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# Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil

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ABSTRACT

Cacao agroforestry systems (AFS) are characterized by accumulating large amounts of soil organic carbon (SOC). However, information on the influence of shade trees on SOC stock up to 100 cm depth is scarce in the literature. The objectives of this study were to quantify the SOC storage under different cacao AFS, natural forest and pasture to a depth of 100 cm; and to evaluate the origin of SOC using the $^{13}C$ isotopic ratio as an indicator of relative contribution of trees ($C_3$ plants) and grass ($C_4$ plants), after 4 years of pasture conversion into cacao and rubber AFS. SOC was determined by dry combustion in six layers (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm). The natural abundance of $^{13}C$ technique was used only on cacao and rubber lines in contrast to the SOC accumulated by pasture before conversion into AFS. The SOC stock in a depth between 0–100 cm was significantly high in the pasture and in both younger cacao and rubber AFS (4 years old). Systems that were more than 20 years old 'cabruca', cacao and *Erythrina* and cacao and rubber system (20 years) had lower SOC stocks and did not differ significantly from the natural forest. In the surface layers of soil there were significant differences in the SOC stock. However, below 20 cm all the systems were similar to each other. The SOC stock in the first 20 cm accounted between 31 and 44% of total SOC stored in the 100 cm in the seven systems, followed by 19–23% at a depth of 20–40 cm, 15–18% at a depth of 40–60 cm and 11–14% in the last two depths. After four years of establishment cacao and rubber AFS were the most efficient systems in the accumulation of SOC in the first 20 cm of soil and consequently up to 100 cm deep. Cacao was more efficient than rubber tree to accumulate $C_3$-derived C. While the rubber increased by almost 70% of $C_3$, cacao increased 131%. After the 40 cm of depth the SOC is still from the original natural forest.



## 1. Introduction

Cacao (*Theobroma cacao* L.) is a main agricultural commodity in many tropical countries (Hartemink, 2005). The main cacao-producing countries include Ivory Coast, Ghana, Indonesia, Nigeria, Cameroon and Brazil, which account for 82% of the world's cacao production (FAOSTAT, 2015). Since the 2010/2011 crop, Africa accounted approximately for 70% of the total produced in the world, Oceania around 13%, the American continent (South and Central America) ranges between 13 and 16% and Brazil contributes approximately 5% (CONAB, 2014; Midlej and Santos, 2012). However, in the late 80s and mid 90s there was a significant decrease in cacao production in Brazil, resulting from the witch's broom disease, caused by *Moniliophthora perniciosa*, and also by reduced commodity prices. As a result, there was the progressive impoverishment of the cacao region, where producers have abandoned the producing areas of cacao and converted them into pasture, and also by illegal exploration of shade trees with high value timber (Johns, 1999; Marques et al., 2012). However, in the last 20 years, the recovery of cacao production with plantation of resistant genetic material to witches' broom disease, combined with the rise of the commodity value are changing this negative picture, with an increase in production of almost 100% (CONAB, 2014).

In Brazil, the main cacao-producing areas are: south of Bahia, Amazon region, and coastal tableland of southern Bahia and northern of Espírito Santo. Specifically in southern Bahia, the largest planted area in Brazil, cacao crops are grown on about

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700,000 ha (Fontes et al., 2014) and are inserted in the central corridor of the Atlantic Forest, one of the main centers of endemism of this biome, which has gone through a continuous process of elimination and fragmentation (Lobão et al., 2012). Two typical cacao production systems are used both by smallholder (5–8 ha) and large farmers (approximately 300 ha) in this region: (1) traditional cultivation system, an area of approximately 399,000 ha, wherein the cacao plantations are implanted under natural forest; and herbaceous, shrub and individuals of the upper canopy are eliminated to provide increased light input, resulting in extensive agroforestry called 'cabrucas' with 600 cacao $ha^{-1}$ (Fontes et al., 2014); (2) cacao plantations are established in areas where all native forest has been removed; cacao plants, in a density of 1100 cacao $ha^{-1}$, are shaded with banana and *Erythrina glauca* mainly because is a $N_2$ fixing tree legumes, rapid growth, proper height and little dense crown (Müller and Gama-Rodrigues, 2012; Lobão et al., 2012; Gama-Rodrigues et al., 2010). This plantation system grew out of the 1960s, when CEPLAC (Executive Committee of the Plan of Cacao Farming) initiated a broad program aimed a significant increase in cacao production at the expense of massive introduction of fertilizers, chemical control of insects and diseases and also reducing the cacao shading, eliminating 50–70% of the shade trees of the Atlantic Forest (Johns, 1999).

The cacao crop is now in an expansion and renovation phase, in which more productive and resistant (to diseases) varieties are used. Furthermore, in attempt to raise the cacao production, CEPLAC has recommended that *Erythrina* should be replaced by rubber trees, because this type of tree does not generate any additional revenue to cacao producers. The high economic value of rubber tree is due to latex and honey production and also by wood for multiple uses, which improves and diversifies farmer income sources. In addition, rubber tree shows rapid growth, little competition with other species and allows planting spacing with density that enables sustainable use of the two commodities (Marques et al., 2012).

