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Eucalyptus Carbon Stock Research in an Integrated Livestock-Forestry System in Brazil

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Abstract: Eucalyptus plantations play an important role in capturing and storing atmospheric carbon, mitigating global climate change. Forest management policies encouraging integrated livestock-forestry systems require quantitative estimates of temporal and spatial patterns of carbon storage for these agricultural systems. This study quantified the effects of eucalyptus management and arrangement on carbon stock dynamics in integrated livestock-forestry (ILF) systems versus monoculture eucalyptus plantings. Arrangement and management resulted in equal storage of carbon in both monoculture and ILF systems (34.7 kg per tree). Both factors are important to better understand how forest species in integrated systems stock carbon and how this can compensate for other agricultural system components, such as cattle. The extent to which ILF systems offset beef cattle (*Nellore*) emissions was determined by estimating changes in carbon stock over time for *Eucalyptus urophylla* × *E. grandis*, clone H13, under three scenarios (S) of wood use. These scenarios were (S1) tree growth without thinning, (S2) trees used for biomass energy without thinning, and (S3) 50% of trees used for biomass energy at five years old and 50% of trees used for both timber and energy after eight years, considering the full life cycle of eucalyptus. The S1 and S3 systems can stock 510 and 358 metric tons (t) of CO_2 ha^{-1}, respectively, while S2 emits 112 t CO_2 ha^{-1} of biogenic carbon.

Keywords: carbon mitigation; carbon sequestration; carbon storage; climate change

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1. Introduction

Planted forestry species are cultivated in forest-like ecosystems established by planting and/or seeding during the process of afforestation and reforestation [1,2]. Such agroforestry mainly occurs for wood biomass production [3]. These agro-ecosystems can contribute to global climate change mitigation since trees are natural carbon sinks. Trees absorb carbon dioxide from the air to grow, and the carbon is stored in their trunks, leaves, branches, and roots [4]. On average, carbon makes up half of a tree's dry weight [5], so the more a tree grows, the more carbon it can store.

Brazil has robust technical knowledge and successful experience with planted agroforestry, which can sustain year-round productivity [6]. The country is also investing in technology to improve integrated agricultural systems that can have four possible combinations: (1) integrated crop-livestock (ICL), also known as an agro-pastoral system; (2) integrated crop-forestry (ICF), or an agroforestry system; (3) integrated livestock-forestry (ILF), known as a silvo-pastoral system; and finally, (4) integrated crop-livestock-forestry (ICLF), or an agro-silvo-pastoral system [7]. The adoption of these four types of integrated systems was estimated to grow by 52% from 2016 to 2021, reaching an area of 17.43 million hectares [8]. However, despite much applied research on these types of integrated agricultural systems, the adoption of integrated systems with trees is estimated at only 16% of cattle ranchers and only 1% of soybean and second-crop (*safrinha*) corn producers [9], mainly because of poor knowledge regarding the forest management required for this type of system. Similarly, a 2012–2013 survey of agricultural producers in Mato Grosso state, Brazil, found only 11% of producers used integrated systems with agroforestry components (1% ICF, 5% ILF, and 5% ICLF) [8].

During the United Nations' COP26 climate conference in Scotland in 2021, the Brazilian government presented new targets for reducing greenhouse gas emissions by 50% by 2030 and being completely carbon neutral in terms of emissions by 2050. For the agricultural sector, the Sector Plan for Adaptation and Low Carbon Emissions in Agriculture (ABC+ Plan) was launched in 2020. The ABC+ Plan aims to reduce 37.9 million metric tons of equivalent carbon emissions by 2030, only for ICLF [10]. The goal of this plan is to expand Brazil's ICLF to 10 million hectares by 2030. About 8.35%, or 17.43 million hectares, of Brazil's agricultural land area was involved in some type of integrated crop-livestock-forestry system in 2020–2021, which includes ICLF in addition to ICF and ILF [11].

It is well known that planted forestry species in agroforestry systems and in monoculture have great differences in carbon stock and tree density depending on the type of system. This presents a couple of research questions. While different agroforestry systems can have different carbon stocks in their trees, can the carbon stock change due to interaction dynamics resulting from different planting arrangements and environmental conditions? How does carbon stock work in integrated crop-livestock-forestry systems, such as integrated livestock-forestry? In monoculture, tree growth dynamics are determined by competition from neighboring trees. This generally involves competition above ground for sunlight and below ground for nutrients and water [12]. In integrated systems, the crops and livestock components promote interactions that vary in time and space [7,13]. The positive or negative interactions involve above-ground sunlight access, below-ground nutrients, and water from the soil, which can vary based on the age of the system components [14]. Finally, what can change the carbon allocation pattern of trees in such integrated agricultural systems?

The goal of this research was to measure carbon stock over time for both monoculture and integrated livestock-forestry (ILF) systems. The first research hypothesis is that there is no difference in total carbon stock between monoculture and ILF systems. However, the second hypothesis posits that there may be differences in carbon stock allocation across different above-ground parts of trees. This is potentially due to a greater availability of light, water, and nutrients, which can result in a disproportional distribution of biomass allocation in some specific tree compartments (i.e., components) as well as differences in tree architecture [15]. The third research hypothesis is that the integrated livestock-forestry system offsets carbon emissions from cattle. To test these hypotheses, ILF versus eucalyptus monoculture systems were compared in terms of carbon emissions versus carbon storage over time. Changes to carbon emissions and storage were calculated for three stages: two, four, and eight years after planting trees. Carbon stock was measured for three types of uses for trees. These uses were tree growth for all three stages, using trees just for energy after four years, and using trees for both timber and energy after eight years.

2. Materials and Methods

2.1. Study Area

Eucalyptus (*Eucalyptus urophylla* × *E. grandis*, clone H13) seedlings were planted both in monoculture (F) and in an integrated livestock-forestry (ILF) system at the experimental field of Embrapa Agrosilvopastoral in Sinop, Mato Grosso state, Brazil (11°51′ S, 55°35′ W) at an elevation of 370 m during November 2011. The climate at the experimental site is classified as tropical continental (Aw) according to the Köppen-Geiger climate classification system, with distinct wet and dry seasons [16]. The annual average temperature is 25.6 °C, and the annual average rainfall is 1974 mm (mm) for 1971 to 2010, which falls primarily during the wet seasons from October to March. The climate is characterized by a dry period extending from April/May to September, with an annual water deficit of 284 mm [17].

