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Managing eucalyptus trees in agroforestry systems: Productivity parameters and PAR transmittance

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ABSTRACT

Agroforestry systems, in which trees and crops are cultivated in rotation, succession, or association with pastures, are alternatives for the sustainable implementation of agriculture. This study estimated the productive characteristics from eight years old eucalyptus trees in different agroforestry systems and transmission of photosynthetically active solar radiation (PAR). These were composed of a pasture of palisade grass (*Urochloa brizantha* "BRS Piatã") and eucalyptus trees (*Eucalyptus urograndis* "GG100") planted in April 2011 in single rows 15 m apart with 2 m in-row spacing, totaling 333 trees ha^{-1}. In 2016, half of the trees were thinned, and the spacing was changed to 15 × 4 m. The two systems were then evaluated using an integrated crop-livestock-forestry system (agrosilvopasture with pasture renewal, ICLF) and an integrated livestock-forest system (silvopasture with no pasture renewal, ILF). Each system had 12 paddocks of 5000 m^2. In ICLF, pasture was renewed in one-third of each replication of area (two paddocks) per crop year, where the grass was simultaneously sown with corn for silage. Pasture renewal was carried out in the 2013–2014, 2014–2015, 2016–2017, and 2017–2018 growing seasons. Data were collected in April 2016 and June 2019, when 110 trees were harvested to determine wood volume and 28 to gather wood rings and samples of the canopy, roots, and carbon content. These data were used to build the equations for estimating stem volume (m^3 $tree^{-1}$) and tree biomass (kg $tree^{-1}$). Stem diameter at breast height (DBH, 1.3 m above the ground) and tree height (H) were measured in 10% of the trees in each plot to estimate stem volume and biomass; these were compared by *t*-test (5%). PAR was measured continuously from 2013 to 2019 at 70 cm aboveground with linear quantum sensors at the four ICLF positions across the tree line. Using these data, equations for volume = exp[(− -10.21 + 1.68 × ln(DBH)+1.29 × ln(H)] and biomass = exp[−3.88 + 2.41*ln(DBH)+0.62 × ln(H)] were built. The stem volume was greater in ICLF (225.7 m^3 ha^{-1}) than in ILF (215.2 m^3 ha^{-1}) ($p = 0.0369$). The total biomass was 148.3 Mg ha^{-1} for ICLF and 141.0 Mg ha^{-1} for ILF, with no significant differences between systems. The agroforestry systems accumulated 64.5 Mg ha^{-1} of carbon in tree biomass by eight years after system implementation. The basal area of trees in both agroforestry systems showed a strong relationship with the transmission of PAR to the pasture.

1. Introduction

Livestock production plays a major role in Brazilian agribusiness. Although this has traditionally been conducted predominantly on pasture, in recent decades these systems have been undergoing constant intensification, including increased animal stocking rates (Oliveira et al., 2014). However, greenhouse gas (GHG) emissions associated with livestock, especially methane, account for most such emissions related to agricultural activities. New production systems based on pasture recovery have been proposed to mitigate these emissions by increasing soil carbon stocks and reducing carbon footprints (Oliveira, 2015; Figueiredo et al., 2017).

Agroforestry systems such as livestock-forest integration (or silvopasture, ILF) and crop-livestock-forest integration (or agrosilvopasture,

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ICLF) have been applied in this context. These systems have the potential to mitigate GHG emissions by removing carbon from the atmosphere and storing it in biomass and soil, mainly when the tree component is present (Dube et al., 2002; Almeida et al., 2011; Carvalho et al., 2014; Salton et al., 2014). Trees can be inserted into established grasslands or deployed simultaneously with pasture formation (ILF), as well as in systems where pasture is renewed or cultivated in rotation with crops (ICLF) (Balbino et al., 2011; Gil et al., 2015).

Agroforestry systems present greater potential for biomass accumulation (Sharrow and Ismail, 2004), which reflects better land-use efficiency (Macedo, 2009; Carvalho et al., 2010). Moreover, the presence of trees also provides microclimate improvements, increasing thermal comfort for animals (Karki and Goodman, 2015; Pezzopane et al., 2019a) and mitigating the effects of climate change on agricultural systems (Bosi et al., 2020).

The potential for carbon accumulation by trees in agroforestry systems is still little-studied in Brazilian conditions; this depends, among other factors, on the species used and their management and population density (Tsukamoto Filho, 2003; Gutmanis, 2004; Ofugi et al., 2008; Muller et al., 2009). Some uncertainties are attributed to the use of volume and biomass estimators developed using data obtained from conventional tree plantations (with high populations) and their use for plantations in rows (with low populations in integrated systems). In integrated systems, data of carbon accumulation by trees on managed pasture are even scarcer because pasture correction and fertilization are not usually applied given the assumption that such pastures use residual fertilizers from previous crops.

Despite the environmental benefits provided by the presence of trees in agroforestry systems, information regarding tree management practices to maximize these benefits is still scarce in tropical areas. Competition between trees and crops for solar radiation, water, and nutrients is an important factor that limits the adoption of these systems by farmers, especially in systems with high tree population (Santos et al., 2018). Depending on tree population, thinning and pruning should be performed to increase timber quality and decrease competition for resources between trees and crops (Reynolds et al., 2007; Gomes et al., 2019).

