AGRONOMY (AGRONOMIA)

Effect of artificial shading on soybean growth and yield

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ABSTRACT: Soybean (*Glycine max*) stands out in the agricultural scene, being one of the main sources of protein and oil for human and animal nutrition. The aim of this study was to evaluate the growth, radiation use efficiency, and the yield of soybean, cultivated under four levels of artificial shading to simulate the environment provided by an agroforestry system. A field experiment was conducted in Frederico Westphalen, Rio Grande do Sul, Brazil, from December 2015 to April 2016. The experimental design was completely randomized with four levels of shading (0, 30, 50, and 70%) as treatment, and eight collections of plants at specific growth stages. The growth and yield traits of the soybean crop are influenced differently as a function of shade levels. Thus, the simulation of an agroforestry system from artificial shading allowed the recommendation of soybean cultivation for intercropping systems, provided that the interception of solar radiation by the tree component is less than 30%, in order to enable soybean cultivation.

Key words: agroforestry systems; *Glycine max*; growth analysis; meteorological variables; solar radiation

Efeito do sombreamento artificial no crescimento e produtividade da soja

RESUMO: A soja (*Glycine max*) destaca-se no cenário agrícola mundial, sendo uma das principais fontes de proteína e óleo para nutrição humana e animal. O objetivo deste estudo foi avaliar o crescimento, a eficiência do uso da radiação e a produtividade da soja cultivada sob quatro níveis de sombreamento artificial visando similar o ambiente proporcionado por um Sistema agroflorestal. Um experiment de campo foi conduzido em Frederico Westphalen, Rio Grande do Sul, de dezembro de 2015 a abril de 2016. O delineamento experimental empregado foi o inteiramente casualizado com quatro níveis de sombreamento (0, 30, 50 e 70%) como tratamento, e oito coletas de plantas em estádios específicos de crescimento. As características de crescimento e produtivas da cultura da soja são influenciadas diferentemente em função dos níveis de sombreamento. Assim, a simulação de um Sistema agroflorestal a partir de sombreamento artificial permitiu a recomendação do cultivo da soja para sistemas consorciados, desde que a interceptação da radiação solar pelo componente arbóreo seja inferior a 30%, a fim de viabilizar o cultivo da soja.

Palavras-chave: sistemas agroflorestais; *Glycine max*; análise de crescimento; variáveis meteorológicas; radiação solar

Introduction

Soybean (*Glycine max* (L) Merrill) is a unique agricultural crop because it is one of the main sources of protein and vegetable oil (Matsuo et al., 2016), and is widely used for human and animal nutrition. Brazil is recognized as one of the world's leading soybean producers, with 35.82 million hectares of planted area and an estimated production of 115.34 million tons of soybeans (CONAB, 2018).

The growth and development of plants is heavily influenced by meteorological variables, which in combination with other environmental and physiological factors, determine the productive potential of the crop (Caron et al., 2017). One of the most influential meteorological variables for phytomass production in plants is solar radiation. Solar radiation plays a critical role in plant growth and development, solar radiation use efficiency is a determinant characteristic in plants (Caron et al., 2014).

Soybean has a relatively high solar radiation interception owing to its large leaf area and rapid production of leaflets until auto-shading occurs (Casaroli et al., 2007). The sun's rays that fall on a shading screen have their direction altered, thereby modifying the average solar radiation flux reaching the soybean plants and targeting photoassimilates, affecting the yield and yield traits of the crop.

According to Sanquetta et al. (2014), the dynamics of solar radiation in shading conditions can be modified, mainly by formation of a microclimate, where there is the attenuation of the air temperature, and possibly an increase in the fraction of diffuse solar radiation, which is considered a determinant in the conversion efficiency of photoassimilates. The lower availability of solar radiation in shaded crops may not be limiting to plant growth by virtue of diffuse solar radiation, which, being multidirectional, is more efficient at penetrating the plant's canopy (Buriol et al., 1995).

The use of shading screens to analyze the response of plants in the understory presents advantages over natural shading, such as that provided in an agroforestry system, because it is possible to isolate the effect of the intensity of solar radiation from other interferences such as competition for water and nutrients (Pivatto et al., 2014). However, natural shading modifies both the intensity and quality of incident radiation in the sub-forest (Paciullo et al., 2011), whereas shading screens, while efficiently reducing the solar radiation intensity, do not alter the quality of solar radiation (Huber & Stuefer, 1997).

