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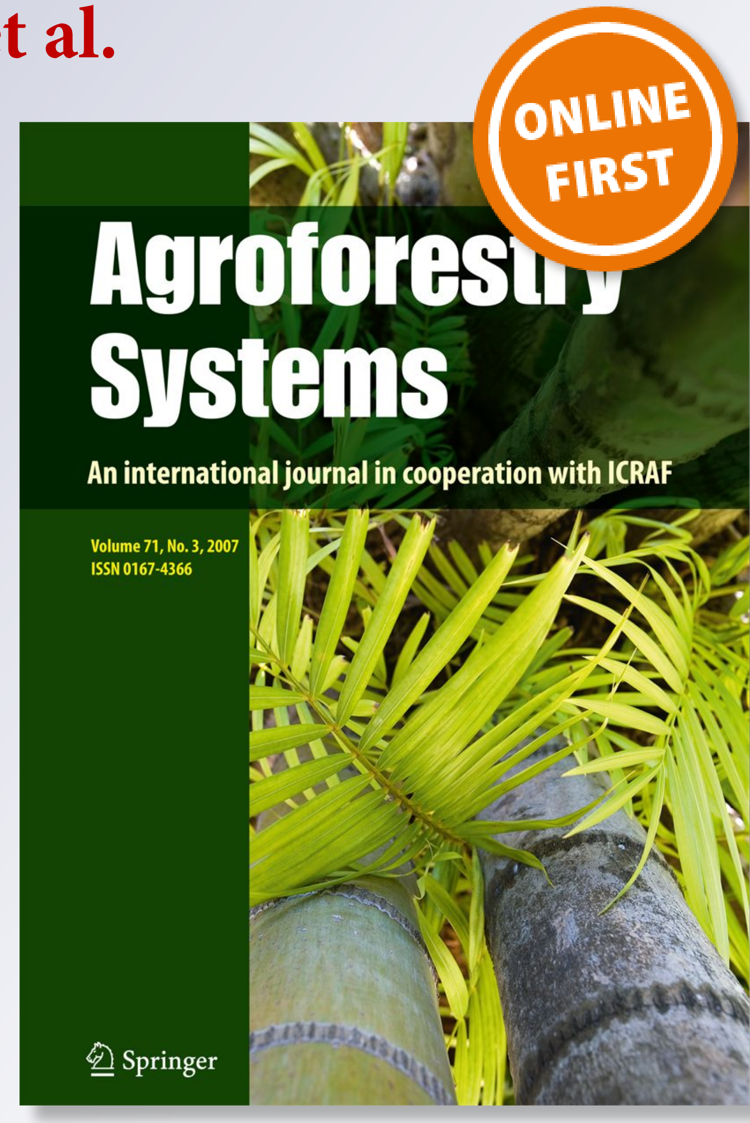

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# Silvopastoral management of beef cattle production for neutralizing the environmental impact of enteric methane emission

Leonardo de Oliveira Resende · Marcelo Dias Müller · Marta Moura Kohmann · Luís Fernando Guedes Pinto · Laury Cullen Junior · Sergio de Zen · Luiz Felipe Guanaes Rego

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**Abstract** It is well recognized that commercial beef cattle production systems have a major impact on climate change, mainly due to the emission of enteric methane ($CH_4$). The objective of this research was to evaluate if integrating animal + pasture + timber production in silvopastoral systems (SPS) would help neutralize the impact of enteric $CH_4$ emission by facilitating carbon storage as soil organic carbon (SOC). This paper reports a study conducted in Brazil with a herd of 150 cows in 100 ha of *Urochloa brizantha* with *Eucalyptus urograndis*, on four tree configurations: SPS 1-clone GG-100 at 2 × 3 × 15 m spacing; SPS 2-clone i-144 at 2 × 3 × 15 m; SPS 3-clone GG-100 at 3 × 15 m; and SPS 4-clone i-144 at 3 × 15 m. Based on data collected through eight consecutive years, the gas balance was estimated. For all SPS treatments average, the carbon dioxide equivalent ($CO_2$e) of additional C stock exceeded the emissions. Considering only C sequestration from trees, the average $CO_2$e sequestration was − 26.27 Mg·$CO_2$e ha$^{-1}$, while the average emissions of $CO_2$ e was 23.54 Mg·$CO_2$e ha$^{-1}$ for enteric $CH_4$ + pasture + tree, giving a net balance of − 2.73 Mg·$CO_2$e ha$^{-1}$. The "loss" of $CO_2$e analyzed was compensated by the soil C sequestration in long-lived SOC pools, enhancing the resilience of farming systems by increasing soil organic matter and soil fertility capacity, mitigating greenhouse gas emissions, therefore, providing benefits in livestock production and for environmental remediation.

