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Agroforestry for Recovering Soil Organic Matter: A Brazilian Perspective

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ABSTRACT

The recovery of soil organic matter (SOM) can be considered as one of the most important goals in recovering soil quality. The evaluation of changes in SOM levels as a result of soil management practices is essential to identify strategies to increase agricultural production, avoid soil degradation, and decrease the emission of greenhouse gases. Agroforestry systems are considered to be a suitable land use alternative to maintain SOM levels through the supply of litter and root residues. In Brazil, no-tillage is widely accepted as a soil management alternative to enhance soil organic carbon (C) sequestration in different ecosystems. Nevertheless, only few studies have been conducted to evaluate the effect of agroforestry on SOM recovering. Interest in agroforestry has increased in the last decade, especially its adoption by smallholding agriculture. The most consistent Brazilian agroforestry experiences have been developed basically in three main macro-regions of the country: the North, Northeast and Southeast Regions. In the North, multistrata agroforestry designs are preferentially adopted in the Amazonian Region, whereas silvopastoral, agrosilvopastoral and alley cropping are mainly adopted in the Northeast Region. Coffee-agroforestry systems are examples of well established agroforestry experiences in the Southeast. The potential of soil C sequestration by agroforestry systems in Brazil varies substantially among the different regions. The potential of organic C storage depends on the design of the systems, tree species, climate and soil characteristics. The biomass production (through litterfall) in some Brazilian agroforestry systems may vary from 1.39 to 25.92 Mg ha^{-1} year^{-1} and the respective potential for organic C storage from 0.62 to 11.66 Mg ha^{-1} year^{-1}.

Keywords: Atlantic coastal rainforest, coffee-agroforestry, environmental service, soil carbon sequestration
Abbreviations: ICRAF, world agroforestry centre; **MDG**, millennium development goals; **SOM**, soil organic matter; **WEHAB**, water, energy, health, agriculture and biodiversity

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INTRODUCTION

Agroforestry is considered to be a promising technique to achieve sustainable land use with the potential to preserve soil organic C, delay soil degradation, increase the extractable water pool and enhance water uptake, and promote both social and economic benefits (Schroeder 1995; Garrity 2004; Cannavo *et al.* 2011). One of the most important benefits of agroforestry to the environment, especially to soil, is its potential to increase SOM stocks, which is considered a key factor in the improvement of fertility of highly weathered soils. In this paper agroforestry can be defined as "*a collective name for land-use systems in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both; there are usually both ecological and economic interactions between the trees and other components of the system*" (Young 1997).

In Brazil, no-tillage management has been considered the most important technique to achieve soil conservation (Machado and Silva 2001). However, its application has been addressed to almost exclusively large agricultural land holdings. In this context, agroforestry is still an incipient land use option in Brazilian agriculture. Nevertheless, interest in agroforestry has increased in last decade, especially regarding its adoption by smallholding agriculture, which has vital importance in national food production. Despite an increase of agroforestry adoption, only few data are available in the Brazilian literature reporting its effects on the environment, and few studies are devoted to measure the potential of SOM storage by converting conventional into agroforestry systems.

In this paper we aim to present and discuss the potential of agroforestry in restoring SOM based on the Brazilian experience. It begins by discussing the importance of agroforestry for world food production and soil management. Then, we present the effects of agroforestry on SOM improvement highlighting the role of residue quality on SOM dynamics. We try to show the potential of litter production and soil C accumulation in different agroforestry designs

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Invited Review

Table 1 Twelve agroforestry hypotheses for soil management.

Hypothesis related to processes
1. Agroforestry can control runoff and soil erosion;
2. Agroforestry can increase soil water availability in agroecosystems;
3. Agroforestry can maintain soil organic matter and biological activity;
4. Agroforestry can enhance soil physical quality through organic matter maintenance and the effect of tree roots;
5. N-fixing trees species in agroforestry can enhance N cycling and increase N inputs;
6. Agroforestry can improve nutrient cycling from lower to upper soil horizons through tree roots system;
7. Agroforestry can lead to more closed nutrient cycling, therefore to more efficient use of nutrients;
8. Agroforestry can help check the development of soil toxicities;
Hypotheses related to agents
9. The decomposition of tree litter and prunings can improve and/or maintain soil fertility
10. Below-ground input through tree roots are equally important to the soil fertility as that above-ground biomass;
Hypotheses related to systems
11. Agroforestry can be adopted to reclaim eroded and degraded land;
12. The tree component in agroforestry can acquire environmental resources which the crop alone would not acquire.

Adapted from Young (1997).

performed in the Brazilian Regions. In addition, aspects related to the effect of agroforestry on soil humus quality are also addressed. Finally, the paper discusses and points out some of the most important needs of SOM research to improve agroforestry science in Brazil.