Furthermore, monitoring tree-growth variables is important for generating parameters that can help farmers manage livestock production systems, as done by Wall et al. (2010) in silvopastoral systems with poplar (*Populus* spp.) in New Zealand, aiming to maintain pasture productivity at good levels. Nissen and Midmore (2002) also investigated the correlation between stand basal area as an index of competitiveness between trees and intercrops. In this study, we used tree dendrometric variables as parameters to determine PAR transmission in agroforestry systems. This is important for tropical pasture systems that have a reasonable tolerance to shading (Paciullo et al., 2011; Pezzopane et al., 2020a), allowing the generation of tools to help manage trees and optimize such systems.

We hypothesized that: (i) different management strategies in livestock production systems would promote modifications in the growth and yield of trees and in potential carbon sequestration and (ii) there are relationships between tree dendrometric variables and solar radiation transmission in these systems, allowing the generation of information to support their management. We therefore estimated the stem volume, biomass, and carbon stocks of *Eucalyptus urograndis* (GG100 clone) trees (five and eight years old) cultivated in two different agroforestry systems; we then assessed the relationship between tree stand parameters and photosynthetically active radiation (PAR) transmission in these systems.

2. Materials and methods

2.1. Experimental design

This study was conducted in two systems (one ILF and one ICLF) at Embrapa Pecuária Sudeste in São Carlos, São Paulo State, Brazil (21°57′S, 47°50′W, 860 m a.s.l.) from April 2011 to July 2019. The soil at the study site was classified as dystrophic red-yellow latosol, medium-textured/clayey dystrophic (Calderano Filho et al., 1998). The climate is tropical (Köppen classification: Cwa) with two well-defined seasons: dry (from April to September) with an average temperature of 19.9 °C and 250 mm of rainfall, and wet (from October to March) with an average temperature of 23.0 °C and 1100 mm of rainfall.

Table 1
Annual nitrogen fertilization amounts in the crop-livestock-forest integration system (ICLF), where pasture renewal was performed in one-third of each replication of area (two paddocks) per year, and the livestock-forest system (ILF), where pasture was not renewed, from 2013 to 2019 in São Carlos, SP.

System	kg of Nitrogen ha^{-1}						
	Growth season						
	2013/14	2014/15	2015/16 [(1)]	2016/17	2017/18	2018/19 [(1)(2)]	Average
ICLF	151	188	40	141	141	–	110.1
ILF	1566	202	40	132	132	–	110.4

[(1)] Growth seasons without pasture renewal.
[(2)] Growth season without nitrogen fertilization.

Eucalyptus trees (*Eucalyptus urograndis* clone GG100) were planted in April 2011, in single rows, with a nearly east-west orientation and a 15 × 2 m spacing (15 m between rows and 2 m between trees within rows), resulting in a population density of 333 trees ha^{-1}. In July 2016, the trees were thinned (50% removed from each row), changing the spacing to 15 × 4 m (167 trees ha^{-1}). The thinning of the trees was already planned at the beginning of planting and in integrated systems it aims to increase the transmission of solar radiation and improve the quality of the wood from the remaining trees

Each integrated system was 6 ha, split into two experimental areas of 3 ha each. These areas were further divided into six0.5 ha paddocks and managed as rotational stocking systems. A pasture of palisade grass [*Urochloa (syn. Brachiaria) brizantha* (Hochst ex A. Rich.) Stapf cv. BRS Piatã] was managed under rotational stocking, using Canchim steers (cross breed *Bos taurus* Charolais x *Bos indicus*) with stocking adjusted according to pre-grazing forage mass, an occupation period of six days, and a resting period of 30 days.

In ICLF, pasture renewal was performed in one-third of each replication (two paddocks) per crop year, where the grass was simultaneously sown with corn (*Zea Mays* L. var. DKR 390 PRO 2) for silage. Pasture renewal was carried out in the 2013–2014, 2014–2015, 2016–2017, and 2017–2018 growing seasons. During the period between grass-corn sowing and grazing onset, grazing was not conducted in the renewed plots, while in the non-renewed ICLF plots, grazing cycles comprised 9 days of occupation and 27 days of resting.

During the experimental period, lime and fertilizer recommendations were calculated based on soil analysis. Lime was applied to increase the base saturation to 60%, P fertilizer (single superphosphate, 18% P_2O_5) to increase soil P to 12 mg dm^{-3}, and K fertilizer (KCl, 60% K2O) to increase exchangeable K to 3% of soil cation exchange capacity. The production systems received nitrogen fertilization averaging 110 kg N ha^{-1} per growing season (Table 1).

3. Tree measurements

Between 2012 and 2019, half-yearly (April and October) evaluations of tree growth were carried out. Stem diameter at breast height (DBH, 1.3 m above the ground) and tree height (H) were measured in 15 trees from all the paddocks (12) of each system. DBH measurements used a diametric tape and H measurements used a Haglof hypsometer.

Table 2
Diametric classes, occurrence frequency, and number of trees sampled to determine volume and biomass of *Eucalyptus urograndis* (Clone GG100) trees, five and eight years old, in different integrated systems in São Carlos, SP.

