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Diameter growth of eucalyptus trees in agroforestry systems and its relation to air temperature and precipitation

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Abstract In agroforestry systems, such as integrated crop-livestock-forest (iCLF), the agricultural, livestock and arboreal components are explored in the same field in rotation, succession or intercropping. Our objective was to investigate if the diameter growth of eucalyptus in agroforestry systems differs from those cultivated as a planted forest, as well as to assess whether there is a difference in its growth in face of the air temperature and precipitation. The study was held at Ponta Porã, Brazil, a region of humid subtropical climate with hot summers and soil classified as Oxisol, which is fertile, deep and clayey. Dendrometer bands measured the diameter growth of eucalyptus (*Eucalyptus urograndis*) cultivated as a forest and in iCLF, with eucalyptus rows distance of 12.5 × 12.5 m, 12.5 m one side × 25 m another side and 25 × 25 m. The study took place from four years and nine months after transplanting till six years and seven months (22 months monitoring). On iCLF, the inter-row was explored with grain crops (soybean or corn) and pasture. Climate data of air temperature and precipitation were used to investigate their influence or not on diameter growth. Eucalyptus diameter growth is higher when cultivated in agroforestry systems and this growth is as higher as larger is the distance between eucalyptus rows. Precipitation proved to strongly and positively influence the diameter growth, especially when cultivated in agroforestry systems. On the other hand, under the conditions of this study, air temperature showed little or no correlation with eucalyptus diameter growth.

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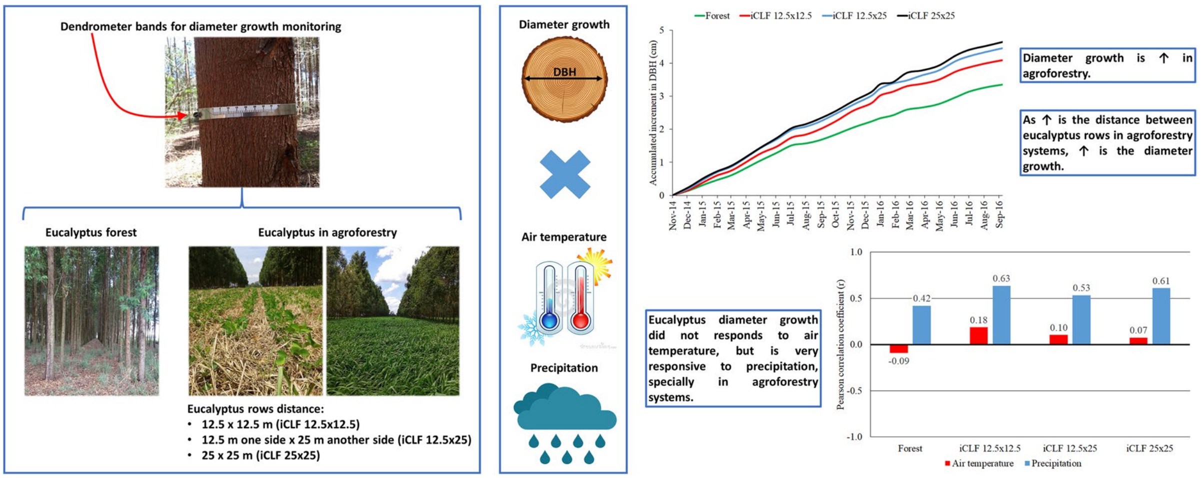
Graphical abstract



Keywords Dendrometer · Diameter at the breast height · Climate change · Water deficit

Introduction

Evaluating the dynamics of trees radial growth is of great importance in order to enhance our comprehension about how forest species responds to the stimuli and variations of climate conditions. Hence, dendrometers has been applied for this purpose for studying tropical species (Komiyama el al. 2019; Vourlitis et al. 2022) and also for temperate ones (D'orangeville et al. 2022; Drew et al. 2022).

According to Fahn et al. (1981), the periodicity of cambium activity looks like to be a consequence of fluctuations in temperature, day length and precipitation, while the endogenous factors related to the species controls growth rhythm.

Eucalyptus (*Eucalyptus* spp.) is the most cultivated forest genus in the world covering an area of around 25 million ha (Elli et al. 2020), with Brazil being the top producer with 7.5 million ha (IBÁ 2022). In Brazil, eucalyptus is used for multiple purposes and presents interesting characteristics for the forest sector. According to Silva (2002), it has high productivity potential because of its smooth adaptation to the climates and soils prevailing in the country.

Although usually eucalyptus is cultivated as a forest, its insertion in the field as a component together with crops and/or pastures can push changes to the production environment, potentially incorporating benefits in favor of the agricultural sustainability. Such integrated production system, an agroforestry one, has been consolidated over time and is called Integrated Crop-Livestock-Forest (iCLF). In it, according to Faria et al. (2015), the agricultural, livestock and arboreal components are explored in the same field in rotation, succession or intercropping. Measuring tree growth of timber trees is crucial to understand the overall growth trends and to better know when farmers/ranchers can potentially harvest timber from intercropped trees.

In tropical regions the climate factors that has been disseminated to be more relevant in explaining the diameter growth responses of eucalyptus are the air temperature and precipitation (Freitas et al. 2017; Elli et al. 2020; Queiroz et al. 2020; Abreu et al. 2022). However, assuming that eucalyptus cultivated as a forest or in an agroforestry system may respond differently to these climate variables, studies regarding this issue are required because they are scarce. Considering this, we hypothesize that the diameter growth response to the air temperature and precipitation of eucalyptus when cultivated in agroforestry systems is different from that of a planted forest.

