Chapter 10

Soil Organic Carbon Sequestration in the Caribbean

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INTRODUCTION

Soil organic matter (SOM) provides services that can be described as "soil fertility" functions from the farmer's viewpoint, and " environmental" functions as they are perceived by society (Feller et al., 2001). This chapter focuses on the environmental functions of SOM for soil organic carbon (SOC) sequestration for the Caribbean region (Biome C).

In Chapter 2, Cerri et al. reported that soil carbon sequestration (SoilCseq) must not be confused with the classical notion of soil C storage. SoilCseq is not only storage of carbon (C) in the soil but also the balance of all greenhouse gases (GHGs = CO_2, CH_4, N_2O) fluxes at the soil-plant-atmosphere interface. This balance is considered for a given area and a given span of time, and expressed on an equivalent C- CO_2 (eqC) basis tak-

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Carbon Sequestration in Soils of Latin America

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ing into account the global warming potential (GWP) of each GHG involved in the balance with reference to CO_2 (Bernoux, Feller, et al., 2005a). This chapter on Biome C does not address consideration the non-CO_2 gases. It is concerned more with soil C storage than SoilCseq. In accord with other chapters, the term "soilCseq" rather than soil C storage is also used in this chapter. The case studies presented in this chapter are those of the French West Indies (e.g., Martinique and Guadeloupe) and Haiti. Indeed, soils of these islands are representative of Biome C.

POPULATION AND LAND USE

Population

The data in Table 10.1 show the change in population between 1961 and 2002. Total population increased at the rate of about 8 to 9 million inhabitants every 20 years due mainly to increase in urban population. The rural population remained relatively constant.

General Land Use for Biome C

The data in Table 10.2 show that agricultural area increased over 40 years from 9.8 to 13.1 Mha and represented about 57.3 percent of the total land area in 2002. Permanent pastures are the dominant land use, but the main change occurred in the permanent crops increasing from 0.93 Mha in 1961 to 2.2 Mha in 2002.

Detailed Land Uses in 2002 for "Arable Land" and "Permanent Crops" for Biome C

Agriculture is characterized by a very large diversity of cultivated plants, including 30 crops. Area planted to sugarcane is the largest, with 27.2 per-

TABLE 10.1. Population of Biome C.

	Population (million inhabitants)		
Area	**1961**	**1980**	**2002**
Rural	12.2	13.4	13.9
Urban	8.3	15.8	23.8
Total	20.4	29.3	37.7

Source: Based on data from FAO, 2004.
Note: Rural population did not increase during the 40-year period.

TABLE 10.2. Land use in Biome C.

Land use	Mha		
	1961	**1980**	**2002**
Total area	23.5	23.5	23.5
Land area (3+4+5)	22.9	22.9	22.9
Agricultural area (31+32+33)	9.8	12.4	13.1
Arable land	3.7	4.9	4.9
Permanent crops	0.9	1.7	2.2
Permanent pasture	5.1	5.9	6.0
Forest and woodland	4.0	4.4	nd
All other land (mountains, urban, mines, etc.)	9.0	6.1	nd
Waterbodies (1-2)	0.6	0.6	0.6

Source: Based on data from FAO, 2004.
Note: Note the importance of permanent pastures but also the increase of permanent crops over the past 20 years.

cent of the total area, and 14 crops represent 82 percent of the total area. Sugarcane, maize, rice, coffee, and banana (including plantain) are the main crops (Table 10.3).

In Martinique and Guadeloupe, banana and sugarcane are the principal crops (Bernoux et al., 2004). In Haiti, however, the cereal-legumes are the dominant agroecosystems.

Martinique's and Haiti's Agricultures

Martinique

Martinique is part of the French West Indies (14°N, 60°W) and an overseas department of France. Its surface area is about 1,100 km^2, and its population is about 433,000 inhabitants (in 2005). The GDP per capita is US$14,400 (in 2003), which is one of the highest in the Caribbean region. Agriculture accounts for 6 percent of GDP, while the industrial sector accounts for 11 percent and services for 83 percent. The economy is mainly based on sugarcane, bananas, tourism, and light industry. Rum and bananas are exported to Europe. Martinique is characterized by a strong decrease in the cropped area between 1973 and 2000 (37 percent decline) and in the number of farms (from 15,284 in 1989 to 8,039 in 2000) (François et al., 2004).

At the end of the nineteenth century, Martinique's agriculture was predominantly based on sugarcane. Today, bananas and sugarcane occupy 30

TABLE 10.3. Area under "arable land" and "permanent crops" for Biome C.

	Area harvested in 2002	
Crop	**ha**	**%**
Sugar cane	1,292,474	27.23
Maize	409,611	8.63
Rice, paddy	401,630	8.46
Coffee, green	297,353	6.26
Cassava	196,110	4.13
Beans, dry	196,047	4.13
Bananas	166,987	3.52
Cocoa beans	162,222	3.42
Plantains	160,430	3.38
Coconuts	139,236	2.93
Sorghum	133,037	2.80
Sweet potatoes	131,599	2.77
Vegetables, fresh	105,521	2.22
Mangoes	102,348	2.16
Partial sum in % sum		82.05
Pumpkins, squash, gourds	76,823	1.62
Oranges	73,774	1.55
Yams	56,026	1.18
Cow peas, dry	50,470	1.06
Tobacco leaves	49,709	1.05
Tomatoes	48,685	1.03
Partial sum in % sum		89.54
Fruit, fresh	43,402	0.91
Groundnuts in shell	41,929	0.88
Grapefruit and pomelos	31,710	0.67
Roots and tubers	28,360	0,60
Cucumbers and gherkins	27,713	0.58
Yautia (cocoyam)	25,506	0.54
Pigeon peas	23,120	0.49
Avocados	21,558	0.45
Partial sum in % sum		94.67
Others (n = 44)		5.33
Total sum		100.00

Source: Based on data from FAO, 2004.

percent and 12 percent of the usable agricultural area, respectively. Bananas represent the main part of agricultural production (58.4 percent). Vegetable crops represent 12 percent of the usable agricultural area and 28 percent of the total production. A large part of the agricultural area is under extensive pastures even if intensive pastures (irrigated and fertilized) have recently been introduced in the southeast of the islands on Vertisols. Most banana farms (43 percent) are <3 ha (they represent 3 percent of production), 4 percent of farms are between 20 and 50 ha (30 percent of production), and 2 percent are >50 ha (50 percent of production). The number of sugarcane farms decreased from 1,100 in 1980 to 300 in 2000.

