Assessment of carbon capture and storage through silvopastoral systems designed for tree harvesting for different end uses

Avaliação da captura e armazenamento de carbono através de sistemas silvipastoris com arranjos de árvores para diferentes usos

F. F. G. D. Leite[1]; F. M. Santos[1]; J. G. da Silveira [2]; A. J. Veroneze[3]; M. D. Müller [4]; I. G. M Ferreira[1]; B. J. R. Alves[5]

[1]Associação Rede ILPF, Brasília-DF, Brasil. fernandagranja@redeilpf.org.br
[2]Instituto de Ciências Agrárias e Ambientais, Universidade Federal de Mato Grosso (UFMT), Sinop-MT, Brasil
[3]Suzano, Imperatriz-MA Brasil
[4]Embrapa Gado de Leite, Juiz de Fora-MG, Brasil
[5]Embrapa Agrobiologia, Seropédica-RJ, Brasil

Abstract

All economic sectors must support strategies to offset greenhouse gasses (GHG) emissions and sequester carbon. One of these practices is the silvopastoral system (SPS), which involves raising animals on a pasture containing trees, which can be managed for wood harvest or not. Thus, the objective of this study was to evaluate the potential of eucalyptus trees to absorb and store carbon in two SPS designs in Brazil. The case study I (CSI) carried out in Maranhão State, is a SPS using eucalyptus whose wood was destined for the pulp and paper industry. In this case, a tree density of 833 plants ha^{-1} was arranged in nine planting lines interspersed with a 30-meter grazing strip. The Case study II (CSII) is in Minas Gerais State, and consisted of a SPS with a plant density of 322 eucalyptus trees ha^{-1} planted in double rows. Considering the eucalyptus cutting cycle in the field, the average C stocks in CSI and CSII in the long term are 15 and 27 Mg ha^{-1}, respectively. Including the time wood products immobilize carbon as they last in nature, a projected permanent C stock of 30 Mg ha^{-1} at the equilibrium is estimated for CSI and 222 Mg ha^{-1} for CSII. The permanent C stock in CSI and CSII is comparable to areas undergoing forest restoration in Brazil, which also provides other externalities such as biodiversity conservation. However, with climate emergency, it is important to highlight the potential of SPS to simultaneously produce food and goods, while sequestering atmospheric CO_2.

Key words: *carbon sequestration; pulp and paper; solid wood; eucalyptus; climate emergency.*

Palavras-chave: *sequestro de carbono; papel e celulose; madeira sólida; Eucalyptus; emergência climática.*

Introduction

All economic sectors must support strategies that contribute to reducing greenhouse gasses (GHG) from anthropogenic sources and, most importantly, to reach a net zero CO_2 emission by 2050 (IPCC, 2019). CO_2 emissions are mainly related to the burning of fossil fuel and to land use change, generally caused by the expansion of agricultural land (Hansen *et. al.,* 2010).

In Brazil, the agricultural sector has always been responsible for a large share of the country's GHG emissions (MCTI, 2022). In this context, the Brazilian Government has launched a national policy to promote climate-smart practices (Polidoro *et. al.,* 2021). In addition, intensified pastures allow higher stocking rates and animal productivity, which can be understood to keep land free for arable expansion and to avoid clearing new areas (Feltran-Barbieri and Féltri, 2021). However, it is not negligible that intensified systems can lead to higher GHG emissions due to the higher stocking rates and soil emissions resulting from the use of agricultural inputs (fertilizers, lime, organic residues, etc) and the associated fossil fuel consumption (Cardoso *et. al.,* 2016; de Figueiredo *et. al.,* 2017). Even if the intensity of GHG emissions is curbed by intensification (Cardoso *et. al.,* 2016), the possibility of an increase in demand for animal protein may lead to an expansion in areas under such intensified systems with a concomitant increase in GHG emissions colliding with climate policy targets.

Atmospheric CO_2 can be removed and stored as soil organic matter or as plant biomass, both reservoirs are generally used to compensate for GHG emissions (Leite *et. al.,* 2023). However, depending on land use history and edaphoclimatic conditions the expected effects of agricultural practices on soil C stock changes can be largely variable (Oliveira *et. al.,* 2023) and eventually irrelevant for GHG emission compensation. On the other hand, C accumulation is easily verified in plant biomass, especially in trees. The use of trees integrated into a crop-pasture succession is referred to as an Integrated Crop-Livestock-Forestry (ICLF) system, which allows for land use diversification (Balbino *et. al.,* 2011) and is also an adaptation measure in tropical regions that reduces heat stress in cattle (Lima *et. al.,* 2019). A variation of ICLF systems is the Silvopastoral Systems (SPS), which is common to many countries, but far from a standard management as it allows many possibilities of tree species, designs, and arrangements (Skorupa and Manzatto, 2019). *Eucalyptus* spp. is more frequently used when trees are to be managed.