The soil at the experimental site at Embrapa Agrosilvopastoral is classified as a clay Hapludox [18]. The soil texture is clayey, with soil particle percentages for sand at 28%, silt at 16%, and clay making up the majority at 56%. The soil chemical characteristics in the 0 to 20 cm layer have been measured with pH in water (1:2.5) equal to 5.7 and organic carbon at 17.1 grams (g) kilograms $(kg)^{-1}$. The soil's content of phosphorus (P-Mehlich) is 13.7 milligrams dm^{-3} with exchanges for potassium (K) at 2.0 mmol dm^{-3}, calcium (Ca) at 23 mmol dm^{-3}, and magnesium (Mg) at 6.6 mmol dm^{-3} [19]. Soil chemical analysis (Table 1) did not show significant differences between the monoculture (F) compared to the integrated livestock-forestry (ILF) treatments [20]. This reflects the soil's agricultural history, which maintained the critical level of quality required for eucalyptus production during the implementation of the experiment.

Table 1. Soil characteristics for eucalyptus in monoculture (F) and in an integrated livestock-forestry (ILF) system.

System/Parameters [1]	pH	P	K	Ca	Mg	Al	H + Al	CEC	SB	V
		mg dm^{-3}				$cmol_c dm^{-3}$				%
Monoculture (F)	5.17 (±0.17)	6.78 (±1.09)	15.8 (±5.05)	1.68 (±0.39)	0.66 (±0.11)	0.00 (±0.00)	5.7 (±0.76)	8.07 (±0.57)	2.38 (±0.45)	29.86 (±6.15)
Integrated Livestock-Forestry (ILF-*Eucalyptus*)	5.15 (±0.22)	3.99 (±1.13)	16.97 (± 4.75)	2.21 (± 0.74)	0.63 (±0.11)	0.00 (±0.00)	4.84 (±1.03)	7.72 (±1.40)	2.88 (±0.77)	37.61 (±7.69)

[1] Values in parentheses are the standard errors.

The eucalyptus plantations were fertilized with 350 kg per hectare (ha) of single superphosphate in the planting groove. After 30 days, 100 g of the three major plant macronutrients, nitrogen, phosphorus, and potassium (NPK), were added with an analysis of 20% N, 0% P, and 20% K (20-0-20). In the integrated system, the livestock area was fertilized with 55 kg ha^{-1} of nitrogen and potassium as K_2O and 60 kg ha^{-1} of phosphorus as P_2O_5 during March 2015, using urea, potassium chloride, and single superphosphate, respectively. In addition, during December 2015, 36 kg ha^{-1} of P_2O_5, 50 kg ha^{-1} of N, and 50 kg ha^{-1} of K_2O were added [19]. Cattle (*Nellore*) were introduced in February 2015 and remained in the area until the pasture canopy was uniformed.

The monoculture eucalyptus (F) treatments were planted in plots that were 1 ha in area, spaced at 3.5 m × 3 m, for a density of 952 trees per ha, which involved a thinning of ~50% of seedlings in 2016. The integrated livestock-forestry system (ILF) was planted in triple rows oriented east-west. Triple rows were planted 30 m apart, with each tree taking up an area of 3.5 m × 3 m = 10.5 m^2, which translates to a density of 270 trees per ha. In 2016, there was a thinning of trees to ~50%, with each tree taking up an area of 3.5 m × 6 m = 21 m^2.

The experimental design for evaluating our system was carried out in plots with an area of 2 ha per plot, which is considered to be enough area to raise the livestock necessary for the animal component of the ILF system. The experimental plots were organized into four randomized blocks, and the data in these four replicates were collected during 2013, 2015, and 2019. In the ILF experimental plots, three medium trees were sampled per block according to sun exposition: north (N), central (C), and south (S). The trees were sampled in the central row for ILF. In the monoculture control (F), one tree per block in the middle of each treatment was sampled for better data homogeneity. In 2018, one of the replicates of the monoculture treatment was accidentally burned, resulting in three replicates instead of four.

The sampling of trees was determined by the confidence interval of the average of the tree diameters. In order to do this, the breast height (DBH) was obtained based on the continuous forest inventory carried out annually in permanent plots of 81 plants (planted in an area of 850.5 m^2) that are distributed systematically throughout the experiment. The canopy biomass was estimated in separate compartments (components), namely leaves, dead branches, fresh branches, and the tree trunk (Figure 1). The sampled components were dried in an oven at 60 °C to obtain the dry mass for carbon analysis, which was performed using the CHN elemental analyzer (Vario Macro, Elementar Analyser System, Hanau, Alemanha). The carbon stocks were analyzed within trees in the integrated system based on sun exposure (S, C, and N) and between trees in the systems (F and ILF).

