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Soil organic carbon sequestration in tropical areas. General considerations and analysis of some edaphic determinants for Lesser Antilles soils

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Abstract

Some general notions on soil organic carbon (SOC) sequestration and the difficulties to evaluate this process globally are presented. Problems of time- and space- scales are emphasized. SOC erosion, which is generally difficult to evaluate in relation to land use changes, is discussed in detail. Different aspects of SOC sequestration on the Lesser Antilles are presented for a wide range of soil types. Comparisons between soils revealed that the SOC stocks in the Lesser Antilles are highly dependent upon the mineralogy: higher stocks for allophanic (ALL) soils than for low activity clay (LAC) and high activity clay (HAC) soils. But in terms of potential of SOC sequestration (pSeq-SOC, differences between permanent vegetation and continuous cultivation situations), there are no differences between ALL and LAC soils (22.9 and 23.3 tC. ha^{-1}, respectively). On the other hand, the potentials of SOC sequestration were higher for HAC soils (30.8 – 59.4 tC. ha^{-1}, with the higher levels in the less Mg- and Na-affected Vertisol). Sheet erosion is a serious problem for Vertisol with high Mg and Na on exchange complex, causing high dispersability of fine elements. Thus, the lower SOC levels in these soils may be partly due to erosion losses. Laboratory incubations have shown that 37 – 53% of the protected SOC in these soils was located in aggregates larger than 0.2 mm. The effect of agricultural practices on SOC sequestration was studied for the Vertisols. Intensification of pastures led to higher plant productivity and higher organic matter restitutions and SOC sequestration. The gain was 53.5 and 25.4 tC. ha^{-1} for the low and high-Mg Vertisol, respectively (0–20 cm layer). SOC sequestration with pastures also depends upon the plot history with lower mean annual increase in SOC for the initially eroded (1.0 gC . kg^{-1} soil . yr^{-1}) than for the non-degraded (1.5 gC . kg^{-1} soil . yr^{-1}) Vertisol. Loss of SOC in a pasture-market gardening rotation was 22.2 tC . ha^{-1} with deep (30–40 cm) and 10.7 tC . ha^{-1} with surface (10–15 cm) tillage. It was unclear whether the differences in SOC losses were due to mineralization and/or to erosion.

Introduction

Soil organic matter (SOM) provides services which can be described as 'soil fertility' functions from the farmer's viewpoint, and 'environmental' functions as they are perceived by society (Feller et al., 2000). The general aspects of these two points were well documented in the paper of Craswell and Lefroy (this issue), and we shall focus here on the environmental function of soil organic carbon (SOC) sequestration.

For many tropical countries, the environmental challenge (outside the large cities) is to limit deforestation, increase organic matter (OM) storage in cultivated soils and reduce current erosion. All these problems concern the organic carbon (OC) balance for the plant–soil–atmosphere system. Under the economical conditions prevailing in many developing countries, this challenge can be dealt with only through the emergence of new land use alternatives, at the plot level as well as on larger scales (farm, terrain, watershed basin, natural or administrative region). These alternatives should lead to more organic matter restitutions and SOC retention. At each spatial scale, this balance will be controlled by different agricultural and ecological parameters. But different temporal scales must also be considered in relation to the durability of the SOC-sequestration.

In this paper (i) OC and SOC sequestration in the soil–plant system and (ii) the role of some soil attributes and/or agronomical practices on SOC sequestration will be discussed for situations of the Lesser Antilles.

Some general considerations on OC and SOC sequestration in the soil–plant system

The notion of C sequestration refers to the environmental problem of mitigation of the greenhouse effect (Cole et al., 1996). Mitigation is the global anthropogenic intervention to reduce the emissions or enhance the sinks of greenhouse gases (GHGs). For example, the production of sugarcane for energy purposes (sugarcane alcohol) allows a reduction in the use of fossil fuels, resulting in a reduction in GHGs emissions. An increase in the carbon storage in soil or in products derived from agriculture or forestry constitutes C sequestration.

Sequestered OC in the plant–soil system (Seq-C) is the carbon amount removed directly or indirectly from the atmosphere (CO_2, CH_4) and stored in the soil (Seq-SOC) or the plant (Seq-PlC) during a given period and over a given area.

There are several problems arising from the definitions of terms (Bruce et al., 1999) after the Kyoto Protocol (1997) and the Conference of Parties (COP) held in Buenos Aires (1998). We shall briefly address the problems of time- and spatial scales. Many of these points are discussed in Watson et al. (2000).

The time scale

C sequestration is a long-term process. For example, in the Kyoto Protocol, 1990 was taken as the emission base year, whereas the period of 2008 – 2012 was chosen for evaluating the effect of the decisions to be taken later on. A minimum of 20-years duration has thus to be considered. Likewise, in a succession of vegetation types, one must consider the long term effects.

C-Sequestration in the plant or in the plant product compartments

Afforestation is an interesting proposition to sequester C, especially if two conditions are met: (i) the plantation will not disappear for at least 20 years, (ii) the sequestration process will continue in the wood products. Production of timber, for example, helped to extend C-sequestration through construction by 30 years (Roy, 1999). On the other hand, if the afforestation product is firewood, the plant-sequestered C will return immediately to the atmosphere and the CO_2 balance will be nil. Potential for plant-C sequestration is thus reduced to a few alternatives such as long-term reforestation, afforestation and agroforestry practices, with specific production targets. Short to medium term spontaneous or enriched bush, tree- or grass fallows do not lead to a significant OC storage in the plant compartment.