AGROFORESTRY FOR SUSTAINABLE FOOD PRODUCTION AND SOIL MANAGEMENT

Recent discussion at the United Nations has pushed world leaders to agree to set up measurable goals for reducing hunger, poverty, disease, illiteracy, environmental degradation, and discrimination against women (UNDP 2010). The so called "Millennium Development Goals" (MDGs) provide a framework for all nations, and the entire development community, to work coherently together toward this common objective. Other initiatives proposed by the World Summit on Sustainable Development in 2002 provide focus in five key thematic areas: Water, Energy, Health, Agriculture and Biodiversity (WEHAB). Agroforestry has been considered an important strategy to contribute significantly to the achievement of MDGs and WEHAB initiatives (Garrity 2004; World Agroforestry Centre 2008). According to the World Agroforestry Centre (ICRAF) seven key challenges of the agroforestry science in regard to the MDGs and WEHAB:

1. Help **eradicate hunger** through basic food production systems based on agroforestry methods of soil fertility and land regeneration;
2. Decrease of the **rural poverty** through market-driven (local tree cultivation systems), generating income and build assets;
3. Enhancement of rural life quality through advances in **health and nutrition**;
4. Conserve **biodiversity** through integrated conservation-development solutions;
5. Protect **watershed services** through agroforestry-based solutions that enable the rewarding for the provision of environmental services;
6. Assist to better adaptation to **climate change**, and to benefit from emerging carbon markets, through tree cultivation;
7. Build human and institutional **capacity** in agroforestry research and development.

Such key components of the agenda for agroforestry research and development in the context of the MDGs were examined in more detail by Garrity (2004).

Agroforestry acts basically in two different spheres or functions: production and service. The contribution to production is to obtain tree-derived products from the farm, such as fuel wood, fodder and fruit. The relative importance of these products varies according to environmental and socio-economic conditions, and they are important to diversify the output from farms, giving a broader economic base and greater food security. The service functions include shade, reduction in wind speed, control of weeds and fencing. Besides, the most important service function related to agroforestry is its role in soil management, especially regarding the control of erosion, maintenance and/or increase of soil fertility, biodiversity conservation, and improving air and water quality (Young 1997; Jose 2009).

Twelve specific hypotheses postulated by Young (1997) are associated to the main aspects of agroforestry in soil management (**Table 1**). The first group (1-8) refers to processes in plant-soil systems; the second (9-10) is related to above- and below-ground effects of trees on soil; hypothesis 11 refers to the specific role in reclamation of degraded land, whereas hypothesis 12 denotes the relationships between tree-crop competition and production.

ICRAF has identified and proposed six Global Research Priorities (GRPs) for agroforestry adoption (**Table 2**). These priorities are vital to maintaining research focus and achieving impact at high enough levels to address the developmental and environmental challenges (World Agroforestry Centre 2008).

From the Brazilian perspective, so far, agroforestry has not been a widely accepted option for food production and for improving soil quality. While the majority of agricultural commodities attends to the export market (e.g. soy, corn, coffee, sugar, fruits), basic food production is performed almost in its totality by smallholding farming, that historically receive few governmental incentives. There is only little information available in the literature with regard to the effects of agroforestry on Brazilians soils; making it difficult for a broad discussion about the advantages and/or disadvantages of this land-use system as an option for food production and enhancement of environmental quality.

Despite the barriers for its adoption, well established small-farming agroforestry experiences have been useful in proposing new and more sustainable agricultural practices. In Brazil, agroforestry systems have been practiced mainly in three regions: the North, Northeast and Southeast. The type and design of agroforestry systems vary according to the needs of farmers, topography, climate characteristics, tree species, and availability of natural resources. In the North Region, for instance, agroforestry is adopted in degraded areas from the Amazon (Yamada and Gholz 2002; Tapia-Coral *et al.* 2005), being considered a viable alternative to ranching and helping to conserve the remaining Amazonian forest. Other relevant agroforestry experiences in Amazon are described elsewhere (Browder and Pedlowski 2000). In the Northeast Region, agroforestry experiences with cacao (Moço *et al.* 2009), maize in alley-cropping (Marin *et al.* 2006; Marin *et al.* 2007), cotton (Lima 2005), silvopastoral systems (Menezes *et al.* 2002; Tiessen *et al.* 2003; Maia *et al.* 2007) may also be highlighted. Well established agroforestry-coffee systems experiences may be found in the Southeast Region, especially in the Atlantic Coastal Rainforest biome (Cardoso *et al.* 2001). Agroforestry has great potential to solve part of the agricultural

Table 2 Global Research Priorities (GRPs).