Up to now, agricultural production has been intensive, based on high inputs (mechanical tillage, fertilizers, and pesticides), especially for bananas, and food crops and vegetables. With increasing environmental impacts (especially pollution by chlordecone), however, there is a tendency to reduce tillage and fertilizer and pesticide inputs and to use organic residues. For instance, conventional banana systems are replaced with sustainable systems: planting of "in vitro" plants (which highly decreases pesticide inputs), rotation with sugarcane or pineapple. Sugarcane is now harvested without burning to trash. There are still large problems associated with intensive vegetable crops and there is now a strong conviction of practicing organic farming.

Bananas are mainly grown on Nitisols (clayey brown tropical soils) developed on volcanic ash with rainfall of 2,000 to 3,000 mm per year. Sugarcane is grown in drier areas on Ferralsols and Vertisols (1,500 to 2,500 mm per year). Vegetable crops are grown all over Martinique, but especially in the south on Vertisols (driest area, with rainfall of 1,500 mm per year).

Haiti

With a surface area of about 27,750 km^2 (18-20°N, 71.5-73.5°W), and a population of 8 million inhabitants, this country's economy is mainly based on agriculture involving food staples. Yet the country is prone to food deficits. The per capita GDP is about US$460 (www.worldbank.org), which is lower than that of many sub-Saharan African countries, and also much lower than the average for Latin America and the Caribbean.

The land-use changes during the twentieth century (Bellande, 2004, unpublished data) were very important with a substantial decrease in areas occupied by natural ecosystems (from 50,000 to less than 1,000 ha) and under shifting cultivation (from 800,000 ha to 15,000 ha), a decrease (from 450,000 to 2000 ha) in "tree crops" (coffee- fruit- banana- root crop intercropping) and a large increase (from 75,000 to 1,050,000 ha) in cropland and urban land (from 2,000 to 50,000 ha).

An average peasant farmer comprises a family of about five, land holdings of about 2 ha, and one or two hand tools (hoe, machete) for cropping. About 80 percent of these farms are located in the uplands, under humid seasonal climates (7 to 9.5 months humid), where highly weathered and leached soils (Fe-Al oxides, Ferralsols) are dominant (Cabidoche, 1994). Others are located in the lowlands, under wet-dry climate (4.5 to 7 months humid) and on Vertisols, Mollisols, and shallow soils as dominant soil types. Only 11 percent of the lowland agricultural land is irrigated.

In the uplands, climatic conditions allow cropping throughout the year. The bean-maize intercrop (BMI) for instance, very common in these regions, can be grown either twice a year on the same field or once a year, in rotation with a market gardening crop or in rotation with a short fallow of about eight months. This fallow, during which only some annual wild species have time to grow and be grazed by the few animals, may have an important impact, not only on C sequestration, but more particularly, on the decrease of *Fusarium* inoculum for the following bean crop (Clermont-Dauphin et al., 2003). The use of fertilizers and pesticides is often limited to cash crops. For example, on the limestone Plateau des Rochelois, (altitude of 900 m) the 60-day cabbage crop (*Brassica oleracea* D.C) introduced into the rotation along with the BMI receives on average 128-35-133 $kg{\cdot}ha^{-1}$ N-P-K in the form of urea, triple superphosphate, and potassium sulphate, respectively.

In the lowlands, cereal-legume intercrops are the dominant system. Main species on irrigated land are bean, maize, and rice. In contrast, sorghum, cowpea, pigeon pea *(Cajanus cajan),* and cassava *(Manihot utilissima)* are dominant crops in the nonirrigated land. There is no fallowing, and each farmland is cropped every year. Mineral fertilizer is mainly used on irrigated lands.

Whatever the climatic region, most of the crop residues are returned to the soils of each farm. These residues are partly grazed by the cattle tethered on the fields after harvest and partly decomposed as a source of organic matter. The woody parts are piled up and burned on the fields before replanting. With grain yields ranging from 0.3 to 1 $Mg{\cdot}ha^{-1}$ for bean, and 0.5 to 1 $Mg{\cdot}ha^{-1}$ for maize and sorghum, respectively, these Haitian annual cropping systems leave on the fields between 0.5 to 2 $Mg{\cdot}ha^{-1}$ of residues each year. There is no off-farm input of crop residues or organic matter.

The forest land meets about 71 percent of the energy needs of Haiti, which corresponds to about three to four times higher than the annual forestry or agroforestry production estimated at about 1.6 million m^3 (BDPA/SCET-AGRI/World Bank, 1990). Beyond the reduction of the forest area, one can underline that in many situations it has been to a certain extent replaced with small clusters of different types of mixed tree crop systems with a range of tree densities. These do not appear as large continuous areas of perennial cover but nevertheless integrate different degrees of tree cover. The wooded area in Haiti is not a remainder of a secondary or tertiary forest but mainly a combination of perennial and annual crops established by peasant farmers on the deeper soils under humid conditions.

Soil degradation in Haiti is mainly caused by water erosion on steep lands cropped annually. The rate of soil loss is 46 $Mg \cdot ha^{-1}$ per year (Table 10.4). The area affected by erosion is about 900,000 ha (BDPA/SCET-AGRI/World Bank, 1990).

SOILS OF BIOME C: TYPES, DISTRIBUTION, CONSTRAINTS, AND DEGRADATION

The main soil types according to the FAO classification and the soil map of the Caribbean biome are presented on Figure 10.1. Eight dominant soil types are Andosols, Vertisols, Gleysols, Nitisols, Ferralsols, Lixisols, Alisols, and Luvisols. The available soil map at 1:5,000,000 scale is rather crude. As an example, only three soil types are mapped on the FAO soil map for Martinique and Guadeloupe: Ferralsols, Alisols, and Luvisols, whereas the dominant soils are Andosols, Nitisols, Ferralsols, and Vertisols (Colmet Daage and Lagache, 1965).