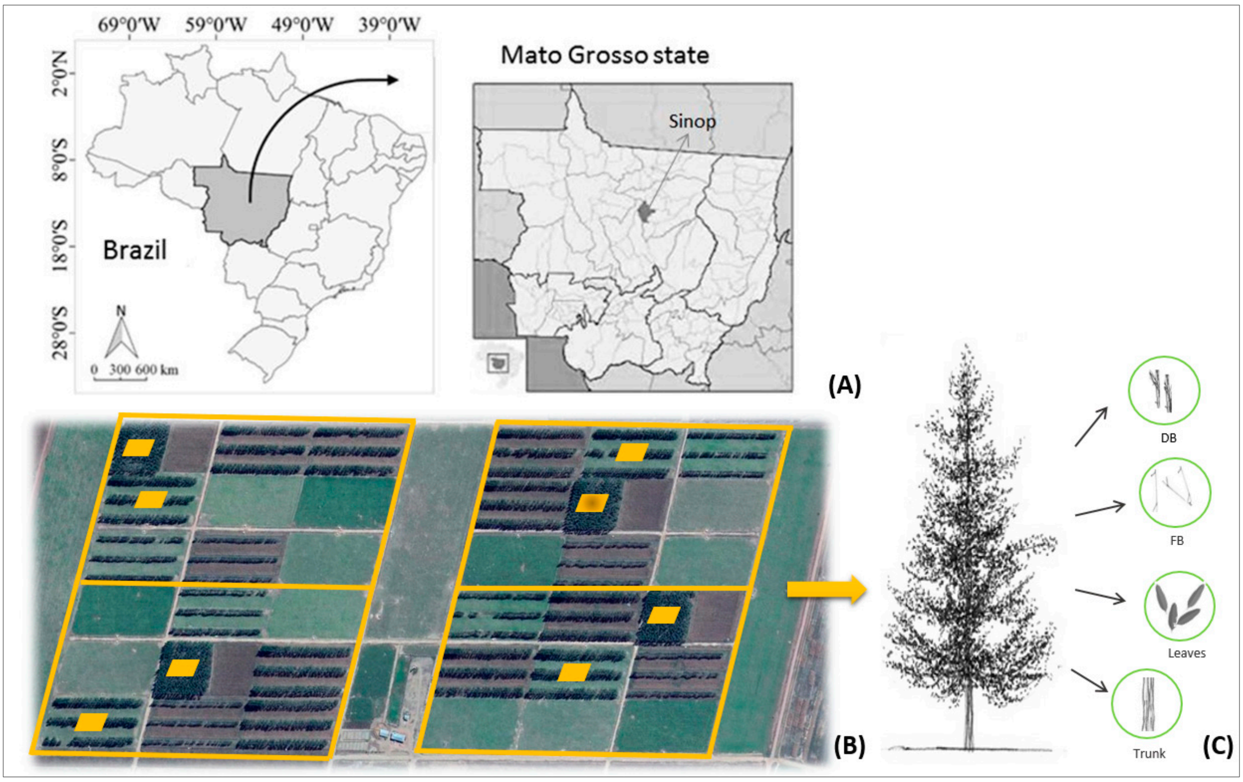


Figure 1. (**A**) Experimental area, (**B**) experimental design, and (**C**) sample collection scheme, where DB = dead branches and FB = fresh branches. Sources: (**A**) Cornélio Alberto Zolin and (**B**) Gabriel Rezend Faria.

The percentage of wood used as roundwood (i.e., tree timber that has not been squared by sawing or hewing) for sawmills, poles, and moors, as well as for biomass energy, was obtained through market research. This was estimated by adjusting the tapering function specified in the equation:

$$d_i/DBH = b_o + b_1 h_i/h + b_2(h_i/h)^2 + b_3(h_i/h)^3 + b_4(h_i/h)^4 + b_5(h_i/h)^5 \quad (1)$$

In this case, the fifth-degree polynomial was used, which allowed estimating the volume of forest assortments as shown in this equation:

$$V = \frac{\pi}{40000}\int_{h1}^{h2}\left(b_o + b_1 h_i/h + b_2(h_i/h)^2 + b_3(h_i/h)^3 + b_4(h_i/h)^4 + b_5(h_i/h)^5\right)^2 dh \quad (2)$$

where d_i is the diameter in position i (cm), DBH is the diameter taken at 1.3 m from the soil (cm), h_i is the height in position i (m), h is the total height (m), and b_j represents model parameters [21].

Usable wood is optimized for logs with the longest length and the highest commercial value, with the remaining logs classified in lower quality classes, typically with shorter lengths. The part of the log shaft with a diameter of less than 11 cm up to the limit of 5 cm was used for firewood sawed to 1 m in length. The number and volumes of wood pieces used for roundwood, firewood, etc. were entered into an electronic spreadsheet in Excel.

2.2. Carbon Dioxide Equivalent Stocks in Three Scenarios

Differences in carbon stock were measured in metric tons (t) per hectare (ha) (t ha^{-1}) between eucalyptus monoculture (F) and integrated livestock-forestry (ILF) treatments. Once this difference is proportional to the tree density in each system, it is possible to better understand carbon behavior. This was accomplished by showing the amount of carbon stock, in t CO_2 ha^{-1}, over the eight years of the experiment across the three scenarios diagramed in Figure 2.

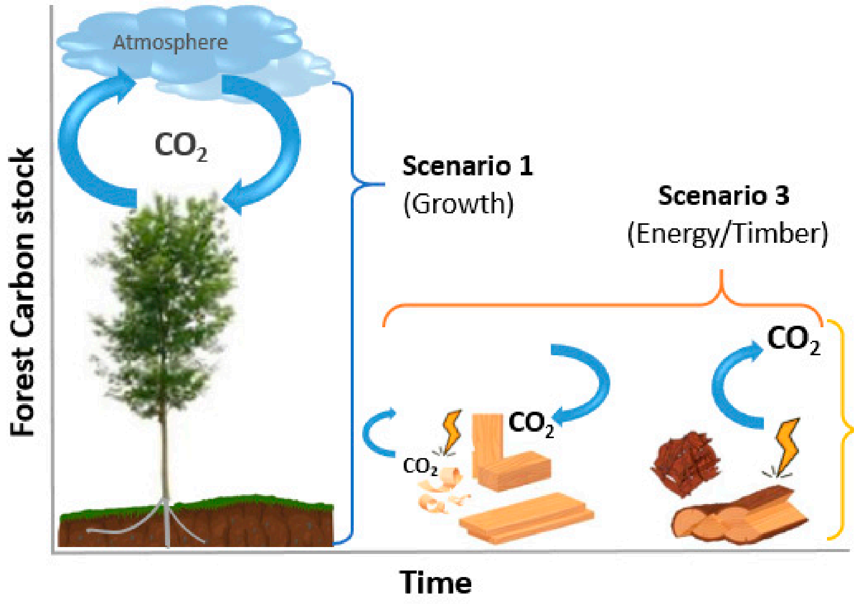


Figure 2. Three scenarios for monoculture eucalyptus (F) and integrated livestock-forestry (ILF) systems: (1) Scenario 1 of forest growth without thinning; (2) Scenario 2 of using trees for energy purposes without thinning; and (3) Scenario 3 where trees are used for both energy and timber. Scenario 2 assumes 100% of trees are used for energy. Scenario 3 harvests 50% of trees after five years for energy and then harvests the remaining 50% of trees for both timber and energy (residues) after eight years of age.

