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RESEARCH ARTICLE

Growth and solar radiation use efficiency of corn cultivated in agroforestry systems

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ABSTRACT

Agroforestry systems are a more sustainable alternative to food and energy production without compromising existing agroecosystems. In this context, the study aimed to analyze the growth characteristics and the solar radition use efficiency of corn cultivated in different arrangements of agroforestry and monoculture systems. The study was conducted in the experimental area of the Laboratory of Agroclimatology of the Federal University of Santa Maria, Campus of Frederico Westphalen – RS, Brazil. The experimental design was a complete randomized block, arranged in a factorial scheme of 3 × 2 × 2 representing two arrangements of agroforestry systems (Intercrop I and Intercrop II) and the monoculture of corn; two forest species, *Peltophorum dubium* (Spr.) Taubert, denoted as *P. dubium* and the hybrid *Eucalyptus urophylla* S.T. Blake × *Eucalyptus grandis* Hill ex Maiden, denoted as *Eucalyptus*; and two crop years (Crop I and Crop II), with four replicates each. The growth rates varied between the different systems, with the highest values recorded for the absolute growth rate in the monoculture system, in both crop years, for the relative growth rate in the *Eucalyptus*-Intercrop I-Crop I and monoculture system-Crop II plots, and for the net assimilation rate in the *Eucalyptus*-Intercrop II in both crop years. The solar radiation use efficiency was varied between the different systems, with greater values of efficiency found in the *Eucalyptus*-Intercrop I-Crop I and in *Eucalyptus*-Intercrop II-Crop II plots. Therefore, different agroforestry arrangements influence corn growth; however, further studies related to this subject are needed as it is a way to optimize land use.

Keywords: Forest species; Shading; Solar radiation; Understory

INTRODUCTION

Agroforestry systems (AS) consist of an alternative agricultural production, characterized by the simultaneous cultivation of crop and forestry species in the same production area. These systems are used in order to increase and differentiate agriculture and forestry production, while retaining existing natural resources. Besides, it refers to the intensive land management that potentiates the biological interactions created when forest crops are combined with annual crops (Malua et al., 2005).

Corn (*Zea mays*) is one of the main cereals grown in the world, which is widely used in the subsistence of rural populations, for large external markets catering to human consumption, but is mainly used in the manufacture of animal feed (Pavão and Ferreira Filho, 2011). Thus, the intercropping of corn with forest species emerges as a sustainable alternative for extending the area of cultivation.

The growth and development of different species in the same area promotes dynamic interactions between the plant communities. In areas where forest species are present, there is continuous growth in height, canopy projection, and the leaf area index (LAI), which modifies the distribution of resources over time (Müller et al., 2014). The amount of solar radiation available within the understory is directly related to the growth of the forest component (Soares et al., 2009), since it modifies the solar radiation dynamics

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and thus the amounts that can be intercepted by the annual crop (Elli et al., 2016).

Plants that are grown in the shade, such as in an AS, tend to present morphological changes in order to become more efficient in the interception and transformation of solar radiation to chemical energy through photosynthesis (Coelho et al., 2014b). According to Caron et al. (2012a), the amount of radiation that the plants absorb is a determinant of the photosynthetic rates which can then become a limitation to the accumulation of biomass, growth, and for development of plants.

Corn is a C4 metabolism plant, that is, it presents higher concentration of CO_2 in the active site of Rubisco, maintaining high concentration of CO_2/O_2, and eliminating photorespiration (Taiz et al., 2017), which it derives from places with intense solar radiation. Thus, when grown under reduced amounts of solar radiation, a decrease in the crop growth rates is expected (Magalhães et al., 2002).

According to Dias-Filho (2002), plants with C4 metabolism, such as corn, tend to have reduced photosynthetic capacity in environments with less solar radiation availability. Additionally, studies have shown that shading can promote changes in plant growth characteristics, such as absolute growth rate and net assimilation rate of sugarcane (Schwerz et al., 2018), leaf area index (Yang et al., 2019), biomass production and protein content of corn (Pezzopane et al., 2019).

