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Soil Organic Matter Changes in Agroforestry and Organic Farming in the Semi-Arid Region of Northeastern Brazil

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ABSTRACT

The development of management strategies aiming to increase soil quality in Brazilian semi-arid regions, including the improvement of soil organic matter (SOM) status, is still scarce. In general, most of the traditional farming practices adopted in agricultural fields in Northeast Brazil (semi-arid) contribute to reduce SOM levels. Thus, alternative management practices must be implemented to improve soil quality in different agricultural production systems. Within this context, agroforestry and organic farming have been considered suitable management options to cope with the semi-arid climate despite of its environmental constraints. This study aimed at presenting results from well established experiments on agroforestry and organic farming performed in Sobral, Guaraciaba do Norte and Ubajara counties, all located in the State of Ceará, Brazil. In agroforestry, agrosilvopastoral and silvopastoral designs may be considered as important options to increase soil organic C stocks, with consequences in the different SOM pools, including labile C. Organic farming has been implemented in both small and large scale agriculture, and it also represents a good strategy to increase the status of SOM, even in sandy soils as observed at Ubajara county. Obviously, agronomic, economic and social aspects should be linked to the environmental benefits brought about through the adoption of agroforestry and/or organic cultivation. Notwithstanding, the discussion involving the improvement of food production in Brazilian semi-arid must regard both types of agroecosystems as suitable options to increase the status of SOM, which represents the starting point for recovering soil quality, and consequently, enhancing productivity.

Keywords: agrosilvopasture, carbon management index, carbon stocks, humic substances, labile C

Abbreviations: AF, agroforestry system; **CMI**, carbon management index ; **FAF**, fulvic acid fraction; **HAF**, humic acid fraction; **HUM**, humin fraction; **MAOC**, mineral associated organic carbon; **POMC**, particulate organic matter carbon; **SOC**, soil organic carbon; **SOM**, soil organic matter

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INTRODUCTION

Soil organic matter (SOM) content in semi-arid regions is usually low mainly due to the low addition of residues to the soil, as well as to the photodecomposition of organic material (Austin and Vivanco 2006). Primary plant production and soil biological activity are the two main biological processes governing inputs and outputs of SOM in the soil, and the equilibrium between these two characteristics determines the SOM cycling dynamics (Six *et al.* 2002). Most of the traditional farming practices developed in Northeast Brazil (semi-arid domain) has contributed to the depletion of organic inputs. In this Region, the natural vegetation (Caatinga) has been modified by deforestation and land degradation, as a result of shifting cultivation, grazing, wood extraction (charcoal and firewood) (Sampaio *et al.* 1993; Campello *et al*. 1999; Lucena *et al*. 2007). Furthermore, slash and burn agriculture is very common in this region which has favored great losses of SOM, promoted soil erosion, and intensified CO_2 emissions. In general, intensive agricultural practices coupled with adverse environmental conditions bring about soil degradation in Brazilian semi-arid regions. The maintainance or increase of soil organic carbon (SOC) in the semi-arid is important for soil quality restoration (e.g. enhancing soil fertility), maintenance of humidity, and also for reducing carbon emissions in the atmosphere. Therefore, alternative management practices are needed in order to improve soil quality in different

