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Agronomic performance of soybean crops under integrated production systems in the Southwestern Brazilian Amazon biome

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ABSTRACT: Soybean is an alternative crop to be used in intensified land use systems and recovery of degraded areas in Brazil. Thus, the objective of this study was to evaluate the agronomic performance of soybean crops under integrated production systems in the Southwestern Brazilian Amazon biome. Soybean crop was grown in alleys with widths of 18, 30, and 42 m between the 4-row tree sets of eucalyptus and evaluated in two agricultural years (2016-2017 and 2017-2018). Plant height, first pod insertion height, number of grains per pod, number of pods per plant, 100-grain weight, and grain yield of soybean plants at maturation stage were evaluated in different distances from the eucalyptus (10, 20, 30 and 45% of the alley width). The lowest mean grain yield was found for the alley of 18 m in the 2017-2018 agricultural year. The proximity of soybean plants to eucalyptus trees affects negatively the grain yield, plant height, first pod insertion height, plant population, and number of pods per plant. The crop-livestock-forest integration system, with the forest component consisting of 5-year-old eucalyptus trees (technical age for harvest), resulted in higher soybean grain yields for the alley of 42 m. The growth of soybean crops in alleys of 18 m between 4-row tree sets of 5-year-old eucalyptus trees is not recommended for the Southwestern region of the Brazilian Amazon biome.

Key words: *Glycine max*, ecological intensification, crop-livestock-forest integration, sustainable production

Desempenho agronômico da cultura de soja em sistemas integrados de produção no sudoeste do bioma amazônico brasileiro

RESUMO: A cultura da soja é uma alternativa de uso em sistemas de intensificação do uso do solo e para recuperação de áreas degradadas no Brasil. Com isso, objetivou-se avaliar o desempenho agronômico da cultura em sistemas integrados de produção na região sudoeste do bioma amazônico brasileiro. Foram avaliadas lavouras de soja distribuídas em faixas de 18, 30 e 42 m de largura em sistemas agrossilvipastoris consolidados com renques quádruplos de eucalipto, durante dois anos agrícolas. Foram avaliadas a altura de plantas e de inserção da primeira vagem, número de grãos por vagem, número de vagens por planta, massa de 100 grãos, rendimento de grãos de soja na população final de plantas no estádio de maturação localizadas em cinco posições de semeadura a partir dos renques de eucalipto. O menor rendimento médio de grãos foi obtido no espaçamento de 18 m no segundo ano agrícola. A proximidade das plantas de soja do eucalipto diminui o rendimento de grãos, a altura de plantas e de inserção de primeira vagem, a população de plantas e o número de vagens por planta. Em sistema integração lavoura-pecuária-floresta, com componente florestal de eucalipto consolidado aos cinco anos de idade (Idade Técnica de Colheita), as maiores produtividades de grãos de soja foram observadas no espaçamento entre renques de 42 m de largura. Não se recomenda o cultivo de soja em faixas de 18 m de largura em sistema integrado envolvendo o eucalipto em renques quádruplos com cinco anos de idade na região sudoeste do bioma amazônico brasileiro.

Palavras-chave: *Glycine max*, intensificação ecológica, integração lavoura-pecuária-floresta, produção sustentável

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Introduction

Soybean crops have been grown in newly open and agricultural areas in the Amazon region in the recent years (CONAB, 2018), mainly over degraded pasture areas. Areas that were used for livestock farming have been used for soybean crops for indirect recovery of soil fertility (Silva et al., 2018). Soil degradation can be reversed through conservationist practices, which require the adoption and technical information of soil management and cultural practices adapted and appropriate to the region (Passos et al., 2017).

In this context, the substitution of traditional soil management systems in the Amazon region, which involves the use of plows and harrows, deforestation and burning of native forests, or fallow, to more sustainable systems, such as no-tillage and crop-livestock or crop-livestock-forest integration, is a strategy for increasing food production and for an adequate use of natural resources (Tollefson, 2015; Jankowski et al., 2018).