GRPs	Objective
1. Domestication, utilization and conservation of superior agroforestry germplasm;	To increase access to improved germplasm of priority tree species and ensure better functioning of systems that supply tree seed and seedlings.
2. Maximizing on-farm productivity of trees and agroforestry systems;	To develop better understanding of and approaches for enhancing on-farm productivity through improved agroforestry systems. This includes nutrient cycling among trees, animals and crops.
3. Improving tree product marketing for smallholders;	To expand smallholders' access to value chains for agroforestry tree products and to improve marketing strategies and market performance to enhance incomes and livelihoods.
4. Reducing risks to land health and targeting agroforestry interventions to enhance land productivity;	To evaluate the cost effectiveness and outcomes of intervention programmes and to develop national capacity in operational methods and tools of land health surveillance.
5. Improving the ability of farmers, ecosystems and governments to cope with climate change;	To improve the stability of farming systems and livelihood strategies of smallholder farmers in light of current climate variability and long-term climate change.
6. Developing policies and incentives for multifunctional landscapes with trees that provide environmental services.	To help formulate better policies and incentives for maintaining the multifunctionality of landscapes with trees.

Adapted from World Agroforestry Centre (2008)

problems in this region (Mendonça and Stott 2003), since it may contribute to reduce soil erosion (Franco *et al.* 2002) and enhance nutrients and C cycling (Mendonça *et al.* 2001).

In Brazil, the no-tillage system has been widely adopted as a desirable conservation management practice because it reduces soil and water losses and leaves at least 30% or greater soil surface covered by plant residue (Machado and Silva 2001). However, it is worth noting that no-tillage is usually adopted by large-scale agricultural systems, which denotes high costs for its implementation and maintenance, especially at the beginning of cultivation. This fact is still an important constraint for small farming agriculture in adopting no-tillage. Hence, other options of land use in promoting soil conservation, such as agroforestry systems, needs to be investigated as well as in small- and large-scale agricultural lands. Although only little data has been raised from agroforestry experiments in Brazilian soils, some interesting guidelines for food production and environmental conservation for smallholding agriculture, which has an important socio-economic role on the agriculture in the country, have been highlighted.

AGROFORESTRY FOR SOIL ORGANIC MATTER IMPROVEMENT

A general soil-agroforestry hypothesis states that appropriate agroforestry systems have the potential to control soil erosion, maintain SOM and physical properties, and promote nutrient cycling and efficient nutrient use (Young 1997). A more specific hypothesis among the 12 agroforestry hypotheses for soil management (**Table 1**) considers that agroforestry systems may maintain SOM and biological activity at satisfactory levels in order to maintain or improve soil fertility. The main effect of trees in maintaining SOM levels is related to the supply of litter and roots residues, which are important factors in the improvement of soil fertility.

SOM has been recognized as a major factor controlling the soil's ability to deliver agricultural and environmental services, and also to sustain human societies at both local (e.g. maintaining soil fertility) and global (e.g. increasing of C sequestration) scale (Manlay *et al.* 2007). Recent reviews discussing the potential of agroforestry for increasing C sequestration and promoting ecosystem services and environmental benefits are available in the literature (Montagnini and Nair 2004; Jose 2009; Schoeneberger 2009).

In agroforestry systems, the quality of organic residues differs according to the tree component. Therefore, the processes of residues decomposition are different. In natural ecosystems and conventional agriculture systems, the main type of organic residues deposited on the soil surface is the senescent biomass. In agroforestry systems, besides the senescent material, inputs of fresh biomass derived from tree pruning also occur. Thus, the quality and the rates of litter and green leaf decomposition from the same plant may be quite different. This may differentiate agroforestry from natural and conventional systems (Mafongoya *et al.* 1998).

During the last decade, efforts to characterize the SOM were focused on the measurement of its different pools by using techniques based on the degree of solubility of its components submitted to an acid or alkali medium (Swift 1996). More recently, however, the development and adaptation of some techniques allowed the elucidation of important aspects of SOM quality. Besides SOM quantity, the quality (e.g., structure and composition) and distribution of individual organic fractions (e.g., fulvic and humic acids) are important to maintain soil structure and fertility (Ding *et al.* 2006). SOM quality may be defined as its capacity to be used by the soil biota as a source of energy, and/or as C skeleton in its own structure. The response to high SOM quality is an increase in the microbial activity promoting fast decomposition of residues and nutrient availability (Rovira and Vallejo 2002). In tropical regions, especially in the areas with agroforestry systems in Brazil, studies focused on the SOM quality are still scarce. Notwithstanding, some attempts have been performed in different regions as reported elsewhere (Mendonça and Stott 2003; Marin *et al.* 2006; Maia *et al.* 2007; Schwendener *et al.* 2007).