Therefore, the objective of this study was to investigate if the diameter growth of eucalyptus cultivated in agroforestry systems (iCLF) differs from that cultivated as a planted forest, as well as to assess whether

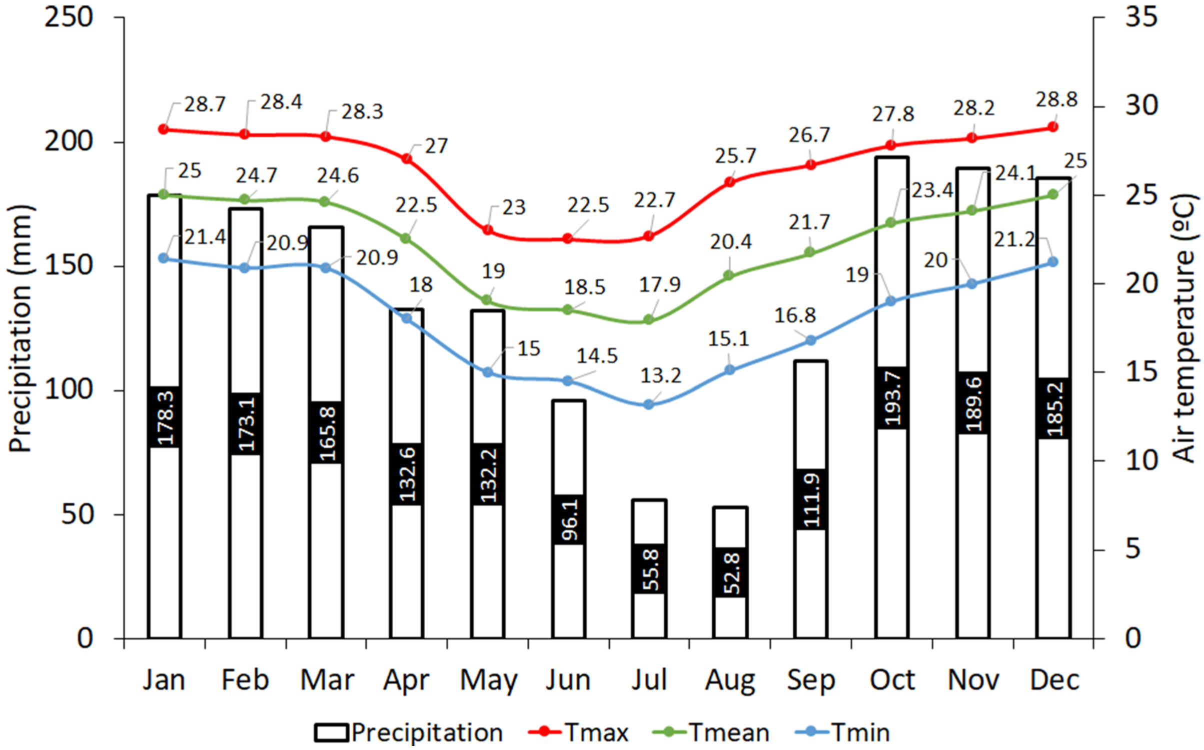


Fig. 1 Climatology of precipitation and air temperature (T) of Ponta Porã, Mato Grosso do Sul State, Brazil. Data obtained from Souza (2018)

there is a difference in its growth in face of the air temperature and precipitation.

Materials and methods

Description of the study area

This study was held at the experimental station of Embrapa Western Agriculture (Brazilian Agricultural Research Corporation) at the city of Ponta Porã, Mato Grosso do Sul State, Brazil (22º32′56″ S; 55º38′56″ W; 680 m above sea level).

Regional climate is classified as Cfa, according to the Köppen-Geiger classification updated by Peel et al. (2007), being defined as humid subtropical climate with hot summers. According to Souza (2018), as disposed in Fig. 1, mean annual precipitation is 1667 mm, being October the rainiest month with 194 mm, and August the driest one with 53 mm (statistics from a database of 47 years and 5 months). Mean annual air temperature is 22 °C, being July the coldest month (average of daily minimum equal to 13.2 °C) and December the warmest (average of daily maximum equal to 28.8 °C) (statistics from a database of 26 years).

The soil over the experimental area is quite homogeneous and is classified as an Oxisol, presenting medium to high fertility, while being deep and clayey (50 to 70% clay). Nonetheless, its clay fraction is a 1:1 type, predominating kaolinite and iron oxide (more than 18%), which is the reason for the water retention capacity in this soil to be lower as compared to other clayey soils. This also implies in higher infiltration rates and lower cation exchange capacity. The topography is flat, with slopes lower than 3%.

Experimental area and treatments

The experimental area (Fig. 2) had 17.3 ha and consisted in a technological reference unit on iCLF maintained by Embrapa Western Agriculture. It had different production systems which were installed for about five years when this study had begun.

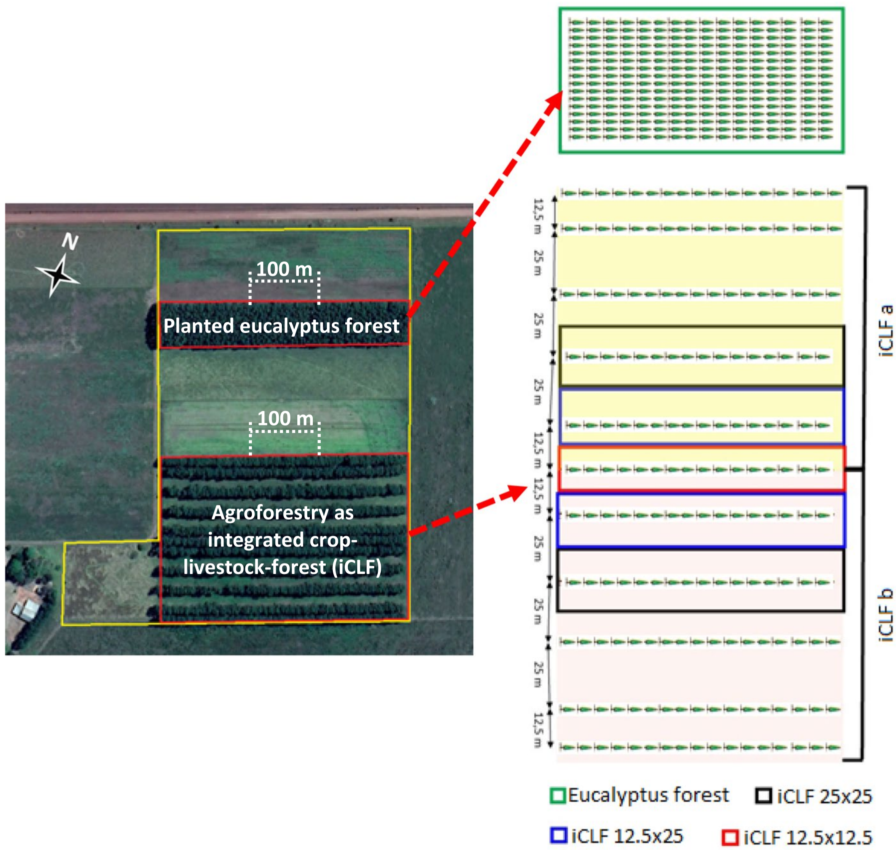


Fig. 2 Satellite image from Google Earth of the experimental area with 17.3 ha (yellow line) at Ponta Porã, Mato Grosso do Sul State, Brazil. In detail, a sketch (not to scale) of the production systems studied here

Previously, the area was uniformly cultivated for 30 years with annual crops. Briefly, at the experimental area the production systems exploited one or more of the following species: soybean (*Glycine max*) as summer crop; corn (*Zea mays*) as off-season crop (from autumn to winter); pasture (*Brachiaria brizantha* cv. Xaraés) all year round; and eucalyptus permanently (*Eucalyptus urograndis*, a hybrid between *Eucalyptus grandis* and *Eucalyptus urophylla*).