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The amount of carbon stored in tree biomass, although easier to measure, is finite and depends on planting density, tree maturity, and forest management (Feliciano *et. al.,* 2018). However, unless changes in field practices that lead to a reduction in GHG emissions, such as the use of forage legumes in pastures to replace fertilizer N (Boddey *et. al.,* 2020), the most immediate solution to minimize impacts, albeit temporarily, is the improvement in C storage in soil and tree biomass.

Generally, the potential for offsetting greenhouse gas emissions is considered only for the time the tree is growing in the field. However, if this biomass is processed into products such as furniture, fence posts, and even pulp for the paper industry, it will extend the "dwell time" or service that trees provide by offsetting greenhouse gas emissions. The final destination of the harvested trees is the main factor that governs the amount of and time at which the C is kept out of the atmosphere (Morales *et. al.,* 2023).

The objective of this work was to evaluate the potential of eucalyptus trees for carbon uptake systems economically suitable to provide wood for pulp and paper industry and to produce furniture in addition to livestock.

Material and methods

Case studies description

Two different arrangements of SPS with eucalyptus trees were evaluated as case studies, reflecting two of the main forest management regimes for this species in Brazil. Case study I (CSI) represents a SPS for livestock production integrated with wood production for the pulp industry. Case study II (CSII) is a SPS for milk production integrated with solid wood production.

Case Study I

The study was carried out in an SPS area of approximately 590 hectares in Ouro Verde farm, Brejo Grande do Araguaia municipality, Pará, Brazil (05°41'13.98" S, 41°30'37.84" W, and 170 m a.s.l.). The region's climate is tropical with a dry winter (Aw) according to Köppen's classification, with a mean temperature of 27.3º C, and irregularly distributed annual precipitation of 1,819 mm. The region is a transition area between the Amazon Rainforest and Cerrado biomes, with a predominance of Ultisols and Oxidols (Soil Survey Staff, 2014) with a sandy-clay texture.

The SPS is composed of *Eucalyptus* spp. clones as part of Suzano S. A's Outgrower System at the Imperatriz Unit established in a palisade grass (*Urochloa brizantha* cv. Xaraés) and Guinea grass (*Megathyrsus maximus* cv.

Mombaça) pastures. The trees are arranged in strips 24 m wide composed of nine rows of trees with interrow space of 3 m and plants spaced 2 m in the row. Tree strips were interspersed with a 30 m pasture area (Figure 1). Then, each hectare of the SPS presented 833 trees.

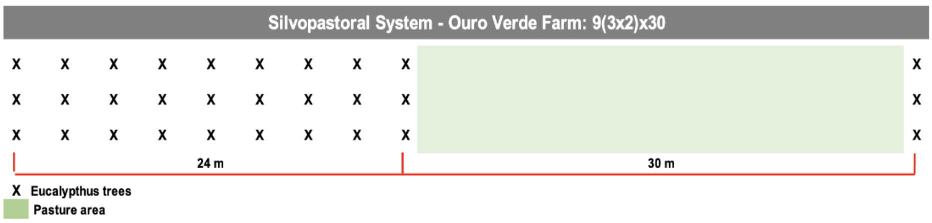

Figure 1. Representation of the silvopastoral system with strips of eucalyptus of 24 m width and of 30 m width for the pasture (Suzano, 2023).

The area received an average application of 800 kg ha^{-1} of dolomitic limestone broadcasted within the eucalyptus strip prior to planting followed by subsoiling to 40 to 60 cm. While the pasture area received a rate of 1000 kg ha^{-1} of limestone. The formulated fertilizer 10-30-10 plus micronutrients was applied at a rate of 250 kg ha^{-1}. The formula 10-02-25 (or even 10-05-20) was broadcast at a rate of 420 kg ha^{-1} plus micronutrients between 6 and 9 months after planting. Ant control was conducted throughout the cycle using sulfluramid-based ant baits. Grass control with glyphosate was performed until cattle entry, approximately 8 months after planting. Pasture areas received appropriate agronomic treatment tailored to local conditions. Continuous forest inventory was conducted at ages ranging from 4.88 to 5.89 years after planting, employing a sampling intensity of 1:10 (1 plot per 10 ha) in 59 plots of 648 m^2 with 54 trees measured. Tree height (Ht) and the diameter at breast height (DBH) were measured to estimate the wood volume.