C-sequestration in the soil

One of the plant by-products is soil organic matter (SOM). In the surface layer (0–20 cm), this compartment has a mean residence time which varies between 20 and 40 yrs for the tropical areas to 40 and 70 yrs for the temperate ones, with some SOM pools very labile (< 1 yr) and others more ‘passive’ (> 100 yrs in surface horizons and even > 1000 yrs in deep horizons). Thus, a small increase in the passive fraction of SOM following a change in the agricultural system or land use, can lead to a significant OC-sequestration for the whole soil–plant system even after the process of plant C sequestration has come to an end. However, a main question remains: how are SOM pools involved in the SOC sequestration process ?

The space scale

Different space scales have to be considered in order to establish a C balance.

Within a landscape unit, plant C transfers have to be considered. We already saw that C transfers in woody products to other environments can carry on the C-sequestration process. Another example is the transfer by herds, if animals graze in one place (savanna, long-term fallows) and are paddocked in another.

In tropical areas, the observed losses or increases in soil carbon stock at the plot level upon changes in

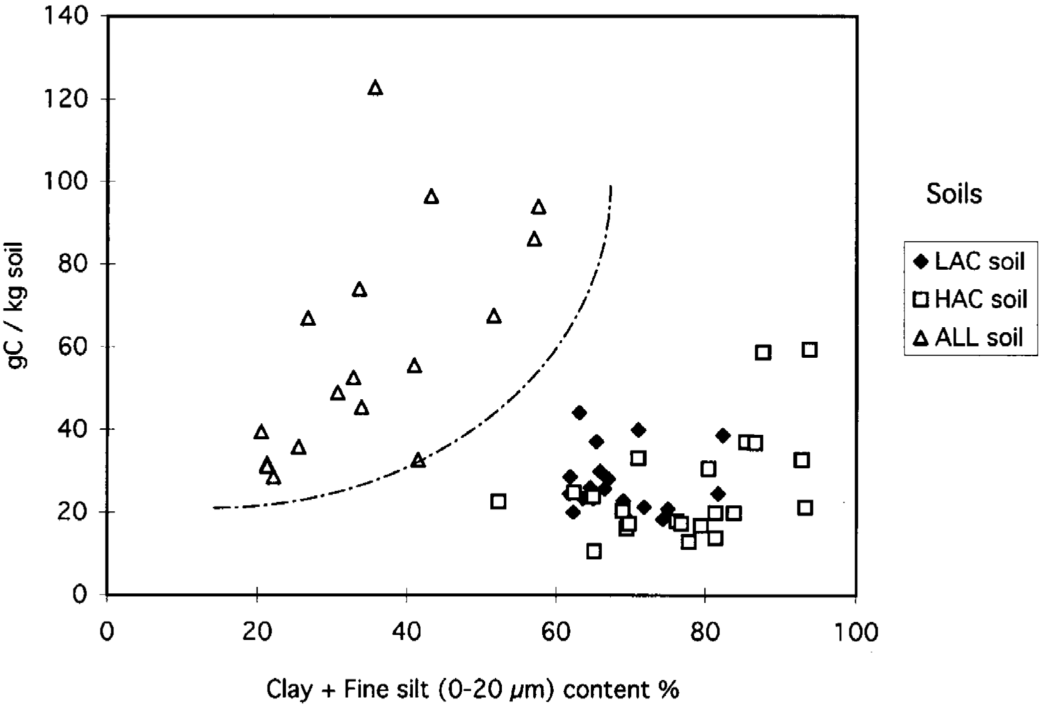

Figure 1. Carbon content (gC . kg^{-1} soil) of soils (0–20 cm) according to their mineralogy and texture: clay+fine silt (0–20 μm) content (%). LAC = low activity clay soils (kaolinitic), HAC = high activity clay soils (smectitic), ALL = allophanic soils. The curved line delimits the domain of allophanic (ALL) soils. Source: BOST Laboratory, IRD, Martinique (unpublished data).

land use are often attributed to mineralization or sequestration processes. However, a considerable part of the observed variations might be due to water or wind erosion transfers and cannot be considered as sequestration (when increase in SOC content) or mineralization loss (when decrease in SOC content). Therefore, in case studies of SOC sequestration, sites for plot studies have to be chosen with a low erosion risk. Nevertheless, for the OC balance at the microcatchment and large basin scale, there is a need for studies that allow a quantification of the mineralization/sequestration process and erosion process.

The edaphic determinants of SOC content and potential SOC sequestration. The example of the Lesser Antilles soils

In the Lesser Antilles, soils are generally relatively young soils developed on volcanic parent material. A large range of situations, in terms of mineralogy and management practices, have been studied (Albrecht et al., 1992; Feller, 1995; Hartmann et al., 1998; Ndandou, 1998; Chevallier, 1999; Blanchart et al., 2000). The selected sites are presented in Table 1 and some of their characteristics in Table 2.

We define, for a given soil and a given climate pattern, the potential of SOC sequestration (pSEQ-SOC) as the difference in the SOC contents between a continuous cultivation system (CC) and a permanent vegetation (PV) system with high plant productivity and organic matter restitution levels. The PV systems correspond generally to the highest SOC content and stocks that can be reached under different land uses[1], and the CC systems to the lowest. We also define improved systems (IS) which represent alternatives to the CC system.

The assessment of SOC sequestration assumes that the plots chosen for the pSEQ-SOC evaluation were theoretically not subject to erosion even if such a field situation does not exist. We chose sites where sheet erosion was apparently limited, with the exception of the Vertisol Ve6 site.

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[1] In some cases, and especially with intensively managed pastures in humid tropical areas, SOC stocks can be higher than those of 'natural vegetation' sites, as in Amazonia (Neill and Davidson, 2000).