Are the French West Indies (Lesser Antilles) and Haiti Representative of the Major Soils of the Caribbean Biome?

Guadeloupe and Martinique are representative of the different Lesser Antilles islands (Figure 10.2) in relation to soils developed on recent volcanic material. Soils are distributed along topo-climato-chronosequences as

TABLE 10.4. Soil losses (1,000 Mg per year) in Haiti.

	Region				
Slopes (%)	**North**	**Transversal**	**West**	**South**	**Total**
0 to 20	105	209	113	109	536
20 to 50	1,591	5,128	1,975	2,881	11,575
> 50	2,962	8,343	10,155	3,068	24,528
Total	4,658	13,680	12,243	6,058	36,639

Source: After BDPA/SCET-AGRI/World Bank, 1990.

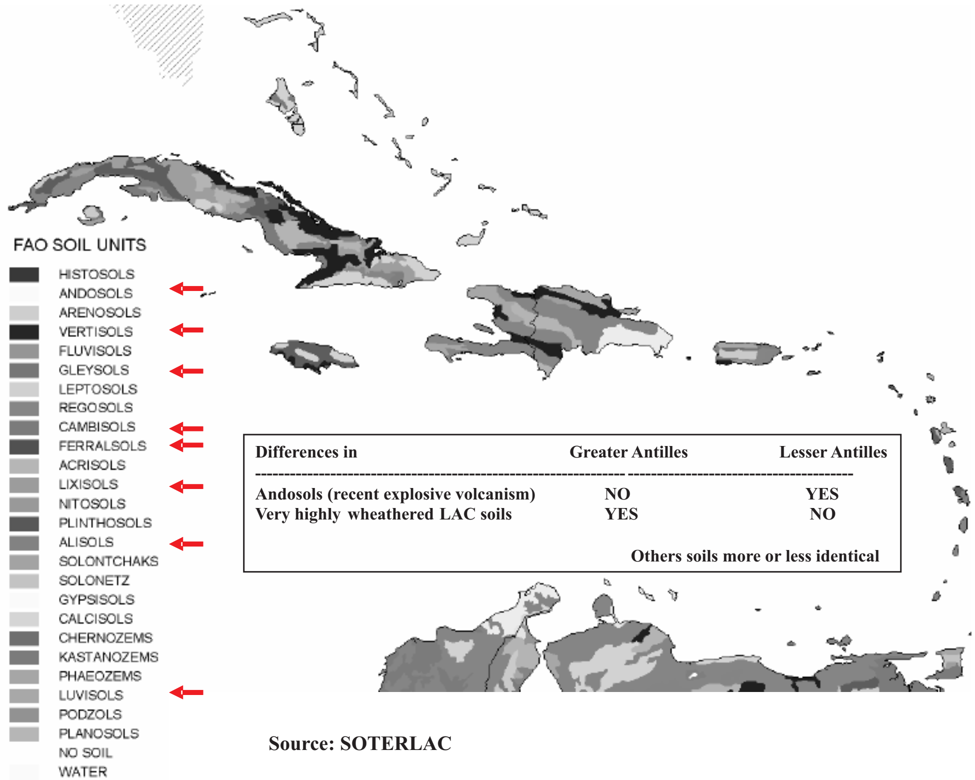

FIGURE 10.1. Main soil types for the Caribbean biome according to FAO classification and Soterlac database. Arrows correspond to the dominant soil types. (See also color gallery.)

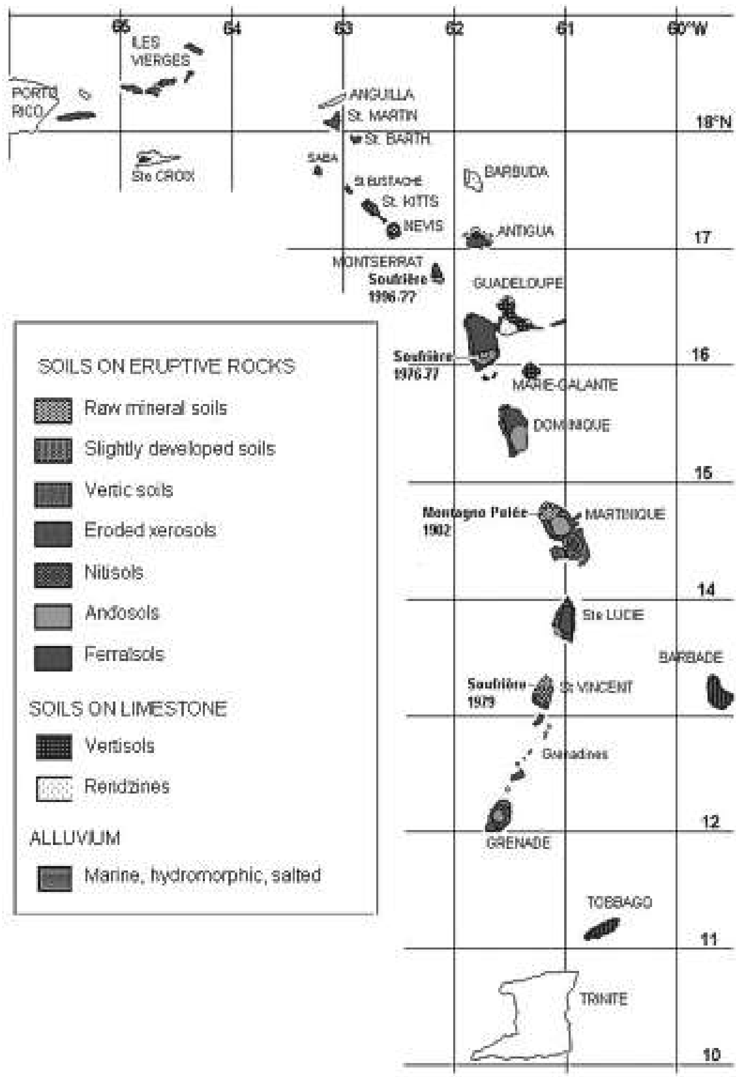

FIGURE 10.2. Martinique and Guadeloupe, representative of the diversity of soil types in the Lesser Antilles (Cabidoche, unpublished data, 1997) according to soil French classification (CPCS, 1967). (See also color gallery.)