Case Study II

The other case study is located in Coronel Xavier Chaves, state of Minas Gerais (21°00'44.75"S, 44°12'28.42"W; 931 m a.s.l.) in the Atlantic Forest biome. It represents a SPS system commonly adopted in dairy farms. The climate of the region is classified as Cwb (Köppen's classification), with two well-defined seasons (humid summer and dry winter). The mean annual precipitation is 1,413 mm and the mean annual temperature is 19.2°C.

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The experimental area consisted of 4.5 ha under a 7.5-year-old SPS, on a gently wavy relief, with slopes of up to 10%. The soil of the experimental area is an Oxisol, with a sandy-clay texture.

The silvopastoral system was composed of trees of the Urograndis hybrid of eucalyptus trees (*Eucalyptus urophylla* S. T. Blake x *Eucalyptus grandis* W. Hill ex Maiden) planted on an *Urochloa brizantha* cv. Marandu pasture. The eucalyptus was planted in strips composed of double rows of trees, with 3 meters between rows and 2 meters between trees. Eucalyptus strips were spaced 28 m, with a population density of 322 trees per hectare (Figure 2). Planting fertilization was carried out by applying 0.15 kg of 9-45-9 NPK per plant, plus two sidedress fertilizations per plant using 0.10 kg of 20-5-20 NPK per plant starting 3 months after planting.

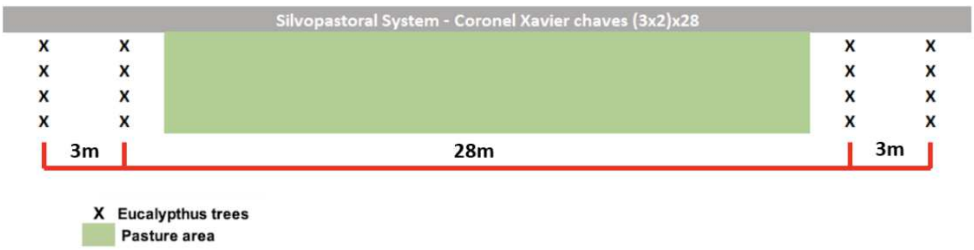

Figure 2. Representation of the silvopastoral system with strips of eucalyptus of 3 m width and of 28 m width for the pasture.

Forest inventory data came from 18 plots of 594 m^2 established, with two lines of nine trees, 3.0 m between rows, and 2.0 m between trees within rows. The plots were 18 m long, with 15 m within each pasture strip, randomly distributed on each row. Tree Ht and DBH were measured simultaneously for all trees inside the plots at 24, 30, 36, 42, 72, and 96 months after planting. Tree volume was calculated by using the volumetric equations developed by Aguiar Júnior *et. al.,* (2023).

Carbon accumulation

For CSI, it was considered a production cycle of 6 years for the purpose of pulp production, while the cycle for wood for the furniture industry in CSII was set to 12.5 years. In the case of CSII, age-dependent Chapman-Richards' model was used to accurately project the growth of eucalyptus trees (Campos and Leite, 2017) as the measured data were obtained from trees with 7.5 years. Accumulated wood biomass for both scenarios was obtained by the product of the measured or estimated wood volume (m^3 ha^{-1}) at cutting time by a wood density of 530 kg m^{-3}. A carbon content of 45% was considered to calculate wood C stock.

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Carbon permanence assessment

After each growth cycle, the C stored in the tree biomass is assumed to be removed when the tree is harvested, but C accumulation restarts with a new tree growth cycle. Therefore, the permanent C stock in a SPS is calculated as the average of accumulated C from the first to the last year of a tree growth cycle. For simplicity, the growth rate of the trees was assumed to be constant, so that C accumulation was linear. In addition to the C storage in trees in the field, the product from harvested wood at the end of every growth cycle also stores C until it is completely degraded to CO_2. The remaining C as a wood product (C_R), after a certain period (t) has elapsed can be represented by the semi-decomposition function: $C_R = C_O*\exp(-kt)$, where C_O is the C content in the wood product at time zero (the amount of harvested wood), and k is the decomposition constant to CO_2. For CSI, in which wood was transformed into paper, cardboard, or similar, the assumed half-life in nature is 2 years. Conversely, the half-life for CSII is 30 years due to the use of wood in furniture production (IPCC, 2013). As the half-life time ($t_{1/2}$) of a product is described by the equation $t_{1/2} = 0.692/k$, k is calculated as $k = 0.692/t_{1/2}$, or k for paper is 0.346 (yr^{-1}) and 0.023 (yr^{-1}) for furniture.

