



Growth and productivity of *Eucalyptus benthamii* in integrated crop–livestock systems in southern Brazil

Silvano Kruchelski · Jonathan William Trautenmüller · Gabriel Agostini Orso · Gilmar Paulinho Triches · Vanderley Porfírio-da-Silva · Anibal de Moraes

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Abstract Integrated crop–livestock systems (ICLS) are production models that promote sustainable intensification and integrate agricultural and forestry production systems, generating a combination of economic and environmental benefits. Knowledge is still scarce about the growth and productivity of the tree component in ICLS, and there is a lack of long-term landscape-scale assessments about the provision

of ecosystem services in ICLS. Our objective was to evaluate the monthly stem volume increment and productivity of *Eucalyptus benthamii*, at 7 years old, using metal dendrometer bands, for three different models of ICLS that integrate trees to the crop (crop–forestry—CF), livestock (livestock–forestry—LF), or both (crop–livestock–forestry—CLF) in southern Brazil. The form factor decreased while increasing age, with 0.516 at 4 years and 0.437 at 6 years after planting. In ICLS, we found the productivity of *E. benthamii* similar to the national averages for monoculture forestry in the United States and Brazil. At 6.5 years after planting, the average annual stem volume increment was 22.7 m³ ha⁻¹ year⁻¹ (LF), 24.6 m³ ha⁻¹ year⁻¹ (CLF) and 25.5 m³ ha⁻¹ year⁻¹ (CF), respectively. The CF production system provided trees with greater accumulated stem volume within 7 years of age. The LF system, on the other hand, provided trees with an equal increment in diameter, but less accumulated stem volume, and, therefore, smaller heights, suggesting that there is interference from cattle and pasture management on the growth and productivity of *E. benthamii*. ICLS are configured as an excellent possibility for vertical expansion of agricultural frontiers, promoting sustainable intensification, as well as can prevent horizontal expansion into new areas, reducing pressure on native forests, and contributing to combating deforestation.

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S. Kruchelski (✉) · G. A. Orso · A. de Moraes
Federal University of Parana, Curitiba, Paraná, Brazil
e-mail: silvanokr65@gmail.com

G. A. Orso
e-mail: gabrielorso16@gmail.com

A. de Moraes
e-mail: anibaldemoraes@gmail.com

J. W. Trautenmüller
Federal Rural University of Amazon, Institute of Agrarian Sciences, Belém, Pará, Brazil
e-mail: jwtraute@gmail.com

G. P. Triches
Federal Institute Catarinense, Blumenau, Santa Catarina, Brazil
e-mail: gilmartriches@gmail.com

V. Porfírio-da-Silva
Embrapa Florestas, Colombo, Paraná, Brazil
e-mail: vanderley.porfirio@embrapa.br

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Introduction

Integrated crop–livestock systems (ICLS) are production systems that combine crop, livestock, and forestry components and are recognized as an excellent strategy to intensify production according to the principles of conservation agriculture in a sustainable way (sustainable intensification, FAO 2010), and offer considerable promise for integrating agriculture and forestry production systems, generating a combination of economic and environmental benefits (Cubbage et al. 2012). ICLS makes it possible to maximize the synergy between components, mimic the natural environment, optimize land use, raise productivity levels, diversify production and generate quality products (FAO 2010; Lemaire et al. 2014; Moraes et al. 2018; Embrapa Territorial 2020).

The growing demand for water, food, and energy puts pressure on natural resources, intensifies competition for land use, and creates challenges for environmental conservation (Lopes et al. 2020). In this context, new agricultural areas can be occupied with the destruction of native forests. This characterizes a horizontal expansion of agricultural frontiers. On the other hand, it is possible to intensify the capital application, changing the technological standard, improving pastures, associating crops, or regenerating degraded areas, characteristics of vertical expansion of agricultural frontiers (Rodrigues and Miziara 2008; Oliveira et al 2014). ICLS can contribute to the verticalization of agricultural frontiers, and also avoid horizontal expansion since its benefits extend even to other locations because the increased production and productivity reduce the pressure on the opening of new areas (FAO and UNEP 2020; Embrapa Territorial 2020).

ICLS optimize land use and provide positive synergistic effects on physical, chemical, and biological soil properties, and help to decrease degradation compared to single land-use strategies (Lemaire et al. 2014; Borges et al. 2019; Embrapa Territorial 2020). According to data from the rural environmental registry (Embrapa Territorial 2020), Brazil allocates

30.2% of its territory to agriculture and of these, 6.6% (which corresponds to 2% of the Brazilian territory) is occupied by ICLS. Brazil has 178.6 million hectares of native and planted pastures (21.2% of the Brazilian territory), 66.3 million hectares of crops (7.8% of the Brazilian territory), and 10.2 million hectares of planted forests (1.2% of the Brazilian territory).

According to Ferreira et al. (2020a), between 2010 and 2018, there was a loss of 31.7 million hectares in Brazilian pasture areas, with 65.6% of these areas showing signs of degradation and, therefore, considered as low-productivity. However, new areas were converted to pastures (30.8 million hectares). During this period, there was a greater loss of pasture areas located in regions that have the ability and infrastructure to support agricultural systems, and there was greater area gain in regions with greater availability of low-cost land, characterized by agricultural frontier regions, mainly constituted by native areas (Ferreira et al. 2020a).

Although pastures provide ecosystem services and have a high capacity to reduce environmental impacts, inadequate intensification to increase production can annihilate these ecosystem services (Lemaire 2012). Pasture areas carry the potential to cause or aggravate environmental impacts (Ferreira et al 2020a). Degraded pastures, due to the very low animal stocking, contribute to the deforestation of native areas, because the farmer tries to keep the cattle population (Borges et al 2019). In this context, the ICLS are an alternative to recover degraded pastures, increase the animal stocking rate and prevent the advance into areas of native forest.

ICLS can mitigate the effects of climate change, such as in silvopastoral and silviagricultural systems, where trees protect pastures and crops from intense solar radiation and wind, reducing evapotranspiration and, consequently, improving the availability of soil water to the understory (Porfírio-da-Silva 2018; Bosi et al. 2020; Sheppard et al. 2020). Furthermore, ICLS have the potential to produce wood and tree biomass without the need for felling trees, by harvesting wood from branches that provides access to considerable amounts of lignocellulosic biomass, while leaving the tree standing (Bohn Reckziegel et al. 2022). However, in silviagricultural systems, shading can decrease grain yield while tree growth progresses (Franchini et al. 2014; Moreira et al. 2018). In contrast, trees in ICLS influence both soil carbon (C) accumulation

and tree biomass carbon accumulation (Douglas et al. 2020). According to Souza et al. (2020), the transformation into soil organic matter is the main way in which atmospheric carbon (CO₂) can be captured and then stored, but it occurs more intensely through its transformation into plant biomass of the tree component. Treeless agricultural systems hardly surpass C stocks when compared to adjacent native vegetation. In this way, a production system hardly obtains a positive balance of C without the insertion of the tree component, since a large part of the immobilized C is found in the trunk of trees (Souza et al. 2020). The ability to store C confirms the importance of agroforestry systems against climate change.