According to Elli et al. (2016), when solar radiation is intercepted by the tree canopy, it can be absorbed, transmitted, or reflected, depending on the angle of incidence of the sun's rays, leaf insertion angle, and leaf area index. The fraction of solar radiation that is transmitted through the canopy and which is available to the plants inside the canopy, can be either direct or diffuse, which conditions the internal microclimate of the system, and may also affect the physiological characteristics of the species grown in the sub-forest (Mendes et al., 2013).

Agroforestry systems are an alternative system for sustainable production, which allow a consortium of agricultural crops and forest species in the same cultivation area, increasing the diversity of the ecosystem, efficiency of soil use, and preservation of natural resources. However, it is necessary to evaluate the effects of the tree component on the annual crops that make up the system, as there is an interspecific competition for water, light, and nutrients (Werner et al., 2017).

Given the importance of soybean crop in Brazil, and the lack of information on this subject, the following hypotheses were generated: i) soybean growth and yield are influenced by different levels of shading; ii) increased shading levels have a negative effect on crop growth and yield. Thus, the growth, efficiency of the radiation use efficiency and the yield of soybean grown under four levels of artificial shading, which were evaluated, in order to simulate the environment generated in an agroforestry system.

Material and Methods

A field experiment was conducted in the city of Frederico Westphalen, Rio Grande do Sul (RS), Brazil (27°23′48″ S, 53°25′45″ W, 490 m altitude). According to the climatic classification of Köppen, the climate of the region is of type Cfa, that is, subtropical humid, with average annual temperatures of 19.1 °C and minimum and maximum temperatures ranging from 0 °C to 38 °C (Alvares et al., 2013). The meteorological data used was obtained from the automatic meteorological station linked to the National Institute of Meteorology (INMET), located 400 m from the experimental area. The soil of the experimental area is classified as typical dystrophic Red Latosol (see Table 1 for the physical chemical composition).

The experimental design was completely randomized with four levels of shading treatments (0, 30, 50, and 70%), and eight plant collections at specific growth stages. At each stage, six plants were collected from each treatment group, totaling 192 plants collected by completion of the experiment.

The sowing was carried out on December 02, 2015, with the aid of a seed drill, using the cultivar NA5909RG that has an indeterminate growth habit and maturity group 6.9, sustaining a final population of 250.000 plants.ha^{-1}. The experimental plot consisted of eight planting lines of 3.0 m, spaced at 0.45 m. The useful part of the four central lines was defined by removing 0.5 m from the extremities. The shading screens used were black in color.

Growth evaluations were performed at 15 day intervals, starting with the plants in stage V1, i.e., the seedlings that present full opening of the first trifoliate on the main stem

Table 1. Chemical composition of the experimental area in the agricultural year 2015/2016. Frederico Westphalen-RS, 2018.

pH (H₂O)	P	K	Ca	Mg	CTC	V	MO
	(mg L^{-1})		(cmol$_c$ L^{-1})			(%)	
5.5	8.4	199.5	4.8	2.2	10.8	69.5	2.5

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(when the leaflet edges of the first trifoliate leaf no longer touch). Subsequent collections were carried out at stages V3, V5, R1, R3, R5.3, R7.2, and R8.2 when they presented more than 50% defoliation, and the harvest was performed at R9 when the plants showed harvest maturation.

The plants collected in the field were taken to the laboratory for sectioning into leaves, stem, flowers, senescent leaves or leaves in the process of senescence, and pods, for later determination of the leaf area of each sample. Plants presenting more than 50% defoliation were considered senescent. After sectioning, the samples were packed in paper bags and kept in an oven with forced air circulation at 60 °C, until constant mass was attained.

The radiation use efficiency was determined by relating the average accumulated dry matter production and the intercepted photosynthetically active radiation, as described by Monteith (1977):

$$TDM = \varepsilon b \cdot PARi \qquad (1)$$

where TDM = total dry matter produced in g.m^{-2}, εb is the efficiency in conversion of the photosynthetically active radiation intercepted in dry matter produced in g.MJ^{-1}, and PARi is the intercepted photosynthetically active radiation in MJ.m^{-2}.