Year after planting (year)	Diameter interval (cm)	Medium diameter at breast height (DBH)	Frequency (%)	Number of cubed trees	Number of trees for biomass
	< 17.8	Medium DBH – 2SD	7	5	2
	17.8–20.3	Medium DBH – 1SD	18	8	3
5	20.3–22.8	Medium DBH	45	15	4
	22.8–25.3	Medium DBH + 1SD	25	8	3
	> 25.3	Medium DBH + 2SD	5	4	2
	< 25.1	Medium DBH – 2SD	5	3	1 (1) [1]
	24.1–28.3	Medium DBH – 1SD	29	20	3 (1)
8	28.3–31.5	Medium DBH	38	26	6 (4)
	31.5–34.8	Medium DBH + 1SD	20	15	2 (1)
	• 34.8	Medium DBH + 2SD	8	6	2 (1)

[1] Number in brackets represents the number of trees that had their roots evaluated at eight years age.

4. Estimating volume, biomass, and carbon pools

An allometric equation was developed to estimate stem volume and tree biomass per area based on tree assessments performed in April 2016 and April 2019, when trees were cut according to the planning for the experimental sites.

Based on the tree-growth measurement data, trees were divided into diameter classes with an amplitude of 2.5 cm (defined according to the variation of the standard deviation (SD)) (Table 2). During cutting, 40 trees for the 2016 evaluation and 70 trees for the 2019 evaluation were selected for rigorous tree scaling and divided into five diametric classes as follows: medium DBH, medium DBH + 1SD, medium DBH-1SD (medium classes), medium DBH-2SD (dominated), and medium DBH + 2SD (dominant). Rigorous tree scaling consisted of measuring the diameters of these 110 trees, using a diametric tape, every 0.2 m up to 1.3 m height, and at each meter above 1.30 m up to the height where the stem had a diameter of 6 cm. The individual volume (V) of the trees was calculated by applying the Smalian formula in successive Sections 1 m long, as presented by Muller et al. (2009):

$$V = \sum_{i=1}^{n} \left(\frac{\pi}{80000}\right)\left(Dx^2 + Dy^2\right)Li \tag{1}$$

where n is the number of sections, Dx is the larger diameter of section i (cm), Dy is the smaller diameter of section i (cm), and Li is the length of the section (m).

The data obtained from rigorous tree scaling were used to adjust the logarithmic model for volume estimation regarding the DBH and H function as described by Schumacher-Hall (1933):

$$lnV = b_0 + b_1 * lnDBH + b_2 * lnH \tag{2}$$

In both evaluations (2016 and 2019), 28 trees (14 in each evaluations) were used to evaluate the biomass of shoots and roots, according Higa et al. (2014). For shoot evaluation, the stem and canopy were separated and the stem was segmented into five parts: the first from 0.10 to 1.3 m in height and the other four distributed in equal segments above 1.30 m to the height where the stem had a diameter of 6 cm.

The diameter at the beginning and end of each segment and segment mass were also measured, then a stem sample (15 cm ring) was obtained from each segment. The samples were sent to a laboratory to determine the moisture content after oven drying at 60 °C until a constant weight was attained. For these samples, the density (ratio of dry mass to volume) and carbon content were determined by an elemental analyzer (Perkin Elmer model CHNS 2400ii) and cellulose and lignin contents were determined by the sulfuric acid method at 72% (Van Soest and Wine, 1968).

The canopy was separated into thin branches (diameter < 2.5 cm), thick branches, leaves, and inflorescences. Then, each fraction was weighed, and two subsamples were removed from each (~500 g for leaves and 1 kg for other components). Leaf samples were used to determine leaf area with an integrator (model LI-3100, Li-Cor, Lincoln, Nebraska, USA). Subsequently, the dry mass of the components was determined after oven drying at 60 °C until a constant weight was attained.

Root mass was assessed by collecting roots with a diameter > 1 cm through excavation. After cleaning and weighing the roots, two samples of ~1 kg were removed to determine dry mass after oven drying at 60 °C until a constant weight was reached. In the 2019 assessment (with trees eight years old), nine of the fourteen biomass trees had their roots evaluated.

Equations similar to those applied for the volume estimations were adjusted for estimating the biomass of the shoots and stems, using the data from the assessed 28 trees. Carbon stocks were determined by multiplying the biomass by the average carbon content.

4.1. Microclimatic measurements and PAR transmittance

Photosynthetically active radiation (PAR) was measured continuously at 70 cm aboveground with linear quantum sensors (CQ311, Apogee, Logan, Utah, USA) at the five ICLF positions across the tree lines (under the tree crown, 3.75. m and 7.5 m. in the southern orientation, and 3.75 m. and 7.5 m. in the northern orientation), and with a point quantum sensor (CS110, Apogee, Logan, Utah, USA) in an open pasture (without trees). These sensors were connected to a datalogger (CR1000, Campbell Scientific, Logan, Utah, USA) programmed to take measurements every 10 s, recording averages every 15 min, and total daily values. PAR transmission by trees was calculated by dividing the PAR incidence at each position in the ICLF system by the PAR incidence in the open pasture. The average transmission of PAR in the ICLF system was obtained by averaging the five positions.