Among all production systems, this study concerned the analysis of eucalyptus diameter growth at the plots cultivated as a forest and in agroforestry, iCLF, as highlighted in Fig. 2, and described below:

- Treatment 1: Eucalyptus forest;
- Treatment 2: Integrated crop-livestock-forest with eucalyptus row distance of 12.5 × 12.5 m (iCLF 12.5 × 12.5);
- Treatment 3: Integrated crop-livestock-forest with eucalyptus row distance of 12.5 m one side × 25 m another side (iCLF 12.5 × 25);
- Treatment 4: Integrated crop-livestock-forest with eucalyptus row distance of 25 × 25 m (iCLF 25 × 25).

In Treatment 1, the eucalyptus forest had a total area of 1.6 ha, being 50 m wide (16 eucalyptus rows) and 320 m long. The plantation design was 3 m between eucalyptus rows and 2 m between trees, totalizing 2560 trees (1600 trees ha^{-1}). Rows were aligned in an almost east to west orientation.

Every iCLF treatment (Treatments 2 to 4) used a single eucalyptus row design, also aligned in an almost east to west orientation, with trees distance of 2 m each other inside a 320 m long row. As disposed in Fig. 2, the total iCLF area of 6.6 ha was splitted into two equal plots (i.e., "iCLF a" and "iCLF b"), in such a way that the eucalyptus inter-row space was cultivated with crops or pastures,

Table 1 Treatments arrangement described sequentially in time according to the rotation plan in iCLF systems. Readers are referred to Fig. 2 for a better comprehension

	Forest	iCLF 12.5×12.5	iCLF 12.5×25		iCLF 25×25	
			iCLF a	iCLF b	iCLF a	iCLF b
Nov/2014—Oct/2015	E	C/P	P	C	P	C
Nov/2015—Sep/2016	E	C/P	C	P	C	P

iCLF: integration crop-livestock-forest; E: eucalyptus; C/P: one side crop, another side pasture; P: pasture; C: crop.

being them rotated every two years. This inter-row cultivation, which followed a rotation plan, started at the moment when eucalyptus trees were planted, i.e., about five years before this study had begun. During the period of this study the systems rotation occurred once in October 2015; that is, the plot "iCLF a" in which we had pasture (*Brachiaria brizantha* cv. Xaraés) started to be cultivated with crops (soybean during the summer and corn intercropped with *Brachiaria brizantha* cv. Xaraés from autumn to winter); on the other hand, the another plot ("iCLF b"), which previously had crops, started to be cultivated with pasture (Table 1).

Trees population in the configuration iCLF 12.5×12.5 was equivalent to 400 trees ha^{-1} (8 rows ha^{-1}), while in the treatment iCLF 12.5×25 it was 300 trees ha^{-1} (6 rows ha^{-1}) and, finally, treatment iCLF 25×25 with 200 trees ha^{-1} (4 rows ha^{-1}).

The eucalyptus was transplanted in February 2010, using seedlings from seeds. They received fertilizers on June 2012, with 2 years and 5 months after transplanting, manually applying 200 mL tree^{-1} of a boron fertilizer source and NPK granular fertilizer 0–20–20.

The crop and pasture components on iCLF were managed wishing to allow them to express a full production considering the environmental conditions in which they were cultivated, by using strategies and technologies similar to those used by reference regional farmers. Pasture was always managed with beef cattle grazing it.

Diameter growth monitoring

A total of 90 trees had its diameter growth monitored, being 15 from the eucalyptus forest, 15 from iCLF 12.5×12.5, 30 from iCLF 12.5×25 (15 at "iCLF a" and 15 at "iCLF b") and, finally, 30 from iCLF 25×25 (also 15 at "iCLF a" and 15 at "iCLF b"). This unbalanced number of evaluated trees was necessary to accommodate the requirement of equally take into account trees samples that were, at a certain moment, experiencing the pasture phase of iCLF as well as the crop phase; e.g., as seen in Table 1, "iCLF 25×25 a" was with pasture from November 2014 till October 2015, while "iCLF 25×25 b" was at that moment with crop, and both were computed in favor of iCLF 25×25 treatment. This procedure avoided to bring bias to the results and was carefully took into account at the moment of statistical analysis.

A few criteria were used to choose the trees to be monitored. First they should be from the central portion of each plot. Therefore, as disposed in Fig. 2, although every tree row was 320 m long, only trees from the 100 m central portion were considered candidates to be monitored. In addition to this, in the case of the eucalyptus forest, from the existing 16 eucalyptus rows, only trees from the four inner rows were allowed to be selected. These precaution were adopted in order to avoid sampling trees influenced by border effect and also to guarantee that sampled trees were exposed to an equilibrium boundary layer where atmospheric conditions was uniform.

After this first criteria, 200 trees of the eucalyptus forest and 50 from the other plots (iCLF 12.5×12.5, iCLF 12.5×25 a, iCLF 12.5×25 b, iCLF 25×25 a, and iCLF 25×25 b) advanced to the second criteria scrutiny. Then, these trees were visually inspected searching for trees that were looking to be healthy and without injuries, tortuosity and branching. Those trees that remained after met this criterion were then numbered and submitted to a random sampling process in order to select the trees that would be continuously monitored in this study.