The estimation of incident photosynthetically active radiation was performed assuming 45% of global solar radiation (Assis & Mendez, 1989), with no difference between days of intense light incidence and cloudy days. The estimate of the intercepted photosynthetically active radiation was determined using the model described by Varlet-Grancher et al. (1989):

$$PARi = 0.95 \cdot \left(PARinc \right) \cdot \left(1 - e^{\left(-k \cdot LAI \right)} \right) \qquad (2)$$

where PARi = intercepted photosynthetically active radiation in MJ.m^{-2}, PARinc = incident photosynthetically active radiation in MJ.m^{-2}, k = extinction coefficient, calculated for each shading condition as well as for full sun, and LAI = leaf area index.

The incident global radiation (W.m^{-2}) was determined in the period between 10 and 12 h at the time of each plant collection. Incident global radiation on the upper stratum and lower stratum layers of the plant canopy was measured with a pyranometer (LICOR PY32164) coupled to a Data logger (LICOR 1400).

The measurement of the leaf area of each sample unit was performed using leaf area integrator LI-COR model 3000, with the unit expressed in em.cm^{-2}. The leaf area index (LAI) was determined from the total leaf area and the area of soil explored by each plant (0.04 m^{-2}):

$$LAI = \frac{LA}{SA} \qquad (3)$$

where LAI = leaf area index; LA = leaf area of the plant in m^{-2}; and AS = soil area explored by the plant in m^{-2}.

The following growth parameters were calculated according to methodology used by Benincasa (2003): biological productivity (BP; g.m^{-2}), absolute growth rate (AGR; g.day^{-1}), relative growth rate (RGR; g.g.day^{-1}), and net assimilation rate (NAR; g.m^{-2}.day^{-1}).

The harvest was carried out on April 19, 2016, when the plants reached physiological maturation. Ten plants were harvested from each plot, and the vegetal material was threshed and the grains weighed in a precision balance with a capacity of 5 kg and humidity corrected to 13%. The yield traits evaluated were: plant height, stem base diameter, number of pods per plant, the total number of grains per plant, and total grain mass of each plant.

The data were analyzed using analysis of variance (ANOVA) in SAS Learning Edition 8.0 (SAS, 2003). When a significant effect of the treatments was verified (F with p ≤ 0.05), a multiple comparison of means was performed by the Tukey test (p ≤ 0.05). To verify the homogeneity of the variances, the Bartlett test was used, while the normal distribution was analyzed using the Shapiro-Wilk test. Results regarding leaf area index and growth rates were detailed through descriptive analysis.

Results and Discussion

The values of the accumulated solar radiation, rainfall, and minimum, average, and maximum air temperature obtained during the experiment are presented in Figure 1. During
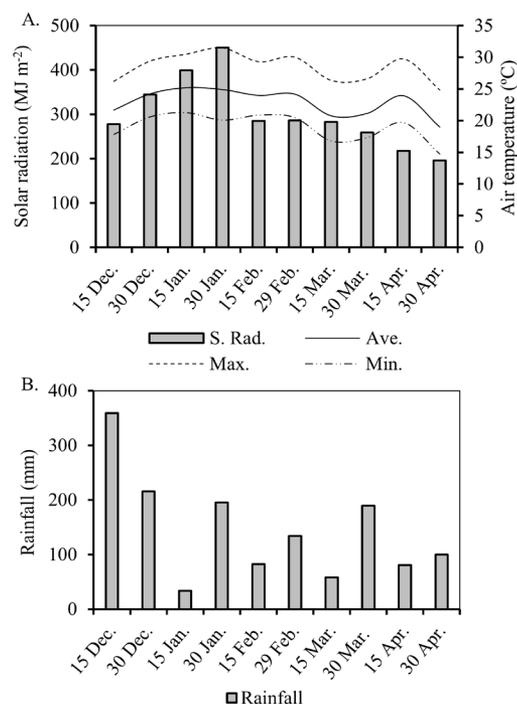
Figure 1. Fortnightly values of the accumulated solar radiation (S. Rad.), average (Ave.), and maximum (Max.) and minimum air temperature (Min.) (A.), and rainfall (B.), during the period of the experiment (02/12/2015 to 19/04/2016). Frederico Westphalen-RS, 2018.

the crop cycle, the accumulated rainfall was 1267.2 mm, air temperature ranged from 20.4 to 25.7 °C, with an average of 23.3 °C, and average solar radiation flux was 19.7 MJ.day^{-1}. Therefore, these variables did not limit the growth and development of the crop.

