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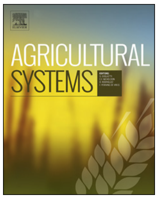

Short-term buildup of carbon from a low-productivity pastureland to an agrisilviculture system in the Brazilian savannah

Thais Rodrigues Coser[a,*], Cícero Célio de Figueiredo[a], Boban Jovanovic[a], Túlio Nascimento Moreira[a], Gilberto Gonçalves Leite[a], Sergio Lucio Salomon Cabral Filho[a], Eiyti Kato[a], Juaci Vitória Malaquias[b], Robélio Leandro Marchão[b]

[a] *Faculty of Agronomy and Veterinary Medicine, University of Brasília, Campus Darcy Ribeiro, 70910-970 Brasília, DF, Brazil*
[b] *Embrapa Cerrados, 73310-970 Planaltina, DF, Brazil*

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ABSTRACT

Agrisilviculture systems that combine two or more species with agricultural practices may potentially increase soil organic matter (SOM) quality due to its diversified and large carbon (C) inputs. The implementation of integrated agricultural systems in Brazil has reached over 11 Mha of area and is a promising strategy to revert widespread land degradation and increase ecological intensification for cropping systems. This study aimed to evaluate the transition of a low-productivity pasture to an agrisilviculture system (corn + *Gliricidia sepium* + *Panicum maximum* cv. Massai) along a four-year field experiment under a clayey Oxisol on SOM fractions, C stocks and C management index (CMI). A native Cerrado vegetation was used as a reference. Soil samples were collected in four cropping seasons: T0 - under low-productivity pasture, T1, T2, T3 – 2nd, 3rd and 4th years after implementing the integrated production system, respectively. Both mineral associated and total soil organic C (TC) increased from T0 to T3. Accordingly, C from the particulate SOM increased by 476%, 305% and 368% at 0.00–0.10, 0.10–0.20 and 0.20–0.40 m layers, respectively, and was found to be the most sensitive indicator for changes in soil management systems. Surprisingly, inert C increased up to 0.20 m layer from T0 to all the other seasons and represented 21 to 42% of TC. C stocks at the 0.00–0.40 m layer increased from 52.6 Mg ha^{-1} at T0 to 66.5 Mg ha^{-1} at T3. The CMI significantly increased from T0 to T3 – reaching CMI of native vegetation (considered CMI = 100%). The no-till agrisilviculture system with the use of *Panicum maximum* cv. Massai and *Gliricidia sepium* managed to accomplish the goal of building up soil organic C and increasing SOM quality, thus showing its potential to be used as a sustainable agricultural practice in terms of soil quality improvement and short-term C sequestration.

1. Introduction

Crop and animal production have important influences on global environmental issues, such as those related to climate change, land degradation, loss of biodiversity and water pollution (Gerber et al., 2013). In Brazil, it is fundamental to consider such influences in order to protect the Brazilian tropical savanna (Cerrado). This hotspot covers about 204 million hectares (approximately 24% of the Brazilian territory), is shelter to 12,070 species of terrestrial plants, and has important groundwater recharge areas that contribute to a large part to the water resources of the Brazilian river basins (Forzza, 2010; Lima and Silva, 2005). Therefore, to decrease deforestation and land degradation in agricultural-environmental-hotspots, ecological intensification of agriculture (EI) has been proposed. The EI process aims at increasing ecological services, crop yields per unit land and time, and soil quality in a sustainable way, by embracing the use of intensive and smart use of the natural functionalities of the ecosystem (Bommarco et al., 2013; Tittonell, 2014).

The Brazilian Federal Government, aiming at reducing deforestation, improving ecosystems services and at stimulating a low-carbon (C) economy has been adopting public policies such as the Low-C Agriculture (LCA) Program (Brazil, 2015). The LCA strategy was launched by the Brazilian government as a national program in 2010 to promote specific agricultural activities based on agricultural best management practices, which involved six major themes. Among these themes and considering Latin America, the restoration of low-productivity pasturelands and the adoption of no-till associated to integrated crop-livestock-forestry-systems, may offset emissions and

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* Corresponding author at: University of Brasília, P.O. Box 4508, Brasília, DF, Brazil.
E-mail address: tcoser@unb.br (T.R. Coser).