The diameter growth monitoring of the selected trees was done almost monthly, from November 2014 (4 years and 9 months after transplanting) till

Fig. 3 Dendrometer band used for measuring eucalyptus circumference at the breast height (CBH; at 1.3 m above soil level)

September 2016 (6 years and 7 months after transplanting), totalizing 22 months of monitoring. Trees circumference at the breast height (CBH) was measured using dendrometer bands (Fig. 3), installed on the trunks at a fixed height of 1.3 m above soil level.

The dendrometers were made up and used following the recommendations described in Botosso and Tomazello Filho (2001). The CBH was measured by means of Eq. 1:

$$CBH = CBH_{initial} + (DR \times 0.2) - \left(DR_{initial} \times 0.2\right) \quad (1)$$

where CBH is the circumference at the breast height (cm), $CBH_{initial}$ is the circumference at the breast height measured on the installation of the dendrometer (cm), DR is the dendrometer reading (in nonius units) and $DR_{initial}$ is the dendrometer reading on its installation (in nonius units).

CBH values were then converted into diameter at the breast height (DBH) using Eq. 2:

$$DBH = \frac{CBH}{\pi} \quad (2)$$

where DBH is the diameter at the breast height (cm) and CBH is the circumference at the breast height (cm).

The DBH data was used to evaluate the diameter growth of the 90 trees from the different treatments. It was done by determining the increment in diameter occurred between two consecutive readings, using Eq. 3:

$$DI = DBH_{final} - DBH_{previous} \quad (3)$$

where DI is the diameter increment observed between two consecutive readings (cm), DBH_{final} is the diameter at the breast height on the late reading (cm) and $DBH_{previous}$ is the diameter at the breast height on the early reading (cm).

This DI was relativized as a function of the time interval (in days) for the respective growth to occur. It was important for the present study because the time interval between readings was not regular, although it was normally almost monthly. Therefore, the daily diameter increment (DI_{daily}) was calculated considering the time opportunity for the trees trunk to grow, as disposed in Eq. 4:

$$DI_{daily} = \frac{DI}{ND} \quad (4)$$

where DI_{daily} is the daily diameter increment (cm day^{-1}), DI is the diameter increment observed between two consecutive readings (cm) and ND is the number of days elapsed between two consecutive readings (days).

In order to compare the DI_{daily} series of each treatment in analysis, the pairwise t-test was applied using R environment (R Core Team 2020), evaluating the mean differences between observations (Toloi and Echeverry 2000). The pairwise t-test was chosen because it is effective in situations like this where there are few observations and the number of samples between treatments is unbalanced. Each treatment was individually tested against the others by means of successive tests in order to identify which groups have means different each other. The correction of Holm-Bonferroni Method was applied for preventing false positives.

Analysis of the relation between diameter growth and climate variables

The climate conditions during the experimental period was evaluated considering air temperature (°C) and precipitation (mm). Climate data was obtained from a weather station maintained by INMET (National Institute of Meteorology), located 7 km far, at Ponta Porã city. Daily data from November 2014 till September 2016 was retrieved, the same period in which the diameter growth of eucalyptus trees was monitored. For air temperature we used daily means, while for precipitation daily totals were used.

For this analysis, first we recalculated the DI_{daily} observed between dendrometers readings in intervals almost bimonthly (±61 days). The same was done for air temperature and precipitation, calculating the average of daily means for the former and the sum of daily totals for the later. This bimonthly approach was adopted in order to consider that the responses of diameter growth in forest species like eucalyptus is not so fast as compared to annual crops, for example, in such a way that these responses may be a consequence of climate stimuli occurred a few weeks or months ago.

The analysis regarding the relation between eucalyptus diameter growth and climate conditions considered the temporal dynamics of DI_{daily} in face of the temporal dynamics of air temperature and precipitation. There was investigated if there is any kind of pattern that allows to suggest which climate conditions may result in higher or lower diameter growth. Furthermore, it was explored the correlation analysis between DI_{daily} and air temperature and precipitation. The Pearson correlation coefficient (r) was used, which assumes values between −1 and +1, evidencing strong and negative correlation when tending to −1, few or none correlation when tending to 0 and strong and positive correlation when tending to +1. The r values were calculated using Microsoft Excel 2019®.

Results and discussion

Diameter growth

When the monitoring had begun (at 4 years and 9 months after transplanting), the eucalyptus trees cultivated as a forest had lower DBH (21.4 cm) as compared to the agroforestry systems (from 22.7 to 23.2 cm) (Fig. 4A and Table 2). After 22 months, this initial difference of 1.3 to 1.8 cm has increased till the end of the monitoring (at 6 years and 7 months after transplanting). At that moment, eucalyptus in the forest presented DBH of 24.7 cm, while the agroforestry systems resulted in DBH of 27.2 to 27.7 cm, therefore a difference of 2.5 to 3 cm.

During the monitoring period the observed increment in DBH (Fig. 4B and Table 2) was higher for the agroforestry systems (4.1 to 4.6 cm) as compared to the forest (3.4 cm). Such increment was as higher as larger the distance between eucalyptus rows, being the values measured for iCLF 12.5×25 and iCLF 25×25 very close to each other (4.5 and 4.6, respectively). On the other hand, treatment iCLF 12.5×12.5 showed a lower value (4.1 cm), demonstrating a certain level of intraspecific competition, but still with a growth pattern that remained higher than that observed for the forest.

The diameter growth rhythm was influenced by the time after the production systems implantation. The average annual increment in DBH before the monitoring period was calculated considering the DBH at the beginning of the monitoring divided by 4.75, which was the time opportunity, in years' equivalent, for the trees trunk to grow until that moment, i.e. 4 years and 9 months. So, the average annual increment in DBH before the monitoring period was equal to 4.5 cm year^{-1} for the forest, what represented 92 to 94% of the growth rhythm observed in the trees of the agroforestry systems (Table 2). However, as disposed in Fig. 4B and Table 2, during the monitoring period this difference has increased, since the annual increment in DBH for the forest (1.8 cm year^{-1}) stayed between 72 and 82% of the observed in the agroforestry systems.

These results are similar to those found by Magalhães et al. (2019), working at the northern Mato Grosso State, Brazil. They evaluated the diameter growth of eucalyptus cultivated as a forest and in different agroforestry systems from 10 months till 56 months old. They found that the diameter growth of eucalyptus in forest and agroforestry was similar until the last evaluation was done, when trees were 56 months old (4 year and 8 months). At that moment the eucalyptus in forest presented lower DBH as compared to those in the agroforestry. Also at the northern Mato Grosso, Tonini et al. (2021) evaluated the behavior of the eucalyptus increment in diameter in forest and agroforestry systems. They also observed that the diameter growth of eucalyptus is higher when cultivated in agroforestry systems.