Eucalyptus species are introduced worldwide to meet the world's demands for fiber and energy, especially for being a woody crop of short rotation with rapid volume growth (Hall et al. 2020). Native to Australia, *Eucalyptus benthamii* Maiden et Cambage is one of the few eucalyptus species recommended for temperate regions such as southern Brazil, South Africa, and subtropical regions of the United States and China, it has good tolerance to drought and cold (withstands temperatures of up to -10°C), it grows fast and has a straight trunk (Paludzyszyn-Filho et al. 2006; Arnold et al. 2015; Yu and Gallagher 2015; Hall et al. 2020). In ICLS, *E. benthamii* grows faster and has lower wood density when compared to forestry monocultures (Kruchelski et al. 2021). *E. benthamii* is considered promising for cellulose or as a bioenergy raw material (Dougherty and Wright 2012; Hart and Nutter 2012; Yu and Gallagher 2015; Stanturf et al. 2018), for biofuel production with high ethanol yields (Castro et al. 2014), and the production of charcoal in short 5-year cycles (Nones et al. 2014).

Tree growth is an important indicator of forest health and productivity. Knowing precisely how trees grow monthly, instead of across years, can lead to a finer understanding of the mechanisms that drive these larger patterns, and the use of dendrometer bands in research forests allows measuring growth at resolutions finer than yearly measurement (McMahon and Parker 2015). Genotype, management, and environment affect tree growth (Kirongo et al. 2010) as well as edaphic and climatic conditions (Yu and Gallagher 2015). However, the volumetric increment of eucalyptus is dependent on the planting spacing, and in forestry monocultures the increment per hectare is greater than in ICLS, but the tree individual volume

increases the greater the spacing, as in the case of ICLS. (Paula et al. 2013; Ferreira et al. 2020b; Watzlawick and Benin 2020).

Reed et al. (2017), in a large systematic review study, state that most studies with agroforestry are carried out within a period of less than or equal to 3 years, and that there is a lack of long-term landscape-scale assessments of the provision of forest ecosystem services. We proposed a study with ICLS beyond 7 years, and our analysis here compared the variable effects of ICLS with independently fixed rotational ages. Integrated forestry and agricultural systems can influence tree growth according to the agricultural/animal component and its management.

We hypothesized that there are differences in *E. benthamii* growth and productivity between different ICLS. The objective was to evaluate the form factor, the monthly increment, and productivity of *E. benthamii* in three different ICLS models that integrate trees with crops, livestock, or both in an experimental area located in southern Brazil.

Materials and methods

The experiment was carried out in the Environmentally Protected Area of the Iraí River Basin located in Pinhais, Paraná, Brazil (Fig. 1). This is an experimental area, a long-term project that assesses ICLS (full description in Dominschek et al. 2018, in Portuguese). More details about climate, soil, and tree management can be found in Kruchelski et al. (2021). The experiment evaluates a land-use intensification gradient of agricultural systems under no-tillage. Land-use intensification was determined by levels of temporal and spatial diversity of agricultural components including monoculture crop, pasture, and forestry, and integrated combinations of these land-uses (integrated/mixed systems). We evaluated three treatments of this experiment, specifically: (1) livestock–forestry (LF): *E. benthamii* integrated to winter (*Avena strigosa*) and summer (*Megathyrus maximus* cv. Áries) pasture with cattle grazing; (2) crop–forestry (CF): *E. benthamii* integrated with summer corn (*Zea Mays*) crop and winter cover of oat (*A. strigosa*) without grazing; (3) crop–livestock–forestry (CLF): *E. benthamii* integrated with a 3-years cattle and 1-year crop rotation. Each treatment was replicated

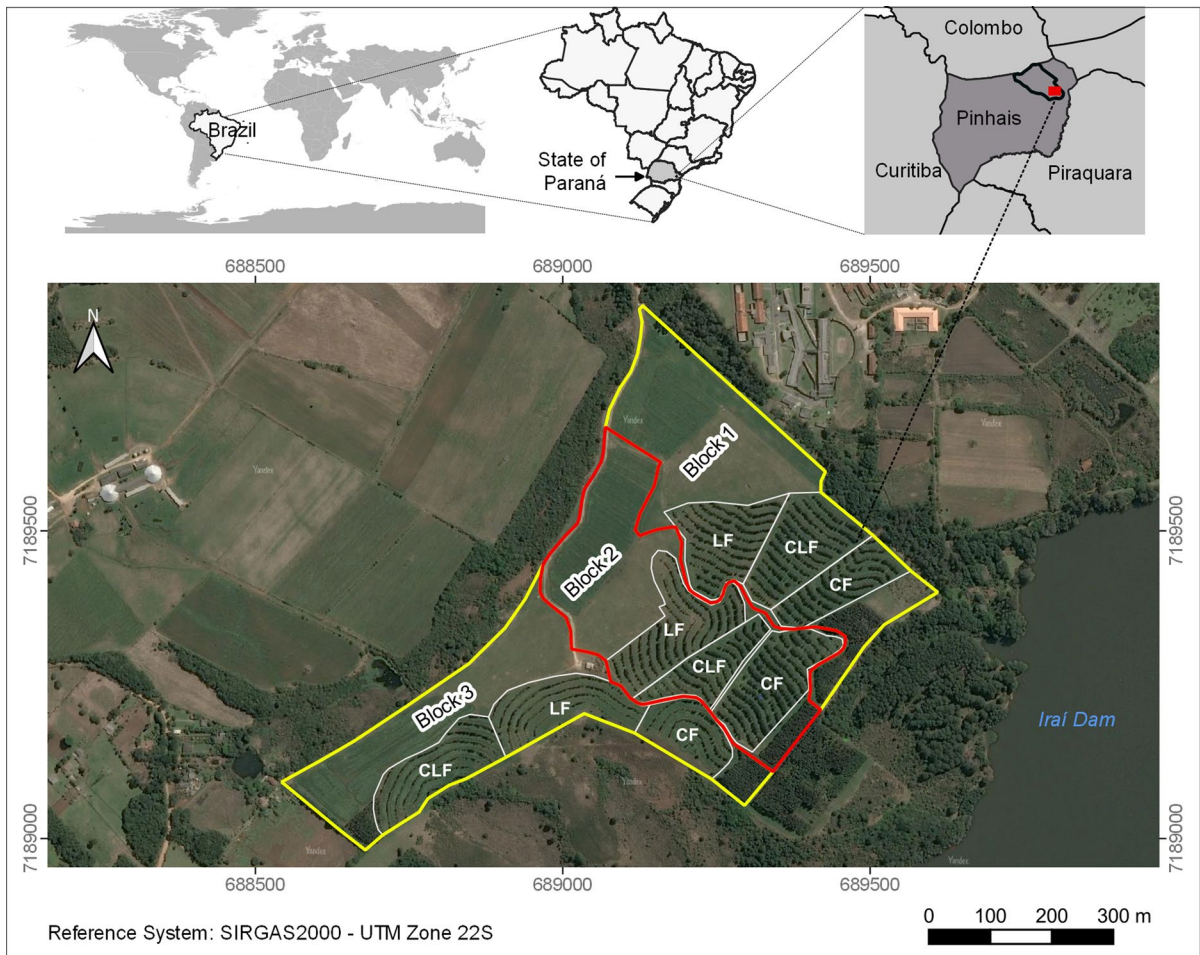


Fig. 1 Experimental area in the Environmentally Protected Area—Iraí River Basin, Pinhais, Paraná, Brazil and three evaluated treatments: livestock–forestry (LF), crop–livestock–forestry (CLF), and crop–forestry (CF)

three times, totaling 9 experimental units (Fig. 1 and Supplementary Information, table SI T1). We did keep all tree rotation times constant for all treatments. The experiment was carried out with a randomized complete block design, three treatments, and three replicates. The blocks were separated according to the variation of soil types and topography.