The basis of integrated systems is the temporal and spatial integration of annual grain or forage crops, livestock production, and forestry (Balbino et al., 2011). The use of intercropping is important for crop-livestock-forest integration systems; it is an old technique used empirically in the past (Maezumi et al., 2018) that still requires experimental scientific evaluations (Morhart et al., 2014) for regionalized technological validation to be adequately used (Salton et al., 2014; Cerri et al., 2018).

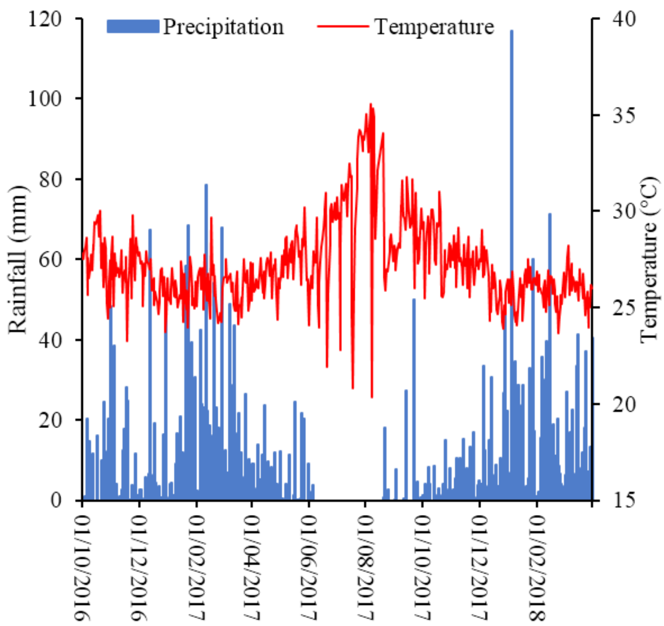
The insertion of a forest component in soybean crop areas results in areas with shades projected by the trees, which result in lower photosynthetic solar radiation and physiological changes in plants between and next to the trees (Werner et al., 2017).

In this context, the objective of this study was to evaluate the agronomic performance of soybean crops under integrated production systems with 5-year-old eucalyptus (*Eucalyptus* spp.) trees during two agricultural years, in the Southwestern Brazilian Amazon biome.

Material and Methods

The experiment was conducted in an experimental area of the Brazilian Agricultural Research Corporation (EMBRAPA), in Porto Velho, Rondônia, Brazil (8° 47' 42" S, 63° 50' 45" W, and 95 m altitude), in the 2016-2017 and 2017-2018 agricultural years. The region has a tropical humid (Am) climate (Alvares et al., 2013), presenting mean annual rainfall depth of 2,200 mm, temperature of 25.5 °C and air relative humidity of approximately 83%. Rainfall and temperature data during the experiment period are presented in Figure 1.

The soil of the experiment area was classified as Oxisol of clayey texture (Passos et al., 2017). The chemical analysis of the soil 0-0.20 m layer before the implementation of the soybean crops in the 2016-2017 agricultural years showed: pH in water of 4.9, 29.8 g kg^{-1} of organic matter, 22 mg dm^{-3} of P, 0.25 cmol$_c$ dm^{-3} of K, 1.99 cmol$_c$ dm^{-3} of Ca, 1.77 cmol$_c$ dm^{-3} of Mg, 1.99 cmol$_c$ dm^{-3} of Al, 8.2 cmol$_c$ dm^{-3} of H+Al, 11.76 cmol$_c$ dm^{-3} of cation exchange capacity (CEC) at pH 7,



Source: INMET Station, Porto Velho, Rondônia, Brazil

Figure 1. Rainfall depths and mean daily temperatures from October 2016 to March of 2018

5.30 cmol$_c$ dm^{-3} of effective CEC, aluminum saturation of 35%, and base saturation of 30%.

The area had been conducted focusing on the recovery of degraded pastures since 2008. Before 2008, it had been used for pastures (*Urochloa brizantha* cv. Marandu) for more than 20 years and presented signs of biological degradation and soil fertility losses. A long-term experiment started in 2011 to evaluate systems and models of crop-livestock and crop-livestock-forest (agroforestry) integrations for the region.