4.2. Statistical analysis

Using the growth measurements and the developed equations, the total biomass, stem biomass, and stem volume for each paddock were determined over the experimental period. As each paddock was treated as an experimental unit, 12 repetitions were evaluated in each production system. The means of total biomass, stem biomass, and stem volume were compared using the probability of difference (PDIFF) of the SAS statistical program using the *t*-test and 5% significance.

Regression analysis using several stand parameters and PAR transmission was carried out using Microsoft Excel. For this purpose, two conditions were considered: the relationship considering the annual growing season (July to the following June) and the relationship considering the greatest forage production period (summer, from October to March). The stand parameters were: diameter (m ha^{-1}) obtained by the sum of DBH per ha, basal area (m^2 ha^{-1}) obtained by the sum of basal area per ha, and volume (m^3 ha^{-1}) obtained by the sum of stand volume per ha.

5. Results

The stem, crown, and root proportions of the assessed trees are

Table 3
Morphometric characteristics and structural determinations of *Eucalyptus urograndis* (Clone GG100) trees, five (2016) and eight (2019) years old, in agroforestry systems in São Carlos, SP.

Variable	2016 (%)	2019 (%)
Stem	72.91 (±1.22)	70.67 (±1.62)
Canopy	12.54 (±1.28)	13.07 (±1.62)
Root	14.55 (±0.40)	16.26 (±0.59)

presented in Table 3. In the second assessment, when the trees were eight years old, a slight increase in the proportion of crown and roots was observed. This may have been a consequence of a reduction in intraspecies competition caused by the increase in spacing between trees promoted by thinning.

The Schumacher-Hall model, adjusted with the data from the rigorous tree scaling and the data collected when the trees were five and eight years old, was used to estimate stem volume (V) as follows:

$$lnV = -10.2101 + 1.6808 * lnDBH + 1.2910 * lnH.(R2 = 0.9824) \quad (3)$$

The equations for estimating stem biomass (Bf), aboveground biomass (Ba), and total biomass (Bt), using DBH and H data and adjusted with shoot biomass and root biomass data, were as follows:

$$lnBf = -4.7039 + 2.0489 * lnDBH + 1.1154 * lnH, (R2 = 0.9831) \quad (4)$$

$$lnBa = -3.7215 + 2.3681 * lnDBH + 0.5610 * lnH, (R2 = 0.9751) \quad (5)$$

$$lnBt = -3.8799 + 2.4145 * lnDBH + 0.6155 * lnH, (R2 = 0.9718) \quad (6)$$

The volume and biomass (stem, shoot, and total) estimations using DBH and H had a low dispersion of the residue (Fig. 1), but did not show tendencies toward under or overestimation for the range of values estimated for all variables studied.

Based on these equations, the total biomass, stem volume, and stem biomass of the eucalyptus trees were effectively determined in the two agroforestry systems (Fig. 1 and Table 4) when the trees were five and eight years old. The total carbon in the whole plant and the stem (Table 4) was calculated using the average carbon content of the samples and the biomass values (45.49%).

The dynamics of the increase in volume and biomass of *E. urograndis* trees are presented in Fig. 2. In the first assessment, performed five years after tree planting, stem volume (p = 0.018), stem biomass (p = 0.0195), and total biomass (p = 0.030) were greater in ICLF than in ILF (Table 4). In the second assessment, performed eight years after tree planting, no differences between systems were observed for all variables (Table 4). When the data for the whole experimental period (total) were analyzed, differences were observed for stem volume (p = 0.0369) and stem biomass (p = 0.0434), with higher values for ICLF. The average total biomass of the two systems was 144.7 Mg ha^{-1}, with 65.15 Mg

Table 4
Biomass and carbon (whole plant and stem) and stem volume of *Eucalyptus urograndis* (Clone GG100) trees, five and eight years old, in different agroforestry systems in São Carlos, SP.

System	Year after planting	Stem			Biomass (Total)	Carbon (total)
		Volume	Biomass	Carbon [(1)]		
		m^3	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}
ICLF	5	140.7 a [(2)]	61.4 a	27.6	86.5 a	38.0
ILF	5	128.9 b	55.7 b	25.1	78.4 b	33.5
ICLF	8	155.3 a	73.4 a	33.0	105.1 a	47.3
ILF	8	150.7 a	71.1 a	32.0	101.8 a	45.8
ICLF	Total [(3)]	225.7 a	104.1 a	46.8	148.3 a	66.8
ILF	Total	215.2 b	98.9 b	44.5	141.0 a	63.5

(1) Obtained by multiplying the biomass value by 0.4549.
(2) Means followed by the same letter in the column do not differ by the T test at 5% of significance.
(3) Total (50% of the fifth year plus the eighth year).