The planting spacing was 14×2 m with seedlings originating from seeds available from Embrapa Florestas. Fertilization was carried out in a system with two annual applications (winter and summer). Details on amounts and formulation as well as details of pruning and thinning up to 2019 can be found in Kruchelski et al. (2021). During this period, two pruning and one thinning were carried out, remaining approximately 175 trees per hectare (Table 1). The

continuity of this description, from 2019 until 2020 (86 months after planting), is presented below.

The second thinning took place 78 months after planting with the removal of all trees from alternate rows, as well as some trees in remaining rows until the final average spacing of 28×6 m was reached (remaining approximately 53 trees ha^{-1} —Table 1). Tree mortality of 15.9% was recorded during the first 3 years post-planting (year 2016—Table 1), resulting from falls by wind, and damage by regional animals (*Lepus europaeus* Pallas and sawing beetles of the Cerambycidae family), and other unidentified causes. Tree management over time, especially in the first thinning, corrected the differences caused by tree mortality (Table 1).

Table 1 Trees arrangement over 7 years of integrated crop–livestock systems

Production systems	Population (trees ha ⁻¹)				Area per tree (m ²)			
	Start 2013	36 months after planting	After first thinning at 44 months	After second thinning at 78 months	Start 2013	36 months after planting	After first thinning at 44 months	After second thinning at 78 months
LF	357	303.7	177.1	54.0	28	32.9	56.5	185.3
CLF	357	320.1	174.7	52.3	28	31.2	57.3	191.2
CF	357	285.1	174.2	51.9	28	35.1	57.4	192.7

Production systems: livestock–forestry (LF); crop–livestock–forestry (CLF); crop–forestry (CF)

For the present study, the monthly stem volume increment and productivity of *E. benthamii* were calculated. For that, the total tree height, and the diameter at breast height (DBH) were measured, and the monthly growth in circumference was registered using metal dendrometer bands. The evaluation was carried out during 3 periods: (1) 2016–2017: between January 2016 to February 2017 (14 months); (2) 2018–2019: between September 2018 to September 2019 (12 months); (3) 2019–2020: between September 2019 to November 2020 (14 months). Initially, 2 evaluation periods were planned (2016–2017 and 2018–2019), but it was decided to continue the experiment in order to verify the growth of the trees also after the second thinning. Chronology of thinning and evaluations carried out in the 3 periods is available in figure SI F1, Supplementary Information. Raw data are available from Kruchelski (2021).

The dendrometer band was made manually with hardened steel tape AISI 301, shiny polished surface, hardness 38 to 43 HC, 12.7 mm wide, and 0.15 mm thick. A stainless-steel tension spring was installed, with a 0.80 mm wire, 9.2 mm outside diameter, and 100 mm long, with a hook at both ends. At each monthly visit, the growth in circumference was recorded and a marking was made for each month recorded (figure SI F2, Supplementary Information).

A total of 180 dendrometer bands were installed, 60 per treatment (20 trees per plot and three plots per treatment). For each treatment, five diameter classes were created based on the diameter distribution, and we selected a number of trees in each class proportional to the number of trees in each diameter class, adding up to 20 trees per plot. For the period 2016–2017, 20 trees were selected in the center of each plot, divided into two subsequent rows with 10 trees next to each other. For the periods 2018–2019

and 2019–2020, the same criterion of 2016–2017 could not be repeated due to the removal of trees in the two thinning, so the trees were randomly selected to be distributed as spaced as possible within each plot. It was also avoided to select trees with very apparent defects (crooked, bifurcated, and broken), since the dendrometer bands could rarely be installed at 1.3 m above ground level for these trees, and usually these trees were selected to be thinned. During 2019–2020 (in April 2020) the second thinning occurred, which implied a decreased number of trees per plot, and this period was completed with 11 trees per plot ($n=99$), with the tree distribution strictness being maintained according to the diameter classes.

The tree total height was measured using a Haglof® model ECII clinometer, and the DBH was obtained by measuring the circumference at 1.30 m above ground level with a measuring tape. The tree height and DBH in 2016–2017 were measured at the end of the period, and tree height at the beginning of the period was calculated using a height-diameter equation obtained with the trees in the same experiment, using the non-linear Gompertz model fitted for each system (Kruchelski et al. 2022):

$$h = \beta_0 \cdot e^{\left(-e^{(\beta_1 - \beta_2 \cdot DBH)}\right)} + \varepsilon$$

where: h is the total height (m), DBH is the diameter at breast height (cm), β_i are the model parameters, and ε is the residual random error.

For the second and third periods (2018–2019 and 2019–2020), tree heights at the beginning of these periods were measured on the field, and the tree heights at the end of these periods were obtained using the same equation as above, using the last diameter measured by the dendrometer bands as input for the height-diameter equations. The root mean square

errors for the models were 1.9899 m, 2.0697 m, and 24,257 m for LF, CLF and CF, respectively.

Form factors were obtained by felling and measuring 33 trees in 2015 (which provided the form factor for the period 2016–2017) and 89 trees in 2019 (which provided the form factor for the periods 2018–2019 and 2019–2020). Form factors are the ratio between the cone volume measured from the felled trees and the cylinder calculated using the DBH and total tree height. After calculating the form factor, a volumetric model was developed to calculate the stem volume of each standing tree. The entire diameter distribution was considered on both occasions. From this information, it was possible to calculate the monthly stem volume increment of each tree, as well as the volume accumulation during the measurement period with dendrometer bands. Consequently, monthly and annual stem volume increments and accumulations per hectare were calculated. Through analysis of variance, using the year of measurement and production systems as factors, the form factor, the annual stem volume increment, and volumetric production were compared. Monthly volumetric increments per hectare of each treatment were compared using a paired *t* test ($\alpha=0.05$). All calculations were performed using the R language (R Core Team 2021).

Results

Through the volume measurements carried out in 2015 and 2019, the calculated stem volumes and form factors had a similar value between systems, and only the year of measurement influenced the results (Table 2). The form factor for 2016–2017 was 0.513, and 0.437 for the years 2018–2019 and 2019–2020.

The average DBH and plant height at the end of the evaluation periods (86 months post-planting) was

34.7 cm and 24.3 m for the CF, 34.2 cm and 24.3 m for the CLF, and 34.1 cm and 21.9 m for the LF production system, respectively. The final distribution of diameters and heights, mean DBH, and mean tree height at 86 months post-planting are available in figure SI F3, Supplementary Information.

Among the analyzed periods, the CF and CLF systems presented a similar volumetric increment for 2016–2017 and 2018–2019, and the LF system had the lower increment (Fig. 2). Only for the period 2019–2020, where thinning occurred, there was a different increment between all systems. There was a considerable difference in the increment between the 2018–2019 and 2019–2020 periods, especially from June onwards.

Conversely, the accumulated stem volume (Fig. 3) was different in two of the three periods analyzed. For 2019–2020, the accumulated volume did not differ for the CF and CLF systems.