**Keywords** Carbon sequestration · Cattle emissions · Greenhouse gases emission · Silvopastoral systems · Sustainable livestock

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## Introduction

Cattle represents the largest animal meat supply for the world's population, with monoculture as the basis of global animal production systems. While monoculture systems (MS) of land-use focusing on the production of single commodities allow increased production of specific, preferred commodities, they may also cause several environmental costs, such as contamination of water resources due to excessive use of industrial fertilizers and pesticides, loss of soils through erosion processes, greenhouse gases (GHG) emissions, expansion of production areas over native forests, and loss of biodiversity (Savory and Butterfield 2016; Rockström 2015). Beef production is the most resource-intense of all protein sources, among the potentially negative environmental impacts of cattle production, the emission of methane ($CH_4$), produced during the digestion process of ruminants—and hence known as enteric $CH_4$—generates a significant ecological footprint (Vermeulen et al. 2012).

Globally, enteric $CH_4$ is the second largest contributor to GHG emissions, accounting for 29% of global agricultural emissions, with $CO_2$ in the first place with 34% (GHG-Protocol Agriculture Guidance 2016; Vermeulen et al. 2012). In Brazil, this number exceeded 50% of total GHG emissions from agriculture during the period of 1970–2014.[1] The high contribution of cattle to the country's total GHG emissions is usually attributed to the model most often adopted: grass-fed cattle in MS, characterized by low production efficiency that increases the ecological footprint of the beef production chain (Strassburg et al. 2014).

Brazil has a herd of approximately 200 million animals, mainly raised in 169 million hectares of open pasture (grass in MS). Due to inadequate pasture management, 70% of Brazilian pastures have some level of degradation, reducing the productivity for a stocking rate average of only 0.7 animals per hectare (Strassburg et al. 2014). This degradation dynamic has also allowed biomass and organic matter losses, releasing C stored from the production system to the atmosphere, and increasing global warming and climate changes (Savory and Butterfield 2016).

According to the Sustainable Development Goals (SDG) from the United Nations (UN), 17 global key issues have to be addressed by the year of 2030 for a more sustainable future. Among the SDGs are responsible production and consumption in food production (SGD 12) and climate action (SGD 13).[2] In response to the challenge of changing the current livestock production system, several proposals for sustainable production models have been made to obtain an acceptable environmental, social, and economic balance (ICLF in numbers 2016; Müller et al. 2011). One such strategy is to enhance carbon sequestration in soil and vegetation to offset the impact of enteric $CH_4$ and even attain negative net GHG emission (Garnett et al. 2016). Some of these initiatives are fostered by the Brazilian Federal Low Carbon Agriculture Plan (*Plano ABC*), a public policy instrument for agriculture and livestock enterprises that presents detailed actions for mitigation and adaptation to climate change (Gouvello et al. 2010). One of the strategies supported by *Plano ABC* is the large-scale adoption of production systems that contribute to C sequestration, improving ecological efficiency in food production. For livestock, the Brazilian National Agricultural Research Agency (Embrapa) strategies include the reduction of monoculture through agroforestry system (AFS) practices, especially the Silvopastoral System (SPS). In Brazil, SPS is practiced mostly through the integration of livestock and commercial Eucalyptus tree production.

Some studies conducted in SPS showed that planting trees and pasture at the same time and in the same space can increase the overall productivity per unit of land area or enterprise (Neves et al. 2004; Soto-Pinto et al. 2010; Silveira et al. 2014). In these conditions, cattle and pasture are subjected to partial shading with lower average temperatures, improving animal well-being through thermal comfort, providing better environmentally-friendly products, lowering rainfall flow velocity and increasing the rate of water infiltration into the soil, decreasing erosion processes, providing more efficient corridors of contact between native forest fragments, and improving the scenic beauty of the rural landscape (Nair et al. 2011; Tonucci et al. 2011; Almeida et al. 2013). SPS increases soil organic carbon (SOC) storage, in finer fractions of soil, which is the most securely stored form of sequestered C in these systems (Nair et al. 2009; Nair 2014). Increasing SOC stock is important for soil fertility improvement, as well as environmental amelioration through C sequestration, which can be

[1] Seeg-Plataform. Available at: http://plataforma.seeg.eco.br/sectors/agropecuaria.

[2] United Nations. Available at: https://sustainabledevelopment.un.org/sdgs.

an efficient strategy for climate change adaptation and environmental conservation (Kaur et al. 2002; Andrade et al. 2008; Howlett et al. 2011; Dube et al. 2012; Nair et al. 2017). However, there is still a knowledge gap regarding GHG balance analyses in beef production. Therefore, the objective of this research was to evaluate if integrating animal + pasture + timber production in SPS would help neutralize the impact of enteric $CH_4$ emission by facilitating carbon storage as SOC.

