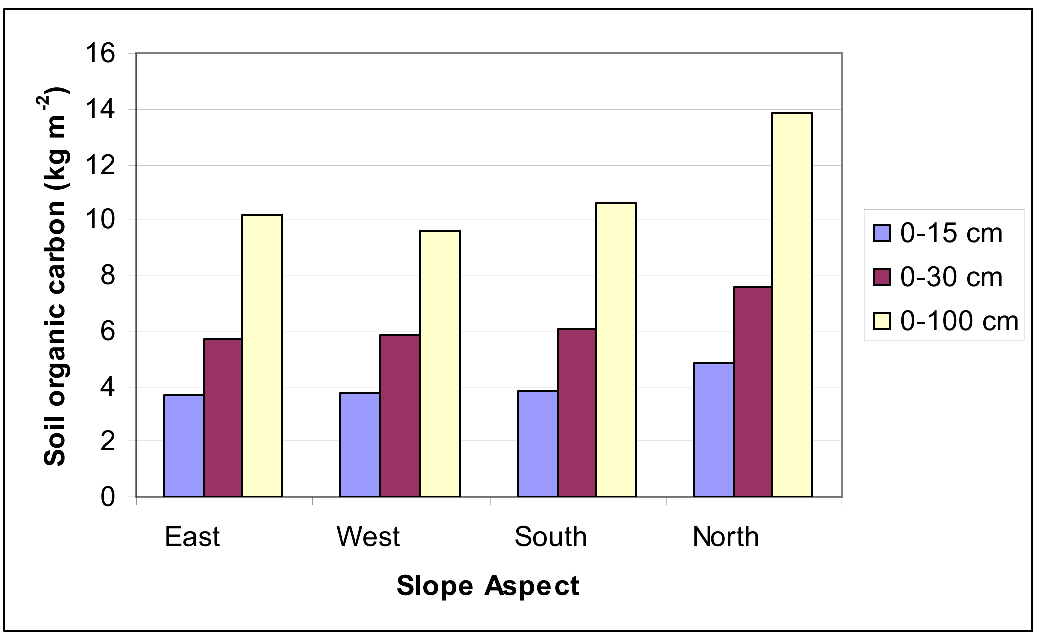
Order	g/kg of nitrogen				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
Inceptisol	1.248	0.598	0.304	0.187	0.164
Oxisol	2.3465	1.441	0.905	0.577	0.4635
Ultisol	2.317	1.35	0.779	0.543	0.325

Land Use	g/kg of nitrogen				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
forest	2.2815	1.2205	0.7475	0.414	0.274
pasture	1.8495	1.216	0.5485	0.373	0.251
agriculture	1.238	0.559	0.368	0.358	0.2935