The volumetric accumulation in the 2018–2019 and 2019–2020 periods was lower in the LF system (Fig. 3), but the annual diameter increments in these same periods, as well as in 2016–2017, were similar to the other systems (Tables 3, 4). The accumulated stem volume of the CF system in 2016–2017 and 2018–2019 was higher than the other two systems and in 2019–2020 higher than the LF system (Fig. 3), this pattern was not repeated in the diametric increment (Tables 3, 4).

Discussion

The form factor can vary between the same tree species according to age (Gomat et al. 2011), according to silvicultural management (Azevedo et al. 2011), or planting spacing (Souza et al 2016). In the present study, the form factor decreases while increasing age,

Table 2 Analysis of variance of the effects of measurement year and production systems on form factor and total volume

Source of variation	Degrees of freedom	Mean squares	
		Form factor	Volume
Year	1	0.1284**	8.7058**
System	2	0.0004 ^{ns}	0.0447 ^{ns}
Year * System	2	0.0027 ^{ns}	0.0532 ^{ns}
Block	2	0.0048*	0.7592**
Coefficient of determination (%)	57.71	54.24	
Coefficient of variation (%)	7.65	50.97	

* significant at 5%;

**significant at 1%; ^{ns}not significant

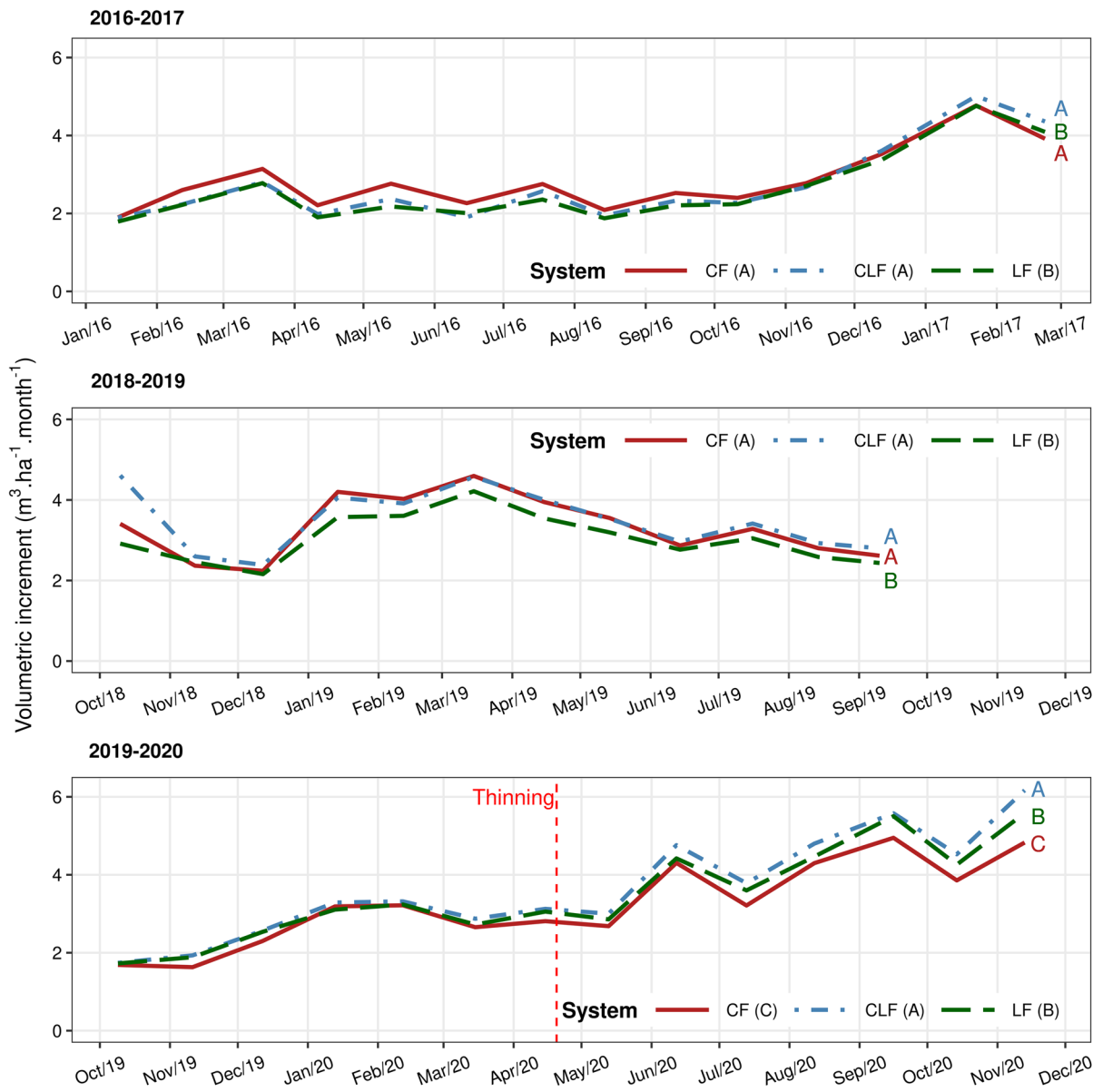


Fig. 2 Monthly volumetric increment ($m^3 \text{ ha}^{-1} \text{ month}^{-1}$) (stem volume) of each integrated system. Uppercase letters at the end of each period and production systems indicate signifi-

cant differences between the systems evaluated based on the paired *t* test. CF: crop–forestry, CLF: crop–livestock–forestry, LF: livestock–forestry

with 0.516 at 4 years and 0.437 at 6 years after planting. This corroborates the work of Soares (2018), who evaluated several trees’ spacing and concluded that the trunk tends to stay more conical, decreasing the form factor while advancing age, because, over time, there is a greater growth of the crown and, therefore, there is increased efficiency of the crown function, and on the other hand, the tree invests more in base

growth (Larson 1969). Gomat et al. (2011) stated that eucalyptus trees become more and more cylindrical as they grow to a certain age, at which point the dominant trees become tapered than the suppressed ones, and this explains the characteristics of the trees in this study because due to the planting spacing and forestry management, the trees had characteristics of dominant trees.