The comparison of the increase in LAI between the different levels of shading is presented in Figure 2. The maximum LAI values were 4.6, 7.0, 6.5 and 4.7, under 0, 30, 50, and 70% shading, respectively, and were observed during the R3 stage, the initial stage of pod formation.

The highest LAI was observed in the 30% shading treatment group. This is owing to greater vegetative growth provided by the microclimate generated inside the shading screen that favored the growth of the plants, and thus, greater uptake of solar radiation. This result demonstrates that increased leaf area in conditions of low solar radiation incidence is one of the plants' responses to increase the plant surface area to capture solar rays (Lenhard et al., 2013).

According to Sanquetta et al. (2014), the production of dry matter by soybean plants is dependent on the amount of accumulated intercepted photosynthetically active radiation, and the plants solar radiation conversion efficiency. The different levels of shading exhibited different efficiency of conversion of solar radiation into dry matter. The highest radiation use efficiency was 4.27 g.MJ[-1], observed at 70% shading, compared to 2.93, 2.11, and 2.06 g.MJ[-1] for shade levels of 50, 30, and 0%, respectively (Figure 3).

Thus, it is inferred that higher levels of shading resulted in increased radiation use efficiency. These results may be related to the growing environment, in that under limited solar radiation, the plants present differences in morphological characteristics, especially of the leaves, due to acclimatization to this treatment condition (Schmidt et al., 2017).

When grown in environments that provide distinct levels of shading, soybean plants present a differential ability to convert the absorbed solar radiation in to photoassimilates. Higher solar radiation incidence is not always linked to greater radiation use efficiency and phytomass conversion, or consequent yield, because the solar radiation may be restricted to the upper canopy (Petter et al., 2016).
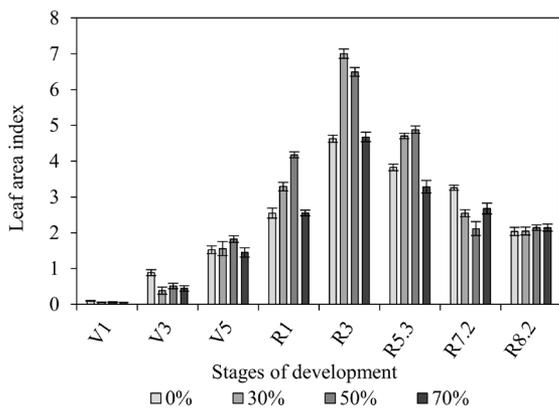

Figure 2. Leaf area index of soybean cultivated under four levels of shading, 0%, 30%, 50% and 70%, throughout the developmental stages. Frederico Westphalen - RS, 2019.
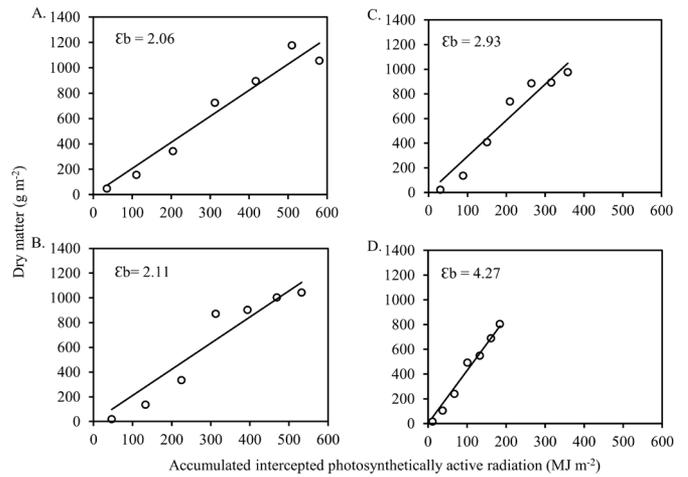
Figure 3. The efficiency of the use of radiation (g.MJ[-2]), of soybean plants grown under four levels of shading, 0% (A.), 30%, (B.), 50% (C.), and 70% (D.). Frederico Westphalen - RS, 2019.

The increased solar radiation use efficiency at 70% shading may be associated with increased amounts of diffuse solar radiation incident within the shading screen, thus modifying the microclimate inside the canopy, promoting greater interception of the radiation by the lower leaves and, consequently increasing radiation use efficiency (Sanquetta et al., 2014). In this way, the growing environment influences the growth and development of plants by modifying the available solar radiation intensity.