## Materials and methods

### Study location

This research was based on the case study of Fazenda Triqueda (21°62′70.44″ S, 43°28′84.45″ W) located in the Paraibuna River Basin, in Coronel Pacheco city, at Minas Gerais State, in the southeast of Brazil. The topography of the area is inclined (approximately 23% slope), with altitudes ranging between 680 and 980 m above sea level. Because of the extensive areas with steep slopes, the use of machinery for agricultural activities is restricted, decreasing options for grain farming (e.g., soy and maize), increasing productivity costs, and consequently, leading to commercial disadvantages when compared to flat areas. The soil at the site was an Oxisol of clayey texture (51% sand, 14% silt, 35% clay): Latossolo Vermelho-Amarelo Distrófico, in the Brazilian classification. The climate is tropical: annual average temperature 19.3 °C; air humidity 75% to 85%; annual precipitation 1600 mm mainly in Summer (Kottek et al. 2006). Fazenda Triqueda (total area 381 ha) is subdivided into preservation areas with native forests (84 ha), riparian areas (80 ha), cattle production under SPS (100 ha), commercial forest of Eucalyptus in MS (100 ha), and others land uses (17 ha). The beef cattle herd was composed of 150 Brangus cows (*Boss taurus* × *Boss indicus*) for calf production.

The production system (pasture + trees) was introduced in different years, configurations and areas for this case study, the grass pasture used for all four treatments was the *Urochloa* (syn. *Brachiaria*) *brizantha* (Marandu). All SPS configurations received the same fertilizer and cultural treatments, but different spacing configuration, plant origin, and partial harvest (thinning), being all trees destined for sawmill wood production, as described below.

Two SPS configurations were in double-row:

SPS 1—initially planted in January 2007 with *Eucalyptus urograndis* (clone GG-100) at 2 × 3 × 15 m spacing (2 m between trees in a row, 3 m between the two rows in a double-row, and 15 m between a pair of double-rows, giving 555 trees $ha^{-1}$). In 2010, the stand was partially harvested removing 50% of the initial stand of trees, leaving approximately 250 trees $ha^{-1}$. These trees will be harvested for timber when they are 12 years old and they attain a diameter at breast height (DBH) of approximately 40 cm.

SPS 2—the same as SPS 01 (above) with the exception that the Eucalyptu*s* clone used was the i-144.

Two SPS configurations were in single-row:

SPS 3—initially planted in January 2010 with *Eucalyptus urograndis* (clone GG-100) at 3 × 15 m spacing (3 m between trees in a row and 15 m between a pair of rows, giving 238 trees $ha^{-1}$). These trees will not have partial harvest; instead, they will be harvested for timber when they are 12 years old and attain approximately 40 cm DBH.

SPS 4—the same as SPS 3 with the exception that the Eucalyptus clone used was the i-144.

### Enteric fermentation $CH_4$ emission from animals

The Brazilian Agricultural Research Corporation (Embrapa) has a network to evaluate GHG dynamics and C balance in agricultural production systems in five Brazilian biomes. This network is comprised of several Embrapa research units, universities, and other national and international research institutions, with the support of public and private initiative agencies. The literature citations for the emission factor range from 56 to 70 kg $CH_4$ $animal^{-1}$ $y^{-1}$ (Alves et al. 2015), as follows:

1. IPCC Tier 1 value: 56 kg $CH_4$ $animal^{-1}$ $y^{-1}$ (for Latin America);
2. IPCC Tier 2 value: 70 kg $CH_4$ $animal^{-1}$ $y^{-1}$ (for Latin America);

3. Embrapa's network value: 66 kg $CH_4$ animal$^{-1}$ y$^{-1}$ (for Brazil);
4. Embrapa's average value in SPS for beef production: 66 kg $CH_4$ animal$^{-1}$ y$^{-1}$ (for Brazil).

The emission factor utilized here is the average value in Embrapa's SPS research areas for beef production (item 4 listed above), since it best represents the study location. This is in agreement with the methodology suggested by IPCC (2014) which indicates that regional and specific emission factors should be used when available. Enteric $CH_4$ emissions were estimated by multiplying the animal stocking rate of 1.5 Animal Unit (AU) ha$^{-1}$ by an emission factor of 66 kg $CH_4$ animal$^{-1}$ y$^{-1}$ (Alves et al. 2015). The value obtained was then multiplied by $CH_4$ global warming potential (GWP) of 28 to obtain emissions in kg $CO_2$e (IPCC 2014) and by eight to estimate total emissions during the 8 years of the experimental period.

## GHG emission from the introduction of SPS (trees + pasture)

Sources of GHG were calculated considering emissions from production, transportation, storage and transfer of agrochemicals (pre-farm), planting, and maintenance activities. Emissions were estimated using the equations presented by the Intergovernmental Panel on Climate Change (IPCC 2014), which provides methodologies for estimating national inventories of anthropogenic GHG emissions by sources and removals by carbon sinks (Table 1). Results are presented in kg$CO_2$e (IPCC 2014).