Given that research about alternative production systems is important, and there is a scarcity of information on the spatial arrangements of forest species and their effects on species cultivated in AS, the following hypotheses were proposed: (i) corn growth varies between different arrangements and forest species used in AS, due to different amounts of incident solar radiation in the understory; and (ii) the solar radiation use efficiency varies among study factors, due to the changes in corn growth dynamics. In order to answer the hypotheses generated, the study aimed to analyze the growth characteristics and solar radiation use efficiency of corn cultivated in different arrangements of agroforestry and monoculture systems.

MATERIAL AND METHODS

A field study was conducted in the experimental area of the Laboratory of Agroclimatology of the Federal University of Santa Maria, Campus of Frederico Westphalen – RS, Brazil (27°23'26"S and 53°25'43"W and 461.3 m altitude). The climate characteristic of the region is of type Cfa, according to the classification of Köppen, with the three coldest months of the year having temperatures ranging from -3 to 18 °C, with an average air temperature of 22 °C in the hottest month, and with rainfall occurring in all months of the year (Alvares et al., 2013).

Daily data for incident solar radiation (MJ m^{-2}), rainfall (mm dia^{-1}), and minimum, medium, and maximum air temperatures (°C) were collected using the Automatic Station of the Instituto Nacional de Meteorologia (INMET), located about 1500 m from the experimental area.

The experiment was conducted during the years 2016 (Crop I), and 2016/2017 (Crop II). The soil of the experimental area is a typical Eutrophic Littoral Neosol, shallow, with rock outcrop, and reasonable natural fertility. The chemical characteristics of the soil are presented in Table 1. Fertilization consisted of the application of 50 kg ha^{-1} of N, 85 kg ha^{-1} of P, and 85 kg ha^{-1} of P for Crop I. For the Crop II, 50 kg ha^{-1} of N, 125 kg ha^{-1} of P, and 70 kg ha^{-1} of K was applied.

The experimental design was a randomized complete block in a 3 × 2 × 2 factorial scheme, representing two arrangements of agroforestry systems and monoculture denoted as Intercrop I, Intercrop II, and monoculture; two forest species, *Peltophorum dubium* (Spr.) Taubert, denoted as *P. dubium* and a hybrid of *Eucalyptus urophylla* S.T. Blake × *Eucalyptus grandis* Hill ex Maiden, denoted as *Eucalyptus*; and two crop years: Crop year 2016, denoted as Crop I and crop year 2016/2017, denoted as Crop II, with four replicates each.

In Intercrop I, the trees were distributed in 6 m spaced rows with 1.5 m between the trees in the planting lines; the corn was distributed in 5 rows and organized in the interval between the rows of trees, totaling 10 lines throughout the system. In Intercrop II, the trees were distributed in rows spaced at 12 m with 3 m between the trees in the planting line; the corn was distributed in 13 lines arranged in between the rows of trees. A total of twelve trees were distributed in Intercrop I and six trees in the Intercrop II, for each experimental unit. The planting of forest species was carried out in September 2007, through manual planting of seedlings, after plowing and grinding the soil. Trees and corn were aligned in the East-West direction. In Table 2, the biometric characteristics of the forest species during the experimental period are shown.

The measurement of height (H), diameter at breast height (DBH), base diameter (BD), and canopy diameter (CD) of the forest species were carried out in both crop years. Height was measured from ground level to the top of the upper leaves, using the Hypsometer Vertex III. The diameter at breast height was measured using a

Table 1: Description of soil chemical characteristics of the experimental unit, for Crop I and Crop II. Frederico Westphalen-RS, Brazil, 2019

Crop	pH	P	K	Ca	Mg	CTC	V	MO
	(H_2O)	(mg/L)		(cmolc/L)			(%)	
I	5.25	4.45	68.5	10.65	2.8	18.4	74.3	3.35
II	5.2	4.5	56.5	8.9	1.8	16.75	64.8	3.45

Table 2: Allometric characteristics, plant height (H), canopy diameter (CD) base diameter (BD) and diameter at breast height (DBH) of forest species, *Peltophorum dubium* e *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden at 9 and 10 years of age. Frederico Westphalen-RS, Brazil, 2019

Crop	Specie	H (m)	CD (m)	BD (cm)	DBH (cm)
I	*P.dubium*	11.68	6.20	19.41	13.70
II	*P.dubium*	12.92	6.43	19.71	14.34
I	*Eucalyptus*	23.08	11.44	41.47	33.97
II	*Eucalyptus*	25.46	12.88	41.85	34.40

tape measure at a height of 1.30 m. The diameter of the base was measured using a tape measure, at a height of 10 cm. The canopy diameter was also measured using a tape measure, by determining the vertical and horizontal dimensions.