Table 1. Description of the studied sites and abreviations

Soil	Site characteristics				
	Site	Soil Order	Island	Mean annual rainfall (mm)	Vegetation
LAC	Fr4	Oxisol	Guadeloupe	3000	Pr, MG
(low activity clay soil)	Fi6	Inceptisol	Martinique	1900	F, JA, Ca
	Fr7	Oxisol	Sainte-Lucie	2700	Jh, Ja, Rv
HAC	Ve4	Vertisol	Guadeloupe	1400	Pr, Jh, SN
(high activity clay soil)	Ve6	Vertisol	Martinique	1300	F, JA, Pr, MG
ALL	Ad5	Andisol	Dominique	3000	JA, BI, Rc
(allophanic soil)	Aw5	Andisol	Dominique	3000	Jh, Ba, Rc
	Pa6	Andisol	Martinique	2300	An
	Ad6	Andisol	Martinique	3200	F, Ca, Ba, An
	Aw6	Andisol	Martinique	3500	F, Pl, Jh, Ba, Rv

Vegetation abbreviations			
An	Pineapple	MG	Market-Gardening
Ba	Banana	Pl	Mahogany plantation
BI	Fruit tree	Pr	Artificial meadow
Ca	Sugarcane	Rv	Food crops
F	Forest	Rc	Food Crops + Market-Gardening
JA	Tree fallow	Rc-fu	Rc + farmyard manure
Ja	Bush fallow	SN	Bare soil
Jh	Herbaceous fallow		

Effects of soil mineralogy and soil texture

There has been much discussion of, and indeed controversy over, differences in the SOM contents of temperate and tropical soils based on climatological gradients (Jenny et al., 1948; Post et al., 1982). Increasingly, evidence suggests that when soils of similar classification (e.g. Order) and land use are compared, SOM contents from temperate and tropical regions largely coincide (Sanchez, 1976). Latitudinal gradients in SOM contents are probably more closely related to differences in permanent properties of the soils, such as mineralogy and texture.

In the soils of Lesser Antilles islands, there is a large diversity of clay type. Three main groups of tropical soils can be defined (Figure 1):

1. the kaolinitic/halloysitic, or low activity clay (LAC) soils (e.g. Inceptisols, Ultisols, Oxisols),
2. the smectitic, or high activity clay (HAC) soils (e.g. Vertisols), and
3. the more or less allophanic (ALL) soils (e.g. Andisols) with large amounts of amorphous or crypto-crystallized minerals.

The SOC content (%) of the 0–20 cm layer is presented in relation to the texture (clay+fine silt, 0–20 μm) in Figure 1 for these 3 groups of soils from different locations.

Allophanic soils (ALL) of the Lesser Antilles

The allophanic character of the ALL soils was well-illustrated for sites Ad5, Aw5, Ad6, Aw6 by the low bulk density with mean values of 0.5 Mg . m^{-3} soil. The water content at field capacity or at pF2.5 of the non air-dried soil (WpF2.5) was high, with mean values of 106.1, 118.8 and 107.1 gH$_2$O.100 g^{-1} soil for PV, IS and CC land use, respectively (Table 2a). For sites Pa/Ad6 and Pa6 corresponding to soils rich in pumice, the bulk density (0.8 mg . m^{-3}soil) was higher and the WpF2.5 lower (51.4 gH$_2$O.100 g^{-1} soil).

In comparison, the mean values for bulk density were 1.0 – 1.1 Mg . m^{-3} soil for LAC and HAC soils,

Table 2. a. Some characteristics of the soil sample (0–20 cm) for the studied allophanic (ALL) soils. For site and vegetation descriptions: see Table 1. The number following vegetation abreviation indicates the duration of the system. For land use: PV = Permanent Vegetation, IS = Improved System, CC = Continuous Cultivation. s.d. = standard deviation, v.c. = variation coefficient, nd = non determined

Site	Land use	Veget.	Clay	Clay+fine silt	C content	bulk density	C stock	WpF2.5
			$g.100\ g^{-1}$ soil		$gC.kg^{-1}$ soil	$Mg.m^{-3}$	t/ha	$gH2O.100\ g^{-1}$ soil
Aw5	PV	Jh10	26.5	57.6	94.0	0.4	82.8	133.2
Ad5	PV	JA30	nd	nd	90.0	0.6	99.0	69.3
Ad5	PV	BI	nd	nd	80.7	0.6	88.8	83.3
Ad6	PV	F	33.7	51.6	67.5	0.6	81.0	76.5
Aw6	PV	F’	9.8	35.6	122.7	0.4	109.3	168.2
mean	**PV**			**48.3**	**91.0**	**0.5**	**92.2**	**106.1**
s.d.	PV			11.4	20.5	0.1	11.9	42.8
v.c.(%)	PV			23.5	22.5	13.7	12.9	40.4
Ad5	IS	Rc-fu	nd	nd	71.2	0.6	78.3	72.4
Aw5	IS	Jh4	nd	nd	86.5	0.3	58.8	126.1
Aw6	IS	Pl60	13.8	43.2	96.5	0.4	80.6	181.7
Aw6	IS	Pl25	9.7	33.6	74.0	0.5	66.6	142.8
Aw6	IS	Jh3	5.7	22.2	28.6	0.8	47.0	71.0
mean	**IS**			**33.0**	**71.4**	**0.5**	**66.3**	**118.8**
s.d.	IS			10.5	26.0	0.2	13.9	47.5
v.c.(%)	IS			32.0	36.4	36.3	21.0	40.0
Aw6	CC	Ca	12.9	41.0	55.5	0.7	72.2	98.3
Aw6	CC	Rv	8.0	33.9	45.4	0.5	49.4	107.6
Aw6	CC	Ba	nd	nd	36.0	0.6	43.4	109.0
Aw5	CC	Ba	26.1	57.0	86.2	0.4	75.8	124.0
Aw5	CC	Ba’	nd	nd	100.3	0.4	88.3	124.0
Aw5	CC	Rc	nd	nd	96.6	0.4	77.3	128.6
Aw5	CC	Rc’	nd	nd	95.5	0.4	76.4	142.0
Ad5	CC	Rc	nd	nd	85.0	0.6	93.5	87.3
Ad6	CC	Ba	19.0	32.8	52.6	0.6	63.1	74.7
Ad6	CC	Ba’	18.4	30.7	48.9	0.6	53.8	75.0
mean	**CC**			**39.1**	**70.2**	**0.5**	**69.3**	**107.1**
s.d.	CC			10.7	24.7	0.1	16.5	23.1
v.c.(%)	CC			27.5	35.2	17.5	23.8	21.6
Ad6	PV	F	16.5	26.7	66.9	0.6	80.3	63.0
Pa/Ad6	CC	An	9.9	20.5	39.4	0.8	62.3	51.4
Pa6	CC	An	11.7	25.5	35.8	0.8	56.6	51.4
Pa6	CC	An’	8.5	21.3	31.7	0.8	50.1	51.4
Pa6	CC	An”	nd	21.3	31.2	0.8	49.3	51.4
Ad6	CC	Ca	24.3	41.5	32.7	0.7	46.4	63.4