The area of the experiment consisted of 4-row tree sets of eucalyptus trees - clone VM01 (*Eucalyptus urophylla* × *E. camaldulensis*) - planted in January 2013 with spacing of 3.5 m between rows and 3 m between plants. The 4-row tree sets had widths of 10.5 m and the alleys had widths of 18, 30, and 42 m. The trees presented mean diameter at breast height (1.30 m) of 18.3 cm and mean height of 19.3 m at the beginning of the experiment. The planting rows were arranged with northeast-southwest direction. The eucalyptus trees were harvested in August 2018, when they reached productive potential, which is detected by their consolidation and maximum mean annual increase in wood production (technical age for harvest).

Soybean crop was grown as first crop, and maize crop for grain production or forage grass were grown in succession, in the alleys between the 4-row tree sets of eucalyptus trees, except in the 2015/2016 agricultural years, when maize intercropped with a grass species [*Urochloa brizantha* (A. Rich.) R. D. Webster, cv. Xaraés] was used due to climatic conditions (Feitosa et al., 2019), also constituting an intensified land use system (Salton et al., 2014; Cerri et al., 2018).

The soybean rows were spaced 0.45 m apart, with a sowing density for an initial plant population of 250,000 ha^{-1}. Soybean seeds of the BRS-Valiosa-RR cultivar were sown in early November 2016 for the 2016-2017 agricultural year, and soybean seeds of the BRS-7780-IPRO cultivar were sown in late October 2017 for the 2017-2018 agricultural year. The sown area had been used for soybean crop before the experiment, using the cultivars BRS-Favorita (2013/2014) and BRS-Valiosa-RR (2014/2015). The maize hybrid LG-6038-PRO was grown in succession to the soybean crop in 2015 and 2016, and the variety BR106 was used in 2014. *U. brizantha* seeds were sown in the maize rows and interrows, simultaneously, using a sowing rate of 10 kg ha^{-1} (seeds with 60% viability in tetrazolium and 60% physical purity). In both agricultural years, the seeds were treated with Carboxin (200 g L^{-1}) + Tiram (200 g L^{-1}), using 250 mL $100kg^{-1}$, and inoculated with *Bradyrizobium japonicum*, using 1.2 million cells per seed. Soil fertilization at sowing consisted of 500 kg of the N-P-K formulation 02-20-18. The other cultural practices were conducted as recommended for the crop.

The evaluated attributes of the soybean plants were: plant population, plant height, first pod insertion height, number of grains per pod, number of pods per plant, 100-grain weight, and grain yield (grains with moisture corrected to 13%). The soybean plants were evaluated in different distances from the 4-row tree sets of eucalyptus (10, 20, 30 and 45% of the alley width), with eight replications per distance in each alley. Half of the samples were collected from the southeast face and half from the northwest face of the plants to avoid effects of plant face orientation in the collection points. In addition, the closest soybean row to the eucalyptus were also evaluated for the same variables. Each sampling point consisted of a double 5-meter row (4.5 m^2).

A randomized block experimental design with eight repetitions was used, in a split-plot arrangement; the plots consisted of the alley widths and the subplots consisted of the distances of soybean plants from the eucalyptus. The data were subjected to joint analysis of variance (both agricultural years) using the Sisvar program (Ferreira, 2019). The means that presented significance by the F test were compared by the Tukey's test at $p \leq 0.05$. The quantitative data were analyzed using polynomial regression analysis in the SigmaPlot 10.0 program (Systat Software, Inc.), using response surface models to evaluate the interactions between alley widths and distances of soybean plants from the eucalyptus, using the Statistica 13.3 program (Tbico Inc., 2017).

Results and Discussion

All variables analyzed were affected by the distance of soybean plants from the eucalyptus (DSE), except number of grains per pod (Table 1). The agricultural years evaluated (2016-2017 and 2017-2018) had no effect only on grain yield. The alley width affected all variables evaluated. However, the interaction between alley widths and DSE was significant ($p \leq 0.01$) for plant height and number of pods per plant. The plant population and number of pods per plant were affected ($p \leq 0.05$) by the triple interaction of the factors evaluated (alley widths, DSE, and agricultural years). Grain yield was affected by the alley width and DSE ($p \leq 0.05$).