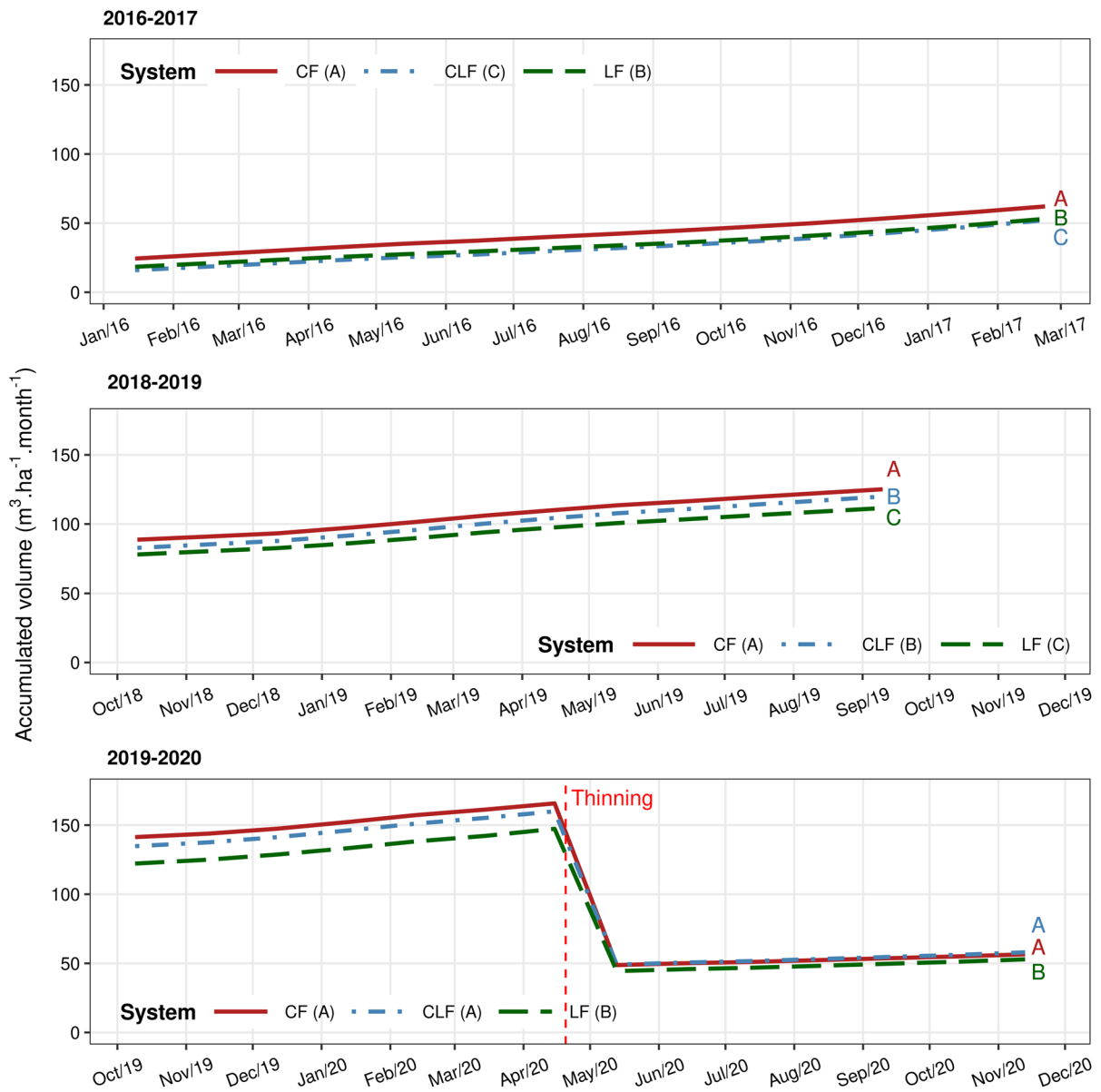


Fig. 3 Stem volume accumulation ($\text{m}^3 \text{ ha}^{-1} \text{ month}^{-1}$) observed in each measurement period for different ICLS. Uppercase letters at the end of each period and production

systems indicate significant differences between the systems evaluated based on the paired t-test. CF: crop–forestry, CLF: crop–livestock–forestry, LF: livestock–forestry

In 2019, Brazil had average productivity in monoculture eucalyptus plantations of $35.3 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, considering all eucalyptus species planted in the country (IBÁ 2020). In the present study, despite planting with larger spacing in ICLS, we found average volumetric increments for the 3 evaluation periods of $36.3 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (LF), $39.1 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (CLF), and $37.6 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (CF), respectively

(see Table 3, values for each period). These were the stem volume gains when the trees were more than 3 years old, however, considering the entire period since planting and ignoring the volume removed with the first thinning, as lower growing plants were removed, the stem volume accumulated at 6.5 years, before the second thinning, represented average annual increment of $22.7 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (LF), 24.6

Table 3 Annual increment in diameter at breast height and stem volume per hectare of the 3 integrated crop–livestock systems for each evaluation period

Production systems	Annual increment in DBH (mm year ⁻¹) and volume (m ³ ha ⁻¹ year ⁻¹)					
	2016–2017		2018–2019		2019–2020	
	DBH	Volume	DBH	Volume	DBH	Volume
LF	46.2	30.3	42.0	36.5	46.2	42.0
CLF	45.9	31.4	38.9	41.8	43.7	44.0
CF	42.6	33.3	39.5	39.9	41.1	39.4

DBH diameter at breast height. Production systems: LF livestock–forestry, CLF crop–livestock–forestry, CF crop–forestry

Table 4 Variance analysis of average annual increment in diameter and stem volume between the year of measurement and production system

Source of variation	df	Mean squares	
		Diameter increment (mm year ⁻¹)	Volume increment (m ³ ha ⁻¹ year ⁻¹)
Year	2	50.06 ^{ns}	253.62 ^{ns}
System	2	24.77 ^{ns}	17.94 ^{ns}
Year * System	4	5.06 ^{ns}	13.40 ^{ns}
Residuals	18	19.43	73.76

df degrees of freedom, ns not significant

m³ ha⁻¹ year⁻¹ (CLF), and 25.5 m³ ha⁻¹ year⁻¹ (CF), respectively. The values we found were lower than the results found by Watzlawick and Benin (2020), who evaluated *E. benthamii* at 6 years of planting and obtained increments greater than 50 m³ ha⁻¹ year⁻¹, in forestry monocultures, planted with a spacing of 2 × 3, 3 × 3, 3 × 4, and 4 × 4 m. Although these authors evaluated the volumetric increment with 6-year-old trees, the greater spacing provided trees with greater individual volume and smaller volume per hectare after 38 months (Benin et al. 2014).

Eucalyptus volume per hectare increment is strongly dependent on the planting spacing and it is well known that forestry monocultures provide greater volumetric increments than ICLS, although tree individual stem volume in ICLS is greater (Paula et al. 2013; Ferreira et al. 2020b; Kruchelski et al. 2021). Hall et al. (2020), however, using growth and production models, in a large study with *E. benthamii* planted in monocultures in the Southeast of the United States found a wide range of productivity that, depending on edaphic and climatic conditions, ranged from 13.7 to 26.4 m³ ha⁻¹ year⁻¹. Hall et al.

(2020) evaluated *E. benthamii* at different planting densities, ranging from 732 to 2292 plants per hectare, with ages ranging from 1 to 13 years old, however, the yield found was lower than what we evaluated in ICLS (Table 3) with a lower density of plants (see Table 1). Yu and Gallagher (2015) also evaluated *E. benthamii* in the southeastern United States (State of Alabama), in an environment considered by the authors as a “productive forest”, at 5 years of age, with a density of 1237 and 1650 trees per hectare, and found an average annual increment of 22.29 and 20.23 m³ ha⁻¹ year⁻¹ respectively, values very close to those found here. Probably the edaphic, climatic, and management conditions in ICLS, such as those in the present study, provided a similar gain in productivity.