respectively, and the WpF2.5 ranged from 32 to 39 $gH_2O.100\ g^{-1}$ soil for LAC soils (Table 2b) and from 43 to 69 $gH_2O.100\ g^{-1}$ soil for HAC soils (Table 2c). Feller and Beare (1997) used the WpF 2.5 to evaluate the intensity of the allophanic character of ALL soils. For the sites studied here, there was a strong relationship between SOC and WpF2.5 ($p < 0.01$). The linear regression equations between SOC and WpF2.5 is given by the Equation 1:

$$\begin{aligned}&\mathrm{SOC_{ALL}}(\mathrm{gC.kg^{-1}soil}) = \\ &0.54(\mathrm{WpF2.5gH_20.100g^{-1}soil}) + 15.4 \\ &r = 0.74;\ r^2 = 0.55;\ n = 26 \qquad (1)\end{aligned}$$

For a given texture, allophanic soils exhibited higher SOC concentrations than the LAC and HAC soils (Figure 1). The large SOC accumulation in Andisols is well known (Wada, 1985) and mainly attributed to very stable humus-Al, Fe-complexes which may be protected from bacteria and enzymes in microaggregates rather than by a specific effect of allophane and associated minerals (Wada, 1985; Boudot et al., 1986; Oades et al., 1989).

We calculated the potential for SOC sequestration (pSEQ-SOC) in the 0–20 cm layer for andisols ALL as the difference in SOC stock mean values of PV and CC land uses from Table 2a. To compare equivalent sets of data, we selected the sites with a WpF2.5 higher than 69 $gH_2O.100\ g^{-1}$ soil (the higher value for LAC+HAC sites). The WpF2.5 (106 and 107 $gH_2O.100\ g^{-1}$ soil) and bulk density (about 0.5 mg . m^{-3} soil) mean values for the selected PV and CC land uses were similar and justify the comparison between PV and CC in the pSEQ-SOC calculation. The mean SOC stocks were 92.2 and 69.3 tC . ha^{-1} for the selected PV and CC, respectively, and the corresponding pSEQ-SOC of 22.9 tC . ha^{-1}. This value is of the same magnitude that of the LAC soils (23.3 tC . ha^{-1}) but lower than that of HAC soils (30.8 – 59.4 tC . ha^{-1}) (see below). Hence, in comparison with LAC and HAC soils, the higher organic carbon stock in ALL soils do not imply a higher potential of SOC sequestration.

Low activity clay soils (LAC) of the Lesser Antilles

Numerous authors have described the relationship between clay (or clay + silt) content and SOM in LAC soils from different locations in the tropics (Feller and Beare, 1997). These studies have generally shown that clay (or clay+fine silt) content is a relatively important determinant of SOM levels in LAC soils. But, for the set of data of the Lesser Antilles, which concerned only clayey soils, the relation between SOC and texture was not significant (r = 0.05; n = 16). This was possibly due to the low number (16) of sites studied.

The mean values of clay+fine silt content for the PV and CC sets of data were similar, 67.4 and 70.9%, respectively, and the bulk density was about 1.1 Mg . m^{-3} soil. Thus, PV and CC could be used for the calculation of the potential for SOC sequestration (pSEQ-SOC) on the 0–20 cm layer of LAC soils. From data in Table 2b, we calculated a mean pSEQ-SOC of 23.3 tC . ha^{-1}, a value similar to that of ALL soils (see above) but lower than that of HAC soils (see below).

High activity clay soils (HAC) of the Lesser Antilles

Few data are available to date for high activity clay (HAC) soils (smectites) in the tropics concerning the relationship between SOC and texture (Dalal et al., 1995; Coulombe et al., 1996). For 52 Vertisols from the West African savanna (mostly in Nigeria), containing >35% clay, Jones (1973) found that SOM was negatively correlated with clay content. In contrast, Yerima et al. (1989) reported a significant positive relationship between SOC and clay content for some Vertisols of Northern Cameroon. The negative relationship noted by Jones may be due to a strong influence of sheet erosion and/or of the vertic properties resulting in contamination of surface horizons with soil from deeper horizons.

Two groups of Vertisols exist in the Lesser Antilles: one group – Calcic Vertisol (Ve4) – is developed from recifal calcareous (dominant formation in Guadeloupe), and a second one – Calco-magneso-Sodic Vertisol (Ve6) – from volcanic materials (dominant formation in Martinique). The cationic exchange complex is dominated by calcium in Ve4 (more than 90% of the CEC) whereas important quantities of exchangeable magnesium + sodium can be found in Ve6 (40% of the CEC) (Blanchart et al., 2000).