The mean soybean grain yield in the 2016-2017 agricultural year (2.124 kg ha^{-1}) was only 3.5% (71 kg ha^{-1}) higher than that found in the 2017-2018 agricultural year (2.053 kg ha^{-1}) (Table 2). The mean grain yield considering the two agricultural years (2.088 kg ha^{-1}) was lower than the Brazilian national average and Rondônia state average in the 2016-2017 (3,364 and 3,061 kg ha^{-1}, respectively) and 2017-2018 (3,394 and 3,056 kg ha^{-1}, respectively) agricultural years (CONAB, 2018). This low grain yield was due to the production system used for the crop, since most soybean crops are grown in systems without the arboreal component, i.e., as monocropping and at full Sun, without interspecific competition for natural resources, which is common in intercropped systems (Machado, 2009; Werner et al., 2017; Passos et al., 2017; 2018; Mantino et al., 2020). However, the maize, livestock, and wood production in the second crop (autumn-winter), generates incomes that minimize financial losses due to the low soybean grain yield (Balbino et al., 2011; Tollefson, 2015).

The highest plant height, first pod insertion height, and number of grains per pod were found in the 2017-2018 agricultural year. Legume crops increase the nitrogen contribution to the agroecosystem over the years (Salton et al., 2014). This is an important nutrient to increase plant biomass (Jankowski et al., 2018). The 100-grain weight found in the 2017-2018 agricultural year was 40.8% higher than that found in the 2016-2017 agricultural year (Table 2).

The lowest 100-grain weight (19.0 g) and first pod insertion height (15.2 cm) means were found in soybean plants in the

Table 1. Joint analysis of variance for agronomic attributes of soybean crops in crop-livestock-forest integration system in the 2016-2017 and 2017-2018 agricultural years

Source of variation	DF	Mean squares						
		Grain yield	Number of pods per plant	100 grain weight	Number of grains per pod	Plant population	Plant height	First pod insertion height
Block (agricultural year)	14	1.33×10^{6}	1.00×10^{3}	1.58×10^{1}	6.03×10^{-2}	2.61×10^{9}	2.62×10^{3}	3.11×10^{1}
Agricultural year (AY)	1	3.05×10^{5}	4.58×10^{3}**	2.69×10^{3}**	3.84×10^{0}	1.67×10^{12}**	3.47×10^{4}**	2.08×10^{2}**
Alley width (AW)	2	2.92×10^{6}**	5.81×10^{2}	7.94×10^{0}	5.89×10^{-2}	1.50×10^{9}	2.18×10^{2}	1.36×10^{1}
AY × AW	2	7.37×10^{5}	1.73×10^{2}	2.04×10^{1}	8.87×10^{-2}	2.12×10^{9}	3.28×10^{0}	4.88×100
Residue 1	28	4.59×10^{5}	3.89×10^{2}	8.98×10^{0}	5.64×10^{-2}	1.29×10^{9}	1.65×10^{2}	1.42×10^{1}
DSE	4	1.42×10^{7}**	4.86×10^{3}**	9.85×10^{0}**	1.25×10^{-1}	6.54×10^{9}**	4.98×10^{3}**	3.65×10^{1}**
DSE × AY	4	9.51×10^{4}	3.51×10^{2}*	3.40×10^{0}	4.49×10^{-2}	6.07×10^{9}**	2.52×10^{2}	2.13×10^{0}
DSE × AW	8	3.78×10^{5}*	4.67×10^{2}**	2.91×10^{0}	7.82×10^{-2}	1.35×10^{9}	3.74×10^{2}**	3.02×10^{0}
DSE × AY × AW	8	6.01×10^{4}	2.71×10^{2}*	3.66×10^{0}	6.28×10^{-2}	1.56×10^{9}*	3.62×10^{1}	5.29×10^{0}
Residue 2	168	1.69×10^{5}	1.21×10^{2}	3.00×10^{0}	6.82×10^{-2}	8.21×10^{8}	1.12×10^{2}	3.26×10^{0}
Mean	-	2.09×10^{3}	3.85×10^{1}	1.37×10^{1}	$2.17x 10^{0}$	1.10×10^{5}	7.30×10^{1}	1.66×10^{1}
CV_{DSE} (%)	-	32.43	51.30	21.82	10.94	32.59	17.61	22.67
CV_{AW} (%)	-	19.68	28.57	12.60	12.02	26.04	14.50	10.89