According to the study carried out in Southern Brazil by Paludzyszyn-Filho et al. (2006), *E. benthamii* forestry monoculture with planting spacing of 2 × 3 m, at 8 years of age, had a diameter increment of 27 mm per year. Yu and Gallagher (2015) found a 25.4 mm increment per year in DBH in 5-year-old *E. benthamii* in the southeastern United States. Our evaluation found average diametric increments for the 3 evaluation periods in the order of 44.8 mm (LF), 42.8 mm (CLF), and 41.1 mm (CF) (see Table 3, values for each period). Tree growth is mainly affected by three factors: genotype, management, and environment (Kironko et al. 2010). Notably, larger planting spacing, as well as ICLS management, can provide trees with a greater diameter size when compared to monoculture (Kruchelski et al. 2021). The data for all the systems evaluated here showed that the stem volumetric accumulation depends not only on the diameter increment but also on a balance between the height growth and diameter increment, since the trees of the CF system presented smaller diameters and

larger accumulated volumes, that is, the growth in height had a preponderant influence on the volumetric accumulation.

The differences in the monthly volumetric increment increased between the systems evaluated from June 2020 to December 2020 (Fig. 2). Possibly, it is due to the thinning carried out two months before this period. This thinning may also have influenced the responses of volumetric accumulations from that same period (Fig. 3), reducing the differences between the three systems. However, the results showed that the CF system was more productive than the other two production systems evaluated in at least two periods (2016–2017 and 2018–2019), and in the period 2019–2020, it was more productive than the LF system (Fig. 3). Possibly this occurred because the crop was managed in the first 2 years after planting the CF system when the pasture was not yet well-formed in the LF and CLF systems, and the trees did not have the necessary diameter size (necessary $DBH \geq 6$ cm, according to Porfírio-da-Silva (2018)) for the entry of animals. Although the external input of nutrients is identical for all evaluated systems, in the LF system the crop plantation does not occur, and in the CLF system, this phase only occurred in the first summer after planting (table SI T1, Supplementary Information). Thus, 2 years of planting in the initial phase may have made a difference for the CF system, making the trees more competitive with each other, with greater gains in height, which over the years provided a greater volumetric increment than CLF and LF. However, the LF system showed a similar diametric increment to the other systems in the three periods evaluated (Table 3). Despite the smaller accumulated stem volume (Fig. 3), that is, as all the systems evaluated contain the same planting spacing, there is an effect of the animal on the tree component, with trees of equal diameter, with lower volumetric accumulation and, consequently, with lower heights. Possibly, the trees of the LF system had this smaller accumulated stem volume due to the cattle presence and the perennial pasture that continuously extract nutrients and water from the site, as well as damage to trees caused by cattle (low and medium intensity damage, regardless of pruning, according to Triches et al. 2020).

However, further research efforts are needed to better understand how the animal ends up affecting

trees in silvopastoral systems, as the effects of trees on animals are already well documented (Silva et al. 2008; Abraham et al. 2014; Oliveira et al. 2018; Porfírio-da-Silva 2018; Chará et al. 2019). Also, recommendations for future studies are: monitoring of tree crowns, whole tree biomass, as well as tree carbon stocks in ICLS, which are ongoing investigations in the experimental area of the present study.

The experimental area of the present study is not only focused on the tree component (this is an important limitation of our studies), but on the systems as a synergistic set, and for this reason, it is necessary to keep the tree management identical between the systems. However, in ICLS we found the productivity of *E. benthamii* similar to the national averages for monoculture forestry in the United States and Brazil (this last country, including other Eucalyptus species). For this reason, producers can consider *E. benthamii* for longer rotations in colder places (down to -10 °C) by integrating: (1) with crops, especially in the initial tree growth phase, when there is no interference of trees on grain yield (Moreira et al. 2018) and when the entry of animals is not recommended, and (2) later with livestock, creating a periodic source of income, according to the size of the intended rotation, or even as a possibility of harvesting in situations of property's financial fragility. Furthermore, if not only tree production is considered, the ICLS, in addition to promoting sustainable intensification based on the synergistic interaction between trees, crops, and/or livestock, provide a broader range of agricultural products and ecosystem services (Shepard et al. 2020). Based on this, ICLS are configured as a great possibility for vertical expansion of agricultural frontiers, allowing the sustainable intensification of agricultural areas, as considered by Rodrigues and Miziara (2008) and Oliveira et al. (2014), as well as avoiding horizontal expansion, reducing pressure on native forest, combating deforestation (Strassburg et al. 2014).

Conclusion

With advancing age, from 4 to 6 years after planting, *E. benthamii* in different integrated crop–livestock systems (ICLS) showed greater conicity, producing thicker trees at the base and, therefore, with the

smallest form factor, similar characteristics of dominant eucalyptus in forestry monoculture.

There were differences between the evaluated production systems. The CF production system provided trees with greater volumetric accumulation within 7 years of age. The LF system provided trees with the same diameter increment as the other systems, but with a smaller accumulated volume, and, therefore, smaller heights, suggesting that there might be interference from cattle and pasture management on *E. benthamii* monthly stem volume increment and productivity.

Authors' contribution SK: Principal author. JWT: Conceptualization, methodology, data collection, statistical analysis, writing. GAO: Statistical analysis, writing, English version, data conference. GPT: Writing, data collection, data conference. VP: Conceptualization, methodology, writing review, data conference, co-advisor. AM: Advisor, conceptualization, supervision, project administration, funding acquisition.

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Data availability The datasets generated and analyzed during the current study are available in the Scientific Database of the Federal University of Parana repository (BDC—Base de Dados Científicos da Universidade Federal do Paraná, in Portuguese) <https://doi.org/10.5380/bdc/81>.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest as well as competing interests.

Ethics approval Not applicable.