**Table 1** References values for $CO_2$e emission from the introduction of SPS (pasture + trees)

| Input | Conversion C emission kg C kg input$^{-1}$ |
|---|---|
| Fuel (l ha$^{-1}$) | |
| Diesel | 0.94 |
| Fertilizer (kg ha$^{-1}$) | |
| Nitrogen | 1.30 |
| Phosphorus | 0.20 |
| Potassium | 0.15 |
| Pesticides (kg ha$^{-1}$) | |
| Herbicide | 6.30 |
| Insecticide | 5.10 |

*$CO_2e$* carbon dioxide equivalent, *SPS* silvopastoral system, *C* carbon, *kg* kilogram, *l* liter, values considering emissions from production, transportation, storage and transfer of agrochemicals (pre-farm), planting, and maintenance activities (Lal 2004)

Table 1 contains the emission factors used for GHG inventory from Year 1 to Year 8 of this research. Due to the slope in the experimental area (23%), all tree planting activities were done with manual labor and therefore have no carbon dioxide ($CO_2$) emissions associated to them. Pasture planting was a fully mechanized operation, with $CO_2$ emission from mechanization considered. It is expected that SPS plantations carried out with full agricultural machinery will present higher consumption of fossil fuel and therefore higher $CO_2$ emissions when compared to the current case study.

## Tree-mediated storage of SOC

Only C retained in organic matter and remaining in long-lived pools (carbon sinks) was accounted for in SOC. In each SPS treatment occupying an area of approximately 15 ha, four sample plots with ten trees each, proportionally distributed to represent the average conditions such as slope and soil type, were marked. Tree inventories were carried out annually with the measurement of DBH and total height of all trees in each sample plot. For trees 0.10 m to 1.90 m tall, the height as well as diameter at intervals of 0.20 m was measured directly. For trees > 1.90 m tall, the estimation was done using digital dendrometer model Criterion RD 1000 (Jorge 2014), and diameters measured at 1.0 m intervals, allowing the Strict volume calculation by the Smalian´s formula (Loetsch and Haller 1964). From Year 3 to Year 8, this activity was repeated annually to obtain a more accurate tree growing curve.

The $CO_2$e was calculated using the linear equation (Silva 1996):

$$t.CO_2e = (V + 25\%) \times (Basic\ Dens. : 0.49) \times (C : 0.42) \times (CO2 : 3.66)$$

where t.$CO_2$e is tons (Mg.) of carbon dioxide equivalent, V is volume of tree (m$^3$), and Basic Dens. is basic density (g cm$^{-3}$) of timber.

For C stock estimation as SOC, it was necessary to first separate trees into different parts (crown, trunk, and roots). Average distribution of Eucalyptus tree biomass and C sequestration were estimated as: 12% in the crown, 23% in the root system, and 65% in the trunk (Paixão et al. 2006; Reis 2006; Gatto 2011). After this, it was assumed that following decomposition of plant materials left behind after tree trunks were removed from the site, 40% and 20%, respectively, of the total C in belowground biomass (roots) and aboveground biomass (tree crown) were retained in soil as SOC (Shepherd and Montagnini 2001; Schroth et al. 2002; Nair et al. 2009).

GHG balance per hectare for enteric $CH_4$ neutralization

The balance between the $CO_2e$ sequestration and emissions from the production system was estimated as follows:

$$CO_2\text{e balance } 1 = \text{SOC } 1 \times \text{A} + \{[(\text{EF } 1 \times \text{Y}) + \text{PE } 1] \times \text{A}\}$$

where $CO_2e$ balance 1 is the balance of carbon equivalent ($Mg.CO_2e$), SOC 1 is trees soil organic carbon ($Mg{\cdot}CO_2e\ ha^{-1}$), A is area (ha), EF1 is emissions from enteric fermentation ($Mg{\cdot}CO_2e\ ha^{-1}$), Y is the number of years (n), and PE 1 is planting emission from trees and pasture ($Mg{\cdot}CO_2e\ ha^{-1}$).

Negative values obtained from these estimates indicate that there is a net GHG removal from the atmosphere through C sequestration, while positive values indicate net GHG emissions.

## Results

$CH_4$ emission from animal enteric fermentation

Total emission from animal enteric fermentation was 2.77 $Mg{\cdot}CO_2e\ ha^{-1}\ y^{-1}$ and 22.16 $Mg{\cdot}CO_2e\ ha^{-1}$ for the entire eight years of research, as explained below:

$$CO_2e = 66 \times 1.5 = 99\ \text{kg of } CH_4\ ha^{-1}\ y^{-1}$$
Multiplying by 28(= $CH_4$GWP: ref section 2.2),
$$99 \times 28 = 2.77\ Mg.CO_2e\ ha^{-1}\ y^{-1}$$
Total for the study period of eight years, 2.77
$$\times\ 8 = 22.16\ Mg.CO_2e\ ha^{-1}.$$

$CO_2$ emission from the introduction of SPS (trees + pasture)

The average of $CO_2e$ emission from the introduction of SPS (pasture + trees) was 1.38 $Mg{\cdot}CO_2e\ ha^{-1}$ (Table 2). The total valued showed on Table 2 (1.38 $Mg{\cdot}CO_2e\ ha^{-1}$), for pasture and tree planting emission, was added to the total enteric $CH_4$ emission (22.16 $Mg{\cdot}CO_2e\ ha^{-1}$), resulting in a value of 23.54 $Mg{\cdot}CO_2e\ ha^{-1}$ for the 8 years of the study period.