Descriptive statistics were presented to report CSI and CSII data. The exponential model of the type "rise to maximum" $f=a.[1-\exp(-b.t)]$ was fit to data to estimate the C stock at equilibrium when tree and product C pools were accounted for together.

Results

The CSI accumulated 68 Mg ha^{-1} of trunk biomass at an incrementing rate of 23 m^3 ha^{-1} yr^{-1} by the end of the first growth cycle. As such, the total C accumulated in harvested material was estimated at about 31 Mg C ha^{-1} (Table 1). Grass biomass supported a stocking rate of 0.75 AU ha^{-1} (1 AU = 450 kg live weight) on a whole area basis. In the CSII, the tree biomass was 84 Mg ha^{-1} with a stock of 38 Mg C ha^{-1} at 7.5 yr with a stocking rate of 2 AU ha^{-1}. Considering the projections provided by the Chapman-Richards growth model (Figure 3) for a 12.5 years cycle, the expected tree volume was 226.7 m^3 ha^{-1}, with a MAI of 18.1 m^3 ha^{-1} yr^{-1}, which is equivalent to an aboveground biomass (stem) of 119.8 Mg ha^{-1} and a carbon stock of 53.9 Mg C ha^{-1}.

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Table 1. Mean, standard error (SE), and coefficient of variation (CV%) for tree biomass, mean annual increment (MAI) and carbon content of eucalyptus trees, and cattle stocking rate (AU ha^{-1}) for the pasture area of Case studies I and II.

	Case Study I (trees at 6 yr)			
	MAI (m^3 ha^{-1} yr^{-1})	Biomass (Mg ha^{-1})	Carbon (Mg ha^{-1})	Stocking rate* (AU ha^{-1})
Mean	23.10	68.32	30.75	
SE	0.81	2.47	1.11	0.75
CV (%)	16.12 %	16.55 %	16.55 %	
Case Study II (projected data for trees at 12.5 yr)				
Mean	18.14	119.83	53.93	
SE	1.49	5.92	2.66	2.00
CV (%)	21.03	21.03 %	21.03 %	

*Estimated in function of animal unit (AU) in the SPS (whole area)

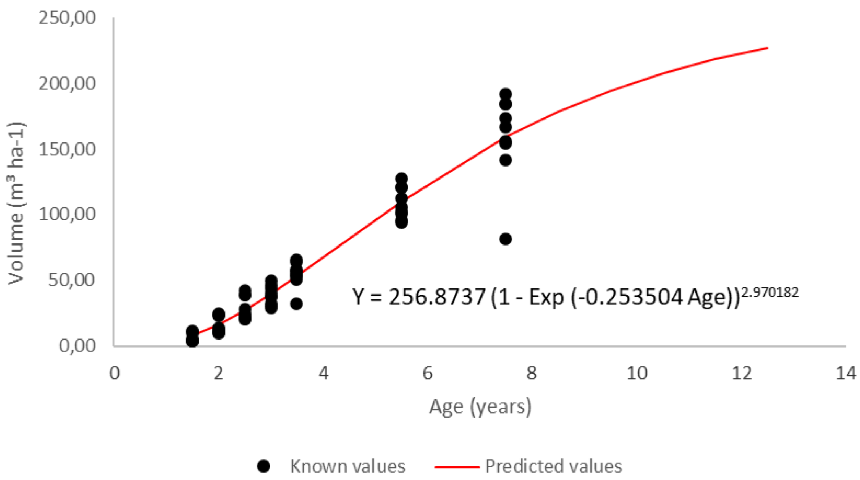

Figure 3. Chapman-Richards growth model to calculate the volume (m^3 ha^{-1}) for the CSII.

Assuming linear C accumulation by trees, for each year, the C stored in CSI accounts for 1/6 of the 30.8 Mg C ha^{-1} accumulated at harvest, while in CSII this value was 1/12.5 of 53.9 Mg C ha^{-1}. Therefore, the permanent C stock in the eucalyptus stand in CSI and CSII was estimated to be the quantity accumulated at the midpoint of the growth cycle, approximately 15 and 27 Mg C ha^{-1}, respectively (Figure 4).

