Silvopasture and Carbon Sequestration with Special Reference to the Brazilian Savanna (Cerrado)

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Abstract The Brazilian savanna, known as the Cerrado, extending over 200 million ha, is the largest neotropical savanna in the Americas. With its ongoing conversion to intensive agriculture since the 1960s, of which cultivated pastures for beef cattle production is a major form, this unique ecosystem is now considered threatened. Given the recognized role of trees in carbon (C) sequestration and greenhouse gas (GHG) mitigation, the silvopastoral system of tree plantation development on pasture lands is considered to be particularly relevant to this region. For the past two decades, eucalyptus-based silvopastoral systems have been established in the Cerrado region by growing agricultural crops (rice and soybean) in the first 2 years followed by *Brachiaria* forage and beef-cattle grazing from the third year of plantation establishment. Recent studies in a variety of situations indicate that agroforestry systems store higher amounts of C compared to single species cropping and grazing systems, both aboveground and belowground. The Brazilian savannas that have characteristically low aboveground C reserves hold considerable stocks of soil organic C, probably as a consequence of previous land use, the history of which is unknown. Most of this C is in a biodegradable form and is likely to be lost to the

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atmosphere when the soil is disturbed during land conversion to agriculture and pasture. Adoption of sustainable land use systems such as silvopasture could reduce this potential hazard. Given the role of the Cerrado in the global C cycle and climatic change, these issues deserve well coordinated investigations.

Keywords Ecosystem degradation • *Eucalyptus* • Grasslands • GHG mitigation • Oxisols • Ruminants

Introduction

Silvopasture refers to the agroforestry practice of integrating trees in animal production systems. Broadly, there are two major forms of silvopasture: grazing and tree fodder systems. In grazing systems, cattle are allowed to graze on pasture under widely spaced or scattered trees, whereas in the tree fodder systems, the animals are stall-fed with fodder from trees or shrubs grown in blocks on farms (Nair 1993; Nair et al. 2008). The grazing system of silvopasture has recently gained prominence as an ecologically sustainable and environmentally desirable approach to managing degraded pasture lands in the industrialized countries (Mosquera-Losada et al. 2005; Garrett 2009). With the recent emphasis on the environmental impact of land use systems, the role of silvopasture and other agroforestry practices in mitigating climate change through carbon (C) sequestration has been a major area of research focus (Nair et al. 2010).

The silvopastoral system of tree plantation development on pasture lands and its role in C sequestration and greenhouse gas (GHG) mitigation are particularly relevant to Brazil, where land use changes in forestry and agricultural sectors are reported to be responsible for more than two-thirds of the GHG emissions (Comunicação Nacional 2004). For example, most of the agricultural areas in the vast Brazilian savanna, known as the Cerrado, are grasslands, of which at least 60% are in some stage of degradation (IBGE 2006). This paper presents an overview of the status of silvopasture in Brazil, and a summary of some recent studies on C sequestration in silvopastoral systems in Florida (USA), Minas Gerais (Brazil), and northwestern and Central Spain. With that background, we will present some perspectives on the GHG – primarily C dioxide (CO_2) – mitigation potential of silvopasture systems in the Brazilian Cerrado, and relate them to other similar ecosystems elsewhere.

Silvopasture in the Brazilian Savanna (Cerrado)

Brazil has a cattle population of 200 million on 100 million ha of cultivated pastures (IBGE 2006). Of these, beef production involves 180 million head, producing 8.0 Tg of meat per year. Growing national and international markets for meat and demand for better quality of meat necessitate important changes to a production system that relies largely on pasture, the production capacity of which has been depleted following years of exploitation. In the Cerrado region of Brazil, cultivated pastures cover about 49 million ha, supporting a herd of 40 million head representing more than 35% of the total Brazilian beef production. Thus, the region accounts for 35–40% of the beef cattle industry both in area and production.

The Cerrado

Savannas are a major component of the world's vegetation, covering one-sixth of the land surface, and accounting for 30% of the primary production of all terrestrial vegetation (Grace et al. 2006). In South America the savanna, mostly distributed in Brazil, Colombia, Venezuela, and Bolivia, feeds three of the major water basins: the Amazon, Paraguay, and São Francisco Rivers (Cochrane et al. 1985). The Brazilian savanna, called the Cerrado (Fig. 1), occurs manly in central Brazil in the states of Mato Grosso, Mato Grosso do Sul, Tocantins, Goias, and western parts of Minas Gerais, and extends over 200 million ha (Batlle-Bayer et al. 2010). The Cerrado is a wet savanna and it consists of a gradient of physiognomies, from grassland (called "campo limpo") to a sclerophylous forest (Cerradão), with over 10,000 species of plants, of which 45% are unique to the Cerrado.