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Invited Mini-Review

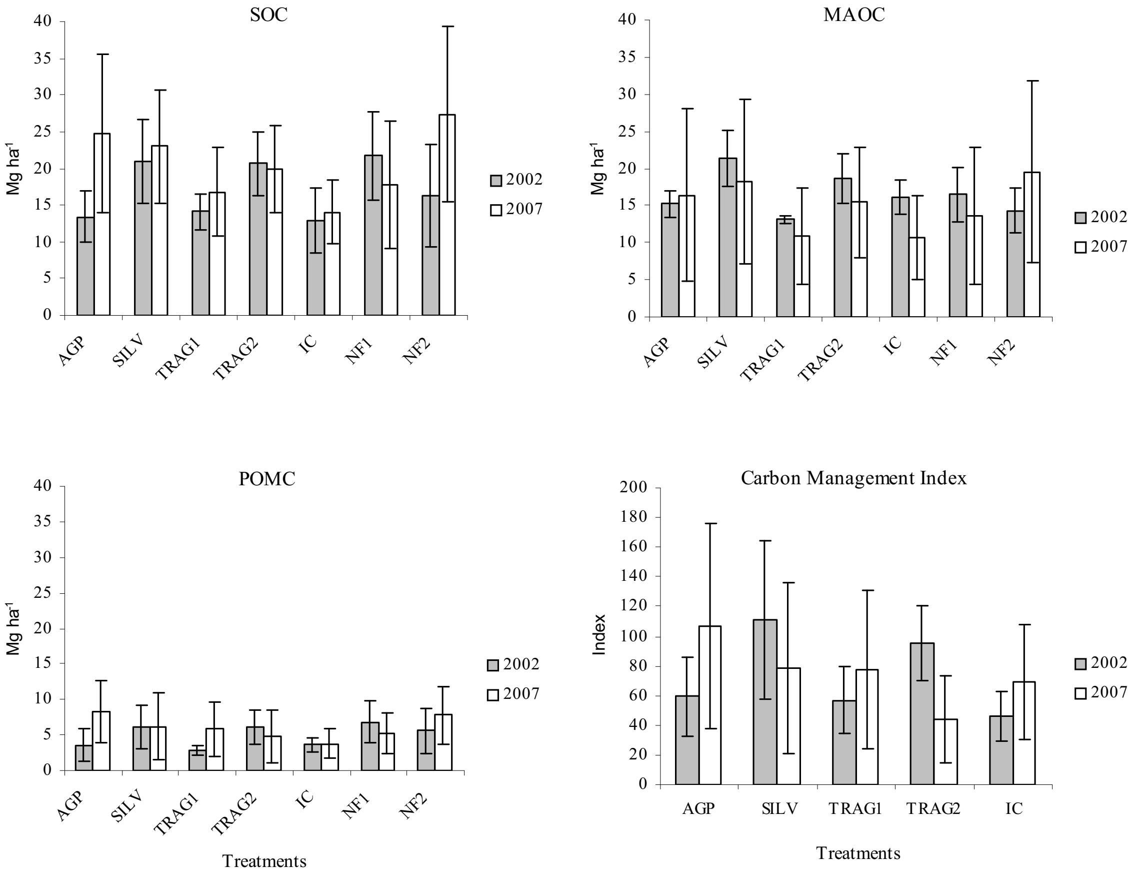

Fig. 1 Soil organic carbon (SOC), mineral associated organic C (MAOC), particulate organic matter C (POMC), and carbon management index in the agroforestry, conventional system and native forest sites in the northeast,. Brazil. Bars represent 1 standard deviation. AGP: agrosilvopasture; SILV: silvopasture; TRAG1 and TRAG2: traditional agrosilvopasture; IC: intensive cropping; NF: native forest (Caatinga). (Adapted from Maia *et al.* 2007 and Nogueira 2009).

agricultural production systems.

Within this context, agroforestry and organic cultivation have been considered as important alternatives that contribute to increasing sustainability of agroecosystems, in both environmental and socio-economic levels (Suresh 2010). Agroforestry systems (AFs) are defined as being a land-use system in which woody plants are grown in association with agricultural crops, pasture or livestock (Young 1997). AFs have been widely recognized as a sustainable food production system, and would be particularly attractive for underdeveloped regions, where the use of external inputs is not feasible (Bresman and Kessler 1997; Nair *et al.* 1999; Maia *et al.* 2007). AFs have the potential to improve soil quality (Maia *et al.* 2006) and increase total SOC storage and different SOM pools by increasing the input of organic residues (Nair *et al.* 1999; Sharrow and Ismail 2004; Maia *et al.* 2007).

Organic agriculture (or organic farming) is also pointed out as a management alternative to improve soil quality, being essentially important for monitoring and restoration of degraded lands. This practice is a holistic system that focuses, among other aspects, on improving soil health through the preservation of physical, chemical and biological soil properties. Organic farming, as adopted in the Ibiapaba Plateau, located in the Northwestern portion of the State of Ceará, has contributed to increase SOC stocks, indicating that the organic management in sandy soils represents a suitable option for recovering SOM levels (Xavier *et al.* 2004).

Our objective was to review the results from well established experiences of AFs and organic farming conducted in the semi-arid and the Atlantic Forest in the state of Ceará, Brazil and evaluates its effects on SOC dynamic.

AGROFORESTRY SYSTEMS

A case study in the Northeast of Brazil

This study was developed in the experimental field of Crioula farm, part of the National Caprine Research Center of Brazilian Agricultural Research Corporation (EMBRAPA Caprinos e Ovinos), situated in the State of Ceará, Brazil. The climate is semi-arid with average annual temperature and rainfall of 30°C and 790 mm, respectively. The dominant soil type was an Ortic Cromic Luvisol. A total of seven treatments in the experimental farm were evaluated from 2002 to 2007, including: agrosilvopasture (AGP), silvopasture (SILV), traditional agroforestry implemented in 1998 (TRAG1), traditional agroforestry implemented in 2002 (TRAG2), intensive cropping (IC), and two areas of native forest (NF1 and NF2). The latter was used for comparative purposes. More detailed information about the sites studied can be found in Maia *et al.* (2007).

In order for better understanding the impacts of the different AFs on SOM dynamic in the Brazilian semi-arid region, the main results obtained between 2002 and 2009 are presented here, which represent the current available data.

1. Effects of agroforestry on different SOM pools

This study was based upon the concept that SOM is composed by three different pools including: i) a passive pool, with turnover time ranging from centuries to millennia; ii) a slow pool with turnover of decades; and iii) an active pool with turnover ranging from hours to months (Parton *et al.* 1998; Sherrod *et al.* 2005). In this work, the slow pool was rep-resented by: i) C from the light fraction (LF) of SOM (i.e. including free and occluded LF) determined in 2002, and ii) C in the particulate organic matter (POMC) determined in the sand fraction in 2007. Humic substances determined in 2002, and the mineral-associated carbon obtained in 2007, were both classified in this work as mineral associated organic carbon (MAOC), and represent the passive pool. Thus, it was possible to compare the results of the main SOM pools over the period from 2002 to 2007.

Between 2002 and 2007 the C stock increased 84% in the AGP treatment when compared with the reference area (NF1). This result was different from the results in 2002 in which the AGP treatment presented lower SOC stock than the NF1 (**Fig. 1**). There was also an increase in SOC for the SILV, TRAG1 and IC treatments, with C stocks increasing by 10, 19 and 8%, respectively. On the other hand, TRAG2 and the reference area NF 1 presented a decrease in C stock of 4 and 19%, respectively.

Regarding MAOC stocks, only the AGP treatment promoted increase of 7% C stocks, whereas SILV, TRAG1, TRAG2 and IC treatments presented decreases of 15, 17, 17 and 44%, respectively (**Fig. 1**). However, despite the substantial reduction of MAOC stocks in the SILV and TRAG2, these treatments maintained MAOC stocks higher than those observed in the reference area (NF1), which is probably related to the higher SOC stocks of these treatments.