SOIL ORGANIC MATTER IN BRAZILIAN AGROFORESTRY SYSTEMS

The evaluation of changes in the SOM as a result of land-use and management is important to identify strategies to increase agricultural production avoiding soil degradation and decreasing greenhouse gas emission (Freixo *et al.* 2002). The conversion of native forests into agricultural systems promotes decreases in soil C and N stocks due to reductions of organic inputs and increase of SOM mineralization and soil erosive process (Bayer and Mielniczuk 1997; Marchiori Junior and Melo 2000; Leite *et al.* 2003). The magnitude and extension of SOM decline, however, depends on the method of conversion, soil management intensity after conversion and physical and chemical soil properties (Lugo and Brown 1993).

Increasing soil C stocks and reducing soil C losses by improved soil management are important strategies for sustainable development. In Brazil, the no-tillage system has been systematically studied as an option to enhance C sequestration (Bayer *et al.* 2000; D'Andrea *et al.* 2002; Leite *et al.* 2003; Sisti *et al.* 2004; Carvalho *et al.* 2009). For instance, Machado and Silva (2001) reported that soils under no-tillage can store (0-10 cm layer) on average 25.1 Mg C ha^{-1} compared to 19.9 Mg C ha^{-1} in conventional cultivation. On the other hand, survivals regarding the potential of C sequestration by agroforestry are scarce in the Brazilian literature.

Schroeder (1994) stated that agroforestry could be considered for increasing C sequestration due to: i) tree component fixes C from the atmosphere via photosynthesis and stores it on soil; and ii) agroforestry may reduce the need of

Table 3 Annual input of biomass and organic C derived from litter, and soil organic C stocks in different agroforestry designs developed in different regions of Brazil.

System	Litter (Mg ha^{-1} year^{-1})		Soil organic C stock (Mg ha^{-1})	Location	Region	Reference
	Biomass	Organic C[/a]				
Multistrata-agroforestry	2.30-7.20		21.6[/b]	Manaus	North	Schroth *et al*. 2002
Açaí-agroforestry	4.47	2.01	-	Pará	North	Santos *et al*. 2004
Cacao-agroforestry	1.45	0.65	-	Pará	North	Santos *et al*. 2004
Agrosilvocultural	3.01	1.35	-	Manaus	North	Tapia-Coral *et al*. 2005
Agrosilvocultural	4.11	1.85	-	Manaus	North	Tapia-Coral *et al*. 2005
Agrosilvopastoral	3.38	1.52	-	Manaus	North	Tapia-Coral *et al*. 2005
Agrosilvopastoral	4.07	1.83	-	Manaus	North	Tapia-Coral *et al*. 2005
Multistrata-agroforestry	10.80	4.86	-	Rondônia	North	Corrêa *et al*. 2006
Alley cropping	11.04	4.97	-	São Paulo	Southeast	Mafra *et al*. 1998
Coffee-agroforestry	10.16	4.57	-	Minas Gerais	Southeast	Arato *et al*. 2003
Coffee-agroforestry	6.10	2.74	-	Minas Gerais	Southeast	Campanha *et al*. 2007
Banana-agroforestry	25.92	11.66	-	Rio de Janeiro	Southeast	Silveira *et al*. 2007
Coffee-agroforestry	5.20	2.34	-	Minas Gerais	Southeast	Jaramillo-Botero 2008
Coffee-agroforestry	4.33	2.37	48.4[/c]	Minas Gerais	Southeast	Duarte 2007; Aguiar 2008
Coffee-agroforestry	2.40	1.45	31.3[/b]	Minas Gerais	Southeast	Duarte 2007; Xavier 2009
Coffee-agroforestry	2.00	1.16	31.4[/b]	Minas Gerais	Southeast	Duarte 2007; Xavier 2009
Coffee-agroforestry	4.33	2.37	28.5[/b]	Minas Gerais	Southeast	Duarte 2007; Xavier 2009
Alley cropping	1.39	0.62	15.6[/b]	Paraíba	Northeast	Marin *et al*. 2006
Agrosilvopastoral	4.10	1.84	31.3[/d]	Ceará	Northeast	Maia *et al*. 2007
Silvopastoral	4.50	2.02	43.0[/d]	Ceará	Northeast	Maia *et al*. 2007
Alley cropping	3.46	1.56	-	Paraíba	Northeast	Marin *et al*. 2007
Cacao-agroforestry	-	-	13.6[/b]	Bahia	Northeast	Barreto *et al*. 2008
Cacao-agroforestry	-	-	41.1[/c]	Bahia	Northeast	Barreto *et al*. 2011
Cacao-agroforestry	-	-	30.3[/c]	Bahia	Northeast	Barreto *et al*. 2011