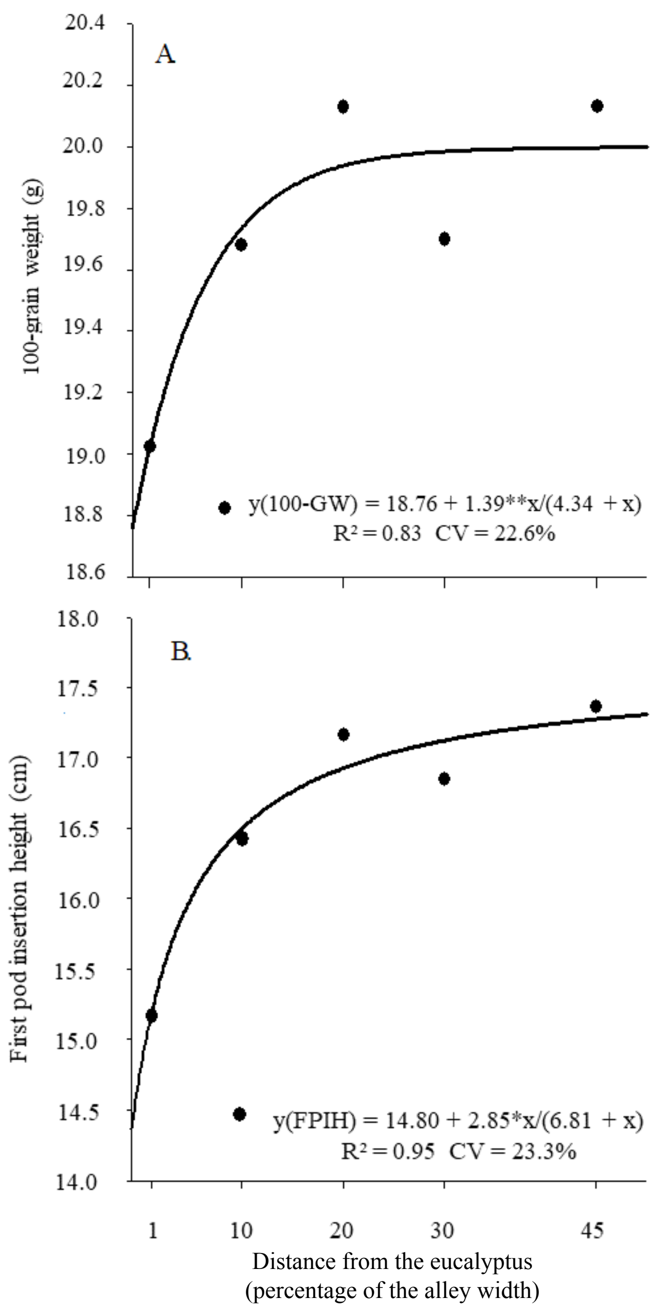
DSE - Distance of soybean plants from the eucalyptus; DF - Degrees of freedom; * - Significant by the F test at $p \leq 0.05$; ** - Significant by the F test at $p \leq 0.01$

Table 2. Grain yield, plant height, first pod insertion height, number of grains per pod, and 100-grain weight of soybean crops under crop-livestock-forest integration system, in the 2016-2017 and 2017-2018 agricultural years

Agricultural year	Grain yield (kg ha^{-1})	Plant height (cm)	Fist pod insertion height (cm)	Number of grains per pod	100-grain weight (g)
2016-2017	2,124.08 a	61.01 b	15.67 b	2.05 b	23.08 a
2017-2018	2,052.77 a	85.05 a	17.53 a	2.30 a	16.39 b
Mean	2,088.42	73.03	16.60	2.17	19.73

Means followed by the same letter in the columns are not different by the Tukey's test at p ≤ 0.05

closest rows to the forest component (Figure 2), regardless of the agricultural year and alley width used (18, 30 or 42 m). The highest 100-grain weight means were found for plants at DSE higher than 20% of the alley width, in both agricultural years, which presented low negative effect of trees on the soybean plant growth and development.