- Young soils on pumices on very recent volcanic material,
- Andosols, Nitisols, and Ferralsols, or
- Andosols, Nitisols, Vertisols, according to the rainfall gradient on older volcanic deposits.

Each island does not have all soil types (i.e., the Vertisols of Barbados do not exist in Ste. Lucia and St. Vincent). However, Martinique and Guadeloupe have all the main soil types of the Lesser Antilles. It is one of the reasons for focusing on these two French West Indies islands for that part of the Caribbean biome.

For the Greater Antilles, the difference from the Lesser Antilles is in the absence of active volcanoes, and thus of Andosols. Even when the parent material is of volcanic origin as basalts in Haiti, St. Domingo, and Jamaica, soils developed on such material have Vertic characteristics. The highlands are developed under conditions of high rainfall and comprise soils derived from sedimentary materials, as hard limestone rather than marly limestone. These conditions give rise to soils of low-activity clays (LAC) and sometimes bauxitic soils as is the case in Haiti and Jamaica. One peculiar case is that of Cuba, where some elevated “diapirs” comprised of peridotites weathered into Ferritic soils (with pure goethite) occur because of the absence of aluminum in the parent material.

The available soil data for Martinique and Guadeloupe, and some complementary data from Haiti’s Vertisols and LAC and bauxitic soils, comprises information on major soils of the Caribbean biome, except those of Trinidad, which are identical to Venezuelan soils.

Determinants of Soil Distribution in the Lesser Antilles

All islands of the internal arc of the Lesser Antilles formed from an explosive andesitic and acid-basaltic subduction volcanism. Parent rocks of soils are generally comprised of andesitic volcanic pyroclasts (pumices and ashes), even if the underlying rock is coral-reef limestone like in Barbados or Guadeloupe Grande-Terre. All minerals of the andesite can be weathered by water, and developed soils are all made up of fine secondary minerals (clays). When rainfall increases, silica and bases are leached during soil weathering, resulting clays are poor in silica, and soil becomes acidic. In the Lesser Antilles, different types of soils rich in secondary minerals occur, depending on the nature of these minerals, which depends on rainfall and soil age (Table 10.5) (Cabidoche et al., 2004 and unpublished data).

TABLE 10.5. Soil distribution in the islands of the Lesser Antilles in relation to rainfall, parent material, and age of the soils.

		Volcanic rocks		Sedimentary rocks	
		Basalt or Andesite		Limestone, marl	Marine alluviums
Rainfall (mm/year)	**Silica and bases**	**10^3-10^4 years old**	**10^5-10^6 years old**	**10^5-10^7 years old**	**10^5-10^7 years old**
1,000	Accumulation; alkaline pH	Vertisol (Smectite Mg+Na)[a]	Vertisol (Smectite Mg+Na)	Calcic Xerosol (Smectite Ca, $CaCO_3$)	Solontchak (Smectite Na)
1,500 (=ETP)	Maintenance; neutral pH			Vertisol (Smectite Ca)	Vertisol (Smectite Mg+Na)
2,000	Exportation; slightly acid pH	Nitisol (Halloysite)	Oxisol (Halloysite, Kaolinite)	Oxisol (Kaolinite, Al and Fe Oxyhydroxydes)	Not Found
> 2,500	Strong to very strong exportation; acidic pH	Andisol (Allophane)	Oxisol (Halloysite, Al and Fe Oxyhydroxydes)	Oxisol (Kaolinite, Al and Fe Oxyhydroxydes)	Not Found

Source: Adapted from Cabidoche, 1994; Cabidoche et al., 2004.
[a]Soil types are FAO classification; predominant secondary minerals are given in parentheses.

In all the islands of the Lesser Antilles, soil properties, in rows on the hillside, vary over short distances. Martinique represents soil properties and constraints observed in the Lesser Antilles (Figure 10.3).

Soils of the Lesser Antilles are not prone to the same fragility observed elsewhere in the tropics and especially in the Greater Antilles. In the latter islands, some soils are less clayey and more sensitive to crusting, erosion, and salinization. The clayey Ferralsols are strongly weathered, but some wet plateaus predominantly contain Ferralsols rich in Al or Fe oxyhydroxides: bauxite in Haiti and Jamaica, and Fersols in Cuba. The Vertisols predominate in areas characterized by a marked dry season.

Soil Constraints and Degradation

The Lesser Antilles

The general clayey nature of the soils of Lesser Antilles leads to high soil organic matter (SOM) content. The high SOM content and the associated important pool of nutrients allow a sustainable cultivation without any external inputs and only under conditions of long fallows and permanent