[a] Calculated considering an average of 45% of C in the litter biomass;
[/b] Soil organic C stock in the 0-10 cm layer;
[/c] Soil organic C stock in the 0-15 cm layer;
[/d] Soil organic C stock in the 0-20 cm layer;
(-): information not available.

deforestation in agriculture by providing alternatives to shifting cultivation. However, a realistic potential of soil C storage by agroforestry systems cannot be easily measured; thus, it must not be broadly generalized, since agroforestry systems varies with system-specific characteristics, including climate, soil type, tree planting densities, and tree management (Montagnini and Nair 2004). Furthermore, there is a lack of reliable estimates on the extent of the area under agroforestry in different ecological zones, especially in Brazil.

In recent studies (Oelbermann *et al.* 2004; Schoeneberger 2009; Takimoto *et al.* 2009) agroforestry is considered as an appealing option for sequestering C on agricultural lands on a global scale. For instance, Montagnini and Nair (2004) stated that smallholder agroforestry systems have the potential to increase C storage at a rate of 1.5 to 3.5 Mg C ha^{-1} year^{-1}.

A realistic potential of C accumulation by Brazilian agroforestry systems is not easily measurable because i) there is an absence of long term agroforestry experiments, ii) the systems vary greatly between the different regions, iii) there is a lack of information regarding the role of agroforestry in soil C sequestration, iv) different designs are used for different purposes, and v) due to the disagreement on the use of several methodologies. Notwithstanding, the available data report that biomass production (through litterfall) in some Brazilian agroforestry systems may vary from 1.39 to 25.92 Mg ha^{-1} year^{-1} and the respective potential for C storage from 0.62 to 11.66 Mg ha^{-1} year^{-1} (**Table 3**).

Little quantitative data on soil organic C storage are available on specific systems in a field scale in Brazilian soils. In the North Region of Brazil, agroforestry has been considered an important management strategy to reduce Amazonian biome deforestation and to increase C sequestration (Browder and Pedlowski 2000; Santos *et al.* 2004). In this region, agroforestry is usually adopted in a multistrata design including fruit trees [e.g. açaí (*Euterpe oleracea* Mart.), cacau (*Theobroma cacao* L.), banana (*Musa sapientum* L.), cupuaçu (*Theobroma grandiflorum* (S) K. Schung), genipapo (*Genipa americana* L.)], palm trees [e.g. peach palm (*Bactris gasipaes* Kunth)], and other woody trees species [e.g. *Gliricidia sepium* Kunth, *Inga edulis* Mart., *Erythrina* sp.]. The majority of studies addressed to evaluate SOM dynamics in Amazonian agroforestry systems are devoted to quantify the litter production and evaluate its contribution to soil organic C storage and nutrient cycling (Santos *et al.* 2004; Tapia-Coral *et al.* 2005; Corrêa *et al.* 2006). For instance, Schroth *et al.* (2002) investigated above- and below-ground biomass and litter accumulation for three multistrata agroforestry systems comparing them to five tree crop monocultures. They reported that depending on species composition and fertilizer input, the multistrata systems yield aboveground biomass varying from 13.2 to 42.3 Mg ha^{-1}, and belowground biomass ranged from 4.3 to 12.9 Mg ha^{-1}, and a litter mass of 2.3 to 7.2 Mg ha^{-1}. These values were substantially higher than for the monoculture systems. The average C stock in the top 10 cm of soil was similar in multistrata agroforestry systems (21.6 Mg ha^{-1}) when compared to primary forestry (22.5 Mg ha^{-1}) and higher than in monoculture systems (19.8 Mg ha^{-1}) and in areas under fallow (17.2 Mg ha^{-1}). In the fastest-growing agroforestry system, the C accumulation rates varied from 3.0 Mg C ha^{-1} year^{-1}, in the low-fertilization treatment, to 3.8 Mg C ha^{-1} year^{-1}, in the full-fertilization treatment. Conclusively, the authors highlighted that a significant result was that the trees with lower litter quality were able to build up and maintain organic matter levels in the topsoil comparable to those in the primary forest. Other studies performed in Amazonian multistrata agroforestry systems also highlight the influence of trees on the activity of soil organisms (Kurzatkowski *et al.* 2004) and in the dynamics of soil organic P and S (Lehmann *et al.* 2001). Only little information is available regarding the influence of trees on the litter quality in Amazonian agroforestry experiments, as studied by Schwendener *et al.* (2007), and there is no report in the effect of litter quality on the SOM pools.