The POMC pool showed basically the same trends of total SOC stocks (**Fig. 1**), but with some differences in the magnitude. In some cases the increase or decrease of POMC was more acute than in total SOC stocks, suggesting that POMC is more susceptible to expressing changes in SOM levels. For example, the treatments AGP and TRAG1 had an increase of 133 and 112%, respectively, on the POMC stocks between 2002 and 2007, which were markedly greater than the total SOC stocks. In the TRAG2 treatment POMC was reduced by 24% while SOC stock was reduced only by 4%. The exception was the SILV treatment, which basically did not present changes between 2002 and 2007, differing from the results for total SOC as well as MAOC.

2. Carbon management index

The C management index (CMI) provides a sensitive measurement of the rate of change in soil C dynamics of agricultural fields relative to a reference area (Blair *et al*. 1995; Leite *et al*. 2003). Values higher than 100% indicate a recovery in SOM levels, and consequently of the soil quality. Considering these aspects, it can be noted (**Fig. 1**) that there were important changes between the treatments during the study period. In 2002, only the SILV treatment presented CMI above 100% (**Fig. 1**); however, in 2007 this treatment showed a substantial decrease in this index. Inversely, the AGP presented an increase on CMI from 2002 to 2007, and it was the only treatment with CMI above 100%, suggesting its potential to promote the recovering of soil quality. Additionally, treatments TRAG1 and IC presented increase in CMI for the assessed period (**Fig. 1**), indicating that there was a recovering of SOM levels.

Although the standard deviation analysis showed no significant differences over the time, results observed from 1997 (when the experiment was established) until 2007 (when the last study was performed) show clear and important changes on SOM. The main changes occurred in the AGP treatment, where, despite the initial C stock losses (i.e., observed in 2002), a substantial increase in the SOC and POMC stocks could be observed in 2007, as well as an increase of the passive organic matter pool (MAOC), although less pronounced. Furthermore, there was also an improvement in the CMI, which is indicative of soil quality recovery. These results confirm the findings of Maia *et al*. (2007) that, based on biological indicators and organic residue inputs, pointed to the establishment of a new state of equilibrium of the soil environment in the AGP treatment.

Similarly, treatments TRAG1 and IC presented a gain in SOC and POMC stocks and an increase in the CMI; however, they showed a decrease in the MAOC (which represents the most stable fraction of SOM). The changes are probably related to the period of 8 and 5 years under fallow in TRAG1 and IC, respectively, that may have promoted the increase of above and belowground organic residue input (i.e. due to the native vegetation regrowth) with a consequent increase of POMC and SOC stocks. However, the reasons for MAOC losses between 2002 and 2007 in these treatments are not clear, since little changes are expected in this SOM pool due to its great stability. Probably, the whole soil profile evaluation associated with a detailed humic substances study may provide a better understanding about the SOM dynamics in such systems, specifically in the TRAG treatments (TRAG1 and TRAG2), which are rotating systems (i.e. usually renewed every 8-10 years). This type of information would be extremely important for determining the correct fallow time in these areas.

Table 1 Semi-variogram parameters for carbon management index (CMI) in the agroforestry and conventional systems, State of Ceará, Northeast Brazil.

Parameters	Treatments				
	AGP	SILV	TRAG1	TRAG2	IC
Model	Exp	Sph	Exp	Exp	Exp
Nugget	66.0	70.0	40.0	80.9	84.0
Sill	620.0	629.7	388.0	270.0	2800.0
Range	15.2	9.0	26.6	10.0	22.5

AGP: agrosilvopasture; SILV: silvopasture; TRAG1 and TRAG2: traditional agrosilvopasture; IC: intensive cropping; Adapted from Nogueira (2009).

A geostatistical evaluation of CMI was also performed by Nogueira (2009), which was presented through the semi-variogram parameters (**Table 1**) and an interpolated surface maps (**Fig. 2**). The fitted parameters for the CMI data showed that the exponential model provided the best fit to the most treatments. In all treatments the relationship between the nugget and the Sill were below 25%, which indicates a high degree of spatial dependence (Cambardella *et al*. 1994). Furthermore, the maximum distance in which the data were spatially correlated ranged from 9 to 27 m (**Table 1**), and these results confirm those found in other attributes (i.e. SOC, POMC and MAOC), where it was observed that the distance of 10 m (data not shown) is the "ideal" to collect soil samples in order to evaluate the SOM dynamic in the studied conditions.

The CMI spatial distribution (**Fig. 2**) obtained through the kriging procedure showed that the AGP treatment had the highest proportion of CMI above 100% suggesting a recovery in SOM status, and consequently, of soil quality. We found that 64% of the area in AGP presented CMI above 100%, whereas SILV, TRAG1, TRAG2 and IC treatments had, respectively, 14, 25, 0.1, and 2.4% of their areas under the ideal CMI (> 100%). Hence, besides corroborating the average CMI and SOM pools findings (**Fig. 1**), this information demonstrates clearly that the positive effects of the AGP treatment are substantially better distributed in the experimental plot, whereas the opposite was observed in the other treatments which can greatly compromise the real sustainability of such systems. Thus, AGP represents a suitable alternative of land use to increase SOM levels and recovering soil quality in Brazilian semi-arid regions.