Eucalyptus plantings for energy and round-wood log use were calculated assuming 50% of the trees were used for energy after carrying out a thinning at five years of age in 2016. The remaining 50% of trees were used for timber and energy after eight years in 2019. The scenarios used in our study reflect the current forest management regime with the objective of producing wood for energy, sawmills, and roundwood logs for poles and posts. In Brazil, the eucalyptus cycle depends on the climate and soil conditions of the property. Eucalyptus trees have to be between 6 and 8 years old for the production of firewood, charcoal, wooden posts, and cellulose. In order to produce trees big enough to be cut for roundwood, eucalyptus trees have to be 12 years old [22].

2.2.1. Scenario 1

Scenario 1 involved forest growth without thinning, where tree CO_2 stock was calculated for both F and ILP systems based on the following equation:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,BAG} + CO_{2\,Root} \tag{3}$$

where $CO_{2\,BAG}$ (t CO_2 ha^{-1}) is equal to the biomass above ground (t) multiplied by the carbon biomass above ground (%) multiplied by 3.67 multiplied by the number of trees ha^{-1}. This is equal to MW CO_2 (g mol^{-1})/MW carbon (g mol^{-1}). The $CO_{2\,Root}$ (t CO_2 ha^{-1}) is equal to $CO_{2\,BAG}$ (t CO_2 ha^{-1}) multiplied by 13.5%. The 13.5% is equal to the root biomass multiplied by 100 and divided by the total biomass, using all eight years of data [22].

The integrated livestock-forestry system (ILF) for Scenario 1 differed in calculating CO_2 stock by using the following equation:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,BAG} + CO_{2\,Root} - CO_{2\,Beef\ production} \quad (4)$$

where $CO_{2\,BAG}$ ($t\ CO_2\ ha^{-1}$) and $CO_{2\,Root}$ ($t\ CO_2\ ha^{-1}$) are calculated similarly to Equation (3) above. The CO_2 from beef production ($t\ CO_2\ ha^{-1}$) equals the system time (years) multiplied by [2.5 livestock units (LU) ha^{-1} × (1993 t CO_2 $herd^{-1}$/962 head $herd^{-1}$ yr^{-1})]/[(368.6 kg $head^{-1}$/450 kg LU^{-1})]. A livestock unit, or LU, equals 450 kg. So 2.5 LU ha^{-1} (2500 kg ha^{-1}) is the average for beef cattle in the livestock-forestry (LF) system, according to Carvalho et al. (2019) [23]. The assumptions of 1993 t CO_2 $herd^{-1}$, 962 head $herd^{-1}$ yr^{-1}, and 368.6 kg $head^{-1}$, which was the weighted average for the beef cattle herd, were obtained from the fourth scenario evaluated by Cardoso et al. (2016) [24].

2.2.2. Scenario 2

The second scenario evaluated used trees for energy, with the clearcutting of trees at 8 years of age. Similar to Scenario 1, Scenario 2 calculated carbon stocks for both eucalyptus monoculture (F) and ILF until 2015. The carbon stock for F was calculated using the following equation:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,BAG} + CO_{2\,Root} - CO_{2\,Energy} \quad (5)$$

where $CO_{2\,Energy}$ ($t\ CO_2\ ha^{-1}$) equals 1.4 t CO_2 t^{-1} multiplied by the mass of the tree trunk (also measured in t) multiplied by the number of trees ha^{-1}. The 1.4 t CO_2 t^{-1} is an emission factor from wood [25,26]. The integrated livestock-forestry system (ILF) differed in calculating CO_2 stock by using the following equation, which involved subtracting the carbon dioxide released from beef production:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,BAG} + CO_{2\,Root} - CO_{2\,Beef\ production} - CO_{2\,Energy} \quad (6)$$

2.2.3. Scenario 3

The third scenario evaluated used trees for both roundwood and energy (e.g., firewood) at four years of age in 2015 and eight years of age in 2019. Carbon stock for F was calculated using the following equation at four years of age:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,Growth} + CO_{2\,BAG} + CO_{2\,Roundwood} - CO_{2\,Energy} \quad (7)$$

where CO_2 sequestered in the form of roundwood equals the mass of carbon in tree trunks (t CO_2) multiplied by the percentage of the tree trunk volume used for roundwood multiplied by the number of trees per ha. The CO_2 Energy component equals the mass of carbon stock in tree trunks multiplied by the percentage trunk volume used for energy purposes (t CO_2) multiplied by the number of trees per ha. The percentages of tree trunk volume used for both roundwood and energy purposes were calculated by the SisILPF Eucalipto software [27].

For the integrated livestock-forestry (ILF) system, the calculation for the carbon stock for four-year-old trees was specified as:

$$CO_{2\,Stock}\ (t\ CO_2\ ha^{-1}) = CO_{2\,BAG} + CO_{2\,Root} + CO_{2\,Roundwood} - CO_{2\,Beef\ production} - CO_{2\,Energy} \quad (8)$$

where $CO_{2\,Roundwood}$ equals the mass of carbon in tree trunks (t CO_2) multiplied by the percentage of tree trunk volume used for roundwood purposes multiplied by the number of trees per ha. $CO_{2\,Energy}$ equals the mass of carbon stock in tree trunks (t CO_2) multiplied by the percentage of tree trunk volume used for energy purposes multiplied by the number of trees per ha.

2.3. Statistical Analyses

To compare carbon stock in trees in the integrated system versus trees in eucalyptus monoculture, a one-way Welch's ANOVA was performed, followed by the Games-Howell post-hoc test for multiple comparisons. These tests were conducted once the homogeneity of variance was not found using Levene's test. The heterogeneity, probably caused by the thinning of trees, resulted in the year 2019 having this characteristic. Statistical analyses were performed using Jamovi from Jamovi Statistics for Windows, Version 2.2 [28].

3. Results and Discussion

3.1. Carbon Stocks in Trees in Monoculture and Livestock-Forestry Integrated Systems

The carbon stock was the same for trees in the integrated livestock-forestry system compared to the eucalyptus monoculture, with both systems averaging 34.7 kg of carbon per tree, which supports our first hypothesis. In other words, the trees' interaction dynamics with other system components, planting arrangements, and environmental conditions did not affect individual carbon stocks (Figure 3A). As expected, the trees' carbon stock increased over the years in both systems (F = 246, $p < 0.001$) at an average rate of 18.6 kg of carbon per year.