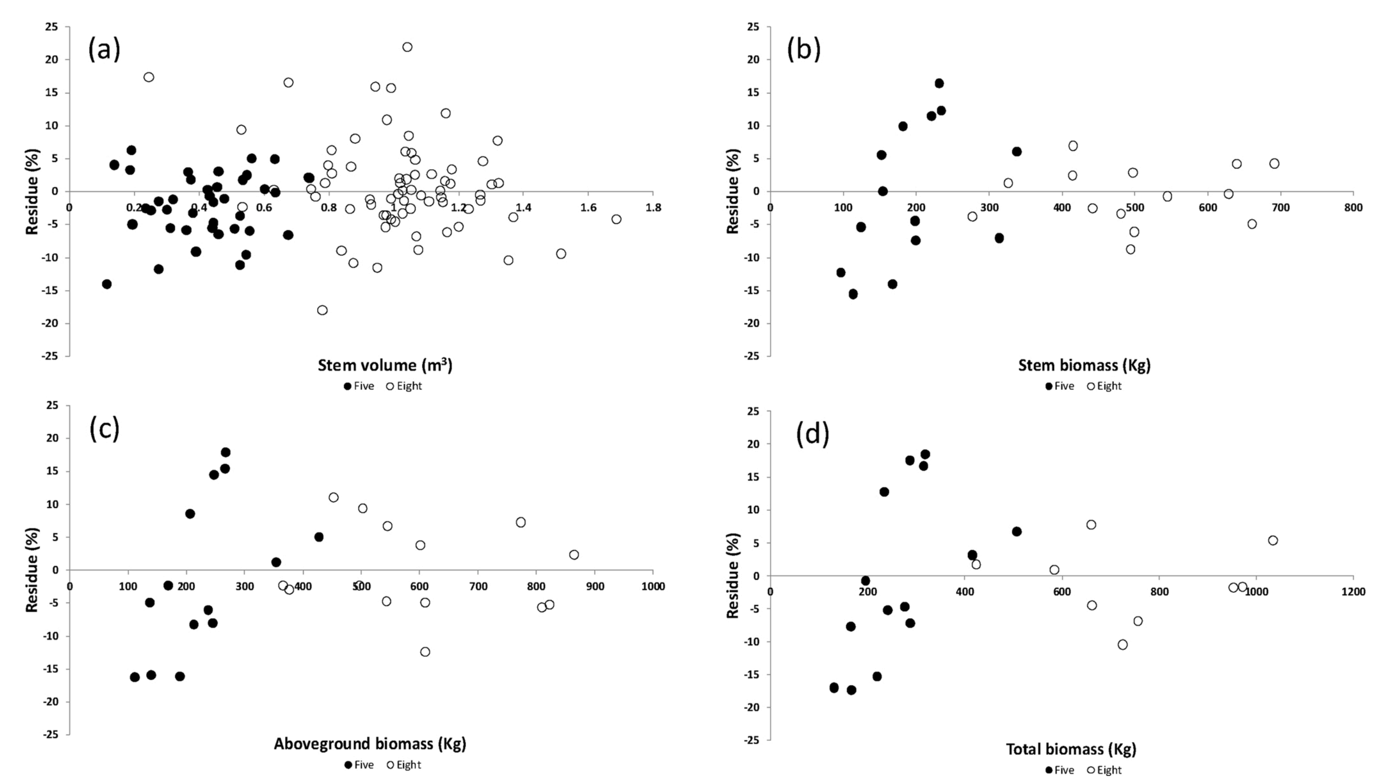

Fig. 1. Residue dispersion for models developed for estimating stem volume (a), stem biomass (b), aboveground biomass (c), and total biomass (d) of *E. urograndis* (GG100 clonal) in agroforestry systems, in the evaluations with five (Five) and eight (Eight) years after tree planting.

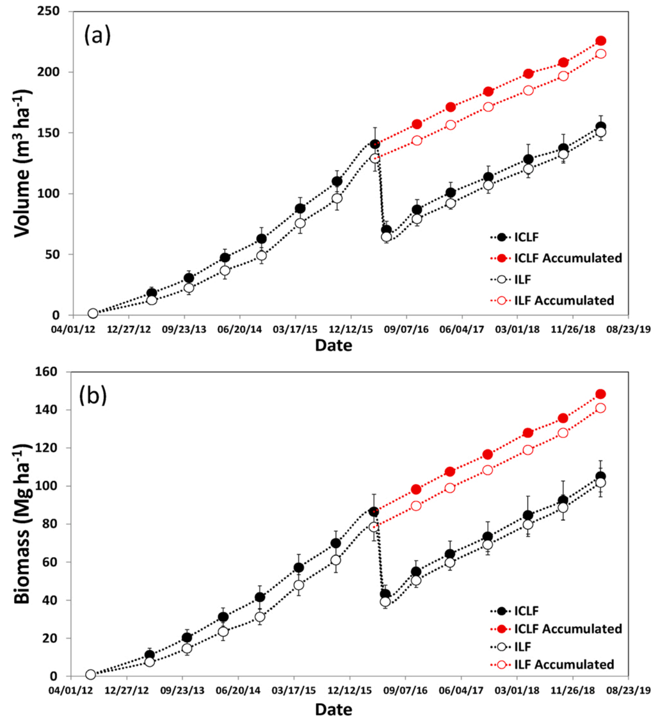

Fig. 2. Stem volume (a) and total biomass (b) of *Eucalyptus urograndis* (Clone GG100) between July 2012 and April 2019, in crop-livestock-forest integration (ICLF) and livestock-forest (ILF) systems in São Carlos, SP, Brazil. The accumulated values (red lines) were calculated by summing the volume and biomass of the trees removed at thinning with the accumulation of the remaining trees (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