ORGANIC CULTIVATION

In recent years, an increase in organic farming has been observed in Northeastern Brazil. In these areas, organic manure could be a vital resource for supplying plant nutrients and replenishing organic matter content. This would further emphasize the need to use organic manure alone or in conjunction with chemical fertilizers for maintenance of soil fertility and sustainability of crop production. Considering this scenario, it is important to foster the understanding of the benefits of organic management for the soil environment and also as a way to evaluate the sustainability of organically cultivated areas. In the State of Ceará, organic farming has shown substantial development in the Ibiapaba Plateau. Results from two studies that evaluated SOM dynamics in cultivated areas under organic manage-

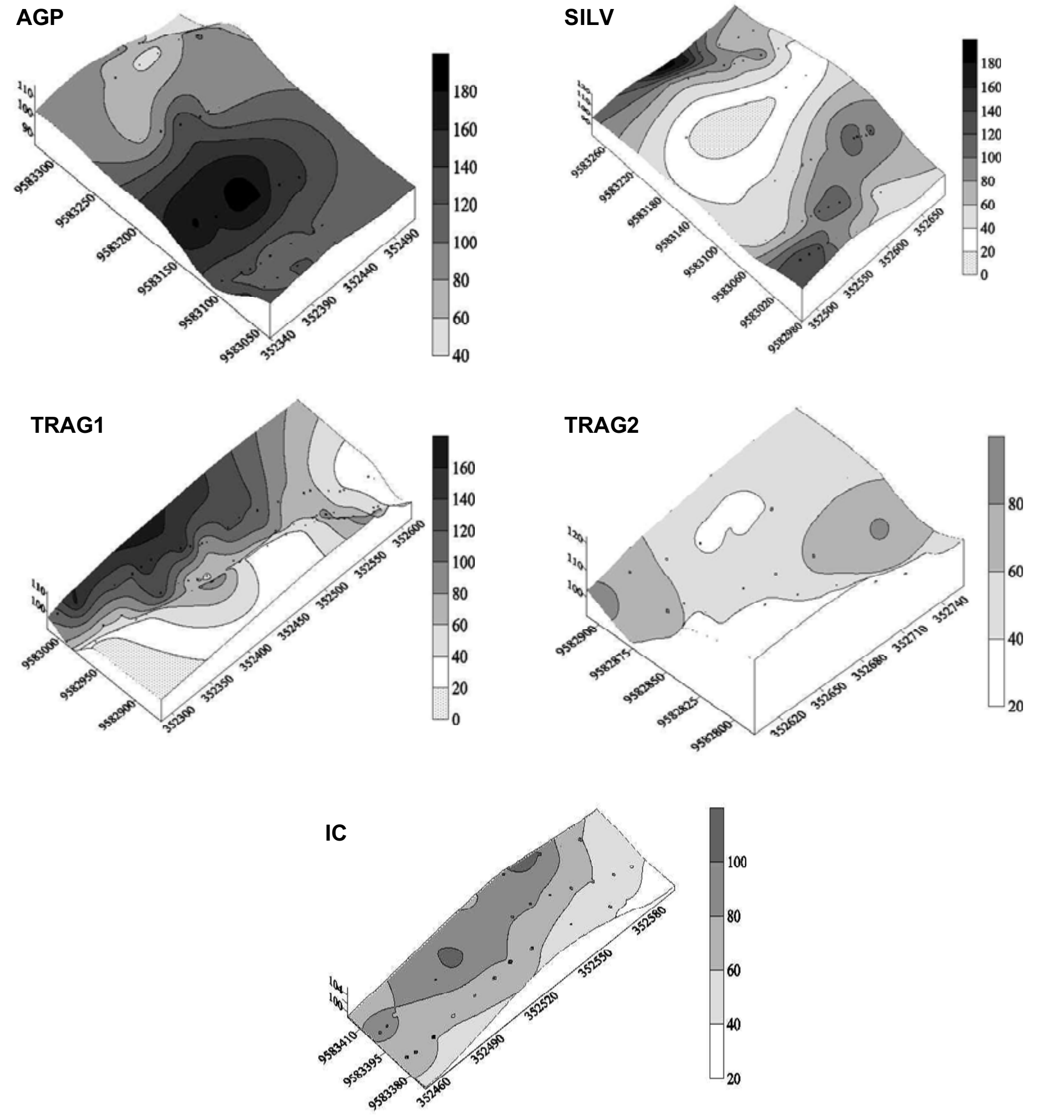

Fig. 2 Spatial variability of the carbon management index (%) in the agroforestry and conventional systems in the Northeast, Brazil. AGP: agrosilvopasture; SILV: silvopasture; TRAG1 and TRAG2: traditional agrosilvopasture; IC: intensive cropping; NF: native forest (Caatinga). (Nogueira, 2009 – authorized by the author).

ment in the Ibiapaba Plateau are presented here.

Study case 1: Organic cultivation in Guaraciaba do Norte County

The studied agricultural farms were located in the Ibiapaba Plateau region, in Guaraciaba do Norte county, State of Ceará, Northeastern Brazil (04° 10′ 01″ S; 40° 44′ 51″ W at 902 m altitude). Samples of a sandy-textured soil (Typic Quartzipsamment, USA soil classification) were collected from three different areas: Area I (6 years with organic farming after 25 years with conventional tillage), Area II (4 years with organic farming after 10 years with conventional tillage), and Area III (4 years with organic farming after 10 years with conventional tillage). Areas under natural forest (NF) (known as Caatinga) were also sampled and used as a reference condition. Total SOC was determined by wet oxidation with sulphur acid and potassium dichromate with external heating (Yeomans and Bremner 1988). The humic acid (HAF), fulvic acid (FAF) and humin (HUM) fractions were obtained according to the method recommended by the International Society of Humic Substances (Swift 1996).

Soil organic C fractionation differing in C lability was performed through adaptation of the method described by Chan *et al*. (2001). Indexes of carbon pools (CPI), the lability (LI) and CMI were obtained according to Blair *et al*. (1995). The total SOC were obtained by the product among C contents, bulk density and the thickness of the soil layer (Burnoux *et al*. 2002). The data were submitted to analysis of variance and means were compared by Tukey's test at 5% probability.

1. Changes in SOC stocks

Total SOC differed depending on the study areas and the management systems adopted (**Table 2**). Overall, organic farming showed highest SOC stocks at 0-10 and 10-20 cm ($P < 0.05$), reflecting positively on soil C stocks. Several authors have observed increase of SOM contents in agroecosystems under organic management (Reganold 1988; Clark *et al*. 1998; Stockdale *et al.* 2002), which may be related to the addition of organic materials such as crop residues and manures. In areas under conventional tillage the intensive soil disturbance during soil preparation as well as the large use of chemical fertilizers may accelerate the SOM mineralization process which results in SOM decreasing (Reganold *et al.* 1987).