The showed an increasing response throughout the evaluation period. The highest biological productivity was observed under 0% shading at the R7.2 stage. Conversely, the absolute growth rate was highest in the 30% shading treatment during stage R3. However, from R5.3 the 70% shading treatment was superior to the 30% shading treatment until the end of the cycle (Figure 4).
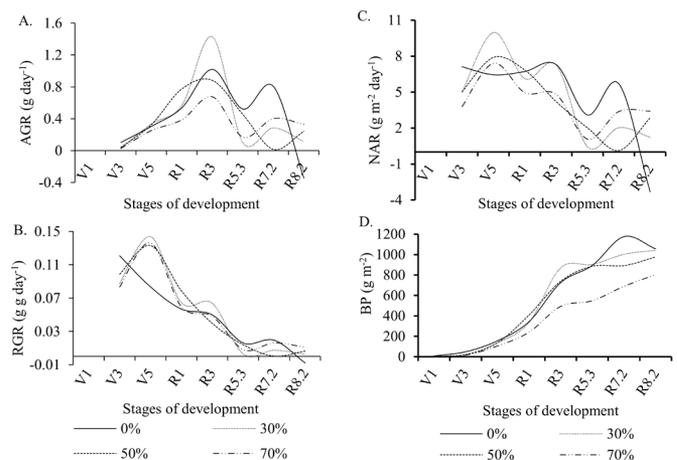
Figure 4. Absolute growth rate (AGR; g.day^{-1}) (A.), relative growth rate (RGR; g.g.day^{-1}) (B.), net assimilation rate (NAR; g.m^{-2}day[-1]) (C.) and biological productivity (BP; g.m^{-2}) (D.) of soybean plants grown under four levels of shading, 0%, 30%, 50% and 70%, throughout development. Frederico Westphalen-RS, 2019.

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The variation in the values of biological productivity and absolute growth rate can be related to the high levels of solar radiation that the plants demand in order to carry out photosynthesis, and thus to reach higher crop growth rates at the beginning of the vegetative phase. The absolute growth rate results are similar to those obtained by Linhares et al. (2014), where the fastest growth rates were observed at the beginning of the vegetative period, and reduced during the maturation period.

The relative growth rate of plants showed the same tendency as the rate of net assimilation, which was highest in the initial stages of growth, and decreased with leaf senescence and physiological maturation. These variables were highest under 30% shading in the V5 stage (Figure 4). Petter et al. (2016) also found a higher relative growth rate of soybean in the early stages of growth and a subsequent decrease.

The relative growth rate and the net assimilation rate declined during the cycle due to the leaf senescence period. Similar results were found by Linhares et al. (2014), who observed higher relative growth rate and rate of net assimilation in the vegetative phase, but these values decreased as the crop cycle continued, and auto-shading interfered with the photosynthetic efficiency of the plants.

The evaluation of plant growth through production and assimilation of dry matter is extremely important as it can inform the development of practices that allow increased productive efficiency of the crop in response to meteorological conditions. Based on the observation of the growth variables, it can be inferred that the meteorological conditions that occurred during the experiment were favorable, resulting in higher absolute growth rate, relative growth rate, net assimilation rate, and biological productivity, for all levels of shading studied.

There were significant differences between the different levels of shading for grain yield, number of pods per plant, number of grains per plant, grain mass per plant, plant height and stem base diameter (Figure 5).

The highest values for yield, number of pods per plant, number of grains per plant, grain mass per plant and stem base diameter were observed under 0% shading, and were significantly different to the 70% shading treatment results. The highest value for plant height was observed in the 50% shading treatment group and this result was significantly different to all other shading treatments.

As shading level increased, the plants showed increased growth, due to greater investment in cell elongation and, consequently, smaller stem diameter. According to Souza et al. (2013), taller plants do not always have higher yields, thus, lower heights in soybean resulted in an increased number of grains per pod, grains per plant and mass of grains, and overall higher production ceiling.