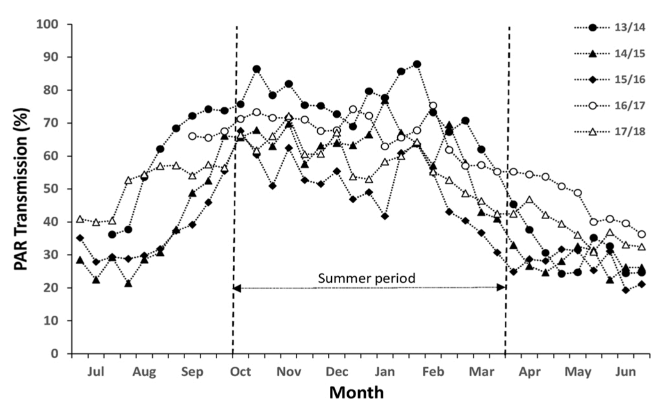

Fig. 3. Photosynthetically active radiation transmission by eucalyptus trees in the integrated livestock-forest system during the six years of the study period in São Carlos, SP, Brazil.

ha^{-1} carbon.

Tree growth and thinning promoted alterations in PAR transmission during the experimental period. Due to the orientation of the tree rows (east-west), the highest values of PAR transmission were observed during spring and summer (summer period) (Fig. 3). During this period, PAR transmission was more important, since environmental factors promoted higher pasture growth, and average PAR transmission varied between 75% (2013–2014) and 52% (2015–2016 and 2018–2019). In autumn and winter, with higher inclination due to the apparent movement of the sun, the trees promoted lower PAR transmission (Fig. 3). Considering the annual average, PAR transmission values varied between 61% (2013–2014) and 41% (2015–2016). Tree thinning performed in 2016 caused an increase in PAR transmission, from 51 to 67%, in the subsequent summers (Fig. 3).

The relationships between the stand parameters of the eucalyptus trees and PAR transmission, considering the annual average and the period between October and March (summer), are presented in Fig. 4. For basal area and volume, the relationship obtained for the summer period presented higher R^2 values than those for the whole year. An inverse relationship was observed between the diameter and PAR transmission. Comparing the three stand variables used, the basal area presented higher R^2 values, with $R^2 = 0.69$ ($p = 0.04$) for the whole year and $R^2 = 0.92$ ($p = 0.002$) for the summer period.

6. Discussion

The proportions of stem and root mass to total biomass were similar to those reported by Tsukamoto Filho (2003) for six-year-old hybrid eucalyptus clones in ICLF with 250 plants ha^{-1} (65.5% and 12.2%, respectively).

The equation for volume estimation was similar to those obtained by Campos and Leite (2002) and Muller et al. (2009). The Schumacher-Hall model presented adequate statistical performance for predicting eucalyptus tree volume using DBH and H measurements. The equation's parameters were similar to those used by Muller et al. (2009), despite different species and row configurations; that study used eucalyptus (*E. grandis*) and mangium (*Acacia mangium*) planted in 30 m apart, totaling 105 trees ha^{-1}.

The higher volume and biomass values observed in ICLF (compared to ILF), mainly when the trees were five years old, could have been due to the better utilization of residual fertilizers when the pasture was renewed by corn sowing, despite the annual nitrogen input being similar between systems (Table 1). Tsukamoto Filho (2003) produced similar results.

The variation of volume accumulation per year ranged from 26.9 (ILF) to 28.2 m^3 (ICLF) ha^{-1} year^{-1}, slightly higher than the values cited by Ofugi et al. (2008), who reported that ICLF with 250–350 eucalyptus trees ha^{-1}, planned for tree-cutting between 8–12 years old, could produce wood at 25 m^3 ha^{-1} year^{-1}. Abrantes et al. (2019) assessed six-year-old *E. urograndis* (clone H13) trees in silvopastoral systems with 227 and 357 trees ha^{-1} and obtained a stem volume of 0.41 m^3 tree^{-1}. In our study, higher volumes (0.60 m^3 tree^{-1} for ICLF and 0.55 m^3 tree^{-1} for ILF) were obtained when the trees were six years old (Fig. 2), possibly due to the effect of differences in system management, especially the pasture renewal process.

Stem biomass ranged from 12.4–13.0 Mg ha^{-1} year^{-1} (ICLF). In such systems, with densities between 200–250 trees ha^{-1}, Tsukamoto Filho (2003) and Muller et al. (2009) found stem biomass from 8.2–10.75 Mg ha^{-1} year^{-1}. Considering only the remaining trees in our study, assessed eight years after planting when the tree population was 167 trees ha^{-1}, stem biomass accumulation varied from 0.054–0.055 Mg tree^{-1} year^{-1}. Tsukamoto Filho (2003) and Muller et al. (2009) reported lower values of stem biomass accumulation (0.041 and 0.043 Mg tree^{-1} year^{-1}, respectively). These differences may be due to tree thinning in our experiment, which promoted lower population density between the fifth and eighth year after planting and/or to tree genetic material.