After the corn was sown, Four 2 m long evaluation plots, distributed across each experimental unit at different locations, were delineated. In the Intercrop I, four lines were positioned at distances of 1.125 m, 2.625 m, 3.375 m, and 4.935 m of the forest species. In Intercrop II, the four lines were positioned at 1.125 m, 5.625 m, 6.375 m, and 12 m. These areas were chosen with the objective of representing the different microclimatic conditions in the area under the canopy of each agroforestry system. For subsequent analysis of the data, the average values of the evaluation sites in each arrangement were calculated. The arrangements of the trees, corn plants, and the evaluation plots are shown in Fig. 1.

In Crop I, the corn was sown on January 25, 2016. In Crop II, sowing was performed on September 16, 2016. In both crops, sowing was carried out with the aid of a fertilizer sowing machine, spaced at 0.75 m between lines, and at a density of 69,334 plants per hectare. The corn hybrid used in the two crops was RB 9110 Pro 2. Some growth characteristics of this hybrido grown in agroforestry systems are shown in Fig. 2.

Growth was evaluated at intervals of 15 days, in which four plants were collected per system per forest species, from the beginning of vegetative growth until the physiological maturation of corn. The plants that were collected were taken to the laboratory where the leaves, stalk, inflorescence, ear, senescent leaves, and leaf discs (for posterior determination of the leaf area of each sample)

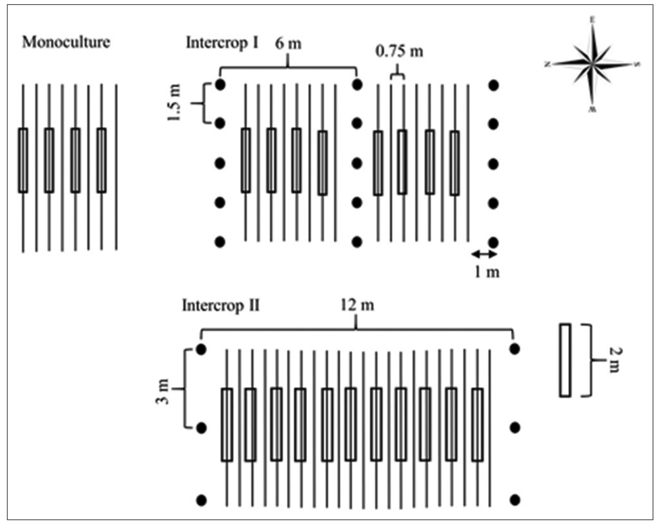

Fig 1. A sketch of na experimental unit of the agroforestry systems (Intercrop I and Intercrop II) and the monoculture. Black circles represent the trees, contínuos lines indicate where the corn is sown, and the rectangles in grey represent the evaluation plots of corn. Frederico Westphalen-RS, Brazil, 2019.

Fig 2. Demonstration of growth characteristics of corn grown in different arrangements of agroforestry: Intercrop I (A) and Intercrop II (B). Frederico Westphalen–RS, Brazil, 2019.

were separated. The leaves were considered senescent when 50% or more of their leaf area was affected. Once the parts were separated, samples were packed in paper bags and kept in a drying oven with forced air circulation at a controlled temperature of 60 °C, until reaching constant mass. The dry matter of the samples was determined with the aid of an analytical balance accurate to 0.0001 g (FA-2204-CI-LC-BI).

The solar radiation use efficiency was determined by relating the average accumulated dry matter production and the photosynthetically active radiation intercepted, according to the equation described by (Monteith, 1977).

$$TDM = \varepsilon b * iPAR$$

Where, TDM = total dry matter produced (gm^{-2}); εb = solar radiation use efficiency ($g\ MJ^{-1}$); and iPAR = intercepted incident photosynthetically active radiation ($MJ\ m^{-2}$).

The incident photosynthetically active radiation (PARi) was estimated taking into account 45% of the global solar radiation (Assis and Mendez, 1989), with no difference between days of intense light and cloudy days. The estimate of the intercepted PARi was determined using the model described by (Varlet-Grancher, 1989).

$$iPAR = 0.95 * \left(PARinc\right) * \left(1 - e^{(-k*LAI)}\right)$$

Where, iPAR = intercepted PARi ($MJ\ m^{-2}$); PARinc = incident PARi ($MJ\ m^{-2}$); k = the extinction coefficient, calculated for each arrangement and agroforestry system as well as for the monoculture.