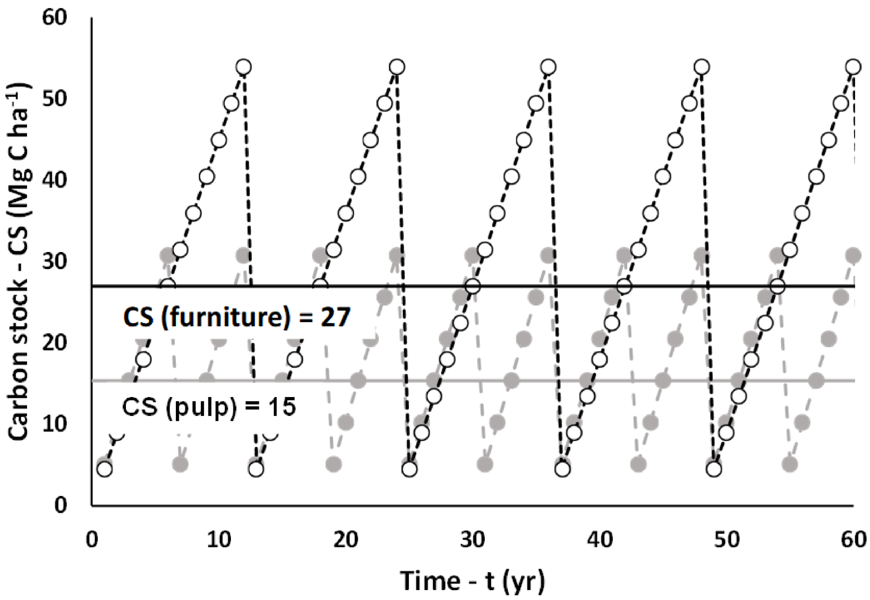

Figure 4. Carbon accumulation during each growth cycle for the eucalyptus tree stands in CSI (gray circles) and in CSII (hollow circles) and the respective permanent C stock (CS) is represented by full gray and black lines.

When considering the C stock immobilized by wood products as they remain in nature along with the C stock in trees growing in the field, this leads to a gradual C accumulation at decreasing rates (Figure 5). This accumulation tends towards an equilibrium point, or a permanent C stock, described as the time when the C amount in the harvested tree equals the amount of C in degrading products. The projected permanent C stock of 30 Mg ha^{-1} is estimated for CSI (Figure 5). When trees are harvested for furniture in CSII, the permanent C stock changes to 222 Mg ha^{-1}.

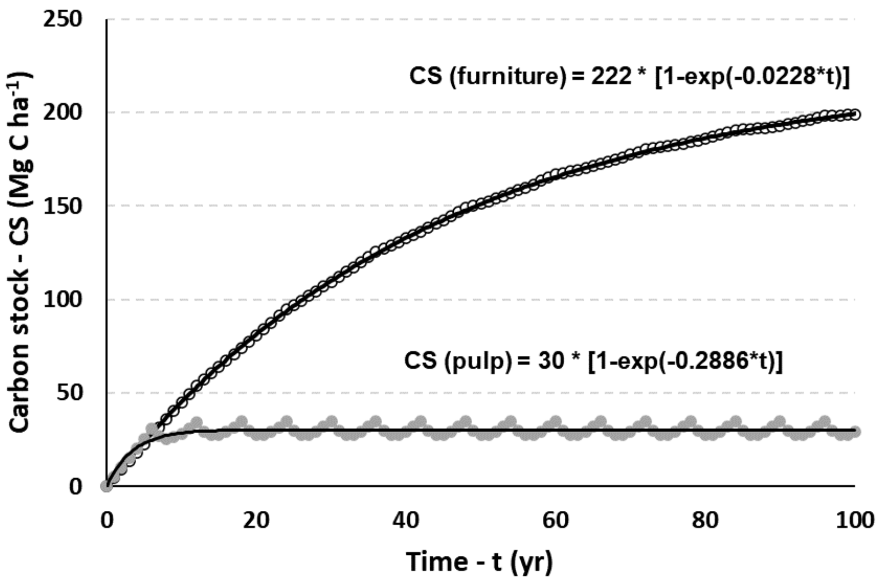

Figure 5. Modeling carbon permanence for the scenarios of pulp and furniture production. The black line represents the function f=a.[1-exp(-b.t)] fitted to the CSI data (gray circles), while the full black-line curve fitted to the CSII data (hollow circles).