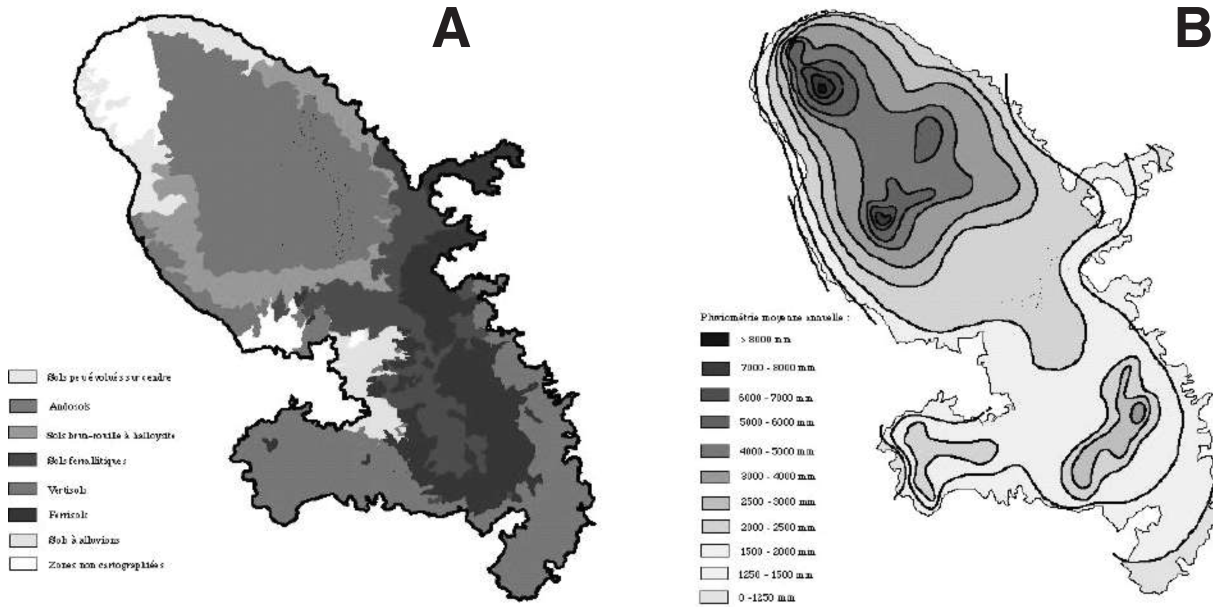

FIGURE 10.3. Simplified soil maps of Martinique (A) and rainfall distribution (B). Andosols in green; Nitisols in orange; Ferralsols in red and purple; Vertisols in blue. (*Source:* Created by authors from data of IRD-BOST after CNRS-IGN, 1976). (See also color gallery.)

cover, which slow down mineralization (Creole gardens, agroforestry). Nevertheless, the development of monoculture and the increase in yield require liming and application of potassium and phosphorus. Use of deep and frequent soil tillage completely alters the importance and functioning of SOM (Table II).

The main constraints of soils of Martinique, apparent after some decades of intensive agriculture (Cabidoche et al., 2004), are summarized in Table 10.6. Soils with Vertic properties exhibit a low level of P and K deficiency but poor physical properties and a low available water capacity. Andosols and Andic soils (young soils developed on volcanic ashes) exhibit K deficiency and Ferralsols P deficiency. All soils are prone to erosion, especially those with Vertic properties.

Haiti

In Haiti the soil degradation is mainly due to erosion by water, especially on annually cultivated land. About 36,639 Mt of soil is lost every year by erosion (BDPA/SCET-AGRI/World Bank, 1990). The magnitude of erosion depends on the slope (Table 10.4).

Cuba

The data on soil degradation for Cuba are shown in Table 10.7 (FAO, 2001). Low SOM contents represent the main soil constraint with negative impact on nutrient depletion, and with attendant degradation of physical properties along with high risks of poor drainage and accelerated water erosion.

TABLE 10.6. Soil-related constraints and degradation for soils of Martinique.

	Deficiency in							
Soil type	**P**	**K**	**Aluminium toxicity**	**CEC decrease**	**Erosion**	**Low water availability**	**Stones**	**Soil strength**
Young soils on pumices and ashes (Arenosols)	+	++			++		++	
Andosols	+	++	+		+		+	
Nitisols	+	+	+		+	+	++	+
Vertic soils	+	+			++	++	++	++
Ferralsols	++	+	++	++	+			
Xerosols	+	+	++	+	+	++		+
Vertisols		+	+		+++	+++	+	++

TABLE 10.7. Extent of soil degradation in Cuba.

Process	Land area affected (1,000 ha)	% total area
Erosion by water	2,900	42.2
Erosion by wind	?	?
Elemental toxicity and salinization	?	?
Acidification:		
pH-KCl < 6.0	1,660	24.8
pH-KCl < 4.6	470	7.0
Nutrient depletion (low OM content)	4,600	69.9
Soil structural decline (compaction)	1,600	23.9
Others		
poor drainage	2,700	40.3
internal drainage	1,800	26.9
low water retention	2,500	37.3
stoniness and rockiness	800	11.9

Source: Based on data from FAO, 2001.

SOIL/CROP MANAGEMENT AND SOC STOCK

Edaphic and Agronomic Determinants of SOC Stocks in Martinique and Haiti

Martinique

In Martinique different determinants of SOC storage were studied for soils with different mineralogies: Andisols (with allophanes ALL), Ferralsols (with 1:1 clay type, low-activity clay [LAC] soils), and Vertisols (with 2:1 clay type, high-activity clay [HAC] soils). Results presented in Feller et al. (2001) are summarized next.

SOC stocks and texture. The SOC stocks strongly depend on soil texture, expressed on a clay+fine silt (0-20 μm) basis (Figure 10.4). The domain defined by the upper (natural vegetation) and lower (continuous cultivation with low level of organic restitution) limits represents, for a given texture, the maximum supplementary (or potential) SOC storage possible (Cpotential of Figure 10.4) when an RMP is adopted on a site corresponding to the lower line. Figure 10.4 shows that Cp varies with the texture, low values for coarse-textured soil and high for clayey soils.

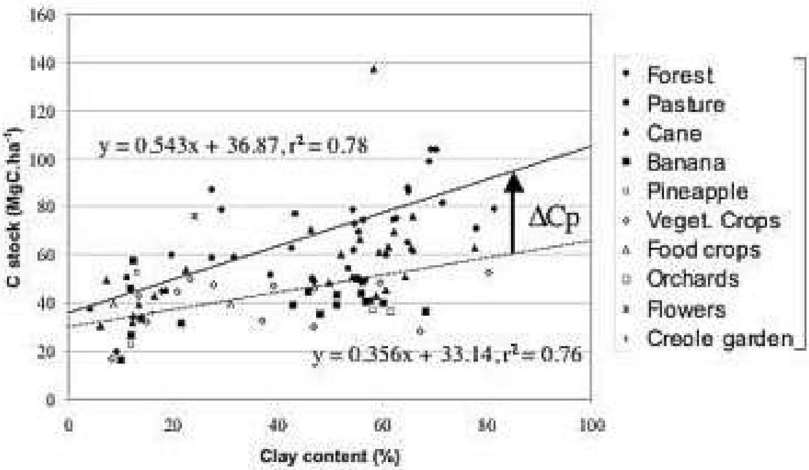

FIGURE 10.4. Variation of SOC stocks (0 to 30 cm) in relation to texture for different agrosystems in Martinique. The upper line represents natural vegetation + artificial meadows, and the dotted lower line all other crops.