The SOC contents at 0-20 cm layer were higher in the Area I (6 years with organic farming) when compared to Areas II and III (4 years with organic farming), suggesting that the time spent under organic farming is an important factor for the soil C storage. The largest C stocks were observed in areas with organic farming. In these areas, SOC contents at 0-20 cm depth were almost twice that of those

Table 2 Soil organic C contents and stocks in areas under organic farming, natural forest and conventional system in Guaraciaba do Norte, State of Ceará, Brazil.

Management	**SOC (g kg^{-1})**			**SOC (Mg ha^{-1})**		
	Area I	**Area II**	**Area III**	**Area I**	**Area II**	**Area III**
0-10 cm						
Organic	20.46 aA	16.30 aB	20.00 aAB	29.46	23.47	26.60
Natural forest	13.38 bA	7.52 bB	9.34 bAB	14.99	10.75	12.05
Conventional	7.34 cA	6.16 bA	8.82 bA	11.08	8.44	14.02
LSD		4.20		-	-	-
10-20 cm						
Organic	13.84 aA	8.12 aB	9.67 aB	20.62	13.07	14.70
Natural forest	7.74 bA	4.29 bA	5.63 bA	10.84	6.13	7.94
Conventional	5.97 bA	4.72 abA	5.98 abA	10.81	7.13	10.29
LSD		3.81		-	-	-
20-30 cm						
Organic	5.71 aA	3.75 aA	6.37 aA	9.36	6.41	10.51
Natural forest	7.46 aA	3.87 aB	6.34 aAB	10.44	5.57	9.64
Conventional	5.43 aB	4.58 aB	8.63 aA	9.66	7.00	14.76
LSD		3.10		-	-	-
30-40 cm						
Organic	4.46 aA	2.59 bA	4.95 aA	7.22	4.27	8.02
Natural forest	6.41 aA	5.14 abA	6.43 aA	9.10	7.40	9.45
Conventional	6.85 aA	6.46 aA	6.51 aA	11.23	9.75	10.74
LSD		2.96		-	-	-
Total Stock						
0-40 cm						
Organic				66.66	47.22	59.83
Natural forest				45.37	29.85	39.08
Conventional				42.78	32.32	49.81

Means followed by the same letter, lower case in the column and upper case in the lines, for the same variable within each depth, do not differ by Tukey's test at 5% level of probability. LSD: least significant difference. Adapted from Alencar (2005).

found in areas under native forest. In relation to areas with conventional tillage, such difference was almost tripled.

The presence of leguminous plants as covering crop in organic management may have favoured the increase of C stocks in the upper soil layers. Several authors have found that the addition of organic residues including organic nitrogen (N) sources (e.g. green manure) has promoted increases in C storage, since the presence of N is crucial to the stabilization of organic C forms in the soil (Knops and Tilman 2000).

2. Changes in soil humic substances

The soil management adopted in Areas I, II and III influenced C content of the FAF, HAF and HUM fractions (**Table 3**). Although there were few changes in SOC below 30 cm in depth, major changes in the distribution were observed between the soil humic substances fractions (**Table 3**). The highest FAF contents were found in Area I (6 years of cultivation) at 0-20 cm in depth, indicating the presence of humic substances less polymerized, more soluble, and with greater charge density (Stevenson 1994). Soils under organic farming and natural forest presented high content of FAF until 20 cm in depth. Below this layer there was great uniformity between FAF contents. At the top layer (0-10 cm) conventional management had negative impact (decrease) on levels of C FAF when compared to those observed in the area under forest.

It is important to note that the decrease of C content in FAF, HAF and HUM in conventional tillage was significant compared to the values observed in the native forest. In Area I, where conventional cultivation was adopted for approximately 25 years, the impact of soil C management was higher than those observed in Areas II and III (**Table 2**). When compared to the reference (native forest), areas under conventional tillage may have presented increased susceptibility to loss of soil C by oxidation (Wilson 1978; Leite *et al*. 2003). Overall, there was a reduction of C content in HAF as soil depth increased. Results revealed changes in the distribution of HAF among Areas I, II and III. As observed for FAF, the area under organic cultivation showed higher C content in HAF at the 0-20 cm depth when compared to both native forest and conventional tillage. The oldest organic area (Area I) showed higher C content in HAF at 0-30 cm depth compared to Areas II and III ($P < 0.05$). In other forest areas and conventional tillage, a uniform distribution of this fraction was observed throughout the soil profile. The highest values of HAF in relation to FAF in conventional tillage reflect a rapid mineralization followed by intense humification (Zech *et al*. 1997). In this case the rapid mineralization may be a result of intense chemical fertilizer additions to the soil in conventional tillage. Under these conditions, the humification pathway seems to be more intense on the soil surface, indicating humic substances with more fulvic features in the subsurface.

The highest C contents were found in the HUM indicating that this is the most abundant humified fraction (**Table 3**). The prevalence of HUM in humic substances was observed in several studies (Stevenson 1994; Sikora and Yakovchenko 1996; Leite *et al*. 2003).