The reduction of the number of pods and grains per plant occurs mainly in response to competition between plants for solar radiation. When subjected to stress conditions, such as the reduced availability of solar radiation in an agroforestry
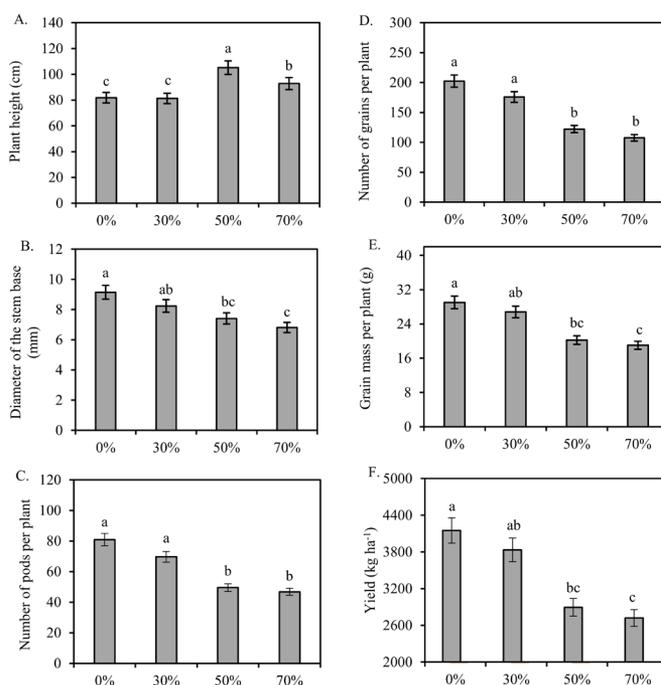
Figure 5. Plant height (A.), diameter of the stem base (B.), number of pods per plant (C.), number of grains per plant (D.), grain mass per plant (E.), yield (F.) of soybean plants grown under four levels of shading, 30, 50 and 70%. Frederico Westphalen - RS, 2019.

system or artificial shading, the plants tend to respond by directing photoassimilates towards stem elongation, and thus grow in search of solar radiation (Taiz et al., 2017) resulting in lower productivity.

The average flux of solar radiation obtained under 0% shading was 19.7 MJ.day^{-1}, considering the transmissivity that occurred between the shading screens, we observed that the mean flow was 13.7 MJ.day^{-1} for the 30% shading treatment, 9.3 MJ.day^{-1} for the 50% shading treatment, and 5.7 MJ.day^{-1} for the 70% shading treatment.

Considering the average values of solar radiation incident to the canopy of the plants, it can be inferred that the average solar radiation flux was not limiting to the growth and development of the soybean plants, except for 70% shading, which was lower than the trophic limit of the crop, which according to Fagan et al. (2010) is 8.4 MJ.day^{-1}. This may have led to lower yields under the 70% shading treatment. Soybean crops present a high energy demand for the conversion of photoassimilates to grains as they are predominantly composed of proteins, rather than other photosynthetic products, such as carbohydrates (Taiz et al., 2017).

In general, it can be inferred that grain yield decreased as a function of shade level, with the largest leaf area available being the determining factor for this variable, as this provides greater incident solar radiation interception, resulting in an increase in the photosynthetic rate. In systems combining annual and forest species proximity of the trees affects soybean productivity (Franchini et al., 2014). According to Balbinot Junior et al. (2016) greater interception of solar

radiation at the beginning of the vegetative cycle, provides a greater accumulation of dry matter in the aerial part and the index of the leaf area, reflecting the increase in grain yield.

The information generated in this study can help in planning implementation of agroforestry systems. The results demonstrated that when submitted to levels of shading greater than 30% a significant reduction in soybean crop occurs and this can make production unfeasible. In this way, the use of spacing and cultivation densities of forest species that provide solar radiation above the critical level identified for the crop, are indispensable for productive success in an agroforestry system.

Conclusions

The growth and yield traits of the soybean crop are influenced by shade level, confirming hypothesis i). With increasing levels of shading, there is a significant reduction in soybean growth and yield, confirming hypothesis ii).

The highest values of radiation use efficiency were observed at 50 and 70% shading; however, even if the plants are able to acclimatize to this growing environment, it does not favor soybean growth or yield.

In this sense the simulation of an agroforestry system via artificial shading, supports recommencing soybean cultivation in intercropping systems, provided that the interception of solar radiation by the tree component does not exceed 30%, so that the plants of the canopy can meet their minimum solar radiation demand, enabling optimal soybean crop cultivation.

Acknowledgements

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