The Cerrado region's typical climate is hot, semi-humid, with pronounced seasonality marked by a dry winter season from May through October. The annual rainfall ranges from 1,200 to 2,000 mm, 80–90% of which occurs during the summer (known, rightly, as the rainy) season between October and April. The mean annual temperature varies from 22°C in the south to 27°C in the north of the region (Bustamante et al. 2006). The soils are generally very old, deep, and inherently poor in nutrients such as phosphorus and calcium. They have high levels of aluminum and low levels of organic matter and pH. Oxisols and Entisols represent approximately 46% and 15% of the area, respectively (Reatto et al. 1998). Due to their low nutrient status and high acidity and aluminum concentration, soil organic matter (SOM) plays a particularly important role in the physical, chemical, and biological processes related to nutrient cycling, soil aggregation, and plant-water availability in the Cerrado (Resck 1998). The Cerrado trees have characteristic twisted trunks covered by a thick bark, and leaves, which are usually broad and rigid. Many herbaceous plants have extensive roots to store water and nutrients. The plant's thick bark and roots serve as adaptations for the periodic fires that sweep the Cerrado landscape. The adaptations protect the plants from destruction and make them capable of sprouting again after the fire.

The Cerrado region has been the focus of intense agricultural expansion since the 1960s, and a large area of native vegetation has been replaced by agriculture, cultivated pastures, and planted forests.[1] Satellite images showed that in 2002, 55% of

[1] EMBRAPA CERRADO (1999).

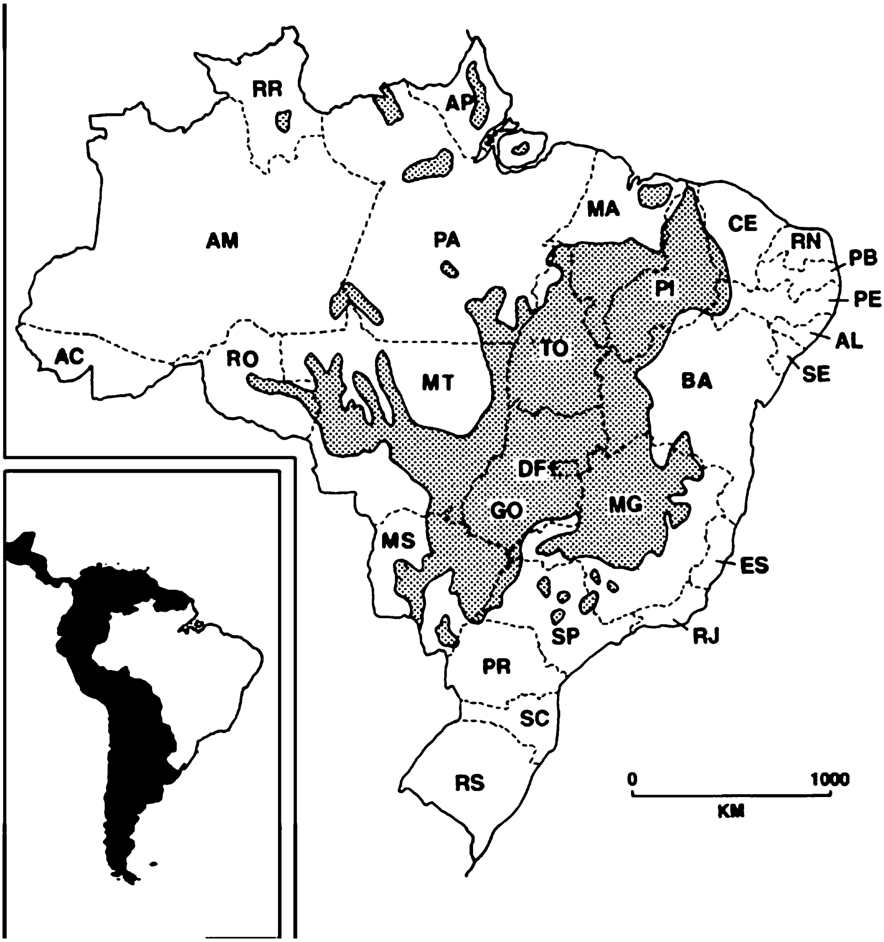


Fig. 1 Distribution of Cerrado vegetation in Brazil (letters are state abbreviations). Those referred to in connection with geographical patterns are: *DF* Federal District; *GO* Goiás; *MA* Maranhão; *MG* Minas Gerais; *MS* Mato Grosso do Sul; *MT* Mato Grosso; *PA* Pará; *TO* Tocantins

the Cerrado had already been transformed (Machado et al. 2004). During the period from 1975 to 1995, the area under crop cultivation in the Cerrado increased from 6.9 to 8.2 million ha (Bustamante et al. 2006). The major crops are soybean (*Glycine max* L. Merr), maize (*Zea mays* L.), rice (*Oryza sativa* L.), and beans (*Phaseolus vulgaris* L.). Soybean is the most important crop and it had its "boom" in the 1980s propelled by growing international demand for it. Cultivated pastures account for the largest agricultural expansion, mostly with the introduction of the African grass of the genus *Brachiaria*. Estimate of the pasture area in the Cerrado ranges from 35 to 50 million ha (Sano et al. 2000). Most of these cultivated pastures have, however, experienced some degree of degradation; they have lost, to some extent, their capacity to produce biomass due to deterioration of soil chemical, physical, and biological conditions.