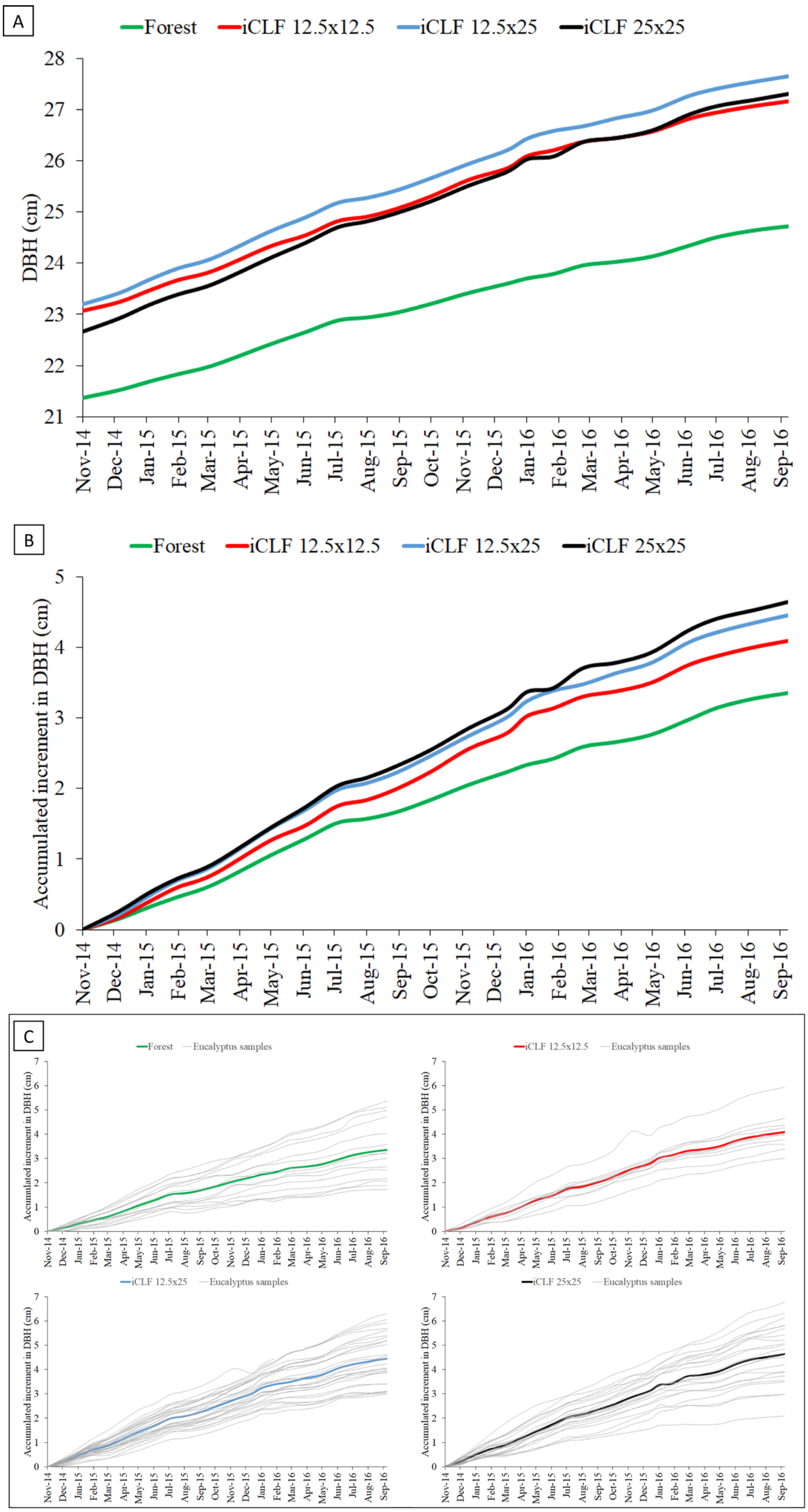


Fig. 4 **A** Diameter at the breast height (DBH) and **B** its accumulated increment of eucalyptus trees in different production systems (forest and iCLF, integrated crop-livestock-forest), from 4 years and 9 months after transplanting till 6 years and 7 months. In **C** a detailed view of the variation in accumulated diameter growth of the evaluated trees and the average for each production system

Table 2 Analysis of eucalyptus diameter growth (DBH; cm) cultivated in different production systems (forest and iCLF, integrated crop-livestock-forest), before the monitoring and during the monitoring period (from 4 years and 9 months after transplanting to 6 years and 7 months)

Production system	DBH_{ini}	DBH_{end}	I DBH_{mp}	AI DBH_{mp}	AI DBH_{bmp}
Forest	21.4	24.7	3.4	1.8	4.5
iCLF 12.5 × 12.5	23.1	27.2	4.1	2.2	4.9
iCLF 12.5 × 25	23.2	27.7	4.5	2.4	4.9
iCLF 25 × 25	22.7	27.3	4.6	2.5	4.8

DBH_{ini} = DBH at the beginning of the monitoring; DBH_{end} = DBH at the end of the monitoring; I DBH_{mp} = increment in DBH during the monitoring period; AI DBH_{mp} = annual increment in DBH during the monitoring period; AI DBH_{bmp} = average annual increment in DBH before the monitoring period.