The highest levels of HUM may be related to its insolubility and resistance to biodegradation, probably as a function of the formation of stable complexes with the mineral soil fractions (Stevenson 1994; Canellas *et al.* 2000). In the top soil, HUM in organic farming was higher than in natural forest and conventional tillage ($P < 0.05$). Most of the total SOC was found in the HUM fraction (40-60%), whereas HAF and FAF represented 20 to 30% of SOC (data not shown). Regarding the condition of semi-arid sandy soils with low addition of organic residues, the HUM fraction has a fundamental role as a reservoir of C in soil. The increase of this fraction in the soil means presence of more stable SOM, and its accumulation in sandy soils is essential for retaining moisture and cations, increasing soil aggregation and nutrient cycling. Area I was more efficient in accumulating C in the FAH and HUM. Intercropping with different vegetable crops coupled with the addition of compost (4 kg m^{-2}) and green manure (legumes and grasses) may be promoting an increase in soil C in their most humified and stable form.

Table 3 Organic C contents in the fulvic acid (FAF), humic acids (HAF) and humin (HUM) fractions in areas under organic farming, natural forest and conventional system in Guaraciaba do Norte, State of Ceará, Brazil.

Management	FAF (g kg^{-1})			FAH (g kg^{-1})			HUM (g kg^{-1})		
	Area I	Area II	Area III	Area I	Area II	Area III	Area I	Area II	Area III
0-10 cm									
Organic	5.33 aA	4.73 aAB	3.52 aB	5.82 aA	3.09 aB	4.63 aA	8.69 aA	8.46 aA	8.95 aA
Natural forest	2.67 bA	2.38 bA	2.28 bA	3.09 bA	1.88 bB	1.62 bB	6.61 bA	2.90 bB	4.25 bB
Conventional	1.21 cA	1.88 bA	2.01 bA	1.25 cA	1.68 bA	2.22 bA	4.62 cA	2.28 bB	4.31 bA
LSD		1.23			1.19			1.82	
10-20 cm									
Organic	4.37 aA	2.24 aB	2.97 aB	4.89 aA	2.16 aB	3.24 aB	5.46 aA	3.40 aB	4.40 aAB
Natural forest	2.00 bA	1.59 aA	1.95 abA	2.05 bA	0.86 aA	0.94 bA	2.89 bA	1.88 bA	2.70 bA
Conventional	1.31 bA	1.55 aA	1.34 bA	1.65 bA	1.29 aA	1.54 bA	2.72 bA	1.89 bA	2.35 bA
LSD		1.46			1.4			1.46	
20-30 cm									
Organic	1.96 abAB	1.41 aB	2.74 aA	1.54 aA	0.48 aB	1.27 bAB	2.68 aA	1.89 aA	2.58 aA
Natural forest	2.37 aA	1.42 aA	1.91 abA	1.65 aA	0.59 aB	0.88 bB	3.14 aA	2.07 aA	2.98 aA
Conventional	1.29 bA	1.37 aA	1.24 bA	0.99 aB	0.91 aB	2.63 aA	2.71 aA	2.04 aA	3.40 aA
LSD		0.95			0.74			1.54	
30-40 cm									
Organic	1.83 aAB	1.40 aB	2.87 aA	0.74 aA	0.07 bA	0.47 cA	1.91 bA	1.32 bA	1.90 bA
Natural forest	1.84 aA	1.28 aA	1.80 abA	1.02 aA	0.74 bA	1.43 bA	3.38 aA	2.72 aA	2.88 aA
Conventional	2.07 aA	1.92 aA	1.62 bA	1.03 aB	1.58 aB	2.68 aA	3.27 aA	2.58 aA	2.48 abA
LSD		1.16			0.82			0.83	

Means followed by the same letter, lower case in the column and upper case in the lines, for the same variable within each depth, do not differ by Tukey's test at 5% level of probability. LSD: least significant difference. Adapted from Alencar (2005).

3. Carbon management index

In general, carbon pool index (CPI), labile carbon (L), lability index (LI) and CMI were higher in the cultivated areas under organic farming than in conventional tillage (**Table 4**). In organic areas the SOC and C in the humic fractions also showed significant increases at the 0-10 and 10-20 cm soil layers.

These results indicate that organic farming may increase the lability of SOM, and great part of the C can be distributed in more stable organic fractions, thus maintaining a better balance on SOM dynamics. Conventional tillage presented lower CMI values than areas under organic farming, especially at the 0-10 and 10-20 cm soil layers. Although the CMI values obtained for conventional tillage did not show loss of C (values around 100%), results revealed a greater potential of organic farming for storing C in the soil.

Table 4 Mean values [(1)] of carbon pool index (CPI), labile carbon (L), lability index (LI) and carbon management index (CMI) in areas under organic farming, conventional system, and natural forest in Guaraciaba do Norte, State of Ceará, Brazil.

Management	Indices			
	CPI	L	LI	CMI
0-10 cm				
Organic	1.95 ± 0.36	1.48 ± 0.53	2.11 ± 0.84	427.45 ± 224.18
Conventional	0.77 ± 0.20	0.72 ± 0.21	1.03 ± 0.39	84.88 ± 48.34
Natural forest		0.72 ± 0.08		
10-20 cm				
Organic	1.80 ± 0.09	1.49 ± 0.31	2.12 ± 0.57	378.60 ± 86.09
Conventional	0.98 ± 0.18	0.64 ± 0.16	0.81 ± 0.06	86.56 ± 20.05
Natural forest		0.72 ± 0.14		
20-30 cm				
Organic	0.91 ± 0.13	1.38 ± 0.05	1.97 ± 0.62	174.11 ± 26.71
Conventional	1.09 ± 0.32	0.79 ± 0.44	1.08 ± 0.51	112.72 ± 59.28
Natural forest		0.74 ± 0.18		
30-40 cm				
Organic	0.66 ± 0.14	0.86 ± 0.16	1.21 ± 0.36	71.10 ± 38.96
Conventional	1.11 ± 0.13	0.74 ± 0.36	0.92 ± 0.63	100.87 ± 59.43
Natural forest		0.85 ± 0.14		

[(1)]Average values compiled from the Areas I, II and III. Values in parentheses indicate the standard deviation. Adapted from Alencar (2005).