SOC stocks and mineralogy. For a given texture, ALL soils (allophanes) always exhibit higher SOC contents and stocks than LAC and HAC soils. The SOC contents and stock do not differ among LAC and HAC (Feller et al., 1991, 2001; Venkatapen et al., 2004).

Feller et al. (2001) reported the following potential Cp for Martinique and/or Guadeloupe soils: 22.9, 23.3, and 30.8 t C·ha^{-1}, respectively, for ALL, LAC, and HAC soils. Hence, the higher SOC stocks in ALL soils do not imply a higher potential of SOC storage (Cp).

Aggregation and SOC protection against mineralization. The positive effect of SOM on aggregate stability is widely reported for tropical soils (Feller et al., 1996). It is also the case for Martinique, especially for LAC as compared to HAC soils. This results in an increasing protection of SOC against mineralization for high values of SOC content and aggregate stability. Chevallier et al. (2004) observed that about 40 percent of the SOC mineralization potential was in a protected form in aggregates of 0.2 to 2.0 mm.

Agronomic determinants. Some agronomic determinants were also studied by Feller et al. (2001). These are summarized here:

- *Plot history:* High rate of SOC sequestration in a Vertisol by fertilizer use and irrigated meadow was significantly higher (1.5 g C·kg^{-1} soil) for nondegraded soil than a degraded (poor in SOM) soil (1.0 g C $\cdot kg^{-1}$ soil).

- *Intensification of agricultural practices:* Fertilization and irrigation of pastures significantly increased SOC stock: 25.4 t $C\cdot ha^{-1}$ for low level to 53.5 t $C\cdot ha^{-1}$ for high rate.
- *Tillage:* Shallow tillage (10 cm) compared to deep tillage (30 cm) decreased SOC at the rate of 66 kg $C\cdot ha^{-1}$ during the first 15 months of cultivation (Blanchart et al., 2004).

Haiti

SOC stocks and texture. A positive linear relationship between clay content and SOC stock is also observed for soils of Haiti (Figure 10.5) at about the same level as for Martinique soils (Figure 10.4). According to soil texture, and for an identical cropping system, there is no significant difference

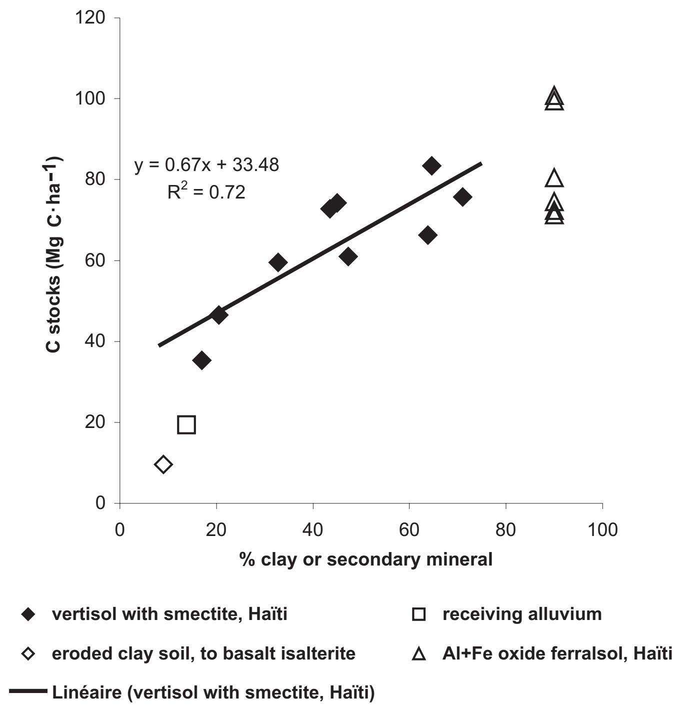

FIGURE 10.5. Variation of SOC stocks (0 to 30 cm) in relation to mineralogy and texture for several soils of Haiti (cereal + legume – short fallow cropping systems).

in SOC stocks of Vertisol or Ferralsol. Within two fields, one prone to soil erosion, the other receiving alluvial sediments, the SOC stock decreased below 30 Mg C·ha^{-1} for the eroded soil.

SOC stocks and pH. Figure 10.6 shows a positive relationship between SOC stocks and pH for the less weathered Ferralsols (medium deep calcic Ferralsol), whereas negative relationships are observed for the highly weathered Ferralsols (deep orthic and Al-Fe oxide). For medium deep calcic Ferralsols and Rendzinas, the positive relationships are due to the well-known effect of $CaCO_3$ on SOC storage. For the two other soil types, an increase in K and P was observed (data not shown) and it is increasing with pH. The results are lower yields (and hence lower SOC restoration) when pH is increasing.

SOC Stocks for the Agroecosystem As a Whole

The SOC stocks for the 0 to 30 cm depth were available only for Martinique and were determined according to soil texture (Figure 10.4) for several agroecosystems on LAC and HAC soils (252 studied sites). Andosols were not involved in these calculations.