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References

- Abraham EM, Kyriazopoulos AP, Parissi ZM, Kostopoulou P, Karatassiou M, Anjalianidou K, Katsouta C (2014) Growth, dry matter production, phenotypic plasticity, and nutritive value of three natural populations of *Dactylis glomerata* L. under various shading treatments. *Agrofor Syst* 88:287–299. <https://doi.org/10.1007/s10457-014-9682-9>
- Arnold R, Li B, Luo J, Bai F, Baker T (2015) Selection of cold-tolerant *Eucalyptus* species and provenances for inland frost-susceptible, humid subtropical regions of southern China. *Aust for* 78(3):180–193. <https://doi.org/10.1080/00049158.2015.1063471>
- Azevedo GB, Sousa GTO, Barreto PAB, Conceição-Júnior V (2011) Estimativas volumétricas em povoamentos de eucalipto sob regime de alto fuste e talhadia no sudoeste da Bahia. *Pesq Florest Bras* 31(68):309. <https://doi.org/10.4336/2011.pfb.31.68.309>
- Benin CC, Wionzek FB, Watzlawick LF (2014) Initial assessments on the plantation of *Eucalyptus benthamii* Maiden et Cambage deployed in different spacing. *Appl Res Agro-technol* 7(1):55–61. <https://doi.org/10.5935/PAeT.V7.N1.06>
- Bohn Reckziegel R, Mbongo W, Kunneke A, Morhart C, Sheppard JP, Chirwa P, Toit B, Kahle HP (2022) Exploring the branch wood supply potential of an agroforestry system with strategically designed harvesting interventions based on terrestrial LiDAR data. *Forests* 13(5):650. <https://doi.org/10.3390/su12176796>
- Borges WLB, Calonego JC, Rosolem CA (2019) Impact of crop–livestock–forest integration on soil quality. *Agrofor Syst* 93:2111–2119. <https://doi.org/10.1007/s10457-018-0329-0>
- Bosi C, Pezzopane JRM, Sentelhas PC (2020) Silvopastoral system with Eucalyptus as a strategy for mitigating the effects of climate change on Brazilian pasturelands. *An Acad Bras Ciênc* 92:1. <https://doi.org/10.1590/0001-3765202020180425>
- Castro E, Nieves IU, Mullinnix MT, Sagues WJ, Hoffman RW, Fernández-Sandoval MT, Tian Z, Rockwood D, Tamang B, Ingram LO (2014) Optimization of dilute-phosphoric acid steam pretreatment of *Eucalyptus benthamii* for bio-fuel production. *Appl Energy* 125:76–83. <https://doi.org/10.1016/j.apenergy.2014.0>
- Chará J, Rivera J, Barahona R, Murgueitio E, Calle Z, Giraldo C (2019) Intensive silvopastoral systems with *Leucaena leucocephala* in Latin America. *Trop. Grassl. Forrajes Trop.* 7(4):259–266. [https://doi.org/10.17138/tgft\(7\)259-266](https://doi.org/10.17138/tgft(7)259-266)
- Cubbage FW, Balmelli G, Bussoni A, Noellemeyer E, Pachas AN, Fassola H, Colcombet L, Rossner B, Frey G, Dube F, Lopes de Silva M, Stevenson H, Hamilton J, Hubbard W (2012) Comparing silvopastoral systems and prospects in eight regions of the world. *Agrofor Syst* 86(3):303–314. <https://doi.org/10.1007/s10457-012-9482-z>
- Dominschek R, Kruchelski S, Deiss L, Portugal TB, Denardin LG, Martins AP, Lang CR, Moraes A (2018). Sistemas integrados de produção agropecuária na promoção da intensificação sustentável—Boletim técnico do Núcleo de Inovação Tecnológica em Agropecuária. Universidade Federal do Paraná, <https://www.aliancasipa.org/wp-content/uploads/2018/12/Boletim-NITA.pdf> Accessed 02 Dec 2021
- Dougherty D, Wright J (2012) Silviculture and economic evaluation of eucalypt plantations in the Southern US. *BioResources* 7(2):1994–2001. <https://doi.org/10.15376/biores.7.2.1994-2001>
- Douglas G, Mackay A, Vibart R, Dodd M, McIvor I, McKenzie C (2020) Soil carbon stocks under grazed pasture and

- pasture-tree systems. *Sci Total Environ* 715:1. <https://doi.org/10.1016/j.scitotenv.2020.136910>
- FAO and UNEP (2020) The State of the World's Forests 2020. Forests, Biodiversity and People, Rome. <https://doi.org/10.4060/ca8642en>
- FAO (2010) An international consultation on integrated crop–livestock systems for development: The way forward for sustainable production intensification. *Integr Crop Manag.* <https://www.fao.org/3/i2160e/i2160e.pdf> Accessed 02 Dec 2021
- Ferreira LG, Oliveira-Santos C, Mesquita VV, Parente LL (2020a) Dinâmica das pastagens Brasileiras: Ocupação de áreas e indícios de degradação—2010 a 2018. Laboratório de Processamento de Imagens e Geoprocessamento. Universidade Federal de Goiás. Disponível em https://files.cercomp.ufg.br/weby/up/243/o/Relatorio_Mapas1.pdf Accessed 22 Nov 2021
- Ferreira MD, Melo RR, Tonini H, Pimenta AS, Gatto DA, Beltrame R, Stangerlin DM (2020b) Physical–mechanical properties of wood from a eucalyptus clone planted in an integrated crop–livestock–forest system. *Int Wood Prod J* 11:12–19. <https://doi.org/10.1080/20426445.2019.1706137>
- Franchini JC, Balbinot Junior AA, Sichieri FR, Debiassi H, Conte O (2014) Yield of soybean, pasture and wood in integrated crop–livestock–forest system in Northwestern Paraná state, Brazil. *Cienc Agron* 45:1006–1013. <https://doi.org/10.1590/S1806-66902014000500016>
- Gomat HY, Deleporte P, Moukini R, Mialoungoula G, Ognouabi N, Saya AR, Vigneron P, Saint-Andre L (2011) What factors influence the stem taper of *Eucalyptus*: growth, environmental conditions, or genetics? *Ann for Sci* 68:109–120. <https://doi.org/10.1007/s13595-011-0012-3>
- Hall KB, Stape JL, Bullock BP, Frederick D, Wright J, Scolforo HF, Cook R (2020) A growth and yield model for *Eucalyptus benthamii* in the southeastern United States. *For Sci* 66(1):25–37. <https://doi.org/10.1093/forsci/fxz061>
- Hart PW, Nutter DE (2012) Use of cold tolerant eucalyptus species as a partial replacement for southern mixed hardwoods. *Tappi J* 11(7):29–35. <https://doi.org/10.32964/TJ11.7.29>
- IBÁ (2020) Indústria Brasileira de Árvores. Annual Report 2020. Brasília. <https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf> Accessed 02 Dec 2021
- Kirongo BB, Kimani GK, Senelwa K, Etiegni L, Mbelase A, Muchiri M (2010) Five year growth and survival of *Eucalyptus* hybrid clones in Coastal Kenya. *J Manaj Hutan Trop* 16(1):1–9. <https://jurnal.ipb.ac.id/index.php/jmht/article/view/3189>. Accessed 02 Dec 2021
- Kruchelski S, Trautenmüller JW, Deiss L, Trevisan R, Cubbage F, Porfirio-da Silva V, Moraes A (2021) *Eucalyptus benthamii* Maiden et Cambage growth and wood density in integrated crop–livestock systems. *Agrofor Syst* 95:1577–1588. <https://doi.org/10.1007/s10457-021-00672-0>
- Kruchelski S, Trautenmüller JW, Orso GA, Roncetto E, Triches GP, Behling A, Moraes A (2022) Modeling of the height–diameter relationship in eucalyptus in integrated crop–livestock systems. *Pesq Agropec Bras* 57:e02785. <https://doi.org/10.1590/S1678-3921.pab2022.v57.02785>
- Kruchelski S (2021b) Raw data—Monthly increment and productivity of *Eucalyptus benthamii* in integrated crop–livestock systems [Dataset]. Scientific Database of the Federal University of Parana repository. <https://doi.org/10.5380/bdc/81>
- Larson PR (1969) Wood formation and the concept of wood quality. *Yale University School For. Bull* n. 74
- Lemaire G (2012) Intensification of animal production from grassland and ecosystem services: A trade-off. *Animal Science Reviews* 7:1–7. <https://doi.org/10.1079/PAVSNR20127012>
- Lemaire G, Franzluebbers A, Carvalho PCF, Dedieu B (2014) Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. *Agric Ecosyst Environ* 190:4–8. <https://doi.org/10.1016/j.agee.2013.08.009>
- Lopes VC, Parente LL, Baumann LRF, Miziara F, Ferreira LG (2020) Land-use dynamics in a Brazilian agricultural frontier region, 1985–2017. *Land Use Policy* 97:104740. <https://doi.org/10.1016/j.landusepol.2020.104740>
- McMahon SM, Parker GG (2015) A general model of intra-annual tree growth using dendrometer bands. *Ecol Evol* 5(2):243–254. <https://doi.org/10.1002/ece3.1117>
- Moraes A, Carvalho PCF, Pelissari A, Anghinoni I, Lustosa SBC, Lang CR, Assmann TS, Deiss L, Nunes PAA (2018) Sistemas integrados de produção agropecuária: conceitos básicos e histórico no Brasil. In: Souza ED, Silva FD, Assmann TS, Carneiro MAC, Carvalho PCF, Paulino HB (eds) *Sistemas integrados de produção agropecuária no Brasil*, 1st edn. Tubarão, Copiart
- Moreira EDS, Gontijo MM, Lana AMQ, Borghi E, Santos CAD, Alvarenga RC, Viana MCM (2018) Production efficiency and agronomic attributes of corn in an integrated crop–livestock–forestry system. *Pesq Agropec Bras* 53:419–426. <https://doi.org/10.1590/S0100-204X201800400003>
- Nones DL, Brand MA, Cunha AB, Carvalho AF, Weise SMK (2014) Determination of energetic properties of wood and charcoal produced from *Eucalyptus benthamii*. *Floresta* 45:57–64. <https://doi.org/10.5380/rf.v45i1.30157>
- Oliveira JC, Trabaquini K, Epiphanyo JCN, Formaggio AR, Galvão LS, Adami M (2014) Analysis of agricultural intensification in a basin with remote sensing data. *Gisci Remote Sens* 51(3):253–268. <https://doi.org/10.1080/15481603.2014.909108>
- Oliveira CC, Alves FV, Almeida RG, Gamarra ÉL, Villela SDJ, Martins PGMA (2018) Thermal comfort indices assessed in integrated production systems in the Brazilian savannah. *Agrofor Syst* 92(6):1659–1672. <https://doi.org/10.1007/s10457-017-0114-5>
- Paludzyszyn-Filho EP, Santos PET, Ferreira CA (2006) *Eucalyptos* Indicados para Plantio no Estado do Paraná. Colombo: Embrapa Florestas, 2006. http://www.agencia.cnptia.embrapa.br/Repositorio/doc129_000hlqx4sov02wx7ha0rww4wo51xqt32.pdf Accessed 02 Dec 2021
- Paula RR, Reis GG, Reis MGF, Oliveira Neto SN, Leite HG, Melido RCN, Lopes HNS, Souza FC (2013) Eucalypt growth in monoculture and silvopastoral systems with varied tree initial densities and spatial arrangements. *Agrofor Syst* 87(6):1295–1307. <https://doi.org/10.1007/s10457-013-9638-5>