Various types of landholdings and producers can be found in the Cerrado biome, ranging from large farms with areas of more than 20,000 ha and a variety of crop fields or cattle, to a large number of “small” farms with areas less than 100 ha. Planted forests are a relatively new land use system in this area that has gained popularity within the last decade; pasture lands are now being rapidly converted by interplanting with fast growing tree species. Large tracts of the Cerrado have also been planted to fast growing trees, especially eucalyptus hybrids (*Eucalyptus* spp.) and pines (*Pinus* spp.), which account for roughly two-thirds and one-third, respectively, of the approximately 5.5 million ha of planted forests in Brazil (ABRAF 2008). Most of these plantations have been planted over the small farmlands that used to raise cattle. This new development, motivated primarily by its monetary advantages, has brought up two major issues: the introduction of non-native tree species in the biome, and the decline – if not elimination – of the traditional activity of cattle rearing. Integrating cattle and trees as in silvopastoral systems offer the advantages of monetary benefits from planted forests and at the same time supports cattle rearing. There might be unexplored advantages via C sequestration too.

Silvopastoral Systems in the Cerrado

Silvopastoral systems were first established in the Cerrado region of Minas Gerais State about 20 years ago and the area under the practice has been increasing steadily since then. Accurate data on the spread of the system are not available; however, the current area under the practice is estimated to be about 14,000 ha (based on the authors’ personal contact with local farms). Other areas of the Cerrado have also been cultivated with silvopastoral systems, mainly in the state of Mato Grosso do Sul. It is perceived (Dubé et al. 2000) that the establishment of silvopastoral systems can reduce the cost of establishment of the whole (beef + timber) system; furthermore, the additional income derived from the crops would be an economic incentive to tree plantation owners during the early years of plantation establishment.

The silvopastoral systems in the Cerrado are established by cultivating one or two annual crops in rows in between the widely-spaced tree rows. Crops such as rice and soybean are cultivated in the first and second year, respectively, after establishing eucalyptus (Fig. 2), the most common tree used in the system. It is planted at the spacing of 10×4 m or 8×4 m. Tree rows are aligned, as much as possible, in the east-west orientation in order to allow highest extent of light penetration to the understory grass between trees. Most planters limit the soil preparation for silvopastoral establishment to the minimum, mainly spot application of herbicides to kill weeds or any undesirable plant in the rows where the trees will be planted. This minimum soil preparation is important to avoid soil disturbance and oxidation of SOM. Soil moisture availability and mild temperature under trees create better

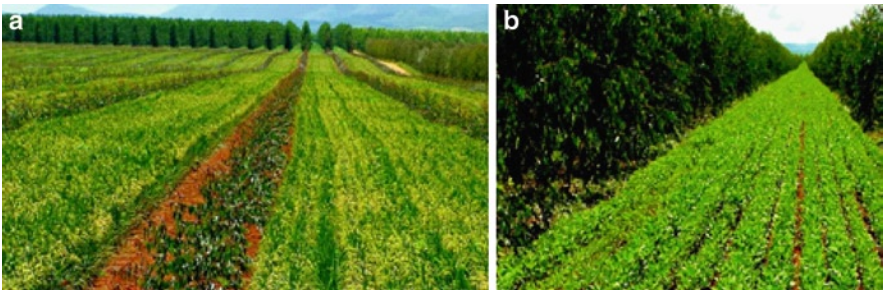


Fig. 2 During the early years of silvopastoral system establishment, agricultural crops are grown in between tree rows: (**a**) first year – rice planted after establishing eucalyptus; (**b**) second year – soybean planted after the rice was harvested. The pasture will be established in the third year after soybean harvest. Fazenda Riacho, Paracatu, Minas Gerais, Brazil

Fig. 3 A silvopastoral system of *Eucalyptus* spp. with *Brachiaria brizantha* (Hochst. Ex A. Rich.) Stapf, as the understory in Fazenda Riacho, Paracatu, Minas Gerais, Brazil. Note that the plants maintain their green color even in the peak dry season when the photo was taken

condition for mineralization of nitrogen (N) which contributes to improving and extending the forage quality in the dry season. In the third year, seeds of the grass *Brachiaria brizantha* (Hochst. Ex A. Rich.) Stapf, are sown to constitute the understory (Fig. 3). Sixty days after sowing the grass seeds, beef cattle are stocked in the area for grazing (Fig. 4).

In spite of the steady increase in the area under silvopasture in Brazil, information about beef cattle production under these systems is relatively scanty. A pioneering

Fig. 4 Beef cattle in the silvopastoral system of eucalyptus and *Brachiaria brizantha* (Hochst. Ex A. Rich.) Stapf, in Fazenda Riacho, Paracatu, Minas Gerais, Brazil

example of the system, which contributed to studies and popularization of this technology, is the "Fazenda Riacho" (Riacho Farm), an agroforestry unit of the Votorantim Siderurgia group, located in the Cerrado region of Minas Gerais. Bernardino et al. (2011) studying the beef cattle performance in the silvopastoral system in this farm reported that fertilizing the understory grass (*B. brizantha*) with N and potassium (K) resulted in increase in higher grass dry matter production and higher meat production per ha; on average, the increase in the animal live weight gain (LWG) was directly proportional to the fertilizer rates used. Fertilization with N and K is considered important in the establishment and management of silvopastoral system in the Brazilian Cerrado (Andrade et al. 2001; Bernardino 2008). Other studies are currently under way to evaluate the effects of doses and sources of N on the productivity of the understory in silvopastoral systems.