The incident global radiation ($W\ m^{-2}$) was measured in each collection of plants, using the radiation measurements incident on the upper stratum and in the lower stratum of the canopy which were recorded between 10:00 and 12:00 with the aid of a pyranometer (LICOR PY32164) coupled to a Data logger (LICOR 1400).

The extinction coefficient (k) was calculated using the following equation:

$$k = -\ln\left(\frac{Rn}{Rt}\right) / LAI$$

Where, k = extinction coefficient; Rn = solar radiation measured under the plant canopy ($MJ\ m^{-2}$); Rt = radiation above the plant canopy ($MJ\ m^{-2}$); LAI = leaf area index. The LAI was determined from the relation between total leaf area and the area of soil occupied by each plant ($0.14\ m^2$), according to the following equation:

$$LAI = LA / SA$$

Where, LA refers to the total leaf area of the plant in m^2 and SA is the soil area occupied by the plant (m^2).

The leaf area was determined by the disc method, as described by Benincasa (2003), and calculated by the following equation:

$$LA = \left(\begin{array}{l} n°discs * punch\ disc\ area) * \\ (DM\ leaves + discs) / DM\ discs \end{array}\right)$$

Where, n° discs = number of discs in the sample; punch area = area of the punch disc in m^2; DM leaves = total

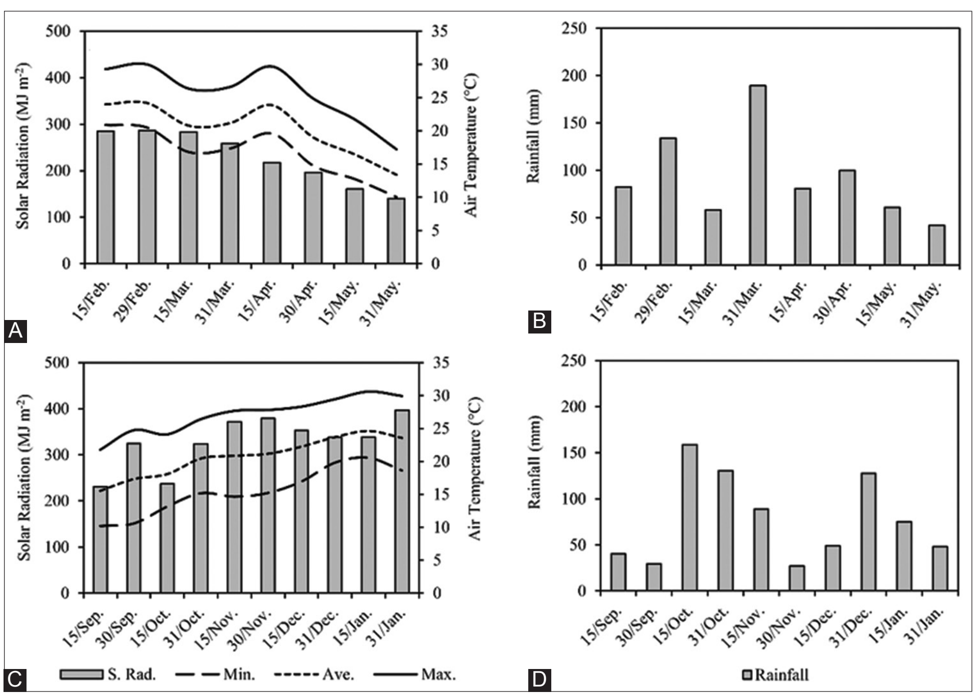

Fig 3. Accumulated incidente solar radiation fortnightly ($MJ\ m^{-2}$) (S.Rad.); Air temperature (°C), minimum (Min.), average (Ave.) and maximum (Max.); rainfall (mm), during the experimental period, during the Crop I (A and B) and Crop II (C and D). Frederico Westphalen–RS, Brazil, 2019.

dry matter of the leaves, in g; and DM discs = dry matter of the disc, in g.