Discussion

Introducing trees into agricultural systems offers an environmental benefit in terms of offsetting GHG emissions through the permanent C storage in their biomass. This would imply storing either 30.8 Mg C ha^{-1} accumulated in CSI or 53.9 Mg C ha^{-1} accumulated in CSII, assuming only the wood production phase after the first cycle. An extra 13% C should be added to each to account for the whole tree biomass (Vieira and Rodríguez-Soalleiro, 2019) and CSI and CSII would neutralize 21 and 18 Mg CO_2eq ha^{-1} yr^{-1}, respectively, which is enough to offset the GHG emissions from cattle, inputs and machinery operations, generally in the range of 3 to 7 MgCO_2eq ha^{-1} yr^{-1} (data from this study; Cardoso *et. al.,* 2016; Figueiredo *et. al.,* 2017). Thus, SPS could be considered neutral for some years (roughly 3 to 10 yr). However, after tree harvesting, GHG compensation ceases. Even if trees start to grow again, the new cycle will only reset the GHG compensation service of the previous cycle (Geng *et. al.,* 2017). Therefore, GHG offset is finite and can be estimated as the equivalent of half the C stocked in trees at the time of harvesting, as displayed in Figure 4. Tree planting density in CSI was 2.5 times that in CSII but permanent C stocks in the first were 1.8 times lower than that of CSII, suggesting that for fast-growing trees growth cycle is more determinant of GHG compensation potential than tree number.

In 2013, the released IPCC guidelines on methods for estimation, measurement, monitoring, and reporting of LULUCF activities introduced the concept of C permanence in wood products (IPCC, 2013) that extended the time C remains out of the atmosphere compensating GHG emissions. Also, the use of wood products generally requires less energy than the production of equivalent non-wood materials, avoiding emissions from fossil fuels (Kohl *et. al.,* 2020). When this concept was considered in CSI and CSII, the C stored initially in trees growing in the field and then in the produced wood processed for pulp or furniture is about two to eightfold the permanent C stock only in the field. Nonetheless, this process also enters equilibrium, which refers to the time when the production of wood equals product degradation. Thus, for the same tree species, the purpose of plantation and in consequence, the half-life of the wood product is much more determinant of the GHG compensation potential of a SPS than growth length or tree planting density (Morales *et. al.,* 2023).

The permanent C stock in CSI and CSII are comparable to areas undergoing forest restoration. Brancalion *et. al.,* (2021) estimated that passive and active restoration techniques resulted in aboveground C stocks of 70 Mg C ha^{-1} and 150 Mg C ha^{-1} after 50 to 60 yr, respectively. Similar stocks were also observed by Zanini *et. al.,* (2021) for the Atlantic Forest biome. This means that one hectare of SPS would provide similar or even higher C compensation than one hectare of restored humid tropical forest if the C stored in wood products is considered. Forest restoration areas also provide other externalities such as aquifer replenishment with water and biodiversity conservation (Chazdon, 2008; Chazdon *et. al.,* 2016). However, in the context of the climate emergency, it is important to highlight the potential of SPS to simultaneously produce timber, fiber, and food while sequestering atmospheric CO_2 (Palmer, 2021). Thus, it is urgent that the silviculture industry align its management to produce assortments that allow the greatest possible carbon offsets using wood and also integrate it with cattle rearing (Kohl *et. al.,* 2020; Chará *et. al.,* 2017).

Conclusions

This is a preliminary study where we bring the data of potential C capture and storage in trees composing SPS. Suitable SPS for the pulp industry requires a high number of trees per hectare to reach a reasonable degree of GHG compensation given the inherent need for a shorter growth cycle when using eucalyptus and the characteristically short half-life that pulp products present. When long-lived products are the purpose of wood harvested from SPS, a very high GHG emission compensation can be expected. For the latter, the potential for compensation may exceed that expected for the same area fully dedicated to active forest restoration. This demonstrates that SPS can be a powerful strategy for animal protein production while addressing the urgency in mitigating climate change.

We are collecting data to calculate the emissions of each system and then be able to do the balance of carbon of the systems, which will be added in the next steps of this study. With this data, it will be possible to check the compensation of GHG that the carbon stored in trees can provide to the system.

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