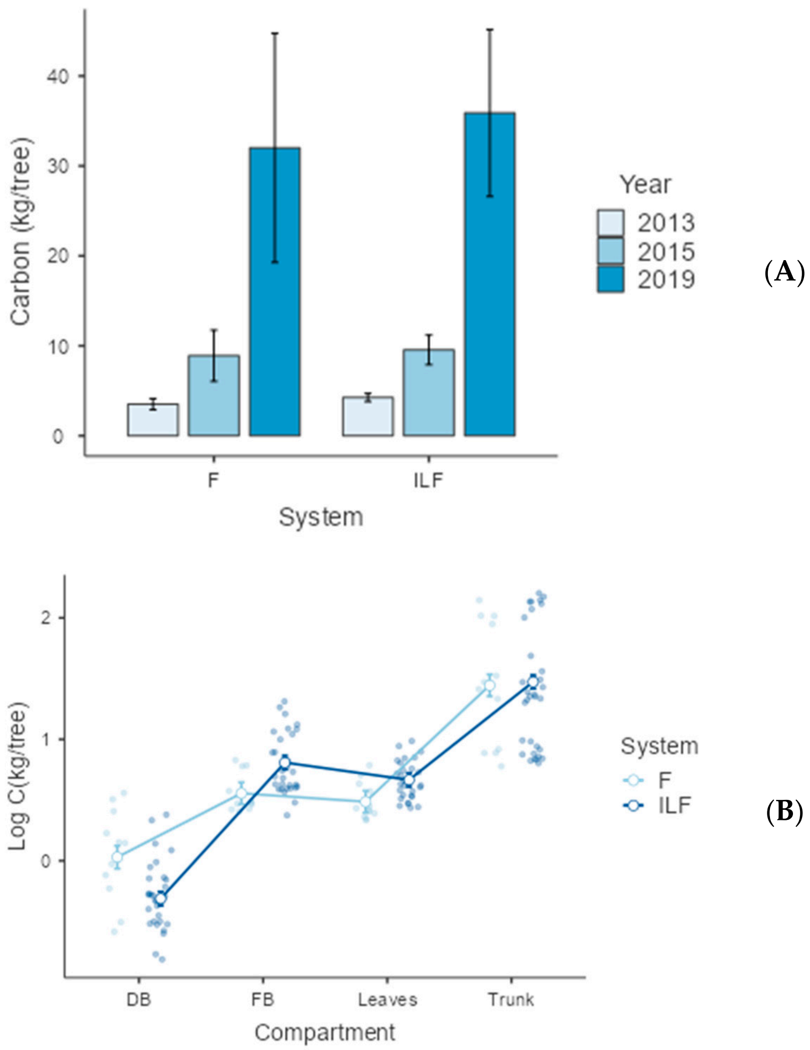


Figure 3. Carbon stock dynamics of eucalyptus in monoculture (F) and integrated livestock-forestry (ILF) over eight years for (**A**) total biomass, kg tree^{-1} (bar plots represent standard deviation) and for (**B**) dead branches (DB), fresh branches (FB), leaves, and trunk (kg tree^{-1}) in log scale (bar plots represent confidence interval).

Since trees in the systems that were evaluated in this study were used or harvested by eight years of age, it was not possible to estimate the maximum carbon stock changes over longer periods of time over a tree's natural lifespan. Eucalyptus trees typically have their maximum carbon accumulation at around 30 years of age. For instance, *E. grandis* and *E. pilularis* attained maximum aboveground accumulated biomass at 27 years of age (394 t ha^{-1}) and 33 years of age (270 t ha^{-1}), respectively; however, the maximum annual accumulation rate was at 5 years (16.4 t ha^{-1} yr^{-1}) and 7 years (15.7 t ha^{-1} yr^{-1}), respectively [29]. Up to 5 years is generally recommended as the time required to establish eucalyptus trees in the rotation for ILF systems, especially when the forest component involves intensive management practices and genetic improvement of the tree species used [30].

In Brazil, the recommendation for harvesting eucalyptus for multiple economic uses involves the thinning of approximately 40% of trees between 5 and 8 years after planting. The trees that are thinned can be sold for roundwood as well as for firewood, which can help cover initial planting costs that have been amortized as well as annual maintenance expenses. Farmers can keep forest stands for longer periods of time to produce timber, which can consequently stock more carbon [31]. While our study did not evaluate carbon accumulation for time periods longer than 8 years, carbon sequestration over longer time frames has been documented. For example, many trees can serve as carbon sinks for ~200 years. In the Pacific Northwest USA, the total biomass of trees increased with age until reaching a maximum at around 30 to 40 years old, and after this time, there was a gradual, incremental decrease [32].