For a set of 22 sites, the SOC concentrations of HAC soils did not differ greatly from those of the clayey LAC soils of the Lesser Antilles (Figure 1). We also found a positive and significant ($p < 0.05$) correlation ($r = 0.48$) between SOC concentrations and clay+fine silt (0-20 μm) content (%):

$$\begin{aligned}&\mathrm{C_{HAC}}\ (\mathrm{gC.kg^{-1}\ soil}) = \\ &0.59\ (\text{clay} + \text{fine silt\%}). - 19.6 \\ &r = 0.48;\ r^2 = 0.23;\ n = 22 \qquad (2)\end{aligned}$$

Table 2. b. Some characteristics of the soil sample (0–20 cm) for the studied low activity clay (LAC) soils of the Lesser Antilles. For site and vegetation descriptions: see Table 1. The number following vegetation abbreviation indicates the duration of the system. For Land use (see text): PV = Permanent Vegetation, IS = Improved System, CC = Continuous Cultivation. s.d. = standard deviation. v.c. = variation coefficient. nd = non determined

Site	Land use	Veget.	Clay	Clay+fine silt	C content	Bulk density	C stock	WpF2.5
			g.100 g^{-1} soil		gC.kg^{-1} soil	Mg.m^{-3}	t/ha	gH2O.100 g^{-1} soil
Fr7	PV	JP10	49.8	61.9	28.6	1.1	65.2	31.9
Fr4	PV	Pr10	63.9	82.3	38.6	1.1	84.2	39.2
Fi6	PV	F	49.0	63.1	44.1	0.9	82.9	40.9
Fi6	PV	F	46.9	65.4	37.1	0.9	69.7	40.9
Fi6	PV	JA	53.8	64.5	23.3	1.3	61.6	41.4
mean	**PV**		**52.7**	**67.4**	**34.3**	**1.1**	**72.7**	**38.9**
s.d.	PV		6.8	8.4	8.3	0.2	10.3	4.0
v.c.(%)	PV		12.8	12.5	24.2	14.6	14.2	10.2
Fr7	IS	Rv2	45.5	65.9	29.9	1.2	68.7	30.5
Fr7	IS	Jh4	41.0	63.6	23.4	1.2	53.9	30.5
Fr7	IS	Rv'2	48.5	71.8	21.3	1.2	49.1	33.2
Fr7	IS	Ja4	44.8	61.8	24.5	1.0	51.0	32.2
mean	**IS**		**45.0**	**65.8**	**24.8**	**1.1**	**55.7**	**31.6**
s.d.	IS		3.1	4.4	3.7	0.1	8.9	1.3
v.c.(%)	IS		6.9	6.6	14.8	4.9	16.0	4.2
Fr7	CC	Rv10	47.4	62.3	20.0	1.1	42.5	29.1
Fr7	CC	Rv'10	51.6	69.2	19.2	0.9	34.9	32.9
Fr4	CC	MG10	58.7	75.0	20.8	1.2	47.7	41.4
Fi6	CC	Ca	48.0	67.0	28.1	1.2	68.0	37.9
Fi6	CC	Ca	46.5	66.5	25.7	1.2	59.1	36.9
Fi6	CC	Ca	71.5	81.7	24.5	1.2	56.4	44.5
Fi6	CC	MG10	60.5	74.3	18.3	1.0	37.0	41.3
mean	**CC**		**54.9**	**70.9**	**22.4**	**1.1**	**49.4**	**37.7**
s.d.	CC		9.2	6.5	3.7	0.1	12.3	5.3
v.c.(%)	CC		16.7	9.2	16.6	9.5	24.9	14.1

The linear regression equation between SOC and texture, given in Equation 2, has a negative value (-19.6) for the Y axis intercept, which makes it an unreliable tool to calculate SOC content of HAC soil in relation to soil texture. Additional data will be required before any general conclusions can be drawn on the effect of soil texture on SOM storage in tropical smectitic soils.

When Ve4 and Ve6 Vertisols (0–20 cm layer) were compared under strictly similar land uses, large differences (Ve4 minus Ve6) in SOC stocks were revealed: 14.1 tC . ha^{-1} for bare soil (Ve4-SN9 minus Ve6-SN5 and), 29.7 tC . ha^{-1} for non-irrigated pasture (Ve4-Jh16 minus Ve6-Jh16), and 57.8 tC . ha^{-1} for fertilized and irrigated pasture (Ve4-Pr15 minus Ve6-Pr15).

These differences in SOC contents and pSEQ-SOC might be explained by: 1. the higher clay content for Ve4 which could be partly responsible for higher SOC stocks values, 2. the different ionic environment, as a result of which the aggregate stability was generally lower and the dispersion index higher for Ve6 than for Ve4 (Blanchart et al., 2000). Consequently:

Table 2. c. Some characteristics of the soil sample (0–20 cm) for the studied high activity clay (HAC) soils of the Lesser Antilles. For site and vegetation descriptions: see Table 1. The number following vegetation abreviation indicates the duration of the system. For land use: PV = Permanent Vegetation, IS = Improved System, CC = Continuous Cultivation. s.d. = standard deviation, v.c. = variation coefficient, nd = non determined