Agroforestry has also been developed in the Northeast Region (NE) of Brazil. Contrary to the North, this region is situated almost in its totality in a semi-arid regime. Rainfall is concentrated in three to five months, ranging from 300 to 1000 mm year^{-1} in different areas of the region. Only 3 to 7% of the agricultural lands can be irrigated due to limitations of soil characteristics and/or water quality and availability (Sampaio and Salcedo 1997). Besides social-economic constraints, the irregular rainfall distribution limits the use of chemical fertilizers due to high costs, making the management of SOM the most important strategy for increasing soil fertility (Menezes *et al.* 2002). In this context, different designs of agroforestry have been proposed, such as agro-silvopastoral (Maia *et al.* 2006), silvopastoral (Wick *et al.* 2000; Menezes *et al.* 2002; Tiessen *et al.* 2003), and alley cropping (Marin *et al.* 2006). Despite of such studies discussions about the benefits of agroforestry in the light of enhancement of environment quality, only few reports (e.g. Maia *et al.* 2007) present thorough discussions about the effects of trees on SOM dynamics. For example, Wick *et al.* (2000) evaluated soil quality changes associated with the conversion of a native thorn forest (Caatinga) into silvopastoral systems in the semi-arid area of the NE Region in Brazil. They measured soil nutrients, organic matter, microbial biomass and soil enzymes. It was reported that the two preserved native tree species maintained high nutrient and organic matter contents and high biological activity levels not only in regard to the grass but also in regard to the native Caatinga. The authors pointed out that the high nutrient and organic matter contents and biological activity levels under these trees indicate that the tradition of preserving native species in pasture and farm lands may reflect a selection for species with high capacity for soil improvement. Another relevant study was performed by Tiessen *et al.* (2003) in areas under silvopastoral systems. They examined the processes underlying the differences in fertility and organic matter in a buffel grass (*Cenchrus ciliaris* L.) pasture that contained two tree species (*Ziziphus joazeiro* Mart., *Spondias tuberosa* Arruda Cam.) preserved from the native thorn forest and a planted agroforestry species (*Prospois juliflora* Swartz D.C). The results showed that all trees maintained C3-derived C at the original thorn forest level, whereas lower levels under pasture were due to organic matter mineralization. Moreover, it was stated that a reasonable best estimate for C mineralization rates is between 25 and 50% loss in 13 years, giving a half life of soil organic C between 13 and 30 years in this untilled pasture. In this respect the authors highlighted that such estimate provided clear evidence for the extreme lability of tropical soil organic C, even under minimal disturbance, reinforcing the importance of managing organic matter inputs and plant cover in tropical land use systems. In a study performed in a semi-arid region of Ceará (Maia *et al.* 2007), total soil organic C stocks and the organic C pools (microbial biomass-C, mineralizable-C, oxidizable-C, free and occluded light fraction, and humic substances) were measured to evaluate the effect of agroforestry on the soil quality. It was reported that agro-silvopastoral and silvopastoral treatments presented a net total and annual input of organic residues greater than the reference area. Furthermore, reductions in the labile C pools suggested that there was a substantial decrease in the quality of soils under those treatments that promoted more intensive soil disturbance, such as intensive cropping system. Silvopastoral system maintained and/or improved the status of the organic C pools, being recommended as a sustainable alternative for soil management applied in crop rotation systems in the semi-arid regions of Brazil. Cacao agroforestry system has been performed in other regions of Northeastern, especially in the State of Bahia, one of the most important states for cacao production in Brazil. Moço *et al.* (2009) reported that the cacao agroforestry systems adopted for growing cacao in the Southern Region of Bahia have beneficial effects on the soil and litter faunal communities, and that the development of a litter layer resulted in higher abundance and diversity of soil fauna. Barreto *et al.* (2008) evaluated different fractions of soil organic C in a comparative study involving native forest, cacao agroforestry system and pasture in the southern region of Bahia. Similar stocks of total soil organic C among all evaluated land-use systems was reported, however, agroforestry increased the total amount of the light fraction due to greater litter production and increased the residues from the root system. Barreto *et al.* (2011) investigated the distribution of oxidizable organic C fractions under cacao agroforestry in Southern Bahia. The potential of C and N storage varied with soil type. Total C and N stocks at 0-50 cm layer were 93.79 and 9.14 Mg ha^{-1}, respectively, in the Latosol, and of 60.96 and 8.56 Mg ha^{-1}, respectively, in the Cambisol. It was found that agroforestry promoted increase of the most labile C form which plays an important role in nutrient cycling and C sequestration processes.