An alternative to the use of inorganic fertilizers is the introduction of forage legumes to constitute part of the understory in silvopastoral systems. Legumes can add N to the system and thus reduce the cost of N input as well as the environmental hazard associated with fertilizer N. They can also enhance the forage quality, resulting in better cattle performance. Paciullo et al. (2004, personal communication)[2] evaluated the weight gain of dairy heifer grazing a silvopastoral system with three

[2] Paciullo DSP, Aroeira LJM, Viana AF, Malaquias JD, Rodrigues NM, Carvalho CAB, Costa FJN, and Verneque RS (2004) Desempenho de novilhas mestiças Europeu x Zebu, mantidas em sistemas silvipastoril ou em monocultura de Braquiária. In: *Reunião Anual da Sociedade Brasileira de Zootecnia*, Campo Grande, SBZ, CD-ROM.

different tree species and an understory of *Brachiaria decumbens* Stapf. and *Stylosanthes guianensis* (Aubl.) Sw. and a pasture with the same grass species. They reported that, while no differences were found between silvopastoral system and grassland in the rainy season, a 40% gain in the heifer weight was noticed under silvopasture in the dry season. Alvim et al. (2005) also found a better weight gain in the dry season for heifers grazing in the understory of a silvopastoral system when compared to *B. decumbens* pasture.

Several studies have indicated the potential of silvopastoral system in beef-cattle production in the state of Rio Grande do Sul. Silva (1998) evaluated the effect of two densities of *Eucalyptus saligna* Sm. plantations, spaced 2×3 m and 2×6 m (1,666 and 833 trees ha^{-1}) and three forage offers (6.0, 9.6, and 13.0%) on the beef cattle performance, and found that the highest LWG per ha 215 kg, in the medium (9.6%) forage offer and lowest tree density (833 trees ha^{-1}). Furthermore, Silva et al. (2001) studied the animal performance, stocking rate, and the residual forage in a silvopastoral system with acacia negra (*Acacia mearnsii* De Wild.) spaced 2×3 m and 2×5 m and two understory species (*B. brizantha* cv. Marandu and *Panicum maximum* Jacq. cv. Gatton). The best results for LWG, animal gain per ha, and stocking rate were obtained with lower tree density, for both understory species. Lucas (2004) studying a silvopastoral system with acacia negra at a stand density of 500 trees ha^{-1} and understory of *P. maximum* cv. Gatton, established for 8 years and grazed during 445 days, found a total LWG of 747 kg ha^{-1} (average of 1.8 kg^{-1} ha^{-1} grazing day^{-1}). These results show a high contrast with the average LWG productivity of 50 kg^{-1} ha^{-1} year^{-1} of the traditional extensive grazing based on native pasture in Rio Grande do Sul State.

Research Results on Carbon Sequestration in Silvopastoral Systems

During the past few years, the University of Florida (UF) Center for Subtropical Agroforestry (CSTAF) has been involved in soil C sequestration studies under a range of agroforestry systems and related land use systems (Nair et al. 2010). The overall objectives were to quantify soil organic matter (SOC) accumulation and sequestration in different types of agroforestry systems in a variety of ecological and geographical conditions, determine C storage in different soil fractions up to at least 1-m depth, and quantify, wherever possible, C contribution by C_3 and C_4 plants (~ trees and herbaceous plants) using natural C isotopic differences between the two groups. The studies included silvopastoral systems in three countries, under different agroecological conditions (Table 1). Detailed descriptions of climate and soil conditions, land use systems, and their management are reported in specific papers published from each study. Briefly, the Florida sites included a silvopasture with slash pine (*Pinus elliottii* Engelm.) and adjacent treeless bahiagrass pasture (*Paspalum notatum* Flüggé). In Spain, two silvopastoral systems were studied: a simulated silvopasture with pine (*Pinus radiata* D. Don) or birch

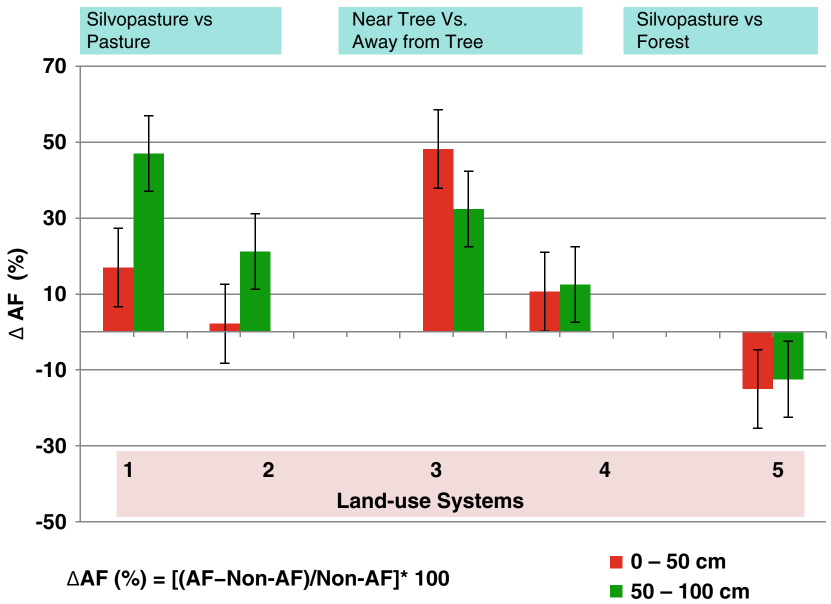
Table 1 Site- and system details of the University of Florida, Center for Subtropical Agroforestry, research sites for carbon sequestration studies under silvopastoral systems