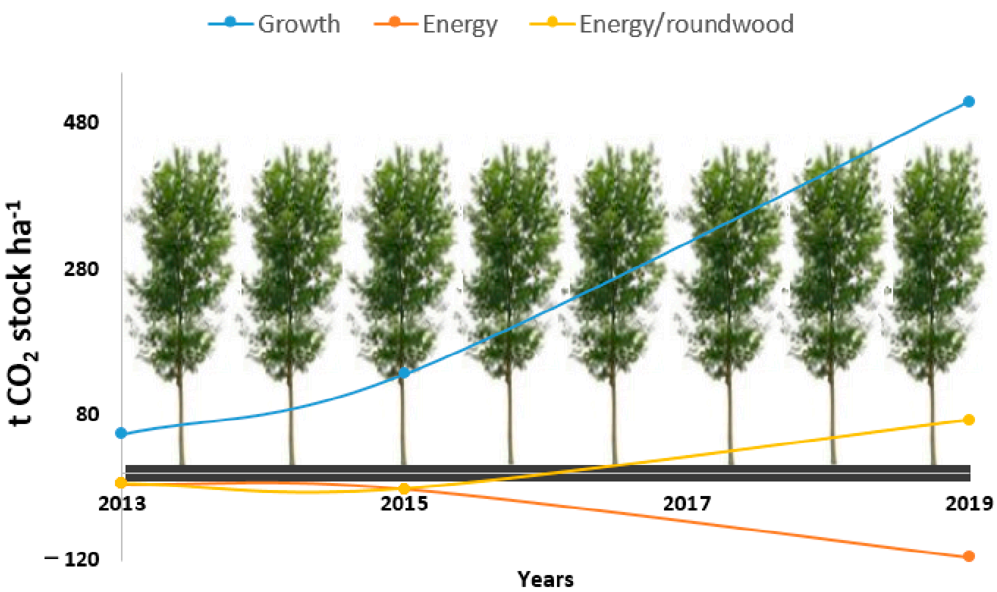
Although the trees in both systems produced the same amount of total biomass, the trees in eucalyptus monoculture (F) tend to produce more dead branches (DB) over time. The integrated system tends to produce more fresh branches (FB) (Figure 3B). The carbon distribution for F is 9.6% DB, 6.3% FB, 5.3% leaves, and 78.8% for the trunks of trees. For the ILF system, the distribution of carbon is 1.2% DB and 12% FB, 7.8% leaves, and 79% for the trunks of trees. Supporting the second hypothesis of this study, this can be attributed to the gaps between rows of trees in integrated systems, which create a considerable amount of edge that can impact the availability of natural resources [33]. This can cause abrupt micro-climatic changes, such as those related to sun light incidence, wind, and other resources, when compared to the interior of forests [34].

Continued exposure to these conditions could result in different growth rates and changes in tree morphology and size [35]. For example, the trees in the integrated ILF system are shorter and more robust than the trees in monoculture because the spacing between trees in the ILF system promotes less competition among trees for available sunlight, water, and nutrients [15]. Another result supporting this effect was observed during the production of logs for sawmills and poles, posts, and poles used for construction. For monoculture, the percentage production of logs over the total volume produced was 0% and 29.5% at 5 and 8 years, respectively, while for ILF this was higher at 19% and 43.9%.

3.2. Three Scenarios for Carbon Dioxide Equivalent Stock in Eucalyptus Monoculture

The monoculture eucalyptus plantings by themselves can stock 63.75 t CO_2 ha^{-1} yr^{-1} over the eight years of stand life (Figure 4). This carbon stock potential could be attractive to help mitigate climate change by storing excess global anthropocentric CO_2 emissions. This could also create new market opportunities for exchanges in carbon credit markets (Scenario 1: *Eucalyptus urophylla* growth over 8 years).

The planted eucalyptus tree species currently have well-defined commercial purposes as sources of industrial-grade timber, round-wood poles, pulpwood for papermaking, and fuel in the form of firewood and charcoal. If trees are used for energy purposes, this represents 14.4 t CO_2 ha^{-1} yr^{-1} of emissions as outlined for Scenario 2 (Figure 4). Meanwhile, the burning of wood for energy is often based on the assumption that the same amount of carbon absorbed during photosynthesis (i.e., biogenic carbon) is released to the atmosphere at the end of the tree's life cycle, with no real net carbon emissions.



Year	Scenario 1 (Growth)	Scenario 2 (Energy)	Scenario 3 (Energy/roundwood)
		$t\ CO_2$ stock ha^{-1}	
2013	54	33	−14
2015	136	99	−21
2019	510	−115	73

Figure 4. Carbon dioxide equivalent stock (t CO_2 ha^{-1}) in monoculture (F) over eight years for three scenarios. Scenario 1 is forest growth without thinning. Scenario 2 uses trees without thinning for energy purposes. Scenario 3 is where 50% of trees are used for energy and 50% of trees are used for both energy and roundwood.

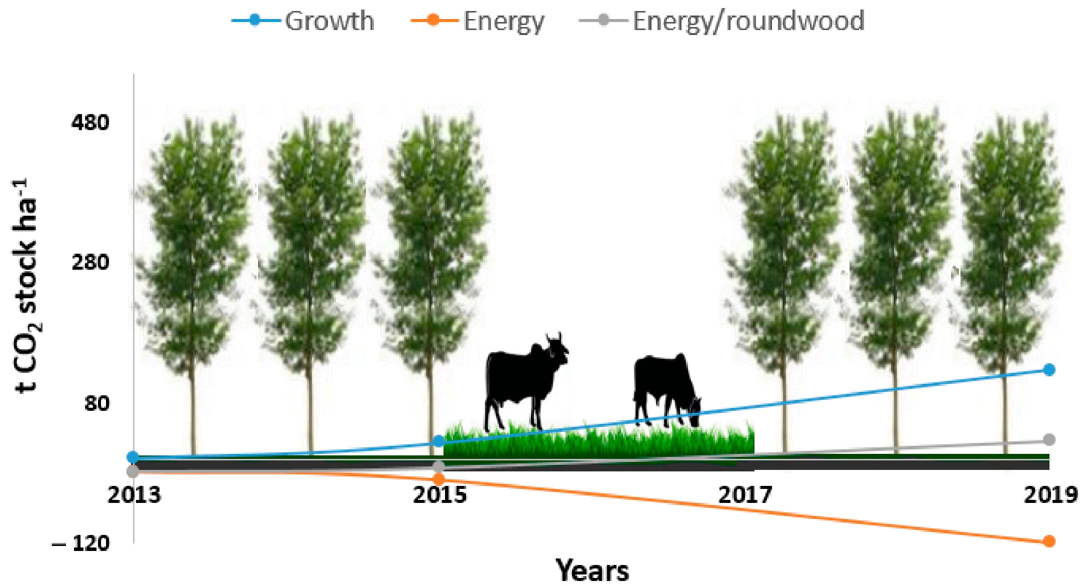
The potential impact of biogenic carbon emissions should not be ignored as a short-term source of greenhouse gas emissions. Biogenic carbon emissions are not insignificant, so this type of emission cannot be excluded during forest life cycle assessment. The exclusion of biogenic carbon emissions could lead to inappropriate comparisons and support inadequate public policy decisions regarding carbon storage [36]. Similar adjustments may have to be made regarding value-added products made from forest timber, such as houses, fence posts, etc. The wood from these structures eventually degrades, releasing CO_2 that was originally stored by the trees used to make them [37].