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reduce greenhouse gas emissions by 31.0% and 25.6%, respectively (Sá et al., 2017). Among Brazil's measures and National Determined Contribution (NDC), there is an incentive to restore 15 million hectares of low-productivity pastures and to increase agroforestry and/or integrated no-till cropland-livestock-forestry systems to five million hectares by 2030 (Brazil, 2015). Although the use of conventional tillage system is still common in Brazil, the adoption of the no-tillage system is currently practiced on > 50% of the annual cropped areas (de Freitas and Landers, 2014). The implementation of integrated agricultural systems in Brazil has reached over 11 Mha of area, where 83% accounts for agripasture, 9% agrisilvipasture, 7% silvipasture and 1% agrisilviculture systems (Embrapa, 2016). In the Cerrado, approximately 68% of anthropized areas are under planted pastures (mostly low-productivity pastures) whereas, 27% and 3.5% are under agriculture and silviculture systems, respectively (BRASIL, 2015).

Low-productivity pastures may potentially be restored and accumulate soil C by reducing animal stocking rates, improving soil fertility by chemical interventions and using leguminous species (Braz et al., 2013; Maia et al., 2009). However, when restoration is achieved through the implementation of integrated systems and no-till management, a high C accumulation rate may be obtained and thus an increase in soil C stocks (Baldotto et al., 2015; Costa et al., 2015). Also, the use of leguminous species, both in pastures and in the production of grain crops, may increase soil organic matter (SOM) contents (Barreto et al., 2012; Beedy et al., 2010; Boeni et al., 2014; Campos et al., 2011). Positive correlations between N availability and C stock in integrated crop-livestock systems have also been observed (Groppo et al., 2015).

Soil C accumulation and its potential to be stored in time will depend on its turnover (or residence time) in the different fractions of the SOM (Coleman et al., 1989; Lisboa et al., 2009). Thus, the rate of soil C sequestration in agroecosystems varies and will depend, for example, on how long conservation practices (FAO, 2015a) have been adopted in the area (Blanchart et al., 2007; Sá et al., 2017). In a representative Cerrado region of Brazil, a diachronic sampling revealed that younger no-tillage crop-land fields (1 to 6 years old) tended to show higher increases (0.41 to 1.46 Mg C ha^{-1} year^{-1}) in soil C stocks than the older (11 to 13 years old) fields (0.32 to 0.37 Mg C ha^{-1} year^{-1}) (Corbeels et al., 2016). With the adoption of no-tillage systems based generally on soybean followed by a cereal crop (maize, sorghum and millet), C stocks may increase to the levels of native vegetation in 11 to 14 years (76.2 Mg C ha^{-1}) considering the 0.00–0.40 m soil layer (Corbeels et al., 2016).

Furthermore, changes in SOM contents may not be detected in newly adopted agricultural production systems when measured by the total organic C (Chen et al., 2012; Figueiredo et al., 2013). However, labile fractions of soil organic matter – such as the particulate organic matter – and the active – such as the microbial biomass – which are associated to the deposition of fresh organic residues in the soil and to rapid turnover rates, are more sensitive to changes in soil management practices (Six et al., 2002; Chen et al., 2012; Figueiredo et al., 2013; Baah-Acheamfour et al., 2015). Conversely, the mineral associated organic matter is chemically more stable due to its higher degree of humification, its interaction with soil mineral phase and within microaggregates (Kögel-Knabner et al., 2008; Lisboa et al., 2009). Therefore, studies on SOM fractions may help to elucidate, precisely, the gains or loss in C contents along the years.

Increases in soil organic matter fractions are commonly associated to changes in soil biological, chemical and physical properties (Lopes et al., 2013; Tirloni et al., 2012). Thus, the isolation of soil organic matter fractions through fractionation procedures will help to understand the ability of certain soil management practices to accumulate and stabilize C and to improve soil quality over the years. Also, the C management index (CMI) has been used as a sensitive indicator of changes in soil quality due to agricultural uses (Nogueirol et al., 2014; Vieira et al., 2007; Zhao et al., 2014). The CMI is calculated from soil total organic C (TC) and its lability, thus indicates soil quality and the dynamics of C in soil (Zhao et al., 2014; Blair et al., 1995). Furthermore, there seems to be a shortage of research that evaluates labile and stable C fractions within time (seasons) in agriculture and pastoral systems. Therefore, strategies that combine a rapid restoration of low-productivity pastures and high soil C accumulation rates should be sought to meet the greenhouse gas emission reduction targets agreed during the United Nations Climate Change Conference in Paris (COP 21, 2015).