Site	Land use	Veget	Clay	Clay+fine silt	C content	Bulk density	C stock	WpF2.5
			g.100 g^{-1}	soil	gC.kg^{-1} soil	Mg.m^{-3}	t/ha	gH2O.100 g^{-1} soil
Ve6	PV	Pr15	65.7	80.4	30.6	1.0	61.1	nd
Ve6	PV	Jh16	62.4	76.1	17.9	1.0	35.7	nd
Ve6	PV	Jh10	34.2	52.3	22.6	1.1	50.6	34.2
Ve6	PV	Pr7	49.7	62.4	24.8	1.0	49.6	45.4
Ve6	PV	JA	54.2	71.0	33.2	0.9	58.4	53.0
Ve6	PV	Jh15	52.2	68.9	20.4	1.1	44.4	50.8
Ve6	PV	Pr10	64.2	85.4	37.1	1.2	87.5	60.6
Ve6	PV	Pr10’	65.8	86.6	36.8	1.1	81.8	68.9
mean	**PV**		**56.1**	**72.9**	**27.9**	**1.0**	**58.6**	**52.2**
s.d.	PV		10.9	11.7	7.5	0.1	17.9	12.0
v.c.	PV		19.4	16.1	26.9	9.1	30.6	23.0
Ve4	PV	Jh16	82.3	92.8	32.7	1.0	65.4	nd
Ve4	PV	Pr15	83.1	93.8	59.4	1.0	118.9	nd
Ve4	PV	Pr15’	75.8	87.6	58.8	1.0	117.5	nd
mean	**PV**		**80.4**	**91.4**	**50.3**	**1.0**	**100.6**	
s.d.	PV		4.0	3.3	15.2	0.0	30.5	
v.c.	PV		5.0	3.6	30.3	0.0	30.3	
Ve6	IS	MG2	65.7	79.4	16.8	1.0	33.5	45.0
Ve6	IS	MG2’	67.8	83.8	19.9	1.0	39.7	50.0
Ve6	IS	PrV-3	53.4	69.5	16.1	1.0	32.2	39.1
Ve6	IS	MG2”	49.3	65.0	23.8	1.0	47.7	37.0
Ve6	IS	PrV+3	63.3	76.8	17.3	1.0	34.7	42.0
mean	**IS**		**59.9**	**74.9**	**18.8**	**1.0**	**37.6**	**42.6**
s.d.	IS		8.1	7.6	3.2	0.0	6.3	5.1
v.c.	IS		13.5	10.2	16.9	0.0	16.9	12.0
Ve6	CC	MG15	69.5	81.3	13.8	1.0	27.7	43.1
Ve6	CC	SN5	64.3	77.8	12.8	1.0	25.7	46.2
Ve6	CC	MG10	55.6	65.1	10.6	1.1	23.2	48.9
Ve6	CC	MG10’	54.8	69.8	17.3	1.0	34.6	45.2
mean	**CC**		**61.1**	**73.5**	**13.6**	**1.0**	**27.8**	**45.8**
s.d.	CC		7.1	7.4	2.8	0.0	4.9	2.4
v.c.	CC		11.6	10.1	20.4	4.4	17.6	5.3
Ve4	CC	SN9	69.5	81.3	19.9	1.0	39.8	43.1
Ve4	CC	Ca50	76.2	93.2	21.3	1.0	42.6	
m.v.	**CC**		**72.8**	**87.3**	**20.6**	**1.0**	**41.2**	**43.1**
s.d.	CC		4.8	8.4	1.0	0.0	2.0	
v.c.	CC		6.5	9.6	4.7	0.0	4.7	

(i) erodibility was much higher for Ve6 than for Ve4. For confirmation, a test for soil erodibility was conducted with a rainfall simulator (surface 1 m^2, rainfall 55 mm . h^{-1} during 30 min, hoed surface). Dependent on the land use, the soil losses ranged between 200 and 500 g . m^{-2} for Ve6 and were always lower than 50 g . m^{-2} for Ve4. Sheet and rill erosion was visible on Ve6 and not observed on Ve4. This probably explained a large part of the differences in SOC stocks observed between the two soils; (ii) SOC could be better protected against mineralization in Ve4 with higher aggregate stability than in Ve6. This hypothesis has to be confirmed.

The mean values of clay+fine silt content for the PV and CC of the available data sets were close, 72.9 and 73.5% for Ve6 and 91.4 and 87.3% for Ve4, respectively. Thus, PV and CC could be used for the calculation of the potential for SOC sequestration (pSEQ-SOC) on the 0–20 cm layer of HAC soils. From the data of Table 2c, we calculated a pSEQ-SOC of 30.8 and 59.4 tC . ha^{-1} for Ve6 and Ve4, respectively. The potential for SOC sequestration for Ve6 was close to that of LAC soils, but was much higher for Ve4. However, we may question the significance of the pSEQ-SOC value of Ve6 for this soil as it may have been subjected to erosion, and it is difficult to conclude either an over- or underestimation of its pSEQ-SOC value. The Ve4 Vertisol exhibits the highest potential of SOC sequestration, about twice that of the VE6 Vertisol and 2.5 times that of the ALL and LAC soils.

Soil aggregation: Example of Vertisols

Complex interactions exist between SOC storage and aggregate stability; i.e. SOC plays a major role in the stabilization of aggregates and this stabilization can reinforce the SOC storage by diminishing SOC losses by sheet erosion and/or by improving the physical protection of SOC against mineralization. Some illustrations of the direct effect of soil aggregation on SOC protection against mineralization are presented.

Ladd et al. (1993) concluded that 'electron microscopy studies (SEM, TEM) have provided the visual evidence to reinforce conclusions drawn from other studies that physical protection mechanisms are important determinants of the stability of organic matter in soil'. Ultramicroscopic observations (TEM) of a tropical vertisol under pasture in Martinique (Feller et al., 1996; Blanchart et al., 2000) agree with this 'visual evidence' that plant cell wall debris, bacteria colonies and amorphous OM can be protected from decomposer organisms in microaggregates as they become encrusted in a dense clay fabric.