Based on the results of dry matter and leaf area, the growth analysis of the variables was conducted. The absolute growth rate (AGR, g day^{-1}), relative growth rate (RGR, g g^{-1} dia^{-1}), and the net assimilation rate (NAR, g m^{-2}) were determined following the methodology described by (Benincasa, 2003). The data were submitted to a descriptive analysis, using SAS Learning Edition 8.0 (2003) (SAS, 2003).

RESULTS AND DISCUSSION

The fortnightly values of the accumulated solar radiation, rainfall, and air temperature (minimum, average and maximum), obtained during the study period are shown in Fig. 3. In Crop I, the air temperature was between 10 and 30 °C, with an average of 20.3 ºC, and the accumulated rainfall was 746.8 mm. In Crop II, the air temperature was between 10.2 and 30.6 °C, with an average of 20.7 °C, and the accumulated rainfall was 775.4 mm. The temperature and rainfall values were within the range considered ideal for growth and development of corn, which according to Cruz et al. (2010), are 10-30 °C and 600 mm.

The highest values of LAI were obtained for monoculture plants, which was 7.66 in Crop I and 8.82 in Crop II (Fig. 4). In Crop I, the critical LAI of the corn was obtained at 57 DAE for all systems. In Crop II, the monoculture plants obtained the critical LAI at 57 DAE, while for the other systems this was achieved at 71 DAE. For some authors, such as (Lauer et al., 2004), have reported that the critical LAI of corn, expressed as the ratio between leaf units per soil unit, varies from 4 to 5. In the present study, all values of LAI obtained were higher than this critical LAI value.

When corn sowing is done at the end of winter, as in Crop I, the occurrence of lower temperatures and lower incidence of solar radiation, thus providing smaller plants with lower leaf area index (Sangoi et al., 2010). Therefore, the temporal difference between sowing times may have influenced the achievement of critical LAI, because depending on the sowing season, microclimatic variations may occur, sometimes resulting in a lower incidence of solar radiation and warmer temperatures.

Differences between systems in corn LAI values may be related to the distribution of forest species as each system presents a difference in the availability of solar radiation below the tree canopy, which can affect the number of leaves in the plants (Schock et al., 2014).

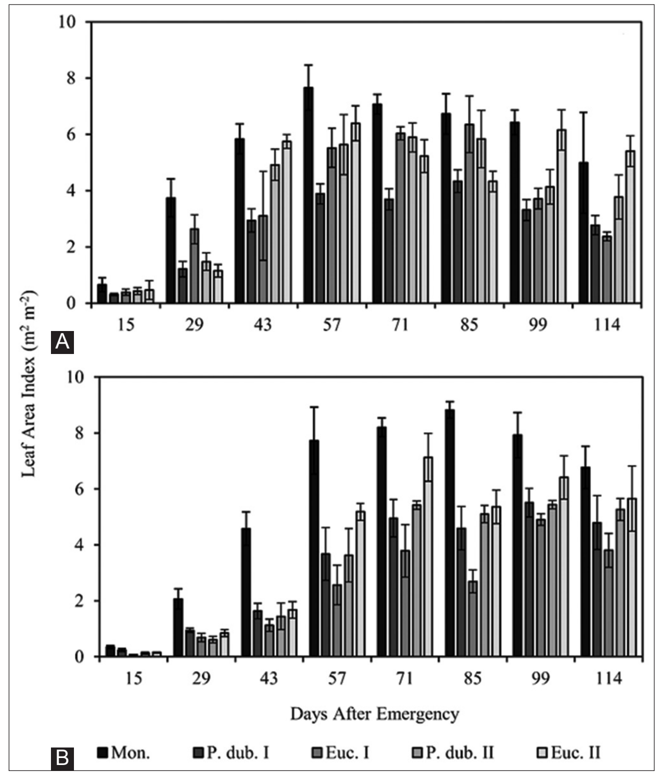

Fig 4. Leaf area index (LAI) of corn grown in an agroforestry system and monoculture, during two crops, Crop I (A) and Crop II (B). Monoculture (Mon.), *P.dubium* Intercrop I (P.dub. I), *Eucalyptus* Intercrop I (Euc. I), *P.dubium* Intercrop II (P.dub. II) and *Eucalyptus* Intercrop II (Euc. II). Frederico Westphalen–RS, Brazil, 2019.

Plants with higher LAI show increased photosynthetic rate, a characteristic that can influence the increase of dry matter and crop yield (Schwerz et al., 2016). This is because the solar radiation is a limiting factor to the growth and development of the plant. Therefore, annual crops grown in a consortium of forest species tend to have lower LAI values due to the lower availability of solar radiation. Paciullo et al. (2007), in a study of *Brachiaria. decumbens*, observed a lower LAI in conditions where the plants were shaded when compared to monocultures where there was no shading.

The conversion efficiency of solar radiation in photoassimilates is directly related to the dry matter production of plants, which can show variations depending on the culture conditions (Caron et al., 2012b). Thus, plants grown in agroforestry systems, which have lower availability of radiation may show variations in the solar radiation use efficiency in dry phytomass.

The highest radiation use efficiency in crop I was found for the *Eucalyptus*-Intercrop I plots, which was 6.5 g MJ^{-1} (Fig. 5). However, for crop II the highest value (3.7 g MJ^{-1}) was observed in the *Eucalyptus*-Intercrop II plots. In our study, as higher efficiencies in the use of solar radiation

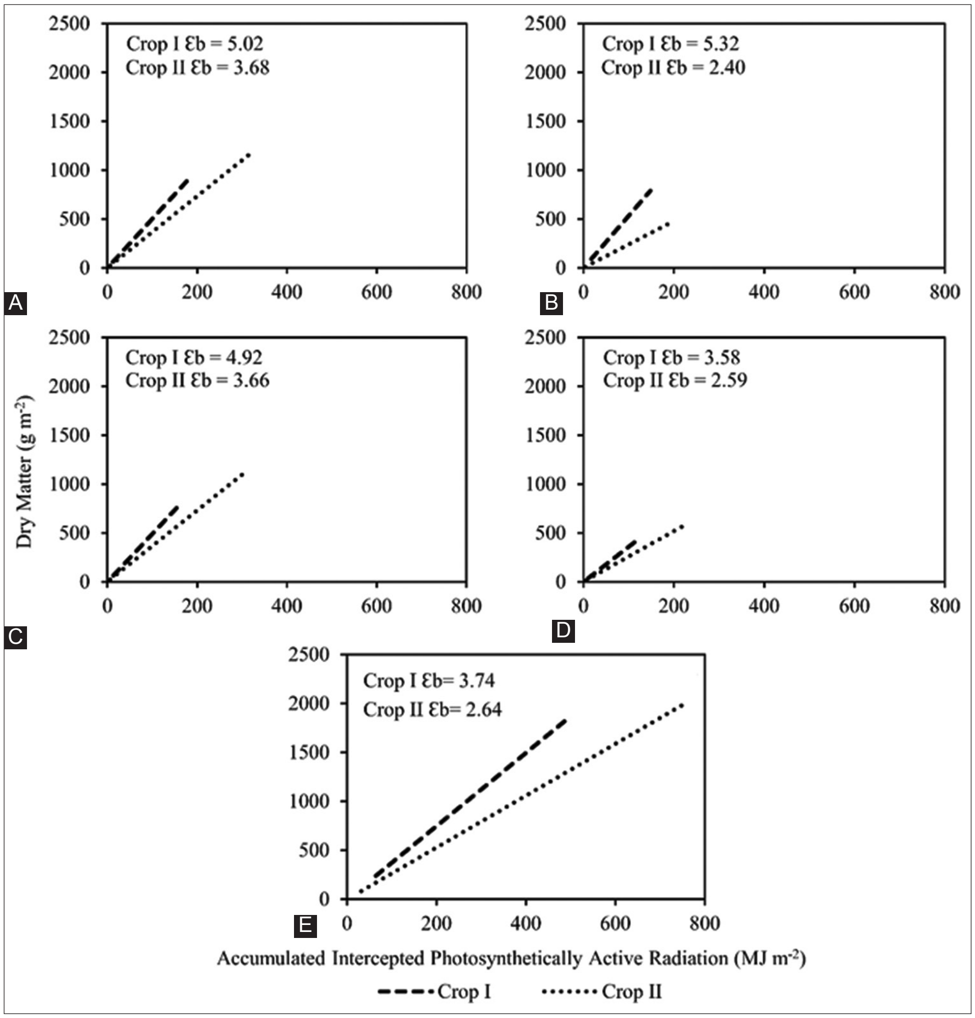

Fig 5. Solar radiation use efficiency (g MJ^{-1}), of corn grown in an agroforestry system and monoculture, during two crops. *P.dubium* Intercrop I (A), *P.dubium* Intercrop II (B), *Eucalyptus* Intercrop I (C), *Eucalyptus* Intercrop II (D) and Monoculture (E). Frederico Westphalen-RS, Brazil, 2019.

occurred in plants with less availability of solar radiation, it can be inferred that the values of radiation use efficiency for corn obtained in Crops I and II are related to the diffuse solar radiation. According to Pilau et al. (2015), the lower availability of radiation in the understory is caused by the interception of the radiation by the tree canopy. However, the efficiency is compensated by the increase of diffuse solar radiation. Other studies Caron et al. (2012b) and Caron et al. (2014) have also reported similar conclusions.

The variations in the amount of solar radiation incident on the corn canopy can be explained by the difference in the distance between the tree rows. In relation to the AS, greater availability of solar radiation can be observed in the understory of *P. dubium*. This can be explained by the fact that *Eucalyptus* species show faster growth and has larger canopy size, consequently interfering with the availability of solar radiation to the canopy of the crop (Paciullo et al., 2007). This differs from the *P. dubium* species, which being deciduous, tends to show defoliation and abscission of branches between the months of July and September and presents more leaves during the months of January and February (Coelho et al., 2014a).

Exotic species, such as *Eucalyptus*, are widely used in agroforestry systems in view of their accelerated growth and commercial value, consolidating the system within a shorter time interval (Grossman et al., 2015). However, native species such as *P. dubium* present viable alternatives due to the size of the canopy, allowing greater availability of solar radiation below the canopy of the trees (Heid et al., 2016).

In this context, it was observed that, with greater shade provided by the forest species to corn, the values of solar radiation use efficiency was higher. This is due to the increase in diffuse solar radiation. According to Aikman (1989), with greater proportion of diffuse radiation, there is greater uniformity of solar radiation inside the canopy, making the plants more efficient in the use of radiation.

Among the corn growth rates that were studied, it was observed that the highest value of AGR was found in Crop I, in the monoculture system, at 86 DAE. However, after the 99 DAE, the AGR in the *Eucalyptus*-Intercrop II plots was superior. On the other hand, in Crop II the highest value was obtained at 99 DAE in the monoculture system (Fig. 6). It was verified that in both the crop years, the monoculture system presented higher values in comparison to the other systems. These results may be related to the greater availability of solar radiation in the monoculture system (Fanti and Perez, 2003), compared to AS, favoring the photosynthetic process and providing a higher LAI. The higher AGR in the *Eucalyptus*-Intercrop II plots at 99 DAE is due can be explained by the anticipation of leaf senescence in the monoculture system, which decreases the AGR.

A maximum RGR value of 0.22 g day^{-1} was recorded in the *Eucalyptus*-Intercrop I plot at 31 DAE, which decreased with time, but stabilized towards the end of the cycle in Crop I. However, in Crop II, the maximum value was 0.18 g day^{-1}, recorded in the monoculture system. The RGR decreased during the cycle due to the growth of the plants, which increased the competition for resources such as water, light, and nutrients. Silva et al. (2010), points out that the RGR for most crops tend to decrease at the onset of their cycle, which is related to the decrease in NAR and LAI values. However, at the end of the cycle, negative RGR values can be found as a result of foliar senescence and bud abortion (Beckmann-Cavalcante et al., 2009).

The maximum values of NAR were obtained in the *Eucalyptus*-Intercrop II plots in both crop years. All systems showed similar trends, decreasing and having peaks of growth in the period in which the grain filling occurred (Lopes et al., 2009), a period when the plant has a greater demand for photoassimilates in the reproductive organs (Machado et al., 1992). Subsequently, a decrease was observed after 114 DAE, the period in which the plant enters the stage of physiological maturation, resulting in a decrease in the dry mass production.

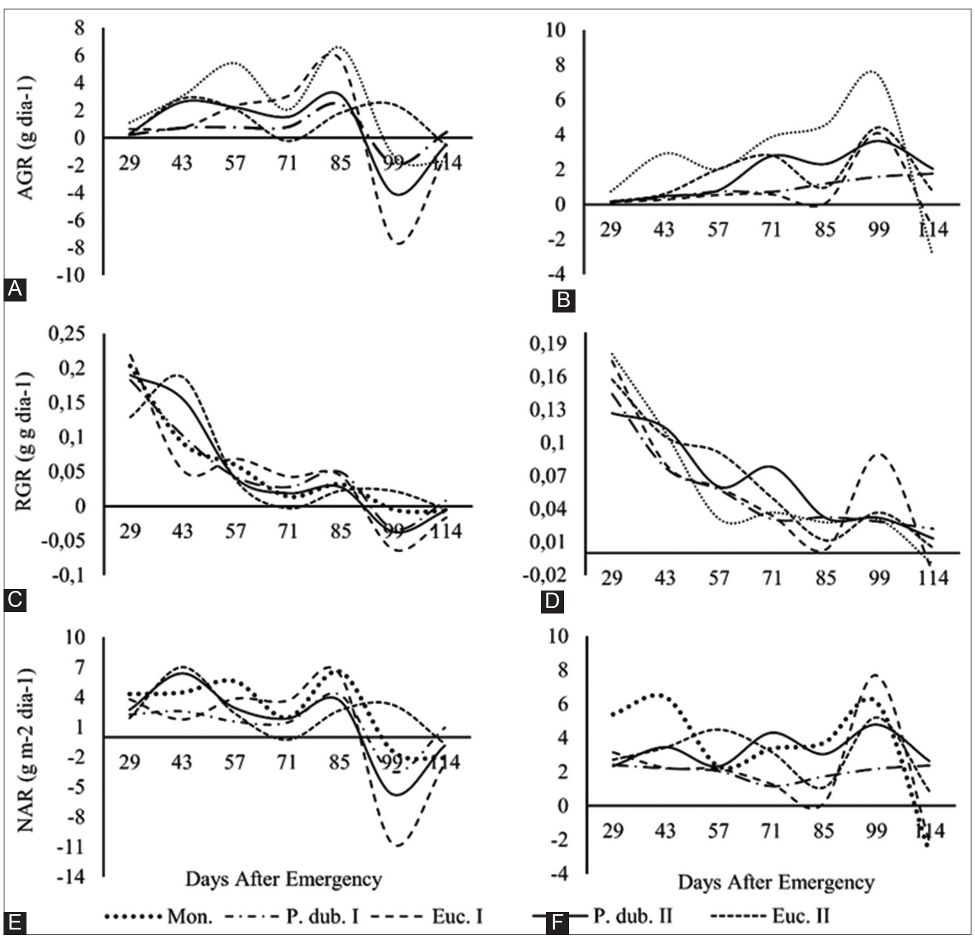

Fig 6. Absolute growth rate (A), (Crop I (A), Crop II (B)), relative growth rate (Crop I (C), Crop II (D)) and net assimilation rate (Crop I (E), Crop II (F)) during the experimental period. Monoculture (Mon.), *P.dubium* Intercrop I (P.dub. I), *Eucalyptus* Intercrop II (Euc. I), *P.dubium* Intercrop II (P.dub. II) and *Eucalyptus* Interccrop II (Euc. II). Frederico Westphalen, Brazil, 2019.

CONCLUSIONS

Growth rates varied between the different systems: the highest value for absolute growth rate was in the monoculture system in both crop years. The highest relative growth rate was obtained in the *Eucalyptus*-Intercrop I-Crop I plots and in the monoculture in Crop II. The highest values for the net assimilatory rate were found in the *Eucalyptus*-Intercrop II plots for both crop years, thus failing to reject the first hypothesis.

There was variation in the solar radiation use efficiency in the different systems: it was most efficient in the *Eucalyptus*-Intercrop I-Crop I plots and in the *Eucalyptus*-Intercrop II-Crop II plots, thus confirming the second hypothesis. Therefore, different agroforestry arrangements influence the growth of corn, however further studies related to this subject are necessary as it is a way of optimizing land use.

Author contribution

Claiton Nardini and Jaqueline Sgarbossa: conduction of the project and development of the written part of the work.

Felipe Schwerz Elvis Felipe Elli: development of the project and organization, planninf of treatments.

Sandro Luiz Petter Medeiros and Braulio Otomar Caron: development of the project and correction of written part.

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