In this study, we evaluated the transition of a low-productivity pasture to a no-till agrisilviculture system in alley cropping with the leguminous tree - *Gliricidia sepium* and the tropical forage - *Panicum maximum* cv. Massai – in a whole four-year field experiment. Different soil organic matter fractions were measured and C stocks were calculated together with the CMI. We hypothesized that the use of a cover crop (*Panicum maximum* cv. Massai) and a forest component (*Gliricidia sepium)* in a maize-crop based system would increase CMI and soil organic matter in its more labile fractions within the first years after land use change. If true, this agrisilviculture system could be adopted in low-productivity pastures and play a major role in sequestering C for climate change mitigation in the Cerrado region of Brazil.

2. Materials and methods

2.1. Local climate and soil description

The experiment was established at the Experimental Farm Agua Limpa, University of Brasilia, Federal District, Brazil (latitude of 15° 56′ S, longitude of 47° 56′ W and altitude of 1090 m). The climate in the region is classified as Tropical Wet – Cwa, according Köppen classification (Alvares et al., 2013), with average annual rainfall of 1439 mm (concentrated between October and March) and mean annual temperatures varying from 16.7 °C to 22.4 °C (Fig. 1).

All treatments were installed in a clayey Oxisol (Typic Haplustox) (Soil Survey Staff, 1998), Latossolo Vermelho according to the Brazilian Soil Classification (Embrapa, 2013) or Gibbsic Ferralsol (IUSS Working Group WRB, 2006). Chemical and physical attributes of the soil (cropping season “zero” – T0) are displayed in Table 1. The mineralogical composition (referred to the oxic horizon – Bw in the Brazilian Soil Classification) of the experimental soil is approximately: 140.1 g kg^{-1} SiO_2, 393.2 g kg^{-1} Al_2O_3, 146.9 g kg^{-1} Fe_2O_3, 0.61 Ki (SiO_2/Al_2O_3), 0.5 Kr ($SiO_2/(Al_2O_3 + Fe_2O_3)$) and 4.3 Al_2O_3/Fe (Campos et al., 2010). Some chemical properties of the Bw-horizon (0.52 to 2.0 m depth) include: sum of bases ($Ca^{2+} + Mg^{2+} + K^{+}$) = 0.1 cmol$_c$ dm^{-3}; cation exchange capacity ($Ca^{2+} + Mg^{2+} + K^{+} + H^{+} + Al^{3+}$) = 3.3 cmol$_c$ dm^{-3}; aluminum saturation = 3.0%; base saturation = 3.6%; and soil organic matter = 16.0 g kg^{-1} (Campos et al., 2010).

2.2. History and description of the experiment

In 2012, the experimental area (approximately one hectare) was under low-productivity pasture – T0 (Table 1, Fig. 2). In December 2012, in order to establish the agrisilviculture system, the area was limed to raise base saturation to 50% (dolomite lime, 1.5 t ha^{-1}), fertilized (87 kg ha^{-1} de P_2O_5), ploughed and harrowed up to the 0.00–0.20 m layer (Table 1, Fig. 2). The corn was sown (as no-tillage) in January 2013 with rows spaced 0.9 m apart, totaling approximately 60,000 plants ha^{-1} (5.4 plants m^{-1}). The corn was fertilized according to crop-specific requirements based on soil chemical analysis (Table 2) (Sousa and Lobato, 2004). In January 2013, the cover crop – perennial grass – *Panicum maximum* cv. Massai was broadcasted at 10 kg ha^{-1} (considering the pure live seed percentage) one day after corn sowing. In the subsequent cropping seasons (2014/2015 and 2015/2016) the perennial grass was controlled by mowing and with reduced doses of herbicide containing paraquat and/or glyphosate (approximately, two weeks later) to control (but not kill) it during corn growth (Table 2). There was no need to weed the plots, except when there were other