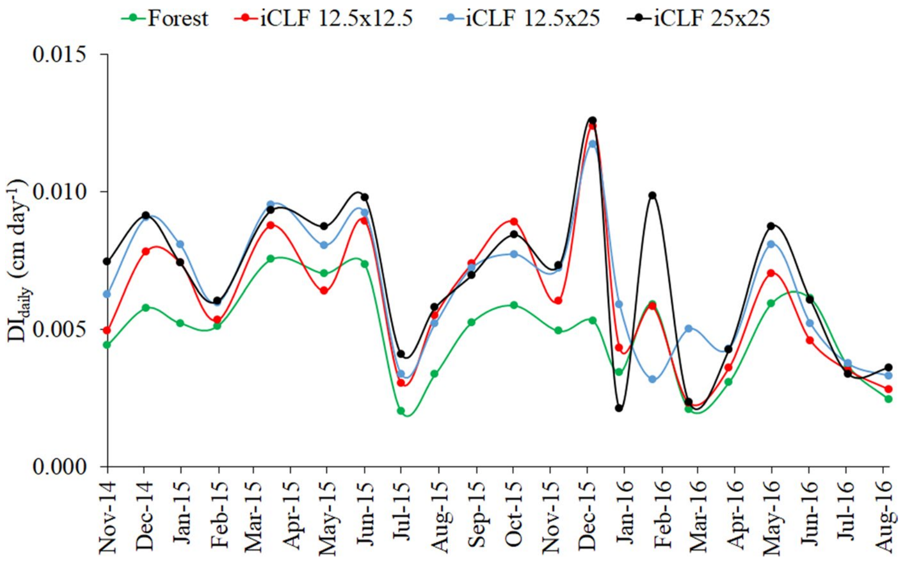


Fig. 5 Daily increment in diameter (DI_{daily}) during the monitoring period for the eucalyptus trees in different production systems (forest and iCLF, integrated crop-livestock-forest)

Table 3 Results of the pairwise t-test applied to the Fig. 5 data series of daily increment in diameter (DI_{daily}) of eucalyptus trees grown in different production systems (forest and iCLF, integrated crop-livestock-forest)

	Forest	iCLF 12.5 × 12.5	iCLF 12.5 × 25
iCLF 12.5 × 12.5	0.0193	-	-
iCLF 12.5 × 25	0.0012	0.1042	-
iCLF 25 × 25	0.0003	0.0314	0.4946

p value ≤ 0.05 means different and > 0.05 means equal

The DI_{daily} of the eucalyptus trees showed some fluctuation during the monitoring period and an overall tendency of higher values when cultivated in the agroforestry systems as compared to the forest (Fig. 5). The mean DI_{daily} was 0.0048, 0.0060, 0.0065 and 0.0068 cm day^{-1} for the forest, iCLF 12.5 × 12.5, iCLF 12.5 × 25 and iCLF 25 × 25 treatments, respectively. Therefore, as compared to the forest, the growth rhythm of eucalyptus in iCLF 12.5 × 12.5 was 25% higher, 35.4% for the iCLF 12.5 × 25 and 41.7% for the iCLF 25 × 25. This finding corroborates with Faria et al. (2015), which states that as bigger as is the distance between eucalyptus rows, higher should be their increment in diameter.

The findings above mentioned was confirmed in the statistical analysis presented in Table 3. Considering the significance level of 95%, the pairwise t-test, applied to evaluate the DI_{daily} series in Fig. 5, rejects the hypothesis that the treatments are similar. According to the results the diameter growth of eucalyptus trees in a forest is lower than all other agroforestry system. In addition, eucalyptus diameter growth in iCLF 12.5 × 12.5 can be considered equal to iCLF

12.5 × 25, but is lower when compared to iCLF 25 × 25. Finally, iCLF 12.5 × 25 and iCLF 25 × 25 can be considered one equal to the other.

In the forest, because it is a dense population (3 m between eucalyptus rows and 2 m between trees), the intraspecific competition is higher if compared to the iCLF systems studied here, since in the later each eucalyptus rows has larger distances between them. As stated by Gilad (2008), the intraspecific competition is a type of competition between individuals of a same species, competing for resources like water, space, light, nutrients, etc., imputing a restricted offer to each individual. This fact justifies the lower values of DBH in the forest, as well as the lower diameter growth rhythm of the trees in it. Although the interspecific competition existing in an agroforestry system may also input some limitation to the diameter growth of eucalyptus (Jose et al. 2004), our results showed that it was less impactful if compared to the competition between individuals of the same species inside a forest.

Similar behavior was observed by Oliveira et al. (2009) in a study conducted at Minas Gerais State, Brazil. The authors evaluated the effect of different planting design over the DBH of an *E. camaldulensis* and *E. urophylla* hybrid, finding that, even for younger trees (18 to 27 months old), the DBH was as lower as the shorter was the spacing between trees at the planted forest. Also, Oliveira et al. (2015) found higher diameter growth and height of a clone of *E. grandis* in an iCLF system as compared to the planted forest, what corroborated the findings of the present study.

The competition between individuals in a production system is not the only factor that influence how they perform in it. The synergisms existing and the way in which the different components of a production system can be complementary one to each other is also important. Fertilizers applied to the crops and even pastures are also of some importance to the eucalyptus. In addition, soils on agroforestry systems are known to be improved as compared to a planted forest and this is a high relevant issue. For example, soybeans on iCLF are important for its ability of biological nitrogen fixation (Jose et al. 2004), providing such important nutrient to the eucalyptus. According to Salton et al. (2014), the pasture is important to improve the soil structure, increase organic matter and ameliorate soil physical properties like porosity and density. Soils on agroforestry systems can better infiltrate and retain rainwater (Zolin et al. 2021). In turn, trees are capable of promoting changes to the microclimate in the inter-row (Pezzopane et al. 2015), in addition to contribute to cycling nutrients. The animals grazing may injury eucalyptus trees, but may also provide some improvement to the environment due to its feces and urine. As noted, agroforestry systems like iCLF are very complex. The better performance observed for the eucalyptus in the agroforestry systems as compared to the forest may also be a consequence of the benefits achieved by using a sustainable production system like it.

Table 4 Monthly precipitation during the experimental period and its comparison to the climate normal. There was assumed as normality limits, 20% above or under the climate normal

Month	Observed (mm)	Climate normal* (mm)	% difference	Situation
Nov-2014	233	189.6	22.9	↑ Above
Dec-2014	136.4	185.2	− 26.3	↓ Under
Jan-2015	264.4	178.3	48.3	↑ Above
Feb-2015	183.4	173.1	6.0	≈ Normal
Mar-2015	177.4	165.8	7.0	≈ Normal
Apr-2015	141	132.6	6.3	≈ Normal
May-2015	262.4	132.2	98.5	↑ Above
Jun-2015	88.8	96.1	− 7.6	≈ Normal
Jul-2015	233.8	55.8	319.0	↑ Above
Aug-2015	17.6	52.8	− 66.7	↓ Under
Sep-2015	246.6	111.9	120.4	↑ Above
Oct-2015	175	193.7	− 9.7	≈ Normal
Nov-2015	302.8	189.6	59.7	↑ Above
Dec-2015	379.8	185.2	105.1	↑ Above
Jan-2016	217.6	178.3	22.0	↑ Above
Feb-2016	356.2	173.1	105.8	↑ Above
Mar-2016	148.6	165.8	− 10.4	≈ Normal
Apr-2016	163.2	132.6	23.1	↑ Above
May-2016	296	132.2	123.9	↑ Above
Jun-2016	37	96.1	− 61.5	↓ Under
Jul-2016	23	55.8	− 58.8	↓ Under
Aug-2016	149	52.8	182.2	↑ Above