Tree-mediated SOC storage in soil

Statistical analysis for SOC increase included two clones (GG 100 and i-144), and used a design of blocks with casualization with parcels subdivided into four repetitions. The Turkey Test was used to determine on which timepoint throughout the research the clones were differentiated in terms of C sequestration. In single-row configuration (Table 3), it was observed that clones differentiated significantly from the fourth year onwards, with an advantage in favor of clone i-144.

In spite of the increased SOC performance by clone i-144 in the annual analysis (Table 3) for single-row, the Turkey Test did not find statistical significance for the average period surveyed, with 5% of probability, this might have occurred due to the high coefficient of variance (41.05%), as follow: clone GG-100 in single-row, average of 12.38, and statistical result "b"; clone i-144 in single-row, average of 15.78, and statistical result "b".

For the double-row configuration, (Table 4), clones significantly differentiated from the third year onwards, with advantage to clone i-144.

Similarly to what was found for the previous analysis (single-row), in spite of improved SOC performance by clone i-144 in the annual analysis (Table 4) for double-row, the Turkey Test did not find statistical significance for the average period surveyed, with 5% of probability, this might have occurred due to the high coefficient of variance (31.39%), as follow: clone GG-100, average of 16.51, and statistical result "b"; clone i-144, average of 18.81, and statistical result "b".

For all treatments, results ranged from − 20.69 $Mg{\cdot}CO_2e\ ha^{-1}$ to − 30.70 $Mg{\cdot}CO_2e\ ha^{-1}$,

**Table 2** The average of $CO_2e$ emission from the introduction of SPS (pasture + trees)

| | Average conversion | | | | |
|---|---|---|---|---|---|
| | Inputs | | C emission (kg C kg input$^{-1}$) | $CO_2$ emission (kg C kg $CO_2^{-1}$) | $CO_2e$ emission (kg $CO_2$ kg $CO_2e^{-1}$) |
| Pasture planting | Fuel (l ha$^{-1}$) | | | | |
| | | 32.99 | 0.94 | 31.01 | 113.69 |
| | Fertilizer (kg ha$^{-1}$) | | mean | | |
| | Nitrogen | 29.32 | 1.30 | 38.12 | 139.76 |
| | Phosphorus | 46.91 | 0.20 | 9.38 | 34.40 |
| | Potassium | 29.32 | 0.15 | 4.40 | 16.13 |
| | Lime | 659.70 | 0.16 | 105.55 | 38.02 |
| Trees planting | Fuel (l ha$^{-1}$) | | | | |
| | | 5.36 | 0.94 | 5.03 | 18.46 |
| | Fertilizer (kg ha$^{-1}$) | | Mean | | |
| | Nitrogen | 25.00 | 1.30 | 32.50 | 119.17 |
| | Phosphorus | 38.50 | 0.20 | 7.70 | 28.23 |
| | Potassium | 88.50 | 0.15 | 13.28 | 48.68 |
| | Lime | 277.00 | 0.16 | 44.32 | 162.51 |
| | Pesticides (kg ha$^{-1}$) | | | | |
| | Herbicide | 5.00 | 6.30 | 31.50 | 115.50 |
| | Insecticide | 11.00 | 5.10 | 56.10 | 205.70 |
| | Total | 1.38 | kg, $CO_2$ ha$^{-1}$ | | |

*$CO_2e$* carbon dioxide equivalent, *SPS* silvopastoral system, *C* carbon, kg kilogram, *l* liter, *ha* hectare, values considering emissions from production, transportation, storage and transfer of agrochemicals (pre-farm), planting, and maintenance activities (Lal 2004)

**Table 3** Tukey test for annual SOC increase in single-row

| Year | GG-100 (SPS 1) | | i-144 (SPS 2) | |
|---|---|---|---|---|
| | SOC average (Mg $CO_2e$ ha$^{-1}$) | Statistical result | SOC average (Mg $CO_2e$ ha$^{-1}$) | Statistical result |
| 3 | 3.77 | b | 4.89 | b |
| 4 | 6.55 | b | 8.41 | a |
| 5 | 10.43 | b | 14.74 | a |
| 6 | 14.92 | b | 18.63 | a |
| 7 | 17.93 | b | 22.32 | a |
| 8 | 20.69 | b | 25.66 | a |

*SOC* soil organic carbon, *SPS* silvopastoral system, *Mg·$CO_2e$ ha$^{-1}$* megagram of carbon dioxide equivalent per hectare

with individual results (Tables 3, 4) in the fowling order: SPS 2 (− 30.70 Mg·$CO_2e$ ha$^{-1}$), SPS 1 (− 28.01 Mg·$CO_2e$ ha$^{-1}$), SPS 4 (− 25.66 Mg·$CO_2e$ ha$^{-1}$), followed by SPS 3 (− 20.69 Mg·$CO_2e$ ha$^{-1}$). It is important to note that the estimates for tree SOC calculation was done between Year 3 to Year 8 of the experiment, therefore SOC was considered as zero for the first three years.