Different methods of physical disruption, including crushing, of bulk soil or aggregate classes have been used to highlight a protective effect of soil aggregation on SOM mineralization (Feller and Beare, 1997). They involve coarse (6–2 mm) or medium (2–1 mm) sievings, fine crushing and ultrasonication. In general, these studies have shown that a large proportion of the physically protected and biologically active organic matter is contained within micropores or is associated with macro- or microaggregates in the form of occluded particulate organic matter (Golchin et al., 1994; Puget et al., 1995).

For the Vertisol (Ve6), we show results obtained from plots with different SOC contents due to different plot histories (Chevallier, 1999). Air dried soil samples were prepared as follows: (i) a gentle manual disruption of the bulk soil into clods of about 1–2 cm diameter, then (ii) a manual and gentle crushing of a subsample of the clods to 5 mm and finally (iii) a strong crushing at 200 μm of a sub-subsample of the clods. Clods larger than 5.0 mm (Ag>5), aggregates smaller than 5.0 mm (Ag0.2–5), and microaggregates smaller than 0.2 mm (Ag<0.2) were thus obtained artificially. SOC mineralization was conducted, on each aggregate class, during 21 days at 28 °C with soil moisture at 80% of the water content at field capacity. The considered land use systems were market-gardening (MG) with low SOC content (12.5 gC . kg^{-1} soil) (in the upper 10 cm of soil), two subplots of a five-year artificial meadow of *Digitaria decumbens* (Pr5a, Pr5b) with intermediate SOC content (17.8 and 20.6 gC . kg^{-1} soil), and a 10-year old artificial meadow of *Digitaria decumbens* (Pr10) with high SOC content (38.2 gC . kg^{-1} soil) (Table 3).

The mineralized carbon (Cm21) increased with SOC content, but for each land use type, Cm21 increased also with decreasing aggregation (Table 3), the higher values being obtained for Ag<0.2. With each step of breakdown, a part of the carbon initially protected within aggregates became available for mineralization. The amounts of 'protected carbon' (PCm) associated with the classes Ag>5 and Ag0.2–5 could be calculated as the differences in Cm measured before and after the crushing process. PCm was expressed in % of the mineralized SOC of the Ag<0.2 class (% cm-Ag<0.2).

About 37 – 53% of the SOC was protected within aggregates larger than 0.2 μm. But the distribution of the protected sites differed with land use:

Table 3. Total carbon, mineralized C (Cm21) in short-term incubation (21 days) and % of protected mineralized C (PCm) in a Vertisol (Ve6) with different land uses and for different modes of preparation of the soil samples. Layer 0–10 cm. Soil sample preparation: clod > 5 mm (Ag>5), aggregates 0.2–5 mm (Ag0.2–5), aggregates <0.2 mm (Ag<0.2)

Site	Sample preparation	Total carbon	Cm21	PCm		
			Ag>5	Ag0.2–5	Total	
		gC . kg-1 soil		% Cm-Ag<0.2		
10 yr Market-	Ag>5	12.5	0.26	22.4	14.6	37.1
Gardening	Ag0.2–5	12.5	0.35			
	Ag<0.2	12.5	0.41			
	Ag>5	17.8	0.32	21.0	18.3	39.2
5 yr Meadow	Ag0.2–5	17.8	0.43			
Site A	Ag<0.2	17.8	0.52			
	Ag>5	20.6	0.39	32.2	20.2	52.5
5 yr Meadow	Ag0.2–5	20.6	0.65			
Site B	Ag<0.2	20.6	0.81			
	Ag>5	38.2	1.04	5.4	31.2	36.6
10 yr Meadow	Ag0.2–5	38.2	1.13			
	Ag<0.2	38.2	1.64			

1. For systems with low or medium SOC contents (MG, Pr5a, Pr5b) SOC was protected in both, the aggregate classes Ag>5 and Ag0.2–5, probably in the form of plant residues located at the periphery of aggregates larger than 0.2 mm
2. For Pr 10, with high SOC content, the protected SOC was preferentially located in the Ag0.2–5 class and probably mainly in form of plant residues occluded in the aggregates.

These results are in agreement with the higher water aggregate stability for Pr10 (Chevallier, 1999).

The agronomical determinants of SOC content and SOC sequestration: Example of Vertisols under planted pastures

The agronomic plot history

As a result of different agronomic histories, different plots on the same initial soil can exhibit different soil properties, and, for a given plant, different levels of plant productivity. These aspects can have a strong influence on the subsequent SOC sequestration. For the Vertisol Ve6, examples of two artificial meadows of *Digitaria decumbens*, under the same management system (fertilization and irrigation) but installed on plots with different agronomic histories (Chevallier, 1999) are compared.

The first plot (P10) was planted with *D. decumbens* after a long period of sugarcane production and 7 years of vegetated fallow. The initial SOC content (0–10 cm layer) before installation of the prairie was 25 gC . kg^{-1} soil. After 10 years, the SOC under *D. decumbens* reached ca. 40 gC . kg^{-1} soil, that is to say a mean annual increase of 1.5 gC . kg^{-1} soil.

The second plot (P5) was planted with *D. decumbens* after a long period of market gardening. Due to high sheet erosion, the initial SOC content (0–10 cm layer) before installation of the prairie was low (13 gC . kg^{-1} soil), aggregate stability was low and runoff high. Five years later, the SOC under *D. decumbens* reached 18 gC . kg^{-1} soil, that is to say a mean annual increase of 1.0 gC . kg^{-1} soil.