As mentioned earlier, harvested biomass can also be used as industrial-grade roundwood, where the carbon stored has a longer life cycle. However, in addition to roundwood, parts of the eucalyptus planting, namely the wood residues, are used for energy. Thus, the amounts of carbon stock from bioenergy and from forest products are determined endogenously by the yield level of both, stocking 9.1 t CO_2 ha^{-1} yr^{-1} for Scenario 3 (Figure 4).

3.3. Three Scenarios for Carbon Dioxide Equivalent Stock in an Integrated System

Supporting the third research hypothesis of this study, the forest in the integrated livestock-forestry system (ILF) can mitigate cattle emissions over the 8-year lifetime of the agroforestry planting. In Scenario 1, the trees stock carbon and also provide shade in the ILF system, which can increase the thermal comfort of animals relative to un-shaded open pasture [38]. For the ILF system in Scenario 1, the carbon stock can be 16.1 t CO_2 ha^{-1} yr^{-1} (Figure 5), which is equivalent to 25% of the carbon stored in the eucalyptus monoculture

(F) system. This use is attractive since animal heat stress can cause a drop in livestock production [39] as well as milk quality [40].



Year	Scenario 1 (Growth)	Scenario 2 (Energy)	Scenario 3 (Energy/roundwood)
	-------------------	t CO_2 stock ha^{-1}	-------------------------
2013	3	−10	−16
2015	25	5	−11
2019	129	−117	28

Figure 5. Carbon dioxide equivalent stock (t CO_2 ha^{-1}) in the integrated livestock-forestry (ILF) system from 2013, 2015, and 2019, for three scenarios. Scenario 1 is tree growth without thinning. Scenario 2 uses 50% of the trees without thinning for energy. Scenario 3 uses 50% of trees for energy and 50% for both energy and roundwood.

However, as beneficial as it is to keep trees in agricultural systems to benefit cattle production, it is critical for producers to have available markets for forest products. At some point, the producer will need to use the trees in the ILF system to generate income. If the region where the farmer is located has attractive markets for energy generation, such as in Scenario 2, the carbon storage from trees will not be able to offset CO_2 equivalent emissions from cattle with an average emission of 8.1 t CO_2 ha^{-1} yr^{-1} (Figure 5). Even though the burning of biomass emits biogenic carbon and that bioenergy operates within the carbon stock system, the forest component of the ILF systems is not able to neutralize carbon emissions from the animals in Scenario 2 (Figure 5).

In the scenario where agricultural producers are located in a region where the wood can be sold for roundwood timber and there is greater added value than for energy purposes, carbon stock can be more favorable than for just energy alone. In Scenario 3, the forest has the capacity to mitigate the action of animals by storing an average of 3.5 t CO_2 ha^{-1} yr^{-1}. However, this is only starting during the eighth year (Figure 5). It is worth mentioning that in this scenario, part of the wood that cannot be used by sawmills can be used to generate energy. This still maintains the neutrality of carbon emissions. This scenario corroborates the concept of "carbon neutral meat," which aims to promote the implementation of more sustainable livestock production systems, especially regarding environmental aspects. The introduction of the tree component into these agricultural systems can neutralize the methane emitted by the beef cattle herd, which can add value to the meat produced in these systems [41].

In 2020, an animal protein company and the Brazilian Agricultural Research Corporation (Embrapa) announced the Viva brand, a new meat line with sustainability attributes. Viva line products come from animals in an integrated livestock-forestry (ILF) production system, which neutralizes methane emissions from beef cattle. Viva products are also marketed with guarantees on enhancing animal welfare within the ILF production system, according to a protocol developed by Embrapa [41].

Despite carbon storage and other environmental benefits, ILF systems have been more challenging to adopt due to Brazilian agricultural producers having to diversify their systems into agroforestry, an unfamiliar enterprise for many crop and livestock producers. Therefore, it has been estimated that only half of agricultural producers in Mato Grosso state would adopt integrated crop-livestock-agroforestry systems [42]. Unlike other sustainable agricultural areas in the western hemisphere where diversification has had more historical precedence [43], integrating forest species into Brazil's crop and livestock systems has had only more recent public policy support [44].

3.4. Comparisons and Contrasts to Previous Studies

The range of carbon stocks per tree that was estimated over all experimental treatments (Figure 3A) was consistent with previous research. Silva et al. (2015) measured carbon stocks for 2.3- to 8-year-old trees of *Eucalyptus* spp., which averaged 38.98 kg per tree in the Paraíba Paulista Valley in São Paulo state, Brazil [45]. Although São Paulo state is in the Atlantic Forest (Mata Atlântica) biome, these results were similar to those of this study, which was conducted in Sinop, Mato Grosso state, Brazil, which is located in the transition zone between the Cerrado savannah and the Amazon biomes.

After eight years, the monoculture eucalyptus system in this study stocked 510 t CO_2 per hectare (ha) due to just tree growth. Assuming half the carbon stocked at four years versus eight years, this translates to 510 $\times$ (4 years/8 years) = 255 t CO_2 ha^{-1}. This is similar to the carbon stocks for Eucalyptus spp. timber ~265 t CO_2/ha after four years in southwestern Punjab, India, in 2020 [46]. However, carbon storage changes over time are typically not linear, especially after thinning. The carbon stock results from this study were higher than those for *Eucalyptus grandis* plantations in grasslands in Sri Lanka, which stocked ~73.4 to 110.1 t CO_2 ha^{-1} after ten years [47].

Using wood for energy reduced carbon stocks for eucalyptus monoculture and integrated livestock-forestry systems in this study. Assuming that trees that were originally planted were used for both roundwood and energy, then 73 t CO_2 ha^{-1} were stocked after 8 years. However, if 50% of trees were used for energy, then 115 t CO_2 ha^{-1} were emitted and not stored due to CO_2 equivalent emissions exceeding carbon stocked by the system (Figure 4). Booth (2018) argues that using wood for energy can be more carbon-neutral under two conditions. First, that energy is generated from tree waste and not the entire tree, and second, that carbon emissions are small relative to the projected time horizon of climate change mitigation [48]. The calculations in this study assume that the trunks harvested after five years are used for energy. Woody biomass waste from monoculture eucalyptus production, such as the pruning of lower branches in the ILF system, was not evaluated in this study. These residues were left in the field for nutrient cycling.