Study case 2: Organic farming in Ubajara County

Different management systems were evaluated in the Ibiapaba Plateau (3° 51′ 12″ S; 41° 5′ 10″ W, at 850 m altitude), State of Ceará. A study was performed aiming at identifying the effects of organic farming and conventional cultivation on the SOC dynamics. Organically managed areas from Amway Nutrilite LTDA farm of Brazil were selected and studied. At this site, Caribbean cherry (*Malpighia punicifolia* L.) has been grown in large-scale under organic production according to biodynamic principles since 1997. More detailed information about the studied sites can be found in Xavier *et al.* (2009).

Samples of a sandy-textured soil (Typical Quartzipsamment, USA soil classification) were collected from different Caribbean cherry plots that were grown under organic production. The establishment of one of the Caribbean cherry plots was preceded by a simultaneous cultivation of legumes and grasses (SCLG). Forty days after planting, the biomass produced by the SCLG (approximately 45 Mg ha^{-1} of fresh residue) was incorporated to the soil surface (0 to 20 cm) as green manure (GrM). The effects of the GrM fertilization (+GrM) as performed in the rows (+GrM_r) and between rows (+GrM_{br}) were evaluated. For comparative purposes an area under conventional system (CS) that was cropped with carrots (*Daucus carota* L.), sugar beet (*Beta vulgaris* L.), beans and corn (*Zea mays* L.), in succession and different times with fallows between crops since 1985 was selected. The sequential use of a subsoiler followed by disc harrow and disk plow was used during the soil preparation before planting. Chemical fertilization and agrochemicals were applied annually. Areas under NF were sampled and used as a reference of steady state.

1. Changes in SOC and N stocks

Among the organic systems, the range of total SOC content varied from 2.5 to 12.6 g kg^{-1}. In the upper soil layer, total SOC and N stocks were significantly greater in the rows compared to those between-rows, in response to organic fertilization. In the other soil layers, SOC and N stocks were similar among all treatments in the organic systems. The CS presented less variation on the SOC contents throughout soil layers when compared to the NF area, indicating the direct effect of plowing on the downward SOC distribution. The GrM fertilization did not affect the total SOC content in the +$GrM_{r,br}$ areas. This lack of response can be associated to the period of six years between soil sampling and green manure fertilization in these areas. Although differences in total SOC content between the +GrM and -GrM areas were not significant, previous findings at the same locations (Xavier *et al*. 2006) have shown that the most sensitive SOM pools (e.g. microbial biomass C and N) were affected by GrM fertilization. The utilization of GrM before the establishment of Caribbean cherry organic system probably had an effect on the SOC mainly in the first year of cropping. Therefore, the incorporation of fresh material should be periodically carried out to achieve positive responses from the use of this material. However, this may not be feasible for perennial crops.

The SOC stocks in the organic systems were significantly lower than in NF, except for the upper soil layer. The SOC reductions in the organically cropped areas compared to NF were 0.22, 1.29, 3.32, and 3.22 Mg ha^{-1} in the layers from 0 to 5, 5 to 15, 15 to 30, and 30 to 50 cm, respectively. The SOC and total N stocks in the CS system did not differ from NF in the 0 to 5 and 5 to 15 cm layers. On the other hand, greater SOC and total N stocks were found in the deepest soil layers in CS compared to NF, representing an increase of 2.11 Mg C ha^{-1} below the effective soil plow zone.

The total SOC stock in the whole soil profile (0 to 50 cm) varied from 29.96 Mg ha^{-1} (-GM$_r$) to 39.60 Mg ha^{-1} (-GM$_{br}$) in the organic cultivation. In comparison to its corresponding native area (NF), SOC stock in the whole soil profile for the organically cropped area decreased in about 8 Mg ha^{-1}. On the other hand, N stock was greater (3.25 Mg ha^{-1}) in the organically cropped areas when compared to NF. Considering the low nutrient content, common in most sandy soils, the increment in N stocks represents an important contribution for N cycling in the organically cultivated sites. Organic management influenced the total SOC and N stocks, mainly in the upper soil layers, as a response to the utilization of organic residues as fertilizer and mulch, especially where compost was applied (+GrM$_r$ and -GrM$_r$). In addition, considering the short time following the conversion of conventional into organic management, SOC and N contents were not sensitive enough to detect the changes in SOM, as reported elsewhere (Xavier *et al*. 2006; Leite *et al*. 2007; Maia *et al.* 2007).

2. Changes in humic substances stocks

In general, C content in humic fractions decreased as soil depth increased. There was a homogeneous distribution of FAF in the soil in all management systems, which was probably due to its greater mobility in the soil compared to that of HAF and HUM (Stevenson 1994). A dominance of HUM followed by FAF and HAF was verified among the management systems in the 0- to 50-cm layer. In general, HUM represented about 66 and 39% of total SOC and N stocks, respectively, in the cultivated areas. The permanence of HUM in the soil is associated to its high insolubility and resistance to the biodegradation, favoured by the formation of stable metallic and/or clay–humic complexes (Stevenson 1994; Rice 2001).

In the organically cultivated systems, there were greater C stocks in the HAF and HUM in the rows, in comparison to between row areas, mainly in the upper soil layer. The NF area presented greater organic C content in the FAF in all soil layers compared to the cultivated areas. In general, no significant differences were found for SOC content among the organic systems when each humic fraction was evaluated separately.