Trees' potential for carbon accumulation in agroforestry systems depends, among other factors, on species and population density. Gutmanis (2004) used *Pinus elliotti* at densities of 200 and 400 trees ha^{-1} to obtain an estimated annual 2.7 Mg ha^{-1} and 4.8 Mg ha^{-1} of accumulated carbon in stems, respectively. This potential seemed to be greater under our conditions for *E. grandis*. Figueiredo et al. (2017), assuming an average wood yield of 26 m^3 ha^{-1} for *E. urograndis* (similar to our volume using 330 trees ha^{-1} until five years after planting and 167 trees ha^{-1} between five and eight years), estimated an average stem carbon sequestration rate of approximately 4.75 Mg ha^{-1} year^{-1}, equivalent to a carbon pool ranging from 5.6 (ILF) to 5.9 (ICLF) Mg ha^{-1} year^{-1}.

These data show the high yield potential of trees in integrated

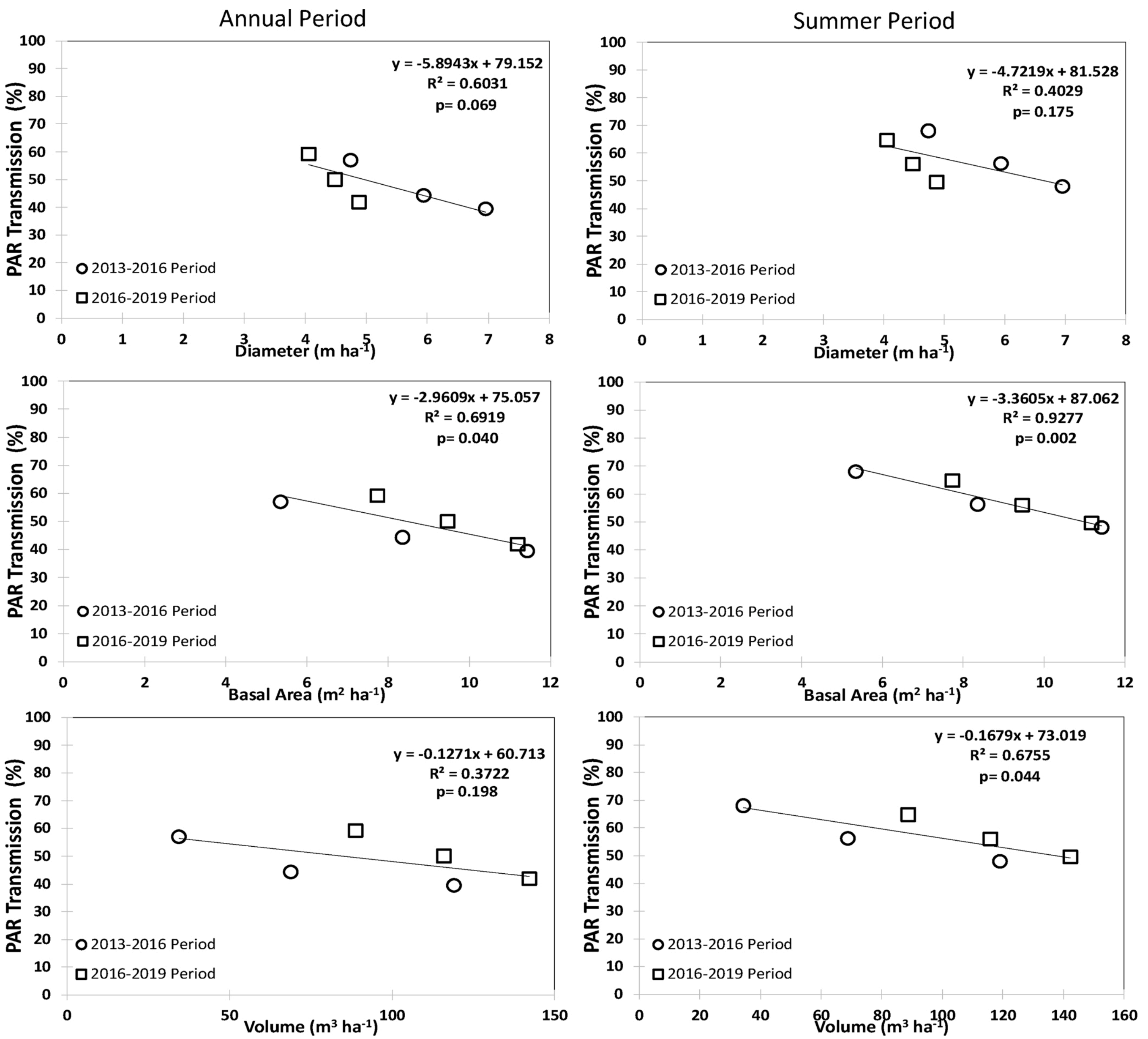

Fig. 4. Relationship between diameter (m ha^{-1}), basal area (m^2 ha^{-1}), volume (m^3 ha^{-1}) and photosynthetically active radiation (PAR) transmission in both agroforestry systems for the 2013–2016 (before thinning) and 2016–2019 (after thinning) growing seasons, considering the annual period (from July to June, left) and summer period (from October to March, right).

systems and the capacity of these systems to remove atmospheric carbon and mitigate GHG emissions. This may be higher than reported in our study, since the potential increase in soil carbon stocks in integrated systems conducted in Brazilian conditions was not considered (Cerri et al., 2007; Carvalho et al., 2014; Salton et al., 2014).