Location; coordinates	Climate (m.a.p, mm; mean temp. range, °C)	Silvopasture system	Land uses	Age (# years since establishment)
Florida, USA; 28° to 29° N; 81° to 83° W	Humid subtropical; 1330; −3 to 28	Slash pine (*Pinus elliottii* Engelm.) + bahia-grass (*Paspalum notatum* Flüggé)	Pasture Silvopasture Pasture Silvopasture	50 12 55 14
Central Spain; 39° 59′ N; 6° 6′ W	Subhumid mediterranean; 600; 8–26	Dehesa: Cork oak (*Quercus suber* L.) silvopasture	Cork oak	80
Northwestern Spain; 43° 9′ N; 7° 30′ W	Humid Atlantic; 1200; 5.8–18	Eur. birch *(Betula pendula* Roth.) with orchard grass, *Dactylis glomerata* L.	Pasture Silvopasture	 15
Minas Gerais, Brazil; 17° 36′ S; 46° 42′ W	Cerrado: Subhumid tropical; 1350; 20–30	*Eucalyptus* spp. with understory of *Brachiaria* spp. (fodder grass)	Forest Silvopasture Pasture	 14

Source: Nair et al. (2010)
m.a.p mean annual precipitation

(*Betula pendula* Roth) with *Dactylis* spp./*Trifolium* spp. in between, with an adjacent treeless pasture on Inceptisols in northwestern Spain; and a traditional dehesa silvopastoral system with cork oak trees (*Quercus suber* L.) on Alfisols in central Spain. In the dehesa system, total C stock was determined near (2 m) and away (15 m) from the tree. The study sites in Minas Gerais, Brazil, included a eucalyptus silvopasture system (*Eucalyptus* spp. with understory of *Brachiaria* spp. as fodder grass) compared with a pasture system and an adjacent forest stand. The soil orders of the study sites included Spodosols and Ultisols (both in Florida, USA), Inceptisols (northwestern Spain), Alfisols (central Spain), and Oxisols (Minas Gerais, Brazil). At each location, soils were sampled to at least 1-m depth from four to six layers (sampling depths) according to replicated experimental design procedures. All soil samples from the different sites were fractionated into three different aggregate-size fractions [macro (2,000–250 μm), micro (250–53 μm), and silt- and clay- sized fractions (<53 μm)], and the C content in each fraction was determined by dry combustion using an automated C analyzer (Thermo Finnegan Flash EA 1112 NC; Thermo Fisher Scientific Inc. Waltham, MA, USA).

The total SOC varied considerably within the different systems to a meter depth suggesting differences in C sequestration potential that reflects climatic conditions, soil types, and the plant species (Fig. 5). The highest SOC stock to a meter depth was in the Oxisols of Brazil (~ 400 Mg ha^{-1}: Tonucci et al. 2011) and the lowest SOC was in the sparsely tree-dominated locations of the dehesa system in central Spain (Mean: 31 Mg ha^{-1}; Howlett 2009).



	Systems; age (# years since AF system installation)	Location	Soil Order
1	Pine + pasture vs. treeless pasture; 30 y	Florida, USA	Ultisols
2	Pasture under birch trees vs. treeless pasture; 15 y	Northern Spain	Inceptisols
3	Under tree vs. away from trees (Dehesa); 80 y	Central Spain	Alfisols
4	Under trees vs. away from trees; Parkland system; >50 y	Segou, Mali	Alfisols
5	Brachiaria + Eucalyptus vs. Treeless forage stand; 30 y	MG, Brazil	Oxisols

Fig. 5 Changes in soil C stock under different agroforestry (Silvopasture) vs. non-AF systems. ΔAF (%) = [(AF − Non-AF) / Non-AF]* 100 (Adapted from Nair et al. 2010)

In the Florida study, silvopastures had greater amounts of SOC stored within a meter soil profile compared to adjacent treeless pastures (Fig. 6). Using stable C isotope signatures, Haile et al. (2010) showed that C in the deeper soil profile was derived from the tree component, i.e. the slash pine of the silvopastoral system. Further, the relatively stable C fraction (<53 μm) was found to be derived from the tree component (Haile et al. 2010). In the study in central and northwestern Spain, the traditional dehesa (cork oak) silvopastoral system with sparse tree density had lower SOC in the whole soil compared to the managed silvopasture system with