In the southeastern region of Brazil, well established agroforestry experiences have been carried out in the Atlantic Coastal Rainforest biome in areas under coffee cultivation through a participatory experimentation (Cardoso *et al.* 2001). Agroforestry reduced the soil erosion process, improved soil quality and nutrient cycling, and increased the diversification of production (Souza and Cardoso 2005). Besides agroforestry has essential role in connecting important remains of Brazilian Atlantic Rainforest (Souza *et al.* 2010). Although several works have been developed in this region, only few are dedicated to the study of SOM dynamics for a better understanding about the mechanisms of agroforestry in soil restoration and environmental quality. Perez *et al.* (2004) studied the impact of a coffee-agroforestry system on the soil quality and found greater soil organic C stocks (litter biomass, light fraction-C, humic substances, and labile C) in the agroforestry when compared to the conventional system. The authors concluded that coffee-agroforestry system may be considered an important alternative to recovering soil quality in the region. In addition, Franco *et al.* (2002) reported lower losses of soil and organic matter in a coffee-agroforestry system in comparison to a conventional system. The effect of agroforestry on P dynamics was studied by Cardoso *et al.* (2003). The authors characterized the soil inorganic and organic P pools at different depths in the agroforestry and monocultural coffee cultivation systems. It was reported that in the agroforestry fields the amount of organic P decreased less with depth and the percentage of organic P in labile pools was higher than in monocultural systems. The authors stated that since the rate of cycling was higher for organic P than for inorganic P, agroforestry would maintain larger fractions of available P to agricultural crops thereby reducing P losses to the unavailable pools. Xavier *et al.* (2011) evaluating soil P distribution in three agroforestry-coffee agroecosystems in the Atlantic Forest biome reported that the distribution and pattern of plant available P forms in the agroforestry is directly associated with the cycling of organic P pool. Agroforestry may increases the proportion of mineralizable Po ($NaHCO_3$–Po + HClconc.-Po), which can favor biological processes on the P cycling. Mendonça and Stott (2003), studying the characteristics and decomposition rates of residues from a shaded coffee system in Southeastern Brazil, reported that the pruning residues presented high polyphenols and lignin contents, high C:N and C:P ratios, and low contents of Ca, Mg, and K. It was discussed that the low nutrient content would not supply sufficient amounts to meet the nutrient demands for the next maize crop. However, the concentration of N and P in the leaves of the pruning residues could be enough to meet the amount of nutrients required to produce two tons of maize. This study showed that if on the one hand the agroforestry system presented great potential to prevent soil erosion and rebuild soil C content, on the other hand, most of the tree-residues, by themselves, would not supply sufficient nutrients to the cropping system. More diversified agroforestry designs could represent a good alternative to cope with the low residue quality. The annual input of biomass in coffee-agroforestry experiments in the Atlantic Forest can vary from 2.0 to 4.3 Mg ha^{-1} corresponding to an annual input of C from 1.1 to 2.4 Mg ha^{-1} (Duarte 2007). In a recent study evaluating

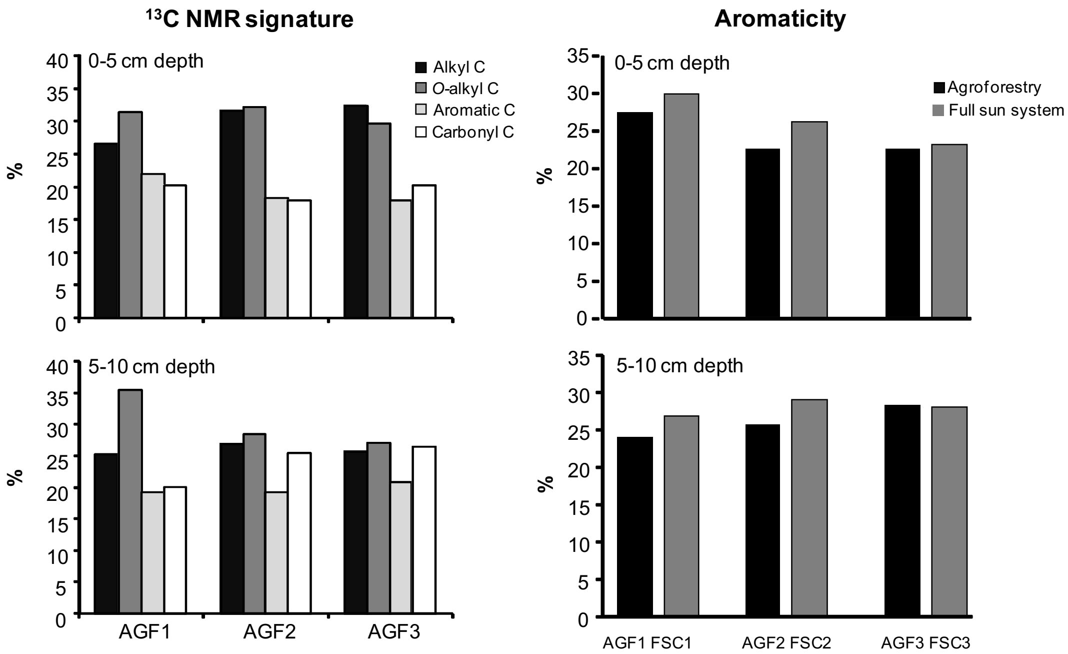

Fig. 1 ^{13}C NMR signature and aromaticity index of humic acids extracted from soils under agroforestry-coffee (AGF) and full sun-coffee (FSC) systems developed in the Atlantic Rainforest biome, southeastern Brazil. Adapted from Xavier (2009).