The potential for carbon sequestration by tree stems in integrated systems is related to their use as solid wood (e.g., lumber, fences or posts), where the carbon sequestered stays stored in the biomass for long periods. In this context, these systems are characterized by dynamic interactions that change over time, especially regarding shading by growing trees (Jose et al., 2004). Therefore, over time, a strong competition between the components is established, mainly for light, which leads to a reduction in grazing productivity that requires control through thinning (Reynolds et al., 2007).

However, wood from partial thinning, especially earlier thinning at five years old, is usually allocated to short-term use, such as firewood and charcoal, in which case this wood should not be considered as carbon sequestration. On the other hand, thinning has a positive effect on timber production and thus on the biomass and carbon of the remaining trees, as shown by Gorgens et al. (2007) and Trevisan et al. (2007).

A system that integrates trees and livestock production aims to create synergy between its components. The interactions between trees that occur in integrated systems, with both positive and negative effects, occur as a function of patterns in resource partitioning (mainly solar radiation, water, and nutrients), which are influenced by the age of each component (Gillespie et al., 2000; Rivest et al., 2013). Integrated systems with high tree population density have a negative influence on pasture productivity, as verified by Santos et al. (2018) in a silvopastoral system with 417 and 715 eucalyptus trees ha^{-1} at five years after planting. In the same area as our study, Pezzopane et al. (2020a) reported a 36% reduction in forage yield in a crop season (2014–2015) before tree thinning was performed in 2016. After thinning, Pezzopane et al. (2020b) reported similar corn and forage yields between shaded and full sun systems.

The management of integrated systems by monitoring their productive components and performing thinning and pruning of trees is necessary to minimize intra- and interspecies competition and help farmers obtain satisfactory productivity (Pollock et al., 2009; Nicodemo et al., 2016; Gomes et al., 2019). For silvopastoral systems, one main objective is to maintain PAR transmission at levels suitable for tropical pasture production. Tropical forages such as *Urochloa spp*. and *Panicum* spp., which are the most commonly used in Brazilian pasturelands, can tolerate 30% shade (Paciullo et al., 2011; Pezzopane et al., 2020a), though this can be 40% for recently planted pastures (Pezzopane et al., 2019b).

Several studies have correlated structural tree parameters with PAR transmission in forest and silvopastoral systems (Comeau and Heineman, 2003; Lhotka and Loewenstein, 2006; Wall et al., 2010). Some parameters related to measurements of tree dimensions, such as those used in our study (tree height and stem diameter), are simple and easily obtained. Other parameters are more difficult to obtain, such as those derived from images related to light capture by the tree canopy (Wall et al., 2010).

In our study, the best parameter for estimating PAR transmission was basal area. Comeau et al. (1998) reported that basal area had a strong relationship with PAR transmission in a paper birch (*Betula papyrifera* Marsh.) stand. In Canada, Comeau (2001) also used this parameter in a forest of boreal aspen (*P. tremuloides* Michx.), with PAR transmission lower than 40% and 60% when the basal area exceeded 14 m^2 ha^{-1} and 8 m^2 ha^{-1}, respectively. In these studies, as in Wall et al. (2010), the relationship between basal area and PAR transmission followed an exponential decrease. In our study, this decrease was linear (Fig. 4), which can be explained by the lower basal area in our system than that in the previous studies.

Information about the relationship between tree growth (expressed here as basal area) and PAR transmission can be an important tool to support tree management in agroforestry systems. Measurements in systems with trees with higher basal areas can expand and validate this tool's use, as suggested by Comeau et al. (1998). For the tropical pastures, 65% of PAR transmission can be considered a limiting value, with lower values being limiting for tropical forage production in integrated systems with trees (Paciullo et al., 2011; Pezzopane et al., 2019b, a). Following the relationship between basal area and PAR transmission (Fig. 4), the basal area of 8 m^2 ha^{-1} indicates the need for some thinning to optimize forage production in such systems.

7. Conclusions

The Schumacher-Hall (1933) model, in its linearized form, presented satisfactory adjustments for estimating the stem volume and biomass of trees in agroforestry systems. Pasture renewal in the first years after system implementation promoted higher initial tree growth, which promoted higher values of stem volume and biomass in the ICLF when the trees were five years old. When trees were eight years old, the ICLF presented higher stem volume than the ILF. The two integrated systems presented a great capacity for carbon accumulation by trees. The basal area of the tree component of the integrated systems was strongly related to PAR transmission, indicating that this relationship can be used to support the management of these systems.

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CRediT authorship contribution statement

José Ricardo Macedo Pezzopane: Conceptualization, Methodology, Resources, Writing - original draft, Funding acquisition. **Cristiam Bosi:** Resources, Formal analysis, Writing - review & editing. **Alberto Carlos de Campos Bernardi:** Conceptualization, Resources, Writing - review & editing, Funding acquisition. **Marcelo Dias Muller:** Methodology, Investigation, Formal analysis. **Patrícia Perondi Anchão de Oliveira:** Conceptualization, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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