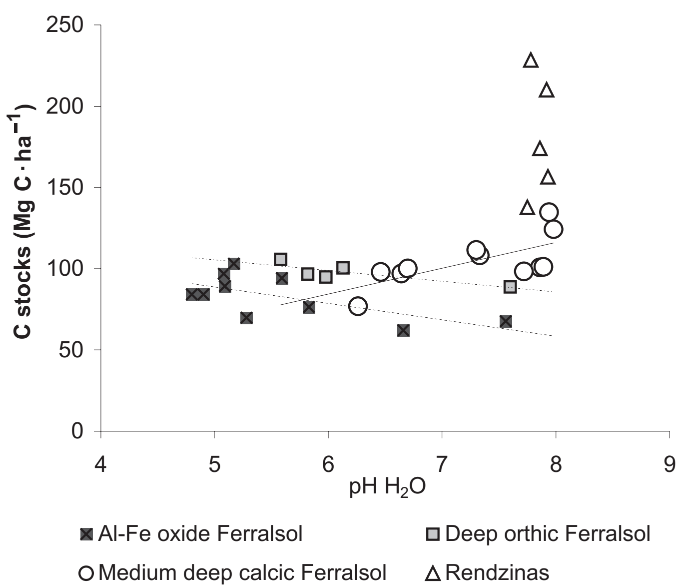

FIGURE 10.6. Variation of SOC stocks (0 to 30 cm) in relation to soil pH for upland soils of Haiti under annual low input cropping systems of staple food.

Venkatapen et al. (2004) reported that SOC stocks were not significantly different among LAC and HAC soils. Therefore, SOC stocks vary only with soil texture, land use, and management practices.

For each agroecosystem, the regression equation between SOC stock and clay+fine silt (c+fs) content (%) was established. The equation and statistical parameters are summarized in Table 10.8. The main RMP for existing agroecosystems in Martinique are sugarcane after banana and planted pastures after intensive (highly [hi] or medium [mi]) market gardening (MG) (Table 10.9). The annual rate of SOC sequestration (SOCseq rate) was low for the sugarcane-banana system but high to very high for the MG-pasture systems, ranging from 0.94 to 2.02 (Mg C·ha^{-1} per year) for coarse and fine-textured soils, respectively.

These data were used in section C to calculate (Table 10.10) the SOCseq rate for different RMPs and for two clay+silt contents: 20 percent (sandy) and 70 percent (clayey) at the Biome C scale.

Recommended Management Practices (RMPs) for Increasing SOC Stocks in the Caribbean Biome

Identifying RPMs comprises the principal goal of the research institutions in the Lesser Antilles and Haiti. It is assumed that these countries are representative of the Caribbean biome.

TABLE 10.8. Parameters of the regression equations between SOC stocks (0 to 30 cm layer) and clay+fine silt content (0 to 20 μm percent) for different agroecosystems in Martinique.

	Parameters				Soil texture (c+fs %)		SOC stocks (Mg C·ha^{-1})	
Land use	**n**	**A**	**b**	**r^2**	**Coarse**	**Fine**	**Coarse**	**Fine**
Forest	15	0.885	16.0	0.68	20	70	33.7	78.0
Meadow	58	0.681	17.9	0.43	20	70	31.5	65.5
Sugarcane	61	0.609	21.3	0.42	20	70	33.5	64.0
Banana	88	0.397	22.4	0.17	20	70	30.4	50.2
MG-hi	11	0.465	12.8	0.48	20	70	22.1	45.3
MG-mi	11	0.361	24.4	0.44	20	70	31.7	49.7
Creole garden	16	0.521	31.9	0.21	20	70	42.3	68.3

Note: Generally considered for a ten-year duration. Soil textures correspond to 20 percent (coarse) and 70 percent (fine) clay+fine silt contents (c+fs %). The regression equation is SOC Stocks (tC/ha) = a (c+fs %) + b.

TABLE 10.9. Calculations of SOC sequestration (Δ SOC) rate for some recommended management practices (RPM).

	Δ SOC stocks		rate (Mg C·ha^{-1}per year)	
RMP (10 yrs)	**Coarse**	**Fine**	**Coarse**	**Fine**
Sugarcane after banana	3.1	13.8	0.32	1.38
Meadow after MG-hi	9.4	20.2	0.94	2.02
Meadow after MG-mi	–0.2	15.8	–0.02	1.58

Note: Generally considered for a ten-year duration. Soil textures correspond to 20 percent (coarse) and 70 percent (fine) clay+fine silt contents (c+fs %). The regression equation is SOC Stocks (tC/ha) = a (c+fs %) + b.

TABLE 10.10. Ranges of the annual rates of soil carbon sequestration (SOCseq rate) with restorative land use and recommended management practices (RMP) in Biome C.

	Range of SOC sequestration rate according to soil texture (Mg C·ha^{-1} per year)	
Alternatives of land use management (RMP)	**Coarse**	**Fine**
No burning of sugarcane[a]		
without no till	nd	0.20
with no till		1.0
Sugarcane after banana	0.32	1.38
5 years planted pastures after degraded soils under market gardening (vegetables & melons)	0.94	2.02
Improved pastures	2.0[a]	nd
No tillage with or without cover crops on cereals and pulses	nd, 0.4[b]	nd, 0.4[b]
or		
Agroforestry on cereals and pulses	nd, 0.5[c]	nd, 0.5[c]

Source: Based on values obtained by IRD in Martinique (Table 8), IRD/CENA in Brazil, and Watson et al., 2000.
Note: Generally considered for a 10-year duration. Coarse and fine textures correspond to 20 percent and 70 percent fine silt+clay contents, respectively, for the 0 to 30 cm layer.
[a]Based on values obtained by IRD/CENA in Brazil (Cerri, Bernoux, Feller, et al., 2004).
[b]Based on a literature review (mean value) by Cerri, Bernoux, Cerri, and Feller, 2004; Bernoux, Cerri, et al., 2005; Balesdent et al., 2005, for tropical and subtropical areas.
[c]Based on Watson et al. (2000) (mean value).
nd: not determined at Martinique for Biome C.

The SOCseq rate for "sugarcane after banana," "5 years planted pastures after degraded soils under market gardening (vegetables and melons)" and "improved pastures" were computed from equations in Table 10.8. For "no burning of sugarcane," data were adapted from recent CENA/IRD research in Brazil (Cerri, Bernoux, Feller, et al., 2004) and for "no tillage" systems from literature data for tropics and subtropics (Cerri, Bernoux, Cerri, and Feller, 2004; Bernoux, Cerri, et al., 2005; Balesdent et al., 2005).

The larger rates were observed for conversion to improved pasture after annual crops or after degraded pastures.