*Climate normal means the expected precipitation to occur based on a long term database (usually bigger than 30 years) and its values were obtained from Souza (2018), as seen in Fig. 1

Relation between diameter growth and climate variables

When compared the monthly measured precipitation and the climate normal (as presented in Fig. 1), stay clear that the experimental period was of above-normal precipitation, since in 12 of 22 months the precipitation was at least 20% above normal, in six months it stayed normal (between 20% above or under normal) and only in four months the precipitation occurred at least 20% under normal (Table 4). Such situation was expected for the region in study because the experimental period went through during an *El Niño* episode, which is a large-scale ocean–atmosphere climate phenomenon linked to a periodic warming in sea-surface temperatures across the central and east-central equatorial Pacific. During *El Niño* episodes the region in study is usually impacted with an increase in the number of rainy days as wells as an increase in the amount of precipitation.

As disposed in Fig. 5 on an almost monthly scale, Fig. 6 refers to an analysis of almost bimonthly data (±61 days) regarding the DI_{daily} and climate variables, i.e. air temperature and precipitation. Precipitation presented much more fluctuation if compared to the air temperature and the graphics in Fig. 6 suggests

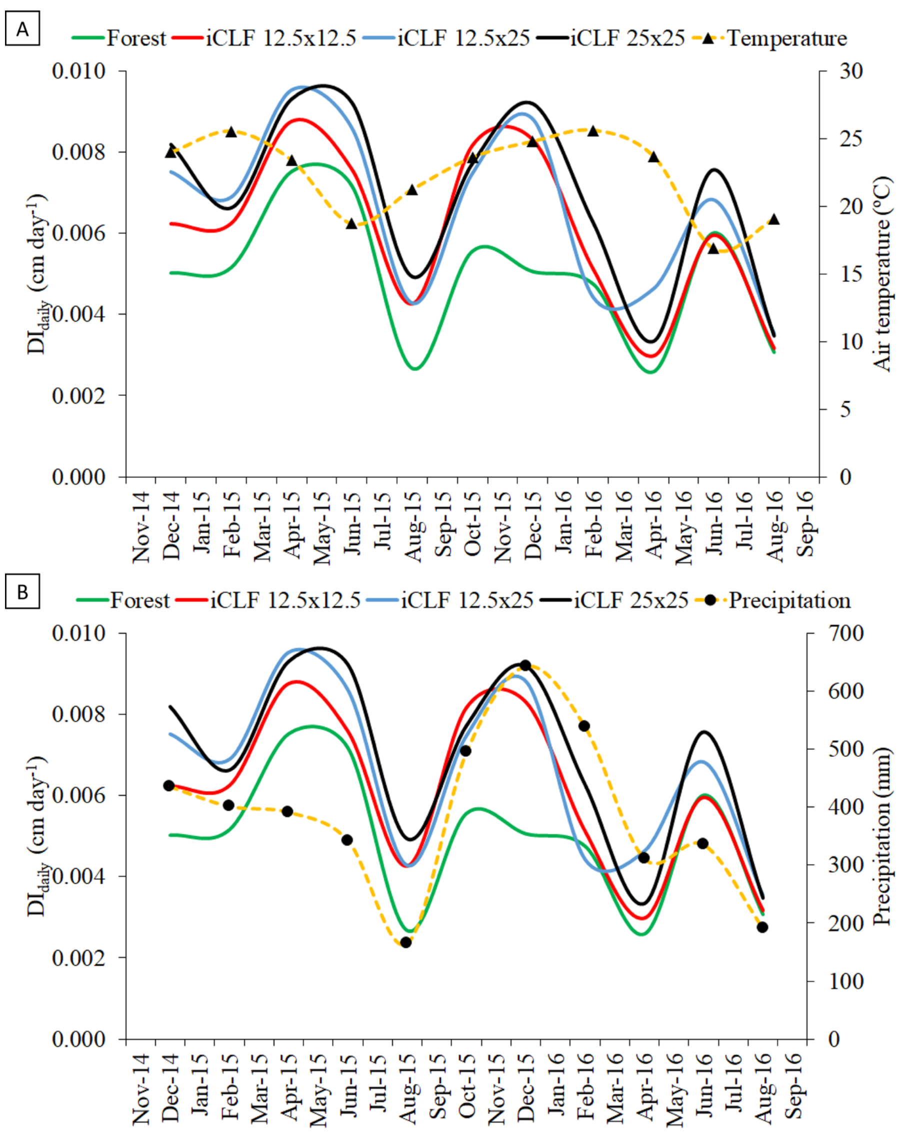
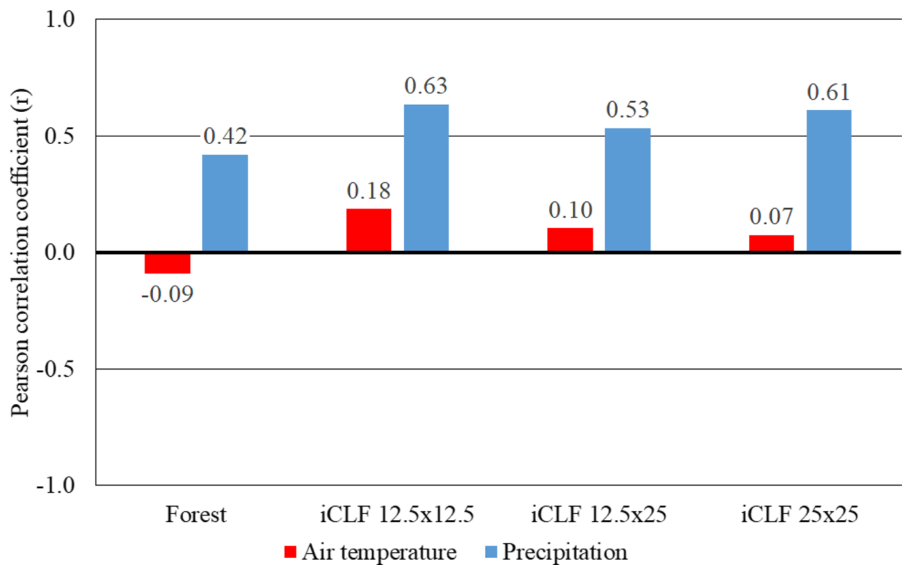