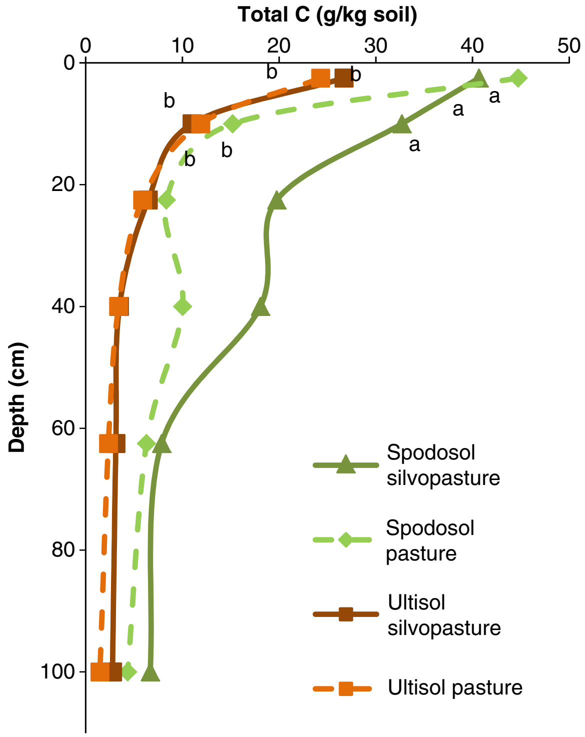


Fig. 6 Soil carbon stock (g kg^{-1}) in various soil layers to 1-m depth in adjacent pasture and silvopasture systems in two soil orders at two Florida locations (Adapted from Haile et al. 2010)

higher tree density (Fig. 7). Within the dehesa system of central Spain, the soil near the tree, compared to that away from the tree, stored more C. In pasture system in Minas Gerais, the AFS (eucalyptus-based silvopasture) had the highest SOC content in the macro-sized- and silt + clay- sized fractions compared with the forest- and pasture soils (Fig. 8).

In addition to the above (silvopastoral) studies, similar studies were conducted in three other countries: in the homegardens in Kerala, India (Saha et al. 2009, 2010); parkland- and other systems in Mali, West Africa (Takimoto et al. 2008, 2009); and shaded cacao systems in comparison with adjacent natural forest in southeast Bahia, Brazil (Gama-Rodrigues et al. 2010). The results from these multi-location (five-country) studies showed that:

1. The amount of C stored in soils depends on soil qualities, especially silt + clay content
2. Tree-based systems, compared to treeless systems, store more C in deeper soil layers under comparable conditions
3. Higher SOC content is associated with higher species richness and tree density
4. Soil near the tree, compared to away from the tree, stores more C

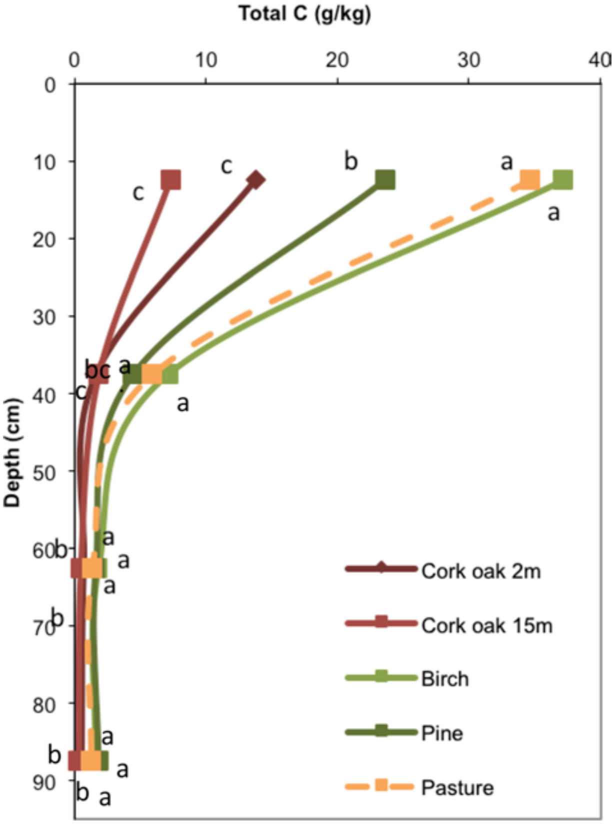
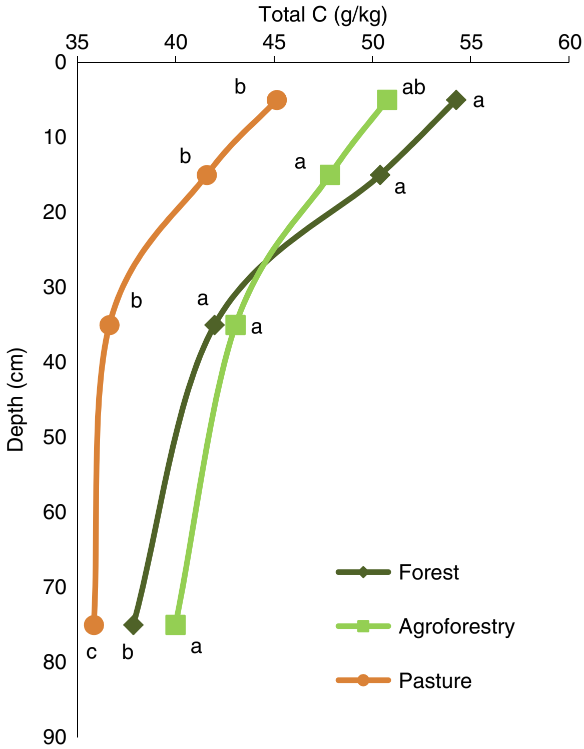