Thus, the SOC sequestration rate under the same pasture and same management was lower where the previous crop had led to a degradation of the soil properties. The lower increase on P5 can be due: (i) to a lower level of organic matter restitutions (roots and litter) as a consequence of the slower establishment of the prairie on a degraded soil, (ii) to a lower protection of the new SOC in the aggregates, in relation to a lower aggregate stability in the degraded soil.

The intensification level

For each of the two Vertisols Ve4 and Ve6, it was possible to compare soils under planted pastures with two levels of intensification (Table 2c): A high level with high fertilization and irrigation (Ve4–Pr15 and Ve6–Pr15), a low level, with low fertilization and no irrigation (Ve4–Jh16 and Ve6–Jh16). As a consequence, plant and animal productivity were much higher for the intensified than for the non-intensified system.

For the two soils, the SOC stocks were much higher for the intensified than for the non- intensified system (Table 2c). From the values in Table 2c, the effect of intensification (differences between Pr15 and Jh16) on SOC storage for the 0–20 cm layer can be estimated to be 25.4 and 53.5 tC . ha^{-1} for Ve6 and Ve4, respectively.

The tillage practice

For the Vertisol Ve6, a site initially under a 10-year artificial and intensive pasture (Pr10) was subdivided into two plots (ST15 and DT15) and cropped to market gardening crops for a 15 months period (2 crops). The type and depth of the tillage differentiated the two plots, a superficial conservation tillage for ST15 (10–15 cm) and a deep ploughing practice for DT15 (30–40 cm) (Ndandou, 1998). DT is the local conventional practice.

A decrease in SOC stock in the 0–40 cm layer was observed in the order:

$$Pr10 > ST15 > DT15$$

with no significant difference (at 0.05 level) between Pr10 and ST15 and between ST15 and DT15 but significant between Pr10 and DT15 (Table 4). The total SOC variations observed were mainly due to the significant differences of the SOC contents of the 0–10 cm layer. As a consequence, for this layer, soil aggregate stability was lower for DT15 and soil erodibility, evaluated in the field with a rainfall simulator (1 m^2, rainfall 150 mm h^{-1} during 30 min., hoed surface) was higher. The soil losses were 0.8 and 3.2 t . ha^{-1} and SOC losses were 3.2 and 9.8 gC . m^{-2} for ST15 and DT15, respectively, after two cropping seasons (Ndandou, 1998). Thus, the superficial conservation tillage ST, in comparison to the conventional tillage DT, could be considered as a favorable agricultural practice.

It is difficult to determine whether the difference in SOC stock between ST15 and DT15 was due to differences in SOC mineralization (protection against mineralization in ST15, a sequestration process) or to a larger SOC erosion in DT15 (a non C sequestration process). From the soil erodibility data and from particle size fractionation of SOM data (Ndandou, 1998), it was surmised that the main process involved was erosion.

The example illustrates the difficulty to conclude in some cases that a clear sequestration process is involved when data on the erosion levels are missing. That is particularly important when different tillage practices are compared.

Conclusions

Many edaphic and agricultural determinants play a major role on SOC stocks in tropical soils. Three points have to be underlined:

1. The soils with the highest SOC stocks under permanent vegetation exhibited not necessarily the highest potential SOC sequestration (pSEQ-SOC) as defined as the difference in SOC stock between continous cultivation and permanent vegetation. As an example, the smaller pSEQ-SOC mean value was found for the Andisol which presented the higher SOC stocks;
2. in the absence of quantitative data on soil erosion and the amount of eroded SOC, it is speculative to interprete the effect of two different treatments on SOC storage solely in terms of C sequestration from the atmosphere. In the comparison of two plots, a fraction of the absolute value of pSEQ-SOC can be due to losses of SOC by erosion in the continuous cultivation plot and not to storage by humification of organic matter restitutions in the permanent vegetation plot. There is a large need of data at the plot level to evaluate quantitatively the role of water or wind erosion in the losses or deposits of SOC (Starr et al., 2000, Roose and Barthès, this issue);
3. some agricultural determinants affecting SOC are poorly documented. Examples are the plot history, the initial soil fertility level or the initial SOC con-

Table 4. SOC contents and stocks of a Vertisol (Ve6) under artificial meadow (Pr10) and after 15 months of market-gardening cultivation with superficial (ST15) or deep (DT15) tillage. Adapted from Ndandou (1998)

Site	Layer (cm)	C (g . kg^{-1} soil) [a]	Bulk density	C (t . ha^{-1}) [b]	
				Mean	s.d.
Artificial meadow (Pr10)	0–10	36.9a	1.07	36.5	6.0
	10–20	21.9b	1.07	23.4	3.8
	20–30	16.4c	1.07	17.5	2.9
	30–40	12.2c	1.05	12.8	1.8
	0–40			93.3	11.0
Market-Gardening (ST15)	0–10	29.3e	0.94	27.5	2.9
	10–20	26.7b	1.00	26.7	3.7
	20–30	15.8c	1.06	16.8	2.5
	30–40	11.1c	1.05	11.7	1.8
	0–40			82.6	7.0
Market-Gardening (DT15)	0–10	21.1b	0.94	19.8	1.5
	10–20	22.6b	1.00	22.6	2.8
	20–30	17.3bc	1.06	18.2	4.7
	30–40	10.0c	1.05	10.5	1.7
	0–40			71.1	7.5

[a] The mean values with a same letter did not statistically differ at the probability of 5% (PLSD test of Fisher). The mean values were calculated from 6 replicates for market-gardening ST15 and DT15 and 20 replicates for artificial meadow. [b] The standard deviations (s.d.) were calculated from mean values and 3 replicates of bulk density.

tent. We saw for the Ve6-Vertisol, the importance of those determinants for the SOC sequestration dynamics under pasture.

Further research on agricultural management effects on SOC levels is needed.

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