Fig. 6 Dynamics of **A** air temperature, **B** precipitation and daily increment in diameter (DI_{daily}) of eucalyptus trees in different production systems (forest and iCLF, integrated crop-livestock-forest)

Fig. 7 Correlation analysis between climate variables and the diameter growth of eucalyptus trees in different production systems (forest and iCLF, integrated crop-livestock-forest)



a connection between DI_{daily} series of all treatments and precipitation, but not with temperature.

The strength of these connections was evaluated by means of the Pearson correlation coefficient (Fig. 7), which revealed little or no correlation between air temperature and eucalyptus diameter growth, both for the forest and agroforestry systems (r values close to 0). This was possibly a consequence of eucalyptus smooth environmental adaptation to the region in study, since there mean monthly air temperature are expected to be regularly between 17.9 and 25 °C, according to Fig. 1. During the experimental period, the bimesters average temperature varied from 16.9 to 25.5 °C. This range is largely considered favorable to eucalyptus growth, as sustained by Queiroz et al. (2020), who considers temperatures from 6 to 31 °C as an adequate range, with optimum values between 18 and 22 °C. In addition to this, one should remember that, as disposed in Table 4, the precipitation during the experimental period was usually above-normal. Such situation had probably ensured to the eucalyptus trees a non-limiting water availability through the most part of the experimental period and this favorable water balance may had contributed to suppress the relevance of the intra-annual air temperature fluctuation. Therefore, this result was different from those found at the northern Mato Grosso by Tonini et al. (2021), since there the authors observed a not so strong, but relevant negative correlation between mean daily air temperature and eucalyptus diameter growth. The results found by us can be endorsed by those found by Ryan et al. (2020). These authors evaluated eight commercial forestry plantations in different production poles in Brazil. In their cross-site study, they concluded that, in situations where water availability was guaranteed (irrigation), the differences in mean annual air temperature between sites did not influenced trees annual increment in biomass. According to the same authors, the mean annual air temperature across the sites was only relevant in situations where water availability was not guaranteed (rainfed). The studied sites had mean annual temperatures varying from 19.4 to 25.7 °C and the authors concluded that, for water limiting conditions, the annual increment in biomass was reduced by the increase in temperature across the sites, like the negative correlation found by Tonini et al. (2021).

Unlike air temperature, precipitation proved to be of great influence over eucalyptus diameter growth, favoring it. This was evidenced by means of the Pearson correlation coefficients that varied from 0.42 to 0.63, with higher values being observed for the agroforestry systems. It demonstrates a major influence of the precipitation over the trees diameter growth when eucalyptus is cultivated in such integrated production systems.

In their study at northern Mato Grosso, Tonini et al. (2021) also evaluated the relation between climate variables and the diameter growth of eucalyptus cultivated in a forest and in agroforestry systems.

They also observed a significant seasonality in eucalyptus diameter growth and that this growth is highly dependent on accumulated rainfall, whereas it is reduced both with water shortage and excess. Based on their correlation analysis, the better correlation coefficient was obtained with precipitation (0.55), considering a 30-day time delay in relation to the diameter growth observed.

Even that eucalyptus is a perennial species with deep root system, precipitation is a crucial factor that strongly drives eucalyptus diameter growth, since it dictates the soil water balance and, consequently, the level in which the eucalyptus water requirement is satisfied. In this regard, although Christina et al. (2017) emphasizes the role of deep roots to the eucalyptus survival during dry periods, the top soil layered roots are the responsible for providing dynamism to the water use and, consequently, to the diameter growth, diminishing it during periods of water restriction and increasing when water is available.

Previous studies in eucalyptus forests demonstrated that the growth parameters are increased by the effect of irrigation. Stape et al. (2004) found that the level of water supply was an important factor that limited trees growth. They also found that, when eucalyptus was irrigated, the wood productivity was increased by 52%, while the water use has increased only 15%. Similar results were found by Reis et al. (2006), showing that irrigation has resulted in trees with increased DBH and wood volume, although trees height were not influenced. Finally, as explained early, Ryan et al. (2020) were conclusive when stating that the water supply is the key resource determining levels of plantation productivity in Brazil. They endorsed the idea that irrigation can aid the eucalyptus to reach its full productivity potential.

Therefore, considering the potential benefits of the irrigation practice to the eucalyptus and taking into account the greater responsiveness of the iCLF to the water availability as compared to a planted forest (previously demonstrated in the present study), these suggests that there is potential for using irrigation in iCLF production systems. This probably should be done using localized irrigation methods, applying water close to the trees rows, instead of spraying it over the whole area, unless there is a wish to also supply water to the inter-row plants. Although the economic feasibility should be considered, the irrigation adoption may perhaps be positive for the eucalyptus growth and precocity in iCLF, what deserves more research because they are scarce.

Conclusions

As compared to a planted forest, eucalyptus diameter growth is higher when it is cultivated in agroforestry systems, like the integrated crop-livestock-forest systems (iCLF) tested in this study. Such diameter growth proved to be as higher as larger is the distance between eucalyptus rows. This finding puts the agroforestry systems as possible alternatives when the farmer intends to harvest timber with a desired diameter in a smaller time interval (precocity) or when the intention is to harvest timber with bigger diameters, to be used in nobler applications. Independent of the wish, the whole field in iCLF still able to be used for other economic activities, such as agriculture or livestock, being the challenge of the farmer or the technicians to equalize the benefits or loss of having less or more trees in the field.

Precipitation proved to strongly and positively influence eucalyptus diameter growth, especially when cultivated in agroforestry systems. Differently, under the conditions of this study, air temperature showed little or no correlation with eucalyptus diameter growth. This suggests that every agronomical practice which can be adopted in order to improve the water availability in rainfed production systems, as well as the use of irrigation, both may be positive for the eucalyptus growth and precocity when cultivated in iCLF.

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Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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