Fig. 7 Soil carbon stock (g kg^{-1}) in various soil layers to 1-m depth, near and away from trees in the cork-oak dehesa (silvopasture) system on Alfisols in central Spain, and under birch and pine tree silvopasture compared with an adjacent pasture on Inceptisols in northwestern Spain (Adapted from Howlett 2009)

Furthermore, C_3 plants (trees) were found to contribute to more stable C in the soil than C_4 plants (grasses) in deeper soil profiles in Florida soils (Spodosols and Ultisols); but this was not the case in the Cerrado soils (Oxisols).

In spite of the limitations of the separate studies upon which this analysis is based, the results show the intrinsic differences and enormous variations in soil C stock among different soils orders and land use systems. Although the studies at the different locations were not designed specifically to compare C stock across soil orders under similar ecological and management conditions, a general trend of higher C stock in soils containing higher amounts of clay and silt was evident. Among the agroforestry and other systems studied, the differences in C stock are up to more than 100-fold. While much of these differences can be attributed to the type of land use systems and ecological regions, there are clear differences among land use systems within the same ecological regions and soil orders. In general, tree-based agricultural systems, compared to treeless systems, store more C. Furthermore, land use history of the site seems to have a major and overriding role in determining the amount of C stored in the soils, such that the previous land use history of a site has the most effect than any other factor in determining the C content in that soil.

Fig. 8 Soil carbon stock (g kg^{-1}) in various soil layers to 1-m depth in adjacent forest, pasture and silvopasture systems on Oxisols at Minas Gerais, Brazil (Adapted from Tonucci et al. 2011)



In summary, available results indicate that AFS store higher amounts of C, compared to single species cropping and grazing systems, in both aboveground and belowground compartments of the system. The C sequestration potential of AFS seems especially significant in the soil, particularly in soil depths below 50 cm (Nair et al. 2010). The extent of C sequestration will, obviously, depend on a number of site-specific factors as well as system management.

Some Perspectives on Silvopasture and Carbon Sequestration in the Cerrado

Grasslands that cover nearly three billion hectare globally, with roughly two-thirds in the tropics and one-third in the temperate region, constitute a major ecosystem of the world. Being semiarid lands, they are resource limited, especially in N and water. Silvopastoralism is a major land use system in the savannas, with extensive grazing under dispersed stands of indigenous trees in the vast African savanna.

Disastrous consequences of human efforts to modify these fragile ecosystems have been exemplified by the recent experiences from intensive cattle production supported by planted pasture in the Cerrado. During the past few decades, the Cerrado ecosystem has undergone extensive degradation because of conversion to agriculture, and this process continues unabated. The increasing demand for dairy products and beef for export markets has led to conversion of large areas of native land to cattle pasture in the Cerrado. From the 1970s, the native savanna grasslands were replaced by cultivated pastures, mostly *Brachiaria* species. Best pasture management practices are aimed at maintaining productivity and full soil cover by adjusting stocking rates to avoid overgrazing and application of fertilizer and lime as required. In general, however, after a few years of pasture establishment, stocking rates are increased without paying adequate attention to pasture management including fertilization, leading to a rapid nutrient-depletion and pasture degradation. As a result, the pastures become degraded within 3–4 years to the extent of being unable to support even average stocking rates. More than 60% of the pastures in the Cerrado are degraded (Batlle-Bayer et al. 2010), and the Cerrado is now regarded as a threatened biome (Cardoso da Silva and Bates 2002; Boddey et al. 2004): an unfortunate but revealing example of an ecological disaster caused by human intervention.

Although liming and fertilization have been recommended for reclaiming the degraded pastures (de Oliveira et al. 2004), the high cost of production and transport, and the high environmental cost associated with these practices make them unattractive options. Introduction of N-fixing legumes in association with improved grasses, and integrated crop-livestock-management systems have been proposed for sustaining grassland productivity in the Cerrado region, but have not yet been widely adopted, partly because the legume + grass mixture of understory could not be sustained for long. Worldwide, improved grassland management (e.g., application of fertilizers, adapted stocking rates, introduction of legumes and irrigation) is reported to have the potential to lead to a significant soil C sink (Conant et al. 2001). However, such results have to be viewed with caution, because many of them have used the degraded pasture system as 'baseline' for the comparison and not the native Cerrado ecosystem.