- Porfírio-da-Silva V (2018) O componente arbóreo em sistemas integrados de produção agropecuária. In: Souza ED, Silva FD, Assmann TS, Carneiro MAC, Carvalho PCF, Paulino HB (eds) Sistemas integrados de produção agropecuária no Brasil, 1st edn. Tubarão, Copiart
- R Core Team (2021) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org/> Accessed 02 Dec 2021
- Reed J, Vianen JV, Foli S, Clendenning J, Yang K, MacDonald M, Petrokofsky G, Padoch C, Sunderland T (2017) Trees for life: the ecosystem service contribution of trees to food production and livelihoods in the tropics. *For Policy Econ* 84:62–71. <https://doi.org/10.1016/j.forpol.2017.01.012>
- Rodrigues DMT, Miziara F (2008) Expansion of the agricultural frontier: an intensification of cattle raising in the Goiás state, Brazil. *Pesq Agropec Trop* 38(1):14–20. <https://repositorio.bc.ufg.br/bitstream/ri/13274/2/Artigo%20-%20Dayse%20Mysmar%20Tavares%20Rodrigues%20-%202008.pdf>. Accessed 02 Dec 2021
- Sheppard JP, Bohn Reckziegel R, Borrass L, Chirwa PW, Cuaranhua CJ, Hassler SK, Hoffmeister S, Kestel F, Maier R, Mälicke M, Morhart C, Ndlovu NP, Veste M, Funk R, Lang F, Seifert T, Toit B, Kahle HP (2020) Agroforestry: an appropriate and sustainable response to a changing climate in Southern Africa? *Sustainability* 12(17):6796. <https://doi.org/10.3390/su12176796>
- Silva LLGG, Resende A, Dias P, Souto S, Azevedo B, Vieira M, Colombari A, Torres A, Matta P, Perin T (2008) Thermal comfort for crossbred heifers in silvipastoral systems. *Embrapa Agrobiologia*. <https://ainfo.cnptia.embrapa.br/digital/bitstream/CNPAB-2010/35754/1/bot034.pdf> Accessed 02 Dec 2021
- Soares KL (2018) *Eucalyptus* sharpening modeling in different planting spaces and optimization of multiproducts for short rotation. Brasília University. Dissertation. https://repositorio.unb.br/bitstream/10482/31563/1/2017_K%20c3%a1litaLuisSoares.pdf Accessed 02 Dec 2021
- Souza RR, Nogueira GS, Murta-Júnior LS, Pelli E, Oliveira MLR, Abrahão CP, Leite HG (2016) Stem form of *Eucalyptus* trees in plantations under different initial densities. *Sci for* 44(109):33–40. <https://doi.org/10.18671/scifor.v44n109.03>
- Souza KW, Pulrolnik K, Guimarães-Júnior R, Marchão RL, Vilela L, Carvalho AM, Maciel GA, Moraes-Neto SP, Oliveira AD (2020). Offsetting greenhouse gas (GHG) emissions through crop–livestock–forest integration. *Embrapa Cerrados-Circular Técnica* (INFOTEC-A-E). <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/215587/1/CT-43-Kleberon-Worsley.pdf> Accessed 02 Dec 2021
- Stanturf JA, Young JP, Perdue JH, Dougherty D, Pigott M, Guo Z, Huang Z (2018) Productivity and profitability potential for non-native *Eucalyptus* plantings in the southern USA. *For Policy Econ* 97:210–222. <https://doi.org/10.1016/j.forpol.2018.10.004>
- Strassburg BBN, Latawiec AE, Barioni LG, Nobre CA, Porfírio-da-Silva V, Valentim JF, Vianna M, Assad ED (2014) When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Glob Environ Change*. <https://doi.org/10.1016/j.gloenvcha.2014.06.001>
- Embrapa Territorial (2020) Agricultura e preservação ambiental: uma análise do cadastro ambiental rural. Campinas. Available in: www.embrapa.br/car. Accessed 02 Dec 2021
- Triches GP, Moraes A, Porfírio-da-Silva V, Lang CR, Lustosa SBC, Bonatto RA (2020) Damage caused by cattle to *Eucalyptus benthamii* trees in pruned and unpruned silvipastoral systems. *Pesq Agrop Bras*. <https://doi.org/10.1590/S1678-3921.pab2020.v55.01275>
- Watzlawick LF, Benin CC (2020) Dendrometric variables and *Eucalyptus benthamii* production in different spaces. *Coloq Agrar* 16(6):111–120. <https://journal.unoeste.br/index.php/ca/article/view/3042/3163>. Accessed 02 Dec 2021
- Yu A, Gallagher T (2015) Analysis on the growth rhythm and cold tolerance of five-year old *Eucalyptus benthamii* plantation for bioenergy. *Open J* for 5(06):585. <https://doi.org/10.4236/ojf.2015.56052>

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