SOM stocks and quality in agroforestry and full-sun coffee systems, Xavier (2009) reported that agroforestry systems were able to recover the SOM levels. Nevertheless, the potential of agroforestry to increase soil C storage depended on system-characteristics in each particular environmental condition. Conclusively, it was stated that the dynamics of C, N and P in the soil was strongly influenced by the quality of the organic residues in the agroforestry systems. The difference in the chemical composition of litter in the studied sites drives the patterns of nutrient dynamics and soil microbiota. In the same study, agroforestry systems enhanced soil aggregation by increasing the amount of more stable macroaggregates and promoted an increased protection of C and N in the microaggregates within macroaggregates. In addition, Xavier (2009) also examined the qualitative changes of soil humic and fulvic acids as influenced by agroforestry by using chemical and spectroscopic techniques including: elemental and functional group analysis, thermogravimetry; Fourier transform infra-red and solid-state ^{13}C nuclear magnetic resonance (**Fig. 1**). The results showed that chemical and structural changes of humic substances were strongly affected by the residue quality, so that agroforestry may favor either more or less humidified humic structures.

FUTURE RESEARCH IN SOIL ORGANIC MATTER IN BRAZILIAN AGROFORESTRY SYSTEMS

Most of the studies on agroforestry in Brazil are conducted in the Amazonian biome. However, considering the impact of agroforestry systems on food production and environmental service by the agriculture, it is imperative to increase new studies in different Brazilian biomes. Isolated contributions are devoted to the other biomes, such as the Caatinga and the Atlantic Coastal Rainforest.

Considering the impact of the organic matter on energy flux in the soil-plant system and on the physical, chemical and biological soil properties, it is very important to improve new research lines to increase our knowledge about the impact of agroforestry on the SOM quantity and quality. In this aspect, studies about the contribution of root systems should be addressed, especially due to their contribution to rhizosphere C input in the soil C stock. In the tropics, most part of soil surface charges, responsible to retain water and cations, are due to the organic matter content and quality, justifying the increase of studies about how agroforestry may affect the development of SOM charges and their dynamics.

Studies focused on SOM and nutrients dynamic in Brazilian agroforestry experiments are still incipient. Investigations about N fixation have been carried out, but little is known about N dynamics in the various agroforestry designs. Aspects involving N leaching, mineralization/immobilization and volatilization should be addressed soon.

Furthermore, the role of soil organisms (macro- , meso- and micro-fauna) in the nutrients dynamic in areas under agroforestry should be more stressed, mainly in respect to N and P dynamic. It is well known that mycorrhiza-plant association is critical on P availability to the plants in the tropical agricultural systems with low external input. Nevertheless, there are few works focusing the effects of mycorrhiza on the rate of P and other nutrient absorption by the plants in agroforestry systems. In soils with high P adsorption capacity, such as tropical Oxisols, the organic matter input in agroforestry fields may reduce P adsorption and increase its availability to the plants. The mechanisms involved in these processes in areas under agroforestry need to be elucidated, regarding different crop covering.

The effect of organisms on the genesis and dynamics of soil aggregates is still little studied. The understanding about the function of soil organisms on these processes is critical to improve our knowledge about water and nutrients dynamic in agroforestry systems.

Increased interest on the development of computational systems in the last decades has optimized the creation of models to simulate the organic matter and nutrient dynamics in forest systems. However, most part of such models was developed to investigate aspects related to monocultural cropping systems. Efforts should be taken to adapt or develop simulation models for evaluating more diversified tropical agroecosystems, such as agroforestry.

The organization of new research groups is urgent aiming to optimize financial and human research resources devoted to agroforestry science. These initiatives may also push governmental and private institutions to support research agroforestry systems. It is important improve agroforestry in a country with a continental territory, such as Brazil, where there is an important effect not only at local but also at regional and global scale. We should consider the great potential of agroforestry in fixing C in the soil and plant biomass, increasing water production, reducing soil erosion, improving nutrient cycling and reducing their losses, and to produce high quality foods in agricultural systems with low energy input and high biodiversity.

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