The Brazilian savannas have small aboveground C reserves compared to forest biomes; but their soils hold considerable stocks of organic C. Bustamante et al. (2006) estimated that soils of the Cerrado region contained an average stock of 117 (range: 100–174) Mg C ha^{-1} (for native Cerrados). In a review of changes in organic C stocks upon land use conversion in the Cerrado, Battle-Bayer (2010) cited reports of SOC stocks ranging from 123 to 209 Mg C ha^{-1} from different locations in the Cerrado. Our own studies (Tonucci et al. 2011) have shown much higher stock of C in the Cerrado soils (Table 2, Fig. 8). It has also been suggested that the land use history of the site could have a major influence on C stock and distribution of C in different size-fractions under in different land use systems. The Cerrado has only recently (four decades) been opened up for conversion to agricultural/livestock/forestry purposes. Unfortunately no information could be obtained about the previous site history dating back to 200 years or more. A preliminary evaluation using ^{14}C dating technique in soils of the forest, pasture and silvopasture sites used in the study sites of Tonucci et al. (2011) suggested the possibility that the Cerrado region

Table 2 Total soil organic carbon storage to one-meter depth in soils in silvopastoral systems at various study sites

Study location	Silvopastoral system	Land use	Soil: Order	Soil: pH	Soil: Bulk density (Mg m^{-3})	Soil organic carbon stock to 1-m depth (Mg ha^{-1})	Reference
Florida, USA; Humid subtropical	Slash pine (*Pinus elliottii* Engelm.) + bahiagrass (*Paspalum notatum* Flüggé)	Pasture	Spodosols	5.5	1.5	66.7	Haile et al. (2008, 2010)
		Silvopasture		5.4	1.5	102	
		Pasture	Ultisols	6.2	1.7	30.8	
		Silvopasture		5.7	1.6	37.3	
Central Spain; Subhumid Mediterranean	Dehesa: Cork oak (*Quercus suber* L.) silvopasture	Away from tree (15 m)	Alfisols	4.1	1.3	26.5	Howlett (2009)
		Near tree (2 m)		4.0	1.3	50.2	
Northwestern Spain; Humid Atlantic	Silvopasture with birch (*Betula pendula* Roth.)	Pasture	Inceptisols	4.2	1.5	133	Howlett et al. (2011)
		Silvopasture		4.2	1.4	150	
Minas Gerais, Brazil; Cerrado: Subhumid tropical	*Eucalyptus* spp. with understory of *Brachiaria* spp. (fodder grass)	Forest	Oxisols	5.1	1.0	353	Tonucci et al. (2011)
		Pasture		5.4	1.2	408	
		Silvopasture		5.2	1.0	353	

See Table 1 for additional site description had previously been under a "high-C-storing" system for a long time (Tonucci et al., personal communication: September 2010). The $\delta^{14}C$ values for various soil depth classes under different land use systems studied by Tonucci et al. (unpublished data) suggest that the organic matter in the surface soil of these systems was of recent addition whereas the C in the lower soil layers had been stored for much longer time periods. These results, although preliminary, suggest that the Cerrado soils stock high amounts of C derived possibly from previous land use, the details of which are unknown. The bottom line is that the Cerrado biome has a high stock of C in soil, probably as a consequence of previous land use; most of this C is in a biodegradable form, and could be lost to the atmosphere with soil disturbance. Adoption of sustainable land use systems such as silvopasture could reduce this potential hazard. These concerns call for well coordinated and detailed investigations on this important issue.

Conclusions

Our studies, though limited, suggest that if sustainable silvopastoral systems could be developed as alternatives to conversion of forest lands to support animal production, the high levels of C footprint of animal production in developing countries could be reduced considerably. Between the two forms of savanna conversions – to produce grass and grain – the former, however, is a lesser evil environmentally, and grass-fed beef, which is far more efficient in overall energy use than grain-fed beef, would leave a lesser C footprint than intensive grain production systems including the grain-based beef. Thus, shifting from input-intensive pasture- and grain production to environment-friendly silvopastoral systems could reduce GHG emission, promote C sequestration in soils, and enhance the soil's resilience by increasing the SOC pool.

Although the Cerrado is a unique ecosystem, many of these projections and perspectives could be applicable to other savanna regions too. The extent to which these results are applicable in the savannas of other continents such as Africa and Asia is unclear, because of not only the differences in soils and other ecological conditions, but also the vast differences in management systems. In most parts of the African and Asian savannas, silvopastoralism consists mostly of extensive animal grazing in open lands with scattered trees with practically no land use intensification involving fertilizers and such external inputs, unlike in the fertilized and management-intensive silvopasture in the Cerrado. Nevertheless, results from the extensive dehesa silvopasture system of Spain as well as other studies from the Parklands (extensive, open grazing) system in Mali, West Africa, indicate the positive role of trees in SOC build-up. Given that globally the savanna ecosystem covers a sixth of the total land area and account for a third of total plant production, the role of savanna silvopastoral systems in global C sequestration and climate change mitigation deserve serious investigation. With the increased awareness of the role of savannas, the Cerrado in particular, in the global C cycle and climate change, the international community has a stake in such efforts.

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