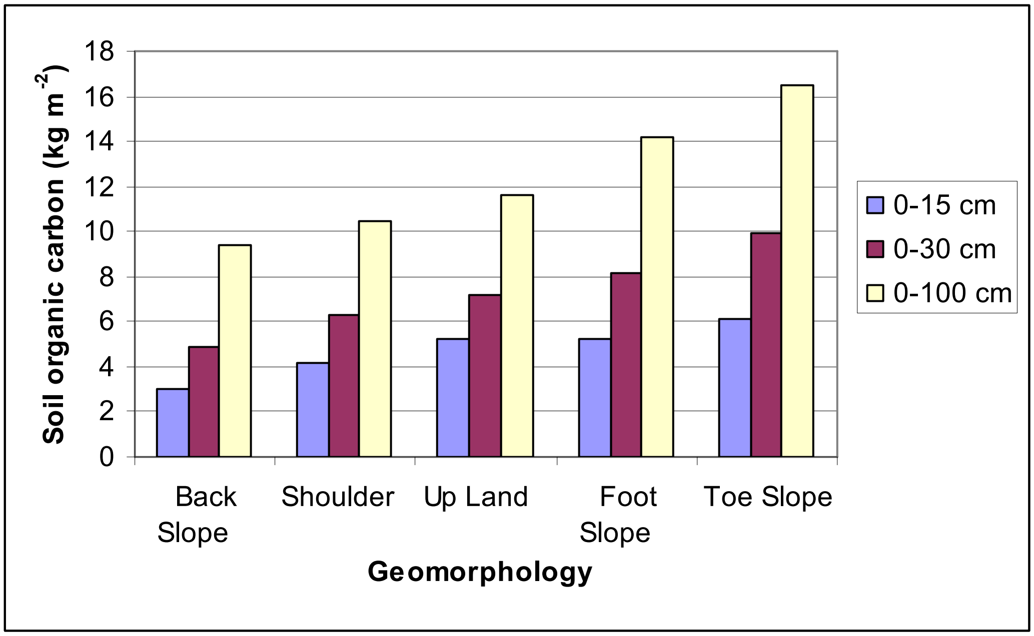
Mapping unit	g/kg of nitrogen				
	0-15 cm	15-30 cm	30-50 cm	50-75 cm	75-100 cm
AoF2	1.84	0.94	0.69	0.35	0.19
CbF2	2.14	1.27	0.74	0.35	0.16
CpF	3.32	1.86	1.01	0.6	0.23
CuF2	1.72	0.99	0.69	0.47	0.22
HmE	2.53	1.13	0.82	0.82	0.32
HmE2	2.8	1.46	0.97	0.64	0.79
HmF	2.54	1.51	0.92	0.66	0.48
HmF2	2.88	1.61	0.85	0.54	0.31
LcF2	1.65	0.93	0.55	0.34	0.24
LgE	2.65	1.26	0.89	0.81	0.21
LgF	2.84	1.68	1.22	0.94	0.94
LME	1.9	1.2	0.6	0.36	0.34
LuF	2.03	1.82	1.14	0.77	0.48
LyFX	5.23	2.24	1.06	0.63	0.79
MaF2	2.26	1.13	0.59	0.28	0.24
MkF2	2.32	1.17	0.85	0.71	0.75
MuF	2.76	1.24	0.56	0.34	0.44
MuF2	1.78	0.76	0.53	0.43	0.6
PeF	1	0.5	0.23	0.13	0.11
PeF2	1.42	0.46	0.19	0.14	0.37
Vm	0.33	0.14	0.12	0.13	0.11

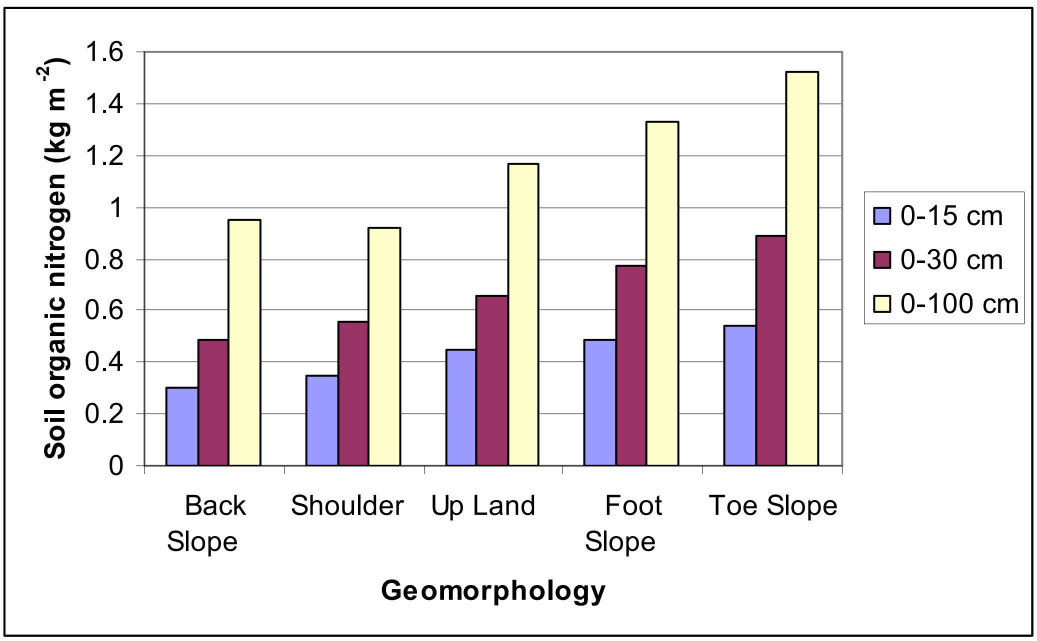
Appendix C. Soil organic carbon and nitrogen by slope aspect and geomorphology





Appendix C. (Continued)