### GHG balance per hectare for enteric $CH_4$ neutralization

For all SPS treatments average, carbon sequestration (− 26.27 Mg·$CO_2e$ ha$^{-1}$) exceeded average emissions of enteric $CH_4$ + pasture planting + tree planting (23.54 Mg·$CO_2e$ ha$^{-1}$), indicating a net GEE

**Table 4** Tukey test for annual SOC increasing in double-row

| Year | GG-100 (SPS 3) | | i-144 (SPS 4) | |
|---|---|---|---|---|
| | SOC average (Mg $CO_2$e $ha^{-1}$) | statistical result | SOC average (Mg $CO_2$e $ha^{-1}$) | statistical result |
| 3 | 5.32 | b | 7.96 | a |
| 4 | 9.32 | b | 12.71 | a |
| 5 | 15.13 | b | 16.57 | a |
| 6 | 19.31 | b | 21.04 | a |
| 7 | 21.97 | b | 23.90 | a |
| 8 | 28.01 | b | 30.70 | a |

*SOC* soil organic carbon, *SPS* silvopastoral system, $Mg{\cdot}CO_2e\ ha^{-1}$ megagram of carbon dioxide equivalent per hectare

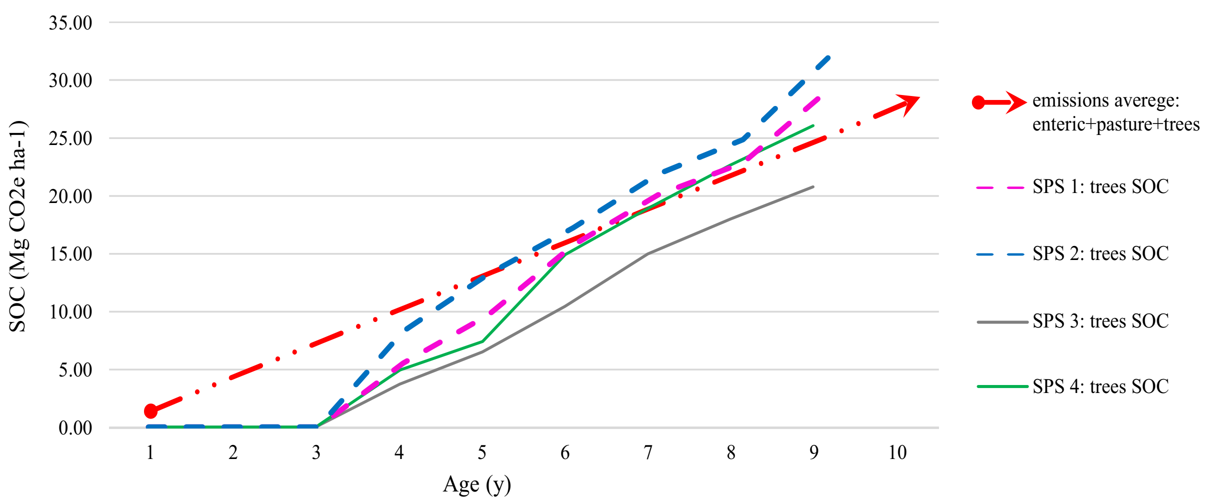


**Fig. 1** Estimated annual cumulative GHG emissions and sequestration per hectare; average GHG emissions include enteric fermentation, planting of pasture, and planting of trees; C sequestration include only trees SOC (soil organic carbon); treatments in double-row at 2 × 3 × 15 m spacing: SPS 1-clone GG-100 and SPS 2-clone i-144; in single-row at 3 × 15 m spacing: SPS 3-clone GG-100 and SPS 4-clone i-144

balance of − 2.73 Mg·$CO_2$e $ha^{-1}$, of C removed from the atmosphere after 8 years.

The GHG balance graph represents individual treatment performance (Fig. 1), among all SPS treatments which obtained the GHG neutralization: SPS 2 (− 7.16 Mg·$CO_2$e $ha^{-1}$), SPS 1 (− 4.47 Mg·$CO_2$e $ha^{-1}$), and SPS 4 (− 2.12 Mg·$CO_2$e $ha^{-1}$); while positive values for SPS 3 indicate GHG emissions of 2.28 Mg·$CO_2$e $ha^{-1}$.

## Discussion

Several Brazilian works have reported SPS C sequestration (or aboveground biomass), with multiple measuring times of total C sequestration inventory for the tree trunk, reporting increased C sequestration (Mg·$CO_2$e $ha^{-1}$ $y^{-1}$), namely: Tsukamoto Filho et al. 2004; Oliveira et al. 2008; Müller et al. 2009; Rocha et al. 2017; Torres et al. 2017; Schettini et al. 2018. These results for C sequestration in the trunk have showed a range from − 5.23 to − 21.15 Mg·$CO_2$e $ha^{-1}$ $y^{-1}$, and an average of − 14.31 Mg·$CO_2$e $ha^{-1}$ $y^{-1}$. These studies have occurred in the same eco-region as this research, but they used total C instead of SOC, making data comparison more complex.