Relative stocks of carbon for the three scenarios of tree growth, energy use, and roundwood and energy use were similar for the integrated livestock-forestry (ILF) system. However, carbon stocks were lower compared to eucalyptus monoculture due to CO_2 equivalent emissions from beef cattle reducing carbon stocks from trees. Carbon stocks (t CO_2 ha^{-1}) for ILF were highest for tree growth (129) followed by roundwood/energy use (28), while just using trees for energy (-117) resulted in CO_2 emissions (Figure 5). The estimates for ILF of 129 t CO_2 ha^{-1} in this study were comparable to previous estimated carbon stocks of 170 t CO_2 ha^{-1} for an integrated crop-livestock-forestry (ICLF) system for Brazil by Figueiredo et al. (2016) [49]. In this ICLF system, eucalyptus was integrated with beef cattle and pasture, with commodity crops also integrated during the earlier establishment years of this system.

3.5. Future Research Directions and Challenges

This research evaluated the above-ground biomass of *Eucalyptus urophylla* in monoculture versus an integrated livestock-forestry system. *Eucalyptus* spp. timber typically constitutes the majority of carbon storage compared to above-ground tree branches, twigs, and leaves, soil surface litter, below-ground roots, and soil carbon storage [46,47]. Carbon storage for below-ground roots, surface litter, and the surrounding soils was not analyzed in this study. This type of study is consistent with monoculture but not with integrated systems. Therefore, future research can analyze these in more detail. Future research can also measure carbon storage in Brazilian integrated forest systems compared to other types of trees, different tree arrangements in integrated systems, and longer tree lifespans. For example, soil carbon was more favorable for fig (*Ficus carica*) trees compared to *Eucalyptus camaldulensis* in the Ahoochar region of Iran [50]. Soil carbon storage was better for Cerrado savannah compared to integrated crop-livestock-forestry systems in Minas Gerais state in Brazil in 2001 [51]. Additionally, future studies can measure carbon stock in all integrated system components for other regions in Brazil.

This study may also underestimate the potential for integrated livestock-forestry (ILF) systems to offset greenhouse gas (GHG) emissions from the beef component of these systems. The calculations of livestock emissions used in this study were based on annual CO_2 equivalent emissions per head of 1993 t CO_2 herd^{-1}/962 head herd^{-1} yr^{-1} = 2.072 t CO_2 head^{-1} yr^{-1} according to Cardoso et al. (2016) [24]. Other studies in Brazil have estimated slightly higher emissions for both tropical and temperate Brazilian beef cattle. For example, the Integrated Farm System Model (IFSM) estimate for *Nellore* beef cattle in the Amazon and Cerrado biomes (2.3575 t CO_2 head^{-1} yr^{-1}) [52] was 13.8% higher than calculated by Cardoso et al. (2016) [24]. Similarly, the IFSM estimate for temperate *Bos taurus* beef cattle in the Pampas biome entering the finishing period (2.582 t CO_2 head^{-1} yr^{-1}) [53] was 24.6% higher. Assuming beef cattle emissions are higher, the agroforestry components of ILF systems may have to be designed to account for higher than expected GHG emissions from livestock.

Climate-smart ILF systems in Brazil can provide more carbon storage [54] compared to the natural succession of second-growth forests [55]. Such integrated systems involving agroforestry in Brazil's Amazon and Cerrado biomes can also reduce soil and nutrient losses compared to no-till commodity cropping systems [56]. Currently, in the Teles Pires River basin in Mato Grosso, the land area is ~60% native vegetation (forest and savannah) and ~40% agriculture and pasture [57], which is where agroforestry could be more broadly integrated into existing pasture or cropland. Outreach to farmers to increase the sustainability of their agricultural systems by adopting ILF should focus on field days during the winter break between crops [58]. Future research can better quantify the below-ground carbon storage for integrated systems in Brazil's Mid-Western region and elsewhere. Additionally, future studies can estimate the economic on-farm benefits and opportunity costs of adopting integrated agricultural systems involving agroforestry both in Brazil and globally.

4. Conclusions

Integrated livestock-forestry systems can help store more carbon in order to help meet global targets for reductions in anthropocentric carbon dioxide (CO_2) emissions. Brazil is at the forefront of such global commitments, having pledged to reduce current CO_2 emissions by 50% by 2030. Eucalyptus was evaluated in monoculture and integrated with pasture and livestock, along with three uses for these trees based on long-term research at Embrapa Agrosilvopastoral in Sinop, Mato Grosso state, Brazil.

The carbon stock for trees in the integrated livestock-forestry system was the same as for trees in monoculture, averaging 34.7 kg of carbon per tree. This likely happened because the trees in eucalyptus monoculture tend to produce more dead branches over time, while the integrated system tends to produce more fresh branches. Additionally, the trees in the integrated livestock-forestry (ILF) system are shorter and more robust than the trees in monoculture due to the "edge effect." These factors can result in a compensatory effect on carbon stocks. In addition, as expected, the trees' carbon stock increased over the years in both systems at an average rate of 18.6 kg of carbon per year.

The monoculture planting of eucalyptus in this study had carbon stock potential (Scenario 1) equal to 510 t CO_2 ha^{-1}, while the ILF system was lower at 129 CO_2 ha^{-1} over the eight years of the experiment. However, if using wood for energy (Scenario 2), the carbon stock for both monoculture and ILF systems resulted in carbon emissions equal to 115 and 117 t CO_2 ha^{-1}, respectively, after eight years. The biogenic CO_2 emitted in this scenario can be excluded by assuming zero emissions for forest monoculture.

On the other hand, the carbon emissions in the ILF system can be neutralized if at least part of the forest is used for roundwood (Scenario 3), and still stock 28 t CO_2 ha^{-1}. The monoculture system in this scenario can stock 73 t CO_2 ha^{-1}. So, for the carbon stock to be considered in ILF systems, the wood from the forest component of the system must be totally or partially used for roundwood timber or to offset greenhouse gas emissions from livestock (e.g., enteric methane emissions).

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