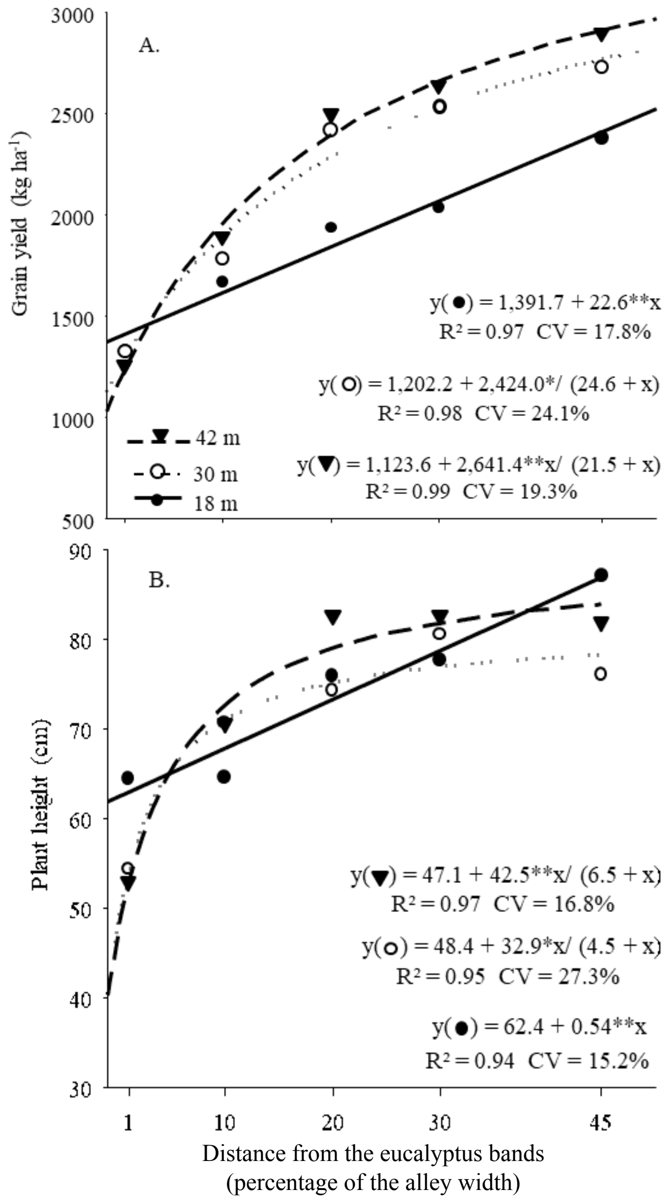


* - Significant by the F test at p ≤ 0.05; ** - Significant by the F test at p ≤ 0.01

Figure 2. 100-grain weight (100-GW) (A) and first pod insertion height (FPIH) (B) of soybean plants as function of distance from the eucalyptus (10, 20, 30, and 45% of the alley width), in crop-livestock-forest integration systems

The first pod insertion height of all treatments was adequate for mechanized harvest, i.e., the heights were within the normal range for cutting in mechanized harvest (Chioderoli et al., 2012).

The effect of DSE and alley width on grain yield and plant height were analyzed through regression analysis, considering both agricultural years (Figure 3). The means of soybean grain yield and plant height in the alley width of 18 m fitted to the linear model, presenting lower grain yield than that found in the alley widths of 30 and 42 m, except for the closest soybean row to the



* - Significant by the F test at p ≤ 0.05; ** - Significant by the F test at p ≤ 0.01

Figure 3. Grain yield (A) and plant height (B) of soybean plants grown as function of distance from eucalyptus in alley widths of 18, 30 and 42 m, in a crop-livestock-forest integration system

eucalyptus (1st row) (Figure 3A.). The lowest means of soybean grain yield in the alley widths of 42, 30, and 18 m (1,124, 1,202, and 1,392 kg ha^{-1}, respectively) were found in the 1st row (Figure 3A).

The competition with eucalyptus trees decreased the soybean grain yield in 44.1% (1,052 kg), 51.5% (1,406 kg), and 56.6% (1,639 kg) in the alley widths of 18, 30, and 42 m, respectively, considering the greatest DