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Dynamics of solar radiation and soybean yield in agroforestry systems

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ABSTRACT

Soybean (*Glycine max* L.) monocropping have had a great socio-economic and environmental impact on the world and agroforestry systems has been considered an alternative for more sustainable production. The aim of this study was to evaluate the effect of different arrangements of agroforestry systems of the species *E. urophylla* x *E. grandis* and *P. dubium* and the pruning of the trees on the dynamics of solar radiation and soybean yield. A field experiment was conducted in Southern Brazil. In order to achieve the objective of the study, the solar radiation transmissivity and the productive performance of the soybean were evaluated. In this study, the soybean yield was determined by the arrangement of the agroforestry system and forest species utilized. The soybean crop cultivated in the understory of the *P. dubium* trees showed the highest yield response. The use of silvicultural practices for the management of forest species should be considered to generate the balance of the productive system. In this context, tree pruning is a viable side for agroforestry systems, as it promotes an increase in the incidence of solar radiation in the understory, resulting in an increase in soybean yield, especially when integrated with *P. dubium*.

Key words: crop systems, solar radiation transmissivity, sustainable production, tree pruning, yield traits.

INTRODUCTION

One of the greatest challenges of Brazilian agriculture is to strike a balance between agricultural production and environmental preservation. For this, it is necessary to satisfy the demand for food and energy without compromising existing agroecosystems (Godfray et al. 2010). The agroforestry systems deserve to be highlighted in this scenario and are a promising strategy in order to achieve these objectives, since they consist of the cultivation integrated between agricultural and forest species.

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In addition, these systems are used for the purpose to maximize the productive system, dilute costs of agroforestry facilities, implementation of sustainable farming practices, as well as in reconstitution, physical, chemical and biological properties of soil (Tracy and Zhang 2008, Salton et al. 2013).

Intercropping is the dominant agricultural strategy in many parts of the world, i.e. sub-Saharan Africa and large parts of Latin America, and intercropping systems provide an estimated 20% of the world's food supply (Altieri 2009, Chappell et al. 2013). Despite improvements already established in monoculture systems, such as intensified use of conservation practices, and the high potential of intercropping systems, reduced studies are conducted with the aim of identifying the forest and agricultural species adaptability to these systems, as well as to evaluate the positive effects of these when in a consortium; therefore, it can be verified that research involving alternative production systems is innovative in Brazil, especially when considered the context of world food production.

Studies are being developed with the objective to generate technical-scientific knowledge using agroforestry systems as an alternative for sustainable production (Pilau et al. 2015, Elli et al. 2016, Schwerz et al. 2017). The premise of this study is to generate a balance between the agricultural production of soybean and forest species, intercropped in order to produce both food and energy. Agroforestry systems have been highlighted globally, being the topic of current research in various parts of the world, such as in Brazil (Oliveira et al. 2016), Japan (Matsuo et al. 2016), Costa Rica (Siles et al. 2010), China (Peng et al. 2009) and United States (Tracy and Zhang 2008). All studies cited aim for the sustainability and preservation of natural resources, but do not present information about the interaction between species proposed in this work, as well as the need to generate a balance in production environments.

Soybean (*Glycine max*) is globally recognized as one of the most important agronomic crops, being one of the main protein and oil sources worldwide (Matsuo et al. 2016). Brazil is one of the major soybean producing countries in the world, with 34.96 million hectares of planted area, providing 109.18 million tons of soybean, resulting in a medium yield of 3.12 Mg ha^{-1} in the crop cycle 2017/2018 (Conab 2017). The use of soybean in agroforestry systems has been considered as an alternative for its sustainable production in threatened ecosystems (Werner et al. 2017). In addition, this system allows for the expansion of the cultivation area, by the insertion of marginal areas and of lower fertility to the productive system, as well as promoting sustainable use of natural resources. Soybean has been grown mainly in monocropping systems, which are characterized by the standardized and simplified methods of monoculture, resulting in the intensive use of available resources (Cordeiro et al. 2015).

The growth and development of different species in the same area, such as in agroforestry presupposes the existence of dynamic interactions that change over time. This is especially relevant in areas which include trees, given their continued growth in height, crown projection, and leaf area index, which can modify the distribution of existing resources (Muller et al. 2014), and in particular solar radiation (Elli et al. 2016). The fraction of solar radiation transmitted through the canopy, available to plants within the understory, can present a direct or diffuse form, which determines the internal microclimate of the system (Pezzopane et al. 2015, Péllico Netto et al. 2015).

Intercropped systems with forest species and annual crops can unleash changes in the dynamics of solar radiation and its transmissivity to the understory, as such solar radiation leads to quantitative and qualitative changes in the understory, in relation to the percentage of the alley covered by the forest species canopy (Caron et al. 2012). Therefore, the spatial arrangement is a management practice that can modify the effect of the tree component in the dynamics of solar radiation. Additionally, planning of the optimal spatial arrangement, associated with the determination of forest species that will be used in the agroforestry systems, determine the balance between solar radiation intercepted by the tree canopy and the amount transmitted to the understory (Soares et al. 2009).

Soybean, a C3 metabolism plant, has a high solar radiation demand, in order to meet its high photosynthetic rates, which makes solar radiation an essential factor in the crop yield (Raines 2011). The interception of solar radiation by the tree component greater than 65% is determinant in the growth and development of some species grown in the understory (Paciullo et al. 2007), due to the trophic limit of each plant. Therefore, management practices, such as canopy conduction and pruning of trees, are necessary to reduce the interference of the tree component on the transmissivity of solar radiation to the understory (Bertomeu et al. 2011). This management allows the cultivation of both tree species and annual crops, in order to generate a balance in the crop system to satisfy the demand of food and energy.

Given the importance of research about alternative production systems and the lack of information on the spatial arrangements of forest species and their effects on the species cultivated in the understory, the following hypotheses were created: (1) soybean yield varies among different spatial arrangements and tree species used in the agroforestry systems; and (2) the pruning of the trees allows an increase of the incident solar radiation within the understory, which will result in an increase in the soybean productive response. Thus, the objective of this study was to evaluate the effect of different arrangements of agroforestry systems of the species *E. urophylla* x *E. grandis* and *P. dubium* and the pruning of the trees on the dynamics of solar radiation and soybean yield.

MATERIALS AND METHODS

STUDY AREA AND EXPERIMENTAL DESIGN

The field experiment was conducted in the city of Frederico Westphalen, Rio Grande do Sul, Southern Brazil, at the coordinates 27º23’48’’ S, 53º25’45’’ W and an altitude of 490. According to the Köppen climate classification, the climate is Cfa, i.e., humid subtropical with mean annual temperatures of 19.1 °C and varying maximum and minimum temperatures of 38 ºC and 0 °C, respectively (Alvares et al. 2013). The soil of the experimental area was classified as typical Entisol Orthents (Cunha et al. 2011) with the following physicochemical composition (Table I). Fertilization was carried out after a soil analysis in accordance with the recommendations for the soybean crop (CQFS-RS/SC 2004).

The experimental design was a randomized complete block, characterized by a factorial arrangement of 2x2x2 defined by two arrangements of agroforestry systems: Intercrop I (6 x1.5m) and Intercrop II (12 x 3m); two tree species, *Peltophorum dubium* (Spr.) Taubert, designated (*P.dubium*) and hybrid *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden, designated (*Eucalyptus*); and two cultivation years: crop year 2013/2014 and 2014/2015, with four replications.

In the Intercrop I system, the trees were distributed in rows spaced 6m and 1.5m between the trees in the planting line; the soybean was distributed in eight rows and arranged in correspondence to intervals between tree rows, with a total of 16 rows throughout the system. In the Intercrop II system, trees were grow in rows spaced at 12m and 3m between trees in the planting line; the soybean was distributed in twenty lines arranged in correspondence to intervals between

TABLE I
Physical-chemical composition of the experimental area in the different crop years (2013/2014 and 2014/2015). Southern, Brazil.

Crop year	pH (H_2O)	P (mg/L)	K (mg/L)	Ca (cmolc/L)	Mg (cmolc/L)	CTC (cmolc/L)	V (%)	MO (%)
2013/14	5.25	4.45	68.50	10.65	2.80	18.40	74.30	3.35
2014/15	5.20	4.50	56.50	8.90	1.80	16.75	64.85	3.45

the rows. A total of 12 trees were placed to Intercrop I and six trees to the Intercrop II systems, for each experimental unit. Forest species were planted in the field in September 2007; which occurred through the manual planting of seedlings, after plowing and harrowing. Both tree and soybean were oriented in rows towards the East and West.

The determination of height values (H), diameter at breast height (DBH) and crown diameter (CD) of forest species were evaluated on 10/15/2013 and 10/20/2014.Tree height was measured from the ground level to the top leaf axils using a Vertex III Hypsometer. The diameter at breast height was measured at a height of 130 cm. For the average crown diameter, vertical and horizontal measurements were performed.

After sowing the soybean, plots were delineated by stakes set two meters long and were distributed at different points in the understory of each experimental unit. In the Intercrop I, four lines were delineated: L1, L2, L3 and L4 evaluation line were positioned at a distance of 1m, 1.9m, 2.8m and 3.7m from the tree line, respectively. Differently, in the Intercrop II L1, L2, L3 and L4 were positioned at 1m, 2.35m, 3.7m and 5.05m, respectively. These plot areas were chosen with the objective to represent existing microclimate conditions in the areas under the canopy of each tree species and Intercrop system, trying to sample point that represented the existing variability of solar radiation availability and competition among intercropping, the center of the plot and the first sowing line of the annual crop. The arrangement of tree, soybean plants and plot of evaluation are shown in Figure 1.

The soybean was sown in the month of November in both crop years, being used the spacing of 0.45m between the sowing lines and a population of 250,000 plants ha^{-1}. In both crop years, was used the cultivar Nidera A RG 6411, which presents determined growth habit, early cycle, and average height. Crop management such as weed and disease control were performed with phytosanitary treatments following the recommendations of products for the crop (Embrapa 2006).

TRANSMISSIVITY EVALUATION

To determine the transmissivity, five measurements of solar radiation were carried out along the productive cycle of the crop, more precisely at 20, 40, 60 and 80 days after emergence and on the day of soybean harvest. With these data were calculated the mean values of transmissivity for each year, species and Intercrop system. The amount of incident global solar radiation was measured using a portable sensor pyranometer (LICOR PY32164) coupled to a Datalogger (LICOR 1400). Incident solar radiation was measured above and under the agroforestry system (in the demarcated plots Figure 1) with a portable pyranometer that recorded measurements in the period from 10 to 12h. Four values were collected per demarcated plot. The transmissivity was calculated by the following equation:

$$T = \frac{(Rn)}{(Rt)} \times 100$$

where, T: rate of transmissivity (%); Rn: solar radiation incident within the agroforestry system

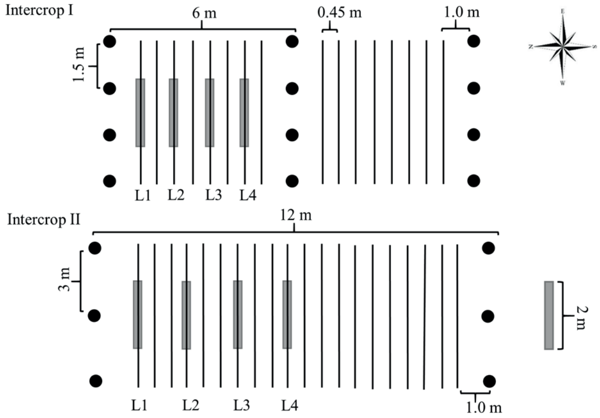

Figure 1 - A sketch of an experimental unit of the agroforestry systems (Intercrop I and Intercrop II), conducted in the agricultural years 2013/2014 and 2014/2015. Black circles represent the trees; continuous lines indicate where the soybean was sown, and the rectangles in gray represent the evaluation plots of soybean. Southern, Brazil.

(W m^{-2}); Rt: solar radiation incident above the agroforestry system (W m^{-2}).

Due to the interference on the solar radiation transmissivity in the first crop year, the forest species were pruned before the sowing of the soybean in the second crop year. The criteria used for pruning were that 50% of the green canopy had to be maintained and that branches had to be removed below the point at which the tree trunk had a diameter of 6-8 cm (Nicodemo et al. 2016). The pruning was performed in order to provide higher radiation availability in the understory.

YIELD TRAITS AND STATISTICAL ANALYSIS

To evaluate the productive performance, the yield traits were analyzed through the collection of four representative plants in each previously demarcated evaluation plot (Figure 1), a total of 16 plants per spatial arrangement and agroforestry system were evaluated, in order to obtain the greatest homogeneity possible. In laboratory, the plant height (PH), as well as the counting of the number of pods per plant (NPP). Additionally, the 1000-grain weight (GW) and the number of grains per plant (NGP). To determine the yield, the total grains obtained in each evaluation plot were weighed and the moisture corrected to 13%.

The values of meteorological variables during the experiment were obtained from the Instituto Nacional de Meteorologia (INMET) linked to the Laboratório de Agroclimatologia (UFSM) located about 200m from the study site at coordinates 27°39'S and 53°43'W. The following meteorological variables were obtained: incident solar radiation (SR, MJ m^{-2}), rainfall (Rain, mm), minimum air temperature (T. Min, °C), maximum air temperature (T.Max, °C) and average air temperature (T. Ave, °C).

The data was statistically analyzed with the software "Statistical Analysis System" (SAS Learning Edition 2003). The presuppositions allowed were: (a) the effects are additive and independent of each other; (b) the errors are jointly independent; (c) the errors have normal distribution, mean zero and common variance (σ). The results were obtained through the analysis of variance and according to the F test, significant differences were found at 5% probability among the study factors. We reject the null hypothesis H0. The Tukey test ($p<0.05$) was used to compare the difference between arrangements, species and crop year.

RESULTS

METEOROLOGICAL CONDITIONS

The air temperature (maximum, minimum and average), incident global radiation, and rainfall values during the crop cycle are shown in Figure 2. The crop year 2013/2014 was characterized by presenting average air temperature of 23.3 °C, ranging from 14.6 °C to 33.3 °C, average solar radiation flux of 25.04 MJ day^{-1}, ranging from 5.3 MJ day^{-1} to 39.2 MJ day^{-1} and cumulative rainfall of 859 mm. Additionally, the crop year 2014/2015 was characterized by presenting average air temperature of 23.0 °C, ranging from 15 to 32.6 °C, average solar radiation flux of 23.15 MJ day^{-}

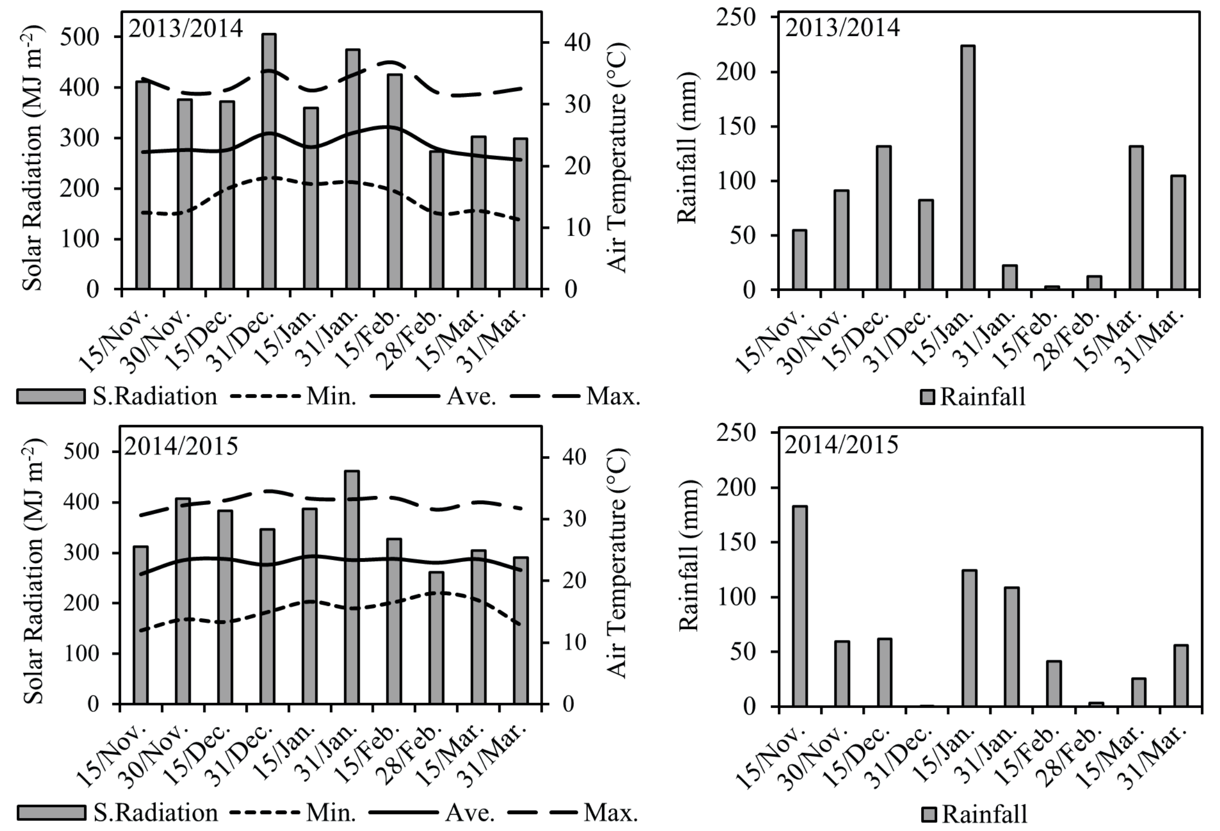

Figure 2 - Monthly average values of minimum, maximum and average temperature, accumulated incident solar radiation, and accumulated rainfall during the experimental period, in two crop years 2013/2014 and 2014/2015. Southern, Brazil.

^{1}, ranging from 5.5 MJ day^{-1} to 42.9 MJ day^{-1} and cumulative rainfall of 663 mm.

TRANSMISSIVITY OF SOLAR RADIATION

The solar radiation transmissivity was determined by the characteristics of the forest species. All growth variables analyzed presented higher values for *Eucalyptus* trees (Table II). In general, considering the two crop years and the two Intercrop systems, we observed values 65.77% higher for the *Eucalyptus* height and 10.42% for the canopy diameter, when compared to *P. dubium*.

The crop year 2014/2015 showed a higher level of transmissivity when compared with the year 2013/2014. Additionally, the largest transmissivity values were obtained for the tree *P. dubium*, being 41.58% higher than the *Eucalyptus*. When compared the tree arrangement, the Intercrop II system presented values 82.58% higher than Intercrop I (Figure 3).

A flux of global solar radiation of 25.4 MJ day^{-1} and 23.15 MJ day^{-1} on average, was recorded in the different crop years 2013/2014 and 2014/2015, respectively. While for the species *Eucalyptus* an average global solar radiation flux within the tree canopy of 4.78 MJ day^{-1} and 10.55 MJ day^{-1} for the 2013/2014 and 2014/2015 crop years, respectively, was found. For the *P. dubium* species, an average global solar radiation flux to below the tree canopy was observed of 9.85 MJ day^{-1} and 12.12 MJ day^{-1} for the 2013/2014 and crop years, respectively.

Yield traits

Soybean yield traits are shown in Figure 4. According to the variance analysis, there was a triple interaction among crop year, Intercrop

TABLE II
Height (H), mean diameter of canopy (Dcanopy) and diameter at breast height (DBH) of *Eucalyptus* and *P. dubium* in two crop years (2013/2014 and 2014/2015) and two Intercrop systems. Southern, Brazil.

Crop year	Species	System	Height (m)	Dcanopy (m)	DBH (cm)
2013/2014	*Eucalyptus*	Intercrop I	21.85	4.13	20.47
2014/2015	*Eucalyptus*	Intercrop I	23.15	4.23	21.57
2013/2014	*Eucalyptus*	Intercrop II	20.30	4.48	23.99
2014/2015	*Eucalyptus*	Intercrop II	24.08	4.81	32.31
2013/2014	*P. dubium*	Intercrop I	7.63	4.02	11.19
2014/2015	*P. dubium*	Intercrop I	9.40	4.84	12.44
2013/2014	*P. dubium*	Intercrop II	6.40	3.33	9.18
2014/2015	*P. dubium*	Intercrop II	7.13	3.62	10.67

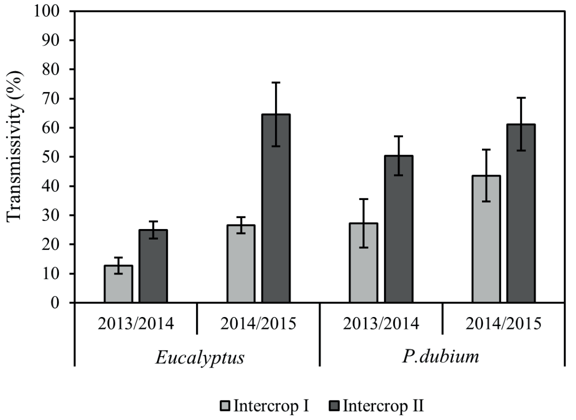

Figure 3 - Solar radiation transmissivity (%) in the understory of an agroforestry system with two forest species *Eucalyptus* and *P. dubium* in two Intercrop systems (Intercrop I and Intercrop II) and two crop years (2013/2014 and 2014/2015). Each bars represent average values ± SE. Southern, Brazil.

system and forest species for the 1000-grain weight while for the number of pods per plant, number of grains per plant and plant height variables, double interactions were observed between crop year and Intercrop system. The variables plant height and total yield showed interaction between crop year and forest species.

The highest values for number of pods per plant and number of grains per plant were observed in the crop year 2014/2015 in the Intercrop II, being 88.50% and 85.29% higher than Intercrop I, respectively. The higher plants were values were obtained in the crop year 2014/2015 for the Intercrop II system, this was possible due to the limitations in the solar radiation availability (Figure 4c, d). For the variable 1000-grain weight the highest values was obtained to the Intercrop II system for the *Eucalyptus* species in the crop year 2013/2014 (Figure 4e), presenting an inverse response to the number of pods per plant and number of grains per plant.

Soybean yield followed the same trend as the solar radiation transmissivity (Figure 5), that is, with the increase in solar radiation transmissivity led to an increase in the yield. The highest values of yield were observed in the crop year 2014/2015 for the species *P. dubium*, being 55.9% higher than to the crop year 2013/2014 for the species *Eucalyptus*.

Furthermore, in the second crop year (2014/2015), due to the pruning of the forest species, there was an increase of 95.2% and 126.7% in soybean yield for *Eucalyptus* and *P. dubium*, respectively. In the management of the forest species through the pruning, the solar radiation available in the understory of the soybean crop increased 142% and 34.9% when intercropped with *Eucalyptus* and *P. dubium*, respectively.

DISCUSSION

In both crop years (2013/2014 and 2014/2015) the average air temperature and accumulated rainfall values were in the ideal range for the

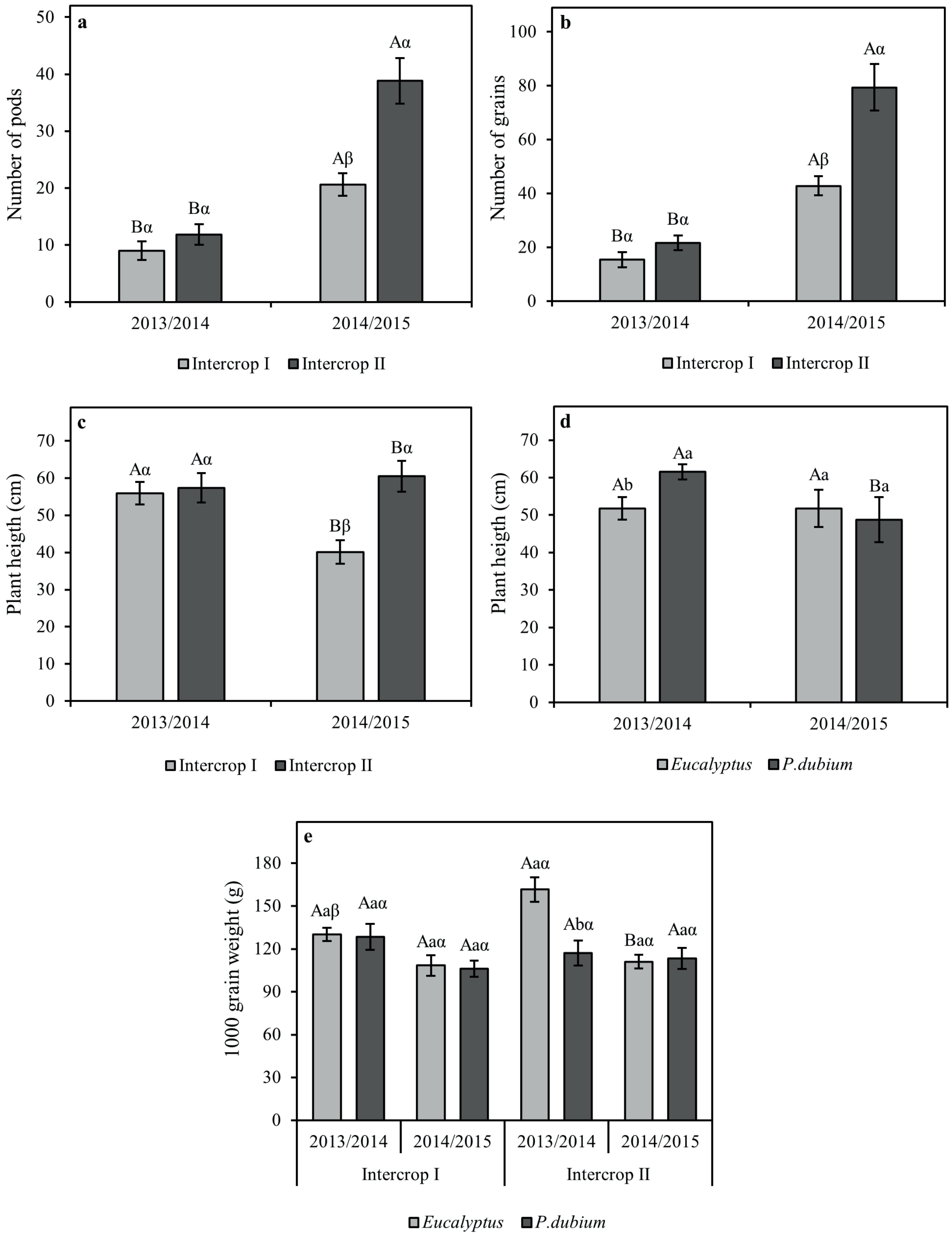

Figure 4 - Yield components of soybean cultivated in agroforestry systems during two crop years (2013/2014 and 2014/2015). Number of pods per plant (**a**), number of grains per plant (**b**), plant height (**c** and **d**) and 1000-grain weight (**e**). Southern, Brazil.

Means followed by the same letters, uppercase comparing the crop years, lowercase the forest species *Eucalyptus* and *P. dubium*, and greek letters comparing the Intercrop systems, have not significant difference by the Tukey test ($p<0.05$). Each bars represent average values ± SE.

adequate soybean development, which according to Embrapa (2013) are within the range of 20 to 30 °C and accumulated rainfall between 450 and 850mm (Figure 1).

The solar radiation transmissivity was determined by the characteristics of the forest species. Therefore, in agroforestry systems, it is necessary to improve some silvicultural management practices, such as crowning and thinning of trees, in order to reduce adverse interactions between trees and annual crops (Siric et al. 2010). Studies of the literature report higher grain yields when forest species were pruned (Siric et al. 2010, Bertomeu et al. 2011). Our results highlights the importance of this technique in integrated production systems.

In the present study, the largest transmissivity values were obtained for the tree *P.dubium* (Figure 3), being a deciduous species, which presents leaf senescence in the colder seasons (winter-autumn) which enable greater radiation availability in the understory. In early summer deciduous species already present a dense crown, however, its crown structure and of the rest of the shaft have smaller size when compared to the *Eucalyptus* (fast-growing species) (Paciullo et al. 2007) which leads to a less interception of solar radiation by the canopy. The *Eucalyptus* tree presents significant increases in length, diameter and crown area along the cultivation years (Wink et al. 2012). This result highlights the importance of appropriate selection of tree species used in the composition of the agroforestry system.

The greater availability of solar radiation in the Intercrop II understory, is related to a lower shading area in the understory when the tree component was cultivated with greater distance between trees. Similar results those obtained in this study were reported by Almeida et al. (2015). Péllico Netto et al. (2015), evaluating the dynamics of solar radiation in the understory of *Acacia mearnsii*, in an experiment conducted in Southern Brazil, have concluded that in the center of the plot, i.e., between rows of trees, more than 70% of the radiation reaches the ground level; however, in the projection and closure of the canopy, the values were significantly reduced to only 20%; confirming the influence of the canopy trees in the interception of incident radiation and thus reducing the availability of radiation for understory crops. Our findings agree with a study carried out by Pezzopane et al. (2015) and Bosi et al. (2014) who reported the high relation between levels of incident solar radiation, and its effect on microclimate, growth characteristics of plants, and soil moisture.

Our findings highlight the importance of silvicultural practices to manage the canopy and the use of a larger spatial arrangement, which provides an increase in the total solar radiation incident in the understory. These techniques were essential in order to obtain satisfactory yields in the agroforestry systems, as they enable the reduction of competition among forest species, as well as between the tree component and the annual crop, providing a balance in the crop system. The results of this study are in agreement with those observed by Prasad et al. (2010), who reported significant increases in the amount of solar radiation transmitted to the understory of the agroforestry systems when the same showed greater distance between trees. In the same way, Elli et al. (2016) highlights that the use of larger spatial arrangements results in a lower interception of the solar radiation by the tree component and can benefits the crop grown in the understory.

The results of number of grains per plant, obtained in this study (Figure 4b), may be related to the greater availability of solar radiation in the understory of the Intercrop II, which results in a higher incidence of solar radiation above the soybean plants, and thus, greater allocation of assimilates for the production of pods and grains. Soybean plants grown under an adequate availability of solar radiation present a greater retention of flowers, a higher number of pods, and consequently greater number of grains when compared with the Intercrop system that present lower levels of solar radiation. High shading conditions reduce the transpiratory flow of the soybean plants, limiting the redistribution of nutrients and photosynthesis, resulting in an increase of the abortion of flowers, and consequently, lower number of pod per plant and lower number of grains per plant (Fioreze et al. 2013).

Furthermore, when grown under reduced availability of solar radiation, the plants showed a greater allocation of photoassimilates for the stem elongation, and therefore, growth in height, in order to intercept more solar radiation (Paciullo et al. 2011, Taiz and Zeiger 2013). In order to achieve greater solar radiation availability in the understory of the Intercrop systems, it is possible also to adopt techniques such as tree pruning and thinning in order to provide a greater growth and development of the annual crop, which is essential for the productive successfulness of the intercropped system.

For the variables 1000-grain weight and number of pods per plant inverse response was observed (Figure 4e, a). Plants grown under low levels of solar radiation showed a greater allocation of photoassimilates to the vegetative growth, reducing significantly the number of pods and consequently the number of grains. However, the grains formed had a higher dry matter weight. These results are in accordance with those obtained by Perini et al. (2012) who reported that the 1000-grain weight is inversely proportional to the number of grains per plant.

Soybean yield followed the same trend as the solar radiation transmissivity (Figure 5). This can be explained due to the greater availability of solar radiation in the understory of the Intercrop system. The higher yield obtained in the 2014/2015 crop cycle shows the importance of the silvicultural practices in the forest species, confirmed in this study when the tree pruning was performed, which affect positively the soybean crop cultivated in the understory.

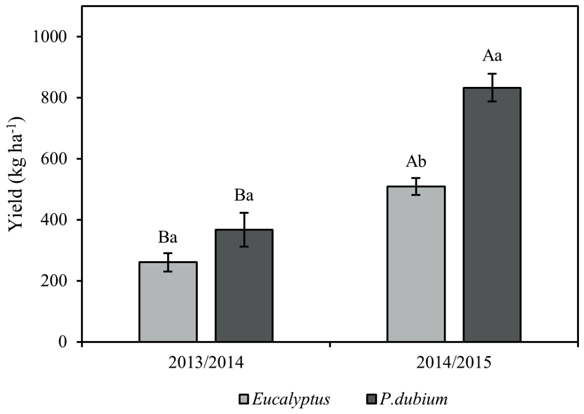

Figure 5 - Yield (Kg ha^{-1}) of soybean cultivated in an agroforestry system, submitted to *Eucalyptus* and *P. dubium* during two crop years (2013/2014 and 2014/2015). Southern, Brazil.
Means followed by the same letters, uppercase comparing the crop years and lowercase the forest species *Eucalyptus* and *P. dubium*, have not significant difference by the Tukey test ($p<0.05$). Each bars represent average values ± SE.

This soybean yield response may be explained due to the influence that the tree component had on the quantity and quality of solar radiation that reaches within the understory of the agroforestry system. The reduction in the productive responses of soybean cultivated in the Intercrop II system may be related to morphophysiological adjustments (Paciullo et al. 2011); for example, as a shade tolerance strategy, these adaptations were not able to compensate a reduction of radiation in the understory tree species and therefore influenced the productive soybean responses. According to Pinto et al. (2005), the main limiting factor above the ground in agroforestry systems is the availability of solar radiation, which together with the competition for water and nutrients limits crop yields in the understory in plants near to the forest species.

The results observed are consistent with those of Peng et al. (2009) and Reynolds et al. (2007), who reported that soybean cultivated in agroforestry systems, showed the highest yield values in the arrangements with the highest incidence of solar radiation; the same was observed by Oliveira et al. (2016), but with the *Zea mays* crop. Diel et al. (2014) reported that in the first two years of the agroforestry system implanted with the species *Eucalyptus* and a distance between the rows trees of 30 m, no significant influence of the forest species on the soybean yield was found.

Solar radiation directly influences in growth, development and yield of crops. Therefore, it can be inferred that difference in the flux of solar radiation explains the majority of the results obtained for the soybean crop in this study. From these values, we can highlight that the average flux of solar radiation was below or next to the trophic limit for the soybean crop, which is 8.4 MJ / dia^{-1} (Fagan et al. 2010), which may limit the crop yield, especially in the 2013/2014 crop year.

This explain the increase of the soybean yield response. Considering the high-energy demand for grain production, the soybean yield is compromised considerably if grown under levels of radiation transmissivity lower than 50%. The demand for solar radiation by the soybean crop is high because its grains are composed mainly of proteins, which present a high energy production cost when compared to the other substances, such as carbohydrates, which are the primary product of photosynthesis and the major component of several crops (Pereira 1989).

Majority of the studies involving agroforestry systems adopt the *Eucalyptus* species to compose the systems, such as the studies conducted by Franchini et al. (2014) and Prasad et al. (2010), due to its fast and uniform growth, ease of adaptation to edaphoclimatic conditions, alternatives of use and high yield (Bahdwaj et al. 2016). However, in this study was confirmed that the use of native species such as *P. dubium* to compose agroforestry systems favors the cultivation of soybean in the understory, as a function of its intrinsic characteristics, mainly related to leaf senescence during autumn/winter season, increasing the amount of solar radiation that could be intercepted by the annual crop.

In this context, the use of native species presents itself as an interesting alternative to compose agroforestry systems, in terms of their economic potential, providing wood and food, as well as favoring the restoration of the biome (Oliveira and Carvalhaes 2016). Moreover, in this study, it was explicit that even in consortium with native tree species, crowning and pruning of the tree component is directly related to the productive success of the annual harvest and, therefore, should be considered in the system management.

Our study highlights the importance of the solar radiation dynamics in integrated production systems. However, it is important to highlight that the difference in the Intercrop system and in the intrinsic growth characteristics of the forest species may have a contribution to the yield values obtained, mainly by the area of the root system of the forest species and competition with the plants in a consortium. In this way, the development of new studies that consider this evaluation factor should also be instigated in order to carry out a complete prognosis of the whole system.

There is little research that studies the dynamics of solar radiation and soybean yield in agroforestry systems. In this way, the information generated in this study is relevant, as it provides information to farmers that can assist in the planning of more ideal agroforestry systems via more efficient arrangements. This is especially relevant in the context of Brazilian law No. 12,651, May 25, 2012, which established a new Forest Code that allows farmers to plant agroforestry systems in areas of permanent preservation (APP) and legal reserves (RL), provided that said systems are subject to a sustainable management plan.

CONCLUSION

Agroforestry systems should consider the benefits of both forest and cultivated species. In this study, the soybean yield was determined by the arrangement of the agroforestry system and forest species utilized. The soybean crop cultivated in the understory of the *P. dubium* trees showed the highest yield response, supporting the first hypothesis.

The use of silvicultural practices of canopy management of forest species should be considered to generate the balance of the productive system. In this context, tree pruning is an adequate way to promote an increase in the incidence of solar radiation in the understory, resulting in an increase in soybean yield, especially when integrated with *P. dubium*, confirming the second hypothesis.

The authors agree that the yield response of soybean cultivated in the agroforestry system did not meet the expectations, due to the relatively low soybean yield. However, the authors believe that the social and environmental benefits provided by the system should be considered, especially in the context of global food production. In this way, this analysis of soybean cultivated in an agroforestry system becomes relevant because provide new sustainable alternatives for farmers in order to increase the diversification of rural properties and to maintain and/or improve the preservation of existing agro-ecosystems.

It is important that new research involving other species should be conducted to make new information available to farmers and making feasible the use of agroforestry systems in threatened ecosystems, such as those in permanent preservation areas (PPA's) and legal reserves (LR's).

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REFERENCES

ALMEIDA JCC, ROCHA NS, NEPOMUCENO DD, ARAÚJO RP, SILVA TO, MORENZ MJF, ABREU JBR, CARVALHO CAB AND MACEDO RO. 2015. Composição mineral de leguminosas forrageiras cultivadas sob diferentes níveis de sombreamento. Semina 36: 367-376.

ALTIERI MA. 2009. Agroecology, small farms, and food sovereignty. Mon Rev 61: 102-113.

ALVARES CA, STAPE JL, SENTELHAS PC, MORAES G, LEONARDO J AND SPAROVEK G. 2013. Köppen's climate classification map for Brazil. Meteorol Z 22: 711-728.

BERTOMEU M, ROSHETKO JM AND RAHAYU S. 2011. Optimum pruning intensity for reducing crop suppression in a *Gmelina*-maize smallholder agroforestry system in Claveria, Philippines. Agrofor Syst 83: 167-180.

BHARDWAJ KK, DHILLON RS, GODARA AS, KUMARO KSBS AND SHEOKAND RN. 2016. Nutrient status and soil chemical properties under different spacings os *Eucalyptus* based agroforestry systems in the semi-arid ecosystem of India. India J Ecolo 43: 756-760.

BOSI C, PEZZOPANE JRM, SENTELHAS PC, SANTOS PM AND NICODEMO MLF. 2014. Produtividade e características biométricas do capim-braquiária em sistema silvipastoril. Pesq Agropec Bras 49(6): 449-456.

CARON BO, SOUZA VQ, COSTA EC, ELOY E, BEHLING A AND TREVISAN R. 2012. Interceptação da radiação luminosa pelo dossel de espécies florestais e sua relação com o manejo das plantas daninhas. Cienc Rural 42: 75-82.

CHAPPELL MJ ET AL. 2013. Food sovereignty: an alternative paradigm for poverty reduction and biodiversity conservation in Latin America. F1000Research 2: 235-253.

CONAB - COMPANHIA NACIONAL DE ABASTECIMENTO.Acompanhamento da Safra Brasileira de Grãos. 2017. Disponível em: http://www.conab.gov.br/OlalaCMS/uploads/arquivos/17_12_12_17_59_52_dezembro.pdf. Acesso em 28 de dezembro de 2017.

CORDEIRO LAM, VILELA L, MARCHÃO RL, KLUTUJCOUSKI J AND MARTA JÚNIOR GB. 2015. Integração lavoura-pecuária-floresta: estratégias para intensificação sustentável do uso do solo. CC & T 32: 15-53.

CQFS - COMISSÃO DE QUÍMICA E FERTILIDADE DO SOLO. 2004. Manual de adubação e calagem para os estados do Rio Grande do Sul e Santa Catarina. Porto Alegre: Sociedade Brasileira de Ciência do Solo – Núcleo Regional Sul, 400 p.

CUNHA NG, SILVEIRA RJC, KOESTER E, OLIVEIRA LD, ALBA JMF, TERRES VC AND LOPES RT. 2011. Estudos de Solos do Município de Frederico Westphalen, RS. Circular Técnica 116.

DIEL D, BEHLING M, NETO ALF AND ISEMNHAGEN ECC. 2014. Distribuição horizontal e vertical de fósforo em sistemas de cultivos exclusivos de soja e de integração lavoura-pecuária-floresta. Pesq Agropec Bras 49: 639-647.

ELLI EF, CARON BO, ELOY E, BEHLING A, SOUZA VQ AND SCHWERZ F. 2016. Productive, morphological and qualitive characteristics of sugarcane in the understory tree species in agroforestry systems. Afr J Agric Res 11(17): 1576-1584.

EMBRAPA – EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. 2006. Tecnologias de produção de soja - Paraná - 2007. Londrina, 217 p.

EMBRAPA – EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. 2013. Tecnologia de Produção de Soja-Região Central do Brasil – 2014. 21ª ed., Londrina, 266 p.

FAGAN EB, NETO DD, VIVIAN R, FRANCO RB, YEDA MP, MASSIGNAM LF, OLIVEIRA RF AND MARTINZ KV. 2010. Efeito da aplicação de piraclostrobina na taxa fotossintética, respiração, atividade da enzima nitrato redutase e produtividade de grãos de soja. Bragantia 69: 771-777.

FIOREZE SL, RODRIGUES JD, CARNEIRO JPC, SILVA AA AND LIMA MB. 2013. Fisiologia e produção da soja tratada com cinetina e cálcio sob déficit hídrico e sombreamento. Pesq Agropec Bras 48: 1432-1439.

FRANCHINI JC, JUNIOR AAB, SICHIERI FR, DEBIAS H AND CONTE O. 2014. Yield of soybean, pasture and wood in integrated crop-livetock-forest system in Northwestern Paraná State, Brasil. Rev Cienc Agron 45: 1006-1013.

GODFRAY HCJ, BEDDINGTON JR, CRUTE IR, HADDAD L, LAWRENCE D, MUIR JF, PRETTY J, ROBINSON S, THOMAS SM AND TOULMIN C. 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967): 812-818.

MATSUO N, KOICHIRO F AND TSUCHIYA S. 2016. Effects of early planting and cultivars on the yield and agronomic traits of soybeans grown in southewestern Japan. Plant Prod Sci 19: 370-380.

MÜLLER MD, PACIULLO DSC, MARTINS CE, ROCHA WSD AND CASTRO CRT. 2014. Desenvolvimento vegetativo de pinhão-manso em diferentes arranjos de plantio em sistemas agrossilvipastoris. Pesq Agropec Bras 49(7): 506-514.

NICODEMO MLF, CASTIGLIONI PP, PEZZOPANE JRM, THOLON P AND CARPANEZZI AA. 2016. Reducing competition in agroforestry by pruning native trees. Rev Arvore 40: 509-518.

OLIVEIRA RE AND CARVALHAES MA. 2016. Agroforestry as a tool for restoration in Atlantic forest: can we find multi-purpose species? Oecologia Australis 20: 425-435.

OLIVEIRA VR, SILVA PSL, PAIVA HN, PONTES FST AND ANTONIO RP. 2016. Growth of arboreal leguminous plants and maize yield in agroforestry systems. Rev Arvore 40: 679-688.

PACIULLO DSC, CARVALHO CAB, AROEIRA LJM, MORENZ MJF, LOPES FCF AND ROSSIELLO ROP. 2007. Morfofisiologia e valor nutritivo do capim-braquiária sob sombreamento natural e a sol pleno. Pesq Agropec Bras 42: 573-579.

PACIULLO DSC, GOMIDE CAM, CASTRO CRT, FERNANDES PB, MÜLLER MD, PIRES MFA, FERNANDES EM AND XAVIER DF. 2011. Características produtivas e nutricionais do pasto em sistema agrossilvipastoril, conforme a distância das árvores. Pesq Agropec Bras 46: 1176-1183.

PÉLLICO NETTO SP, SANQUETTA CR, CARON BO, BEHLING A, SIMON AA, CORTE APD AND BAMBERG R. 2015. Ground level photosynthetically active radiation dynamics in stands of *Acacia mearnsii* De Wild. An Acad Bras Cienc 87(3): 1833-1845.

PENG X, ZHANG Y, CAI J, JIANG Z AND ZHANG S. 2009. Photosynthesis, growth and yield of soybean and maize in a tree-based agroforestry intercropping system on the Loess Plateau. Agrofor Syst 76: 569-577.

PEREIRA AR. 1989. Aspectos fisiológicos da produtividade vegetal. R Bras Fisiol Veg 1: 139-142.

PERINE LJ, JÚNIOR NSF, DESTRO D AND PRETE CEC. 2012. Componentes da produção em cultivares de soja com crescimento determinado e indeterminado. Semina 33: 2531-2544.

PEZZOPANE JRM, BOSI C, NICODEMO MLF, SANTOS PM, CRUZ PGD AND PARMEJIANI RS. 2015. Microclimate and soil moisture in a silvopastoral system in Southeastern Brazil. Bragantia 74: 110-119.

PILAU J, ELLI EF, NARDINO M, KORCELSKI C, SCHMIDT D AND CARON BO. 2015. Desenvolvimento e qualidade do azevém no sub-bosque de angico-vermelho em sistema silvipastoril. Com Sci 6: 437-444.

PINTO LFG, NERNARDES MS, STAPE JL AND PEREIRA AR. 2005. Growth, yield and system performace simulation of a sugarcane-eucalyptus interface in a sub-tropical region of Brazil. Agric Ecosyst Environ 105(1): 77-86.

PRASAD JVN ET AL. 2010. Tree row spacing affected agronomic and economic performance of *Eucalyptus*-based agroforestry in Andhra Pradesh, Southern India. Agrofor Syst 78: 253-267.

RAINES CA. 2011. Increasing photosynthetic carbono assimilation in C_3 plants to improve crop yield: current and future strategies. Plant Physiol 155: 36-42.

REYNOLDS PE, SIMPSON JA, THEVATHASAN NV AND GORDON AM. 2007. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in Southern Ontario, Canada. Ecol Eng 29: 362-371.

SALTON JC, MERCANTE FM, TOMAZI M, ZANATTA JA, CONCENÇO G, SILVA WM AND RETOREA M. 2013. Integrated crop-livestock system in tropical Brazil: toward a sustainable production system. Agric Ecosyst Environ 190: 70-79.

SAS LEARNING EDITION. 2003. Getting started with the SAS Learning Edition. Cary, 200 p.

SCHWERZ F, ELLI EF, BEHLING A, SCHMIDT D, CARON BO AND SGARBOSSA J. 2017. Yield and qualitative traits of surgarcane cultivated in agroforestry systems: Toward sustainable production systems. Renew Agr Food Syst 32: 1-13.

SILES P, HARMAND JM AND VAAST P. 2010. Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agrofor Syst 78: 269-286.

SIRIC D, ONG CK, WILSON J, BOFFA JM AND BLACK CR. 2010. Tree species and pruning regime affect crop yield on bench terraces in SW Uganda. Agrofor Syst 78: 65-77.

SOARES AB, SARTOR LR, ADAMI PF, VARELLA AC, FONSECA L AND MEZZALIRA JC. 2009. Influência da luminosidade no comportamento de onze espécies forrageiras perenes de verão. Rev Bras de Zootecn 38: 443-451.

TAIZ L AND ZEIGER E. 2013. Fisiologia Vegetal. 5ª ed., Porto Alegre, Artmed, 918 p.

TRACY BF AND ZHANG Y. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Sci 48(3): 1211-1218.

WERNER F, BALBINOT AAJ, FRANCHINI JC, FERREIRA AS AND SILVA MAA. 2017. Agronomic performance of soybean cultivars in an agroforestry system. Pesq Agropec Bras 47: 279-285.

WINK C, MONTEIRO JS, REINERT DJ AND LIBERALESSO E. 2012. Parâmetros da copa e a sua relação com o diâmetro e altura das árvores de eucalipto em diferentes idades. Sci For 40: 57-67.