The methodology used in this research has considered that once the trunk was sent to sawmill wood production, its biomass could not be incorporated by the soil as organic matter. SOC data analyses makes this research more conservative, with values reaching approximately 17.84% of the total C sequestration. The decision to adopt this approach considers that the other 82.16% of total plant C sequestration will, at different times, be volatized and re-emitted into the atmosphere. Thus, this portion of non-stable C can be considered as a slow carbon cycle, but not as a carbon sink (or long-term carbon, more stable in the soil). Long-term carbon—more stable in the soil, can occur in four kinds of C sinks (USDA[3]) there are in the Earth: vegetation reservoirs, oceans, the atmosphere, and terrestrial systems; with C equilibrium being a complex dynamic involving the C cycle (flow, exchange, and stock). The C stored in soils is composed of geological C sinks, such as fossil fuels sources and organic matter decomposed present in the soil, as SOC (Lal 2004). Among other forms of C sinks (or long-lived C pools), soils constitute a secure alternative for mitigating GHG emissions, storing approximately twice the amount of carbon present in the atmosphere (Nair et al. 2009). During the tree (or biomass) life, the following phases occur, taking the C cycle into consideration: sequestration, stock, flow, and re-emission. SOC is C converted into organic matter and remains stable in the soil in long-lived pools, which is why sustainable agriculture proposals involving climate change typically address SOC for GHG emissions compensation.

Long-term carbon in SPS can be explained in three phases: 1st phase, *fast carbon cycle*—starting from the photosynthesis process, when plants remove $CO_2$ from the atmosphere, releasing $O_2$ and retaining the C in the plant structure as biomass for a transient period of time; 2nd phase, *slow carbon cycle*—after this, although alive and with good vitality, the plant dynamics presents a partial biomass decomposition by the action of microorganisms, with decomposed biomass being released to the atmosphere partly as C and, another part as SOC; 3$^{rd}$ phase, *long-term C, more stable in the soil*—SOC can be found in different soil density particle sizes and fractions (e.g. size classes: 2000 to 250 μm, 250 to 53 mm, < 53 mm), and the smaller the particle fraction is, more stable is the C in the soil (Nair et al. 2009, 2011; Nair 2014). In a long-term experiment (over 20 years), there was a C increase in the soil under AFS/SPS as well as higher C percentage in AFS/SPS compared to MS, particularly in smaller (silt-and-clay) fractions of soil, indicating the recalcitrant nature and long-term storage of C (Nair 1993; Nair et al. 2008).

Taking this into account and turning to the Brazilian average of C sequestration, calculated per tree trunk, if the value ($-$ 14.31 Mg·$CO_2$e ha$^{-1}$ y$^{-1}$) was treated according to this research methodology, converting total C into SOC, this result would decrease to approximately $-$ 2.55 Mg·$CO_2$e ha$^{-1}$ y$^{-1}$, enabling a better understanding of the similarity of the results. Only two studies addressing SOC were found for SPS in our region (Neves et al. 2004; Tonucci et al. 2011), but in both there was only one measurement, making it impossible to determinate the SOC increment in Mg·$CO_2$e ha$^{-1}$ y$^{-1}$. Also using only one SOC measurement, Silveira et al. (2014) found significant increases in SOC for SPS (21.2 Mg·C ha$^{-1}$), when comparing native rangeland ecosystems (13.9 Mg·C ha$^{-1}$) in Florida (US). Dube et al. (2012) in Chile, reported higher SOC stocks for SPS (193.76 Mg·$CO_2$e ha$^{-1}$) than natural pasture (177.10 Mg·$CO_2$e ha$^{-1}$). These results suggest that planting trees on traditional pastures will promote long-term storage of C in the soil.

For GHG neutralization, Rocha et al. (2017) and Torres et al. (2017) conducted an SPS experiment (Eucalyptus + Brachiaria) in similar ecological and geographical conditions (eco-regions) to this research, finding a net balance which ranged from $-$ 10.92 to $-$ 19.32 Mg·$CO_2$e ha$^{-1}$ y$^{-1}$ (for Rocha) and $-$ 2.81 to $-$ 7.98 Mg·$CO_2$e ha$^{-1}$ y$^{-1}$ (for Torres). Comparing with this research GHG balance, the superior result obtained by Rocha and Torres can be explained because both used total C sequestration instead of SOC, as already explained (in this section).

In Brazil, Eucalyptus forest breeding is a science that has been developing since 1941; initially, the selection was based on the best phenotype, resulting in an evolution of seed performance, later, hybridization and cloning techniques provided an exponential increase in productivity, doubling wood volume production. (Castro et al. 2016). For the Paraibuna

[3] United States Department of Agriculture. Available at: https://www.fs.usda.gov/ccrc/index.php?q=topics/global-carbon.

River Basin, where the experimental area is located, during field research work it was observed that the most common SPS arrangement components are *Eucalyptus urograndis* and *Urochloa brizantha*, with the tree density (trees $ha^{-1}$) and tree genetic origins as the most significant differences.