The CS and NF areas presented similar C content in the FAF and HAF. On the other hand, the highest C content in the HUM occurred in the CS area for all soil layers. The increase of HUM in the CS compared to the natural condition represented an increment of 4.79, 6.88, and 4.52 Mg C ha^{-1} and 210, 330, and 70 kg N ha^{-1} in the 5 to 15, 15 to 30, and 30 to 50-cm layers, respectively. These results emphasize the direct effect of intensive soil management on the genesis of more stabilized organic fractions. Furthermore, the results could also be associated with clay increment with soil depth in the CS area, suggesting the preferential formation of a more stabilized humic fraction (Stevenson 1994; Hayes and Clapp 2001). However, because clay content in both CS and NF areas were similar in all soil layers, except for 0 to 5 cm layer, the highest C HUM stock in the CS area seems to be mainly related to the transport of organic matter to deeper layers by continuous soil plowing procedures (Freixo *et al*. 2002). These results indicate HUM makes up a large portion of SOM and reveals the preferential pathway to the genesis of humic substances, from FAF to HUM. Similar results were reported by Souza and Melo (2000) in a tropical agricultural system under corn production. The N content in the humic fractions presented trends similar to the C content.

3. Carbon management index (CMI)

The absolute value of CMI is not important, but the changes reflect how different management strategies affect the soil C dynamics over time. At the soil surface, organically cultivated systems presented an increase in CMI to 179.2 and 133.4 respectively in the +GrMr and -GrMr areas, but showed decreases to 72.5 and 97.0 in the +GrM$_{br}$ and -GrM$_{br}$, respectively. In the row treatments the increase in CMI seems to be associated with the increase of both CPI and LI, suggesting the rehabilitation of SOM. Furthermore, in between row treatments, the decrease of CMI was more related to a decline on the CPI index, probably due to the lower input of organic residues compared to row areas. A decrease in CMI to 68.7 in CS was also observed and can be mainly related to a decline in the CPI as a result of intensive tillage. There was a substantial increase in CMI as soil depth increased in the CS to 99.6. Such an increase was attributed to an increase in CPI rather than to changes in the LI. It is worth noticing that the increase in CMI in CS at the subsurface occurred at the expense of C transportation caused by soil tillage. In so doing, the interpretation of CMI in such situations must be done carefully. Therefore, our results suggest that in the surface layer, the row treatments of the organic management systems reestablished the SOM content in relation to the steady-state area (Leite *et al*. 2007), whereas the reduction of the CMI in CS may suggest a decline in soil quality (Maia *et al.* 2007) and increased potential for C losses to the atmosphere.

CONCLUDING REMARKS

Naturally, soils in the semi-arid regions are in general poor in organic matter. Among other factors, it is due to the lower biomass production compared to other regions. Notwithstanding, not only climatic factors can be considered as a main contributors for decreasing SOM levels in the semi-arid, but also must include soil management, which has an important role in SOM dynamics. The intensive use of the land by agriculture, including the fast deforestation of native vegetation, slash and burn practice, and soil disturbance has intensified the process of SOM loss. As a result, a decrease in soil quality and, consequently, of the productivity of agricultural lands is easily perceptible.

Regarding this background, the establishment of management systems that favor the build up of SOM in order to improve physical-, chemical-, and biological soil properties, the intensification of the mechanism of nutrient cycling, and the promotion of soil covering aiming at maintaining moisture and protecting the soil surface against erosive processes are very important to semi-arid regions. In this study it has been shown that agroforestry and organic cultivation can be considered as two suitable management options to recover SOM levels and to increase soil quality in a semi-arid region of Northeastern, Brazil.

In agroforestry the agrosilvopasture and silvopasture have been considered the most promissory designs for food and fiber production, and for increasing SOM, which has been evidenced by the increase in the CMI. Such agroecosystems, specially silvopasture, have demonstrated high efficiency in reducing soil erosion (Aguiar *et al.* 2010), recovering soil quality (Maia *et al.* 2006) and increasing organic C stocks (Maia *et al.* 2007). In terms of global impacts, both agroecosystems demonstrated substantial potential to promote soil carbon sequestration, with soils acting as a C sink for atmospheric CO_2.

Organic cultivation has been successfully performed in both small and large scale agriculture as observed in the case studies in Guaraciaba do Norte and Ubajara counties, respectively. In both environmental conditions, organic cultivation has led to an increase in SOM due to the constant input of organic residues (e.g. composting, green manure, organic fertilizers, etc). As for agroforestry, soils under organic cultivation have also presented higher CMI compared to conventional tillage, suggesting soil quality recovery, even in areas under sandy soils, where building up SOC is more complicated due to the inherent characteristics of these soils. In view of the results obtained for both analysed situations, organic cultivation can be considered an important strategy for food production, and C sequestration in Brazilian semi-arid regions. In spite of the environmental constraints associated to climatic conditions (e.g. dry climate, sandy soils, low addition of residues in the soil) the increase of SOM in areas under organic farming brings important benefits to nutrient cycling, water retention, and soil chemistry and fertility with the consequent improvement of soil quality.

Obviously, agronomic, economic and social aspects should be linked to environmental benefits in the adoption of agroforestry or organic cultivation before considering them as a sustainable management option to the semi-arid. Some constraints need further discussion, such as the problem of high dependency of external inputs (off-farm), of organic manure in large scale agriculture, the high demand for human labor in agroforestry systems, as well as the environmental damage caused by the abusive use of organic fertilizers, resulting in the leaching of labile forms of C, N and P from the surface to the deeper soil layers reaching groundwaters.

Some research lines in the study of SOM dynamics need to be strengthened in both agroforestry and organic farming systems. For example, the qualitative aspect of SOM needs to be more stressed in these areas. Furthermore, environmental services including C sequestration must be computed helping the development of public policies for the incentive of friendly agriculture. The mechanisms involving C, N and P cycles in the soil in agroforestry and organic farming are still poorly understood, and need to be clarified. Finally, the modelling of several SOM data obtained in both situations could be very important in the construction of scenarios for Brazilian semi-arid regions, pointing out the most effective management options for recovering soil quality and for increasing food production.

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