Appendix D. Statistical Analysis

Variable	N	R^2	R^2 Aj	CV
kg-m-2 C 0-15	107	0.42	0.34	40.62

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	198.51	13	15.27	5.17	<0.0001
Land use	97.38	2	48.69	16.49	<0.0001
Phase	4.86	1	4.86	1.65	0.2026
Orden	80.96	2	40.48	13.71	<0.0001
Land use*Phase	1.79	2	0.90	0.30	0.7391
Land use*Orden	5.35	4	1.34	0.45	0.7698
Phase*Orden	7.15	1	7.15	2.42	0.1232
Land use*Phase*Orden	1.02	1	1.02	0.35	0.5575
Error	274.63	93	2.95		
Total	473.14	106			

Variable	N	R^2	R^2 Aj	CV
kg-m-2 C 0-30	107	0.50	0.43	37.43

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	574.17	13	44.17	7.09	<0.0001
Land use	219.02	2	109.51	17.59	<0.0001
Phase	2.91	1	2.91	0.47	0.4957
Orden	319.42	2	159.71	25.65	<0.0001
Land use*Phase	4.11	2	2.05	0.33	0.7198
Land use*Orden	13.36	4	3.34	0.54	0.7094
Phase*Orden	13.87	1	13.87	2.23	0.1389
Land use*Phase*Orden	1.48	1	1.48	0.24	0.6268
Error	578.98	93	6.23		
Total	1153.15	106			

Variable	N	R^2	R^2 Aj	CV
kg-m-2 C 0-100	97	0.59	0.52	37.17

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	1999.20	13	153.78	9.08	<0.0001
Land use	363.18	2	181.59	10.73	0.0001
Phase	0.33	1	0.33	0.02	0.8896
Orden	1540.05	2	770.03	45.48	<0.0001
Land use*Phase	3.00	2	1.50	0.09	0.9153
Land use*Orden	39.03	4	9.76	0.58	0.6806
Phase*Orden	53.59	1	53.59	3.17	0.0789
Land use*Phase*Orden	0.03	1	0.03	1.6E-03	0.9686
Error	1405.25	83	16.93		
Total	3404.46	96			

Appendix D.(Continued)

Variable	N	R^2	R^2 Aj	CV
kg-m-2 N 0-15	107	0.34	0.25	41.01

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	1.24	13	0.10	3.70	0.0001
Land use	0.59	2	0.30	11.47	<0.0001
Phase	0.07	1	0.07	2.69	0.1045
Orden	0.48	2	0.24	9.32	0.0002
Land use*Phase	0.02	2	0.01	0.45	0.6393
Land use*Orden	0.03	4	0.01	0.26	0.9001
Phase*Orden	0.04	1	0.04	1.67	0.2000
Land use*Phase*Orden	0.01	1	0.01	0.26	0.6111
Error	2.39	93	0.03		
Total	3.63	106			

Variable	N	R^2	R^2 Aj	CV
kg-m-2 N 0-30	107	0.43	0.35	38.13

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	3.89	13	0.30	5.31	<0.0001
Land use	1.42	2	0.71	12.63	<0.0001
Phase	0.09	1	0.09	1.53	0.2194
Orden	2.04	2	1.02	18.09	<0.0001
Land use*Phase	0.12	2	0.06	1.02	0.3637
Land use*Orden	0.09	4	0.02	0.38	0.8205
Phase*Orden	0.12	1	0.12	2.21	0.1401
Land use*Phase*Orden	0.01	1	0.01	0.25	0.6175
Error	5.24	93	0.06		
Total	9.12	106			

Variable	N	R^2	R^2 Aj	CV
kg-m-2 N 0-100	97	0.47	0.39	39.03

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	13.23	13	1.02	5.78	<0.0001
Land use	2.33	2	1.17	6.62	0.0022
Phase	0.04	1	0.04	0.24	0.6220
Orden	10.02	2	5.01	28.44	<0.0001
Land use*Phase	0.06	2	0.03	0.17	0.8469
Land use*Orden	0.29	4	0.07	0.41	0.8007
Phase*Orden	0.49	1	0.49	2.75	0.1008
Land use*Phase*Orden	3.0E-04	1	3.0E-04	1.7E-03	0.9672
Error	14.63	83	0.18		
Total	27.86	96			