When comparing treatments results, double-row configuration had better SOC increases than single-row (Tables 3, 4), indicating that higher tree density is related to higher C sequestration. Soto-Pinto et al. (2010) observed the same SOC behavior for two SPS treatments in Mexico, with results showing 70.4 $Mg{\cdot}CO_2e\ ha^{-1}$ for SPS with scattered trees and 66.5 $Mg{\cdot}CO_2e\ ha^{-1}$ for pastures + live fences, suggesting that higher tree density would allow higher SOC increase. With regard to tree genetic origin, clone i-144 was better than GG-100 in the double-row (SPS 2 > SPS 1), and also in the single-row (SPS 4 > SPS 3), signaling that clone i-144 is more indicated for the research eco-region. Thus, double-rows with clone i-144 seem to be the best choice, but the next paragraphs will try to show a more holistic overview to support good decision making.

Although higher tree density achieved greater enteric $CH_4$ neutralization, single-row densities can provide greater passage of solar radiation to the pasture, enabling greater production of biomass to feed the animals. To avoid a reduction in pasture production due to excessive shading (more than 30% of the area), canopy lopping should be performed (ICLF in numbers 2016). Alternatively, different planting arrangements can be utilized to allow solar radiation to reach pasture below the tree canopy. For example, a single-row spacing of 3 × 15 m, which results in 13% shading, or double-row of 3 × 3 × 15 m, which reaches 28% shading; other arrangements (triple to quintuple-row) typically do not allow shading under 38% according to Embrapa[4].

The mountainous landscape limits mechanization for tree planting and harvesting, consequently, manual labor practices result in lower net profit margins, and SPS becomes more financially viable with the added value of timber. Trees produced in single-row arrangements are typically used for sawmill wood production, and harvested at age 12 with higher profit margins. Other SPS line arrangements (2, 3, 4 or 5 lines) are generally used in multipurpose wood production and are, almost exclusively, destined to the production of firewood, charcoal, or cellulose. In these cases, harvest occurs in three cycles: at 6 years (first harvest and first coppicing), 12 years (second harvest and second coppicing), and 18 years (final harvest). More harvesting and coppicing activities makes livestock production challenging, due to the need to remove cattle from the pasture in the early stages of plant development, and during planting and coppicing. Taking all these issues into consideration, despite higher SOC increase in double-rows, this research assumes that SPS 4 (clone i-144 in single-row, with lower tree densities) would allow more benefits in livestock production and for environmental remediation for this experimental eco-regions.

It is worth noting that statistical analysis comparing single versus double-row SOC increases were not possible because the areas were planted in different years (double-row in 2007 and single-row in 2010, as mentioned in the "Study location" section). Consequently, these treatments (single vs. double-row) were exposed to different climate and environmental conditions such as rainfall, temperature and type of soil. In addition, due to budget constraints, this research did not consider C sequestration from forage production. As an example, Salton et al. (2011), evaluated the pasture SOC increase in a Brazilian tropical climate site for beef cattle management with permanent pasture grass (*Urochloa brizantha*), and obtained 1.39 $Mg{\cdot}CO_2e\ ha^{-1}\ y^{-1}$. Thus, future studies should address both situations and these data could provide a scientific basis to the development of new hypotheses.

Although SOC increase by SPS in this research was an important environmental capital for the livestock production chain, it was difficult to obtain comparative parameters in similar conditions to this research, since almost all available Brazilian C sequestration data is related to aboveground C sequestration, which corresponds to C temporarily retained as plant biomass, representing the "fast carbon cycle", instead of belowground sequestration retained as SOC, which would represent the "long-term carbon more stable in the soil". This specific SOC increment data is essential for proper GHG balance in livestock chains, that involve long-term benefits, and is needed to face the challenges of developing a safe source of animal protein (milk or beef), consequently, increasing food security and decreasing global warming. Thus, Brazil

[4] EMBRAPA FLORESTAS. Avaiable at: https://www.cnpf.embrapa.br/pesquisa/safs/calc_densidarb.xls

should foster additional research efforts to develop better knowledge on SOC analyses in SPS; this data could be applied for the improvement of food-production systems less demanding of natural resources.

## Final considerations

This research has demonstrated that it is possible to neutralize the emission of enteric $CH_4$ in beef cattle production through SPS trees in Fazenda Triqueda's case study. It also validated that SPS, in addition to providing a source of feed for the animals (pasture biomass), performs C sequestration, as SOC, in a significant scale. The "loss" of $CO_2$e analyzed was compensated by the soil C sequestration in long-lived SOC pools, enhancing the resilience of farming systems by increasing soil organic matter and soil fertility capacity, mitigating greenhouse gas emissions.

This study also assumes that the arrangement with *Eucalyptus urograndis* (clone i-144) for sawmill wood production in a single-row configuration at 3 $\times$ 15 m spacing (238 trees ha$^{-1}$), would allow more benefits in livestock production and environmental remediation for this experimental eco-regions (mountainous landscape). Therefore, the adoption of SPS by cattle ranchers has the potential to consolidate their transition from MS to an AFS, capable of developing a safe source of animal protein (milk or beef), consequently, increasing food security and decreasing global warming.

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