The current scenario of southern Bahia cacao region is the following: cacao was renewed by grafting with clones tolerant to witches' broom in areas where *Erythrina* trees are being replaced by rubber trees, covering an area of approximately 50,000 ha, or, cacao being introduced in rubber tree plantations already established in the region, an area of around 30,000 ha. In addition, the possibility of expansion with the establishment of new cacao and rubber tree plantations (Marques et al., 2012). Despite all the initiative to change the cacao farming system in southern Bahia searching for higher yields, today there are yet a significant amount of 'cabrucas'. The historical fluctuation of the price of cacao on the world market made many farmers give up on the proposed changes, as they learned from previous generations experience, the risk of reduced shading in increasing susceptibility to drought and, or dependence on fertilizers and other agrochemicals (Johns, 1999). In this context, cacao cultivation in Bahia is a good example for agroforestry approach and can be a socio-economic-ecological component appropriate to reduce human pressure on the remaining of Atlantic Forest in southern Bahia (Lobão et al., 2012; Müller and Gama-Rodrigues, 2012).

Cacao agroforestry systems (AFS) with continuous and significant contribution of both above- and belowground biomass accumulation and subsequent turnover of leaf litter, roots, and woody material from the shade species and from cacao provide a continuous stream of organic inputs most of which, following decomposition, is stored into the soil and represent a substantial addition of soil C (Gama-Rodrigues et al., 2011). Besides, cacao AFS maintains many of others ecosystem functions includes control soil erosion because they protect the soil against raindrop impact and reduce runoff velocity and enhance soil fertility by an efficient nutrient cycling (Gama-Rodrigues et al., 2011; Tscharntke et al., 2011; Siebert, 2002) and also conserve the forest biodiversity (Schroth and Harvey, 2007; Gama-Rodrigues et al., 2010, 2011). All these possible environmental service can increase the income for the farmers of these crops, the majority of whom are smallholders, through the incentives from payment-for-ecosystem services and certification schemes.

Effects of land use changes are starting to be included in estimates of life-cycle greenhouse gas (GHG) emissions, so-called carbon footprints (CFs), from food production (van der Werf et al., 2009). In Brazil, for example, deforestation and forest burning account for about 75% of the greenhouse gases (GHG) emissions. The increase in atmospheric concentrations of $CO_2$ and other GHG is the major cause of global warming. Soil carbon (C) sequestration is a mechanism of reducing the $CO_2$ concentration in the atmosphere and depositing it in long term pools of C through afforestation, reforestation, and restoration of degraded lands (Nair et al., 2009a). In this scenario, agroforestry systems play an important role as a land-use system that allows for the mitigation of GHG emissions and helps reduce deforestation and restore degraded soils (Rita et al., 2011; Gama-Rodrigues et al., 2011, 2010). Several studies in the literature suggest agroforestry systems as a system with high potential to accumulate C both aboveground and belowground. For example, Verchot et al. (2007) predicted that the global carbon stock potential (C) of AFS would reach nearly 600 Mt C $year^{-1}$ by 2040 as there is a large area susceptible to land use changes. The carbon storage potential of cacao canopies in AFS range from 33 to 90 Mg C $ha^{-1}$ (Somarriba et al., 2013; Gama-Rodrigues et al., 2011; Cotta et al., 2008). In addition, Barreto et al. (2011) found that the soil organic carbon (SOC) content in the top 50 cm of soil was nearly 100 Mg C $ha^{-1}$ in a cacao + *Erythrina* AFS in southern Bahia. Furthermore, Gama-Rodrigues et al. (2010) observed soil SOC values of more than 300 Mg $ha^{-1}$ in the 0–100 cm soil layer in a cacao AFS (*Erythrina* + cacao and 'cabruca').

An important aspect to be considered in the study of SOC stock which has received increasing interest from the scientific community is soil depth because the main source of C belowground comes from roots (Rasse et al., 2005). Particularly in AFS, the depth is very important, because the root system of shade trees can reach 2 m deep or more (Tscharntke et al., 2011; Lehmann, 2003). Cacao, for example, has a high concentration of roots in the first 60 cm, reaching 1–2 m deep (Silva Neto et al., 2001; Müller and Gama-Rodrigues, 2012). Additionally, according to Rumpel and Kögel-Knabner (2011), most subsoil horizons contribute to more than half of the total soil C stocks. This is because the input of organic material through these horizons is plant roots and root exudates, dissolved organic matter and bioturbation. Some authors even claim that the C subsoil may be more important in terms of source or sink for $CO_2$ than topsoil (Batjes, 1996; Paul et al., 1997; Lorenz and Lal, 2005). There is no consensus in the literature about the sources of C, processes involved in the stabilization and consequent stock of this C in depth, especially in cacao agroforestry systems in which these studies are scarce.

Many species that are commonly found in natural forests and the trees present in cacao AFS use the $C_3$ cycle as a mechanism for assimilating C. By contrast, the $C_4$ cycle is typical of grasses. Regarding the C assimilation pathway, the conversion pathways of natural forests into pastures and pastures into AFS differ, and stable C isotope studies may be useful for understanding the origin of soil organic matter. The $^{13}C/^{12}C$ soil ratio (expressed in $\delta^{13}C$) varies based on the C assimilation pathway of the species that prevails in the system. The species that use the $C_3$ pathway discriminate against $^{13}C$ uptake more than the species that use the $C_4$ pathway. Therefore, the amount of $\delta^{13}C$ is lower (mean values of $-28‰$ for $C_3$ and $-12‰$ for $C_4$) when $C_3$ plants prevail. Several authors have used the natural $^{13}C$ abundance to determine the actual contributions of different species in SOC (Mendonça et al., 2010;