POTENTIAL FOR SOC SEQUESTRATION IN BIOME C

For each RMP the potential for SOC sequestration (potSOCseq) at the biome scale was calculated by the following equation:

$$\text{potSOCseq} = \text{SOCseq rate} \times \text{Surface area}$$

and expressed in

Tg C per year (or 10^3 Mg C per year)

For each agroecosystem in Table 10.11, the considered total surface area (column 1) was extracted from Table 10.3.

The different percentages shown in column 2 were justified as follows:

For "no burning sugarcane": No burning generally implies mechanized harvest, but only for slopes lower than 12 percent. For steeper slopes, harvesting has to be manual and therefore with burning. Hence, only 50 percent of the total surface area was taken into consideration for that RMP.

For the "banana-sugarcane" rotation: 50 percent is probably the maximum proportion of land each year where sugarcane can be incorporated in the rotation. The areas concerned can be under either the present banana plots or sugarcane agrosystem. In the latter case, a small decrease in SOC sequestration is observed with the cultivation of banana in the sugarcane plots.

For "5 years planted pasture (P) after market gardening (MG)": The value of 25 percent was chosen for the following reasons: rotation MG-P was considered for only 50 percent of the present area under MG, and the duration of P (five years) is the half of the time span (ten years) used for the calculation of the SOCseq rate.

For "improved pastures": It is clear that land considered as permanent pastures corresponds probably more or less to abandoned plots, and it is presumptuous to calculate a potential with the total area. Thus, the value of 50 percent has been chosen arbitrarily.

TABLE 10.11. Annual potential of SOC sequestration (potSOCseq) for Biome C (data based on a ten-year scale basis).

Management	Total area extent of the present land use (1,000 ha)	Area under RPM (%)	Total area concerned (1,000 ha)	SOCseq rate (Mg C·yr–1)	Potential SOCseq (Tg C per year or 10^3 Mg C per year)
No burning of sugarcane					
without no till	1,292,474	50	646,237	0.20	0.129
with no till		50	646,237	1.00	0.646
Sugarcane after bananas+plantains					
coarse texture	327,417	50	163,709	0.32	0.052
fine texture	327,417	50	167,709	1.38	0.226
5 years planted pastures after degraded soils under market gardening					
(vegetables and melons)					
coarse texture	334,210	25	83,553	0.94	0.079
fine texture	334,210	25	83,553	2.02	0.169
Improved pastures (max.)	5,972,000	50	2,986.000	2.00	5.972
No tillage with or without cover crops on cereals and pulses	1,226,378	100	1,226. 378	0.40	0.491
or					
Agroforestry on cereals and pulses	1,226,378	50	613.189	0.50	0.307
Total 1 (coarse texture)					6.539
Total 2 (fine texture)					7.503

"No-till and cover plant systems": This system was assumed to apply only to cash crops. The example of Brazil shows that a complete transformation of such agrosystems is possible, and we accept the hypothesis that RMPs be adopted on all lands.

For "agroforestry": It is assumed that this alternative is more difficult to adopt in all situations, and that a significant part of the area (25 percent) will be covered by trees and not by the present crops. For these reasons, 50 percent was chosen.

Note the importance of the improved pasture management in the potential of soil C sequestration. Even no burning of sugarcane associated with no-tillage practice represents only 11 percent of the pasture potential.

Finally, the annual potSOCseq varies from 6.54 Tg C·yr^{-1} for coarse-textured soils to 7.50 Tg C per year for fine-textured soils, and the most important RMP at the biome C scale for SOC sequestration are concerned with improved pastures.

POLICY CONSIDERATIONS

The following policy issues are discussed for Haiti.

All RMPs proposed are not only efficient for SOC sequestration but also for enhancing sustainable plant and animal production.

Haitian farmers usually exist under highly precarious conditions. The cropland is highly eroded and, under low external input, does not produce enough food to meet the needs of the increasing population. It is not surprising, therefore, that in such a context, farmers are concerned more about survival than sustainability. Policy options to encourage adoption of restorative land use in Haiti must take into account four criteria:

1. *The need for an important investment in soil conservation:* The advanced state of erosion on large parts of the land may require, at least for the most degraded fields, drilling holes for tree plantations and implementing physical and not immediately rentable structures (terrace cultivation, drystone walls) in order to retain the soil where it still exists.
2. *Decreasing the population pressure on the most fragile soils:* This can be achieved by increasing the production of annual crops in the less eroded fields, by creating other sources of income for the rural population, by using agroforestry systems for timber and fuel production instead of petrol or charcoal from savannahs.
3. *Financial and technical assistance:* The precariousness in which most Haitian farms exist does not allow them to invest in soil restoration. Technical assistance must be provided for soil restoration and for the improvement of the productivity of annual crops.
4. *Economic incentives for restorative land use:* Any restorative land use must generate incomes for farmers. These land uses are not exclusively for erosion control or sequestering carbon. Economic incentives must be provided for farmers to maintain and increase area under forest cover and agroforestry systems. However, logistical support for marketing and safe export markets with good prices for farmers are conspicuously lacking.

CONCLUSIONS

Biome C is characterized by a very large diversity of ecological, agronomical, and socioeconomic conditions. Diverse conditions make quantification of SOC sequestration difficult at the biome scale. Important simplifications and assumptions must be made. The annual potential of SOC sequestration for Biome C ranges from 6.54 Tg C per year (coarse-texture soils) to 7.50 Tg C per year (fine-texture soils). The main potential of SOC sequestration is obviously for improved pastures (5.97 Tg C per year), and then for nonburned sugarcane (with no-till, 0.65 Tg C per year), no-tilled cereals and pulses (0.49 Tg C per year), agroforestry on cereals and pulses (0.31 Tg C per year), sugarcane after bananas or plantains (fine-texture soils, 0.23 Tg C per year), and pastures after market gardening crops (fine-texture soils, 0.17 Tg C per year). Thus, the main result for a substantial increase in SOC sequestration is a better management of pastures, either with development of improved pastures or by integration of artificial meadows in some rotations as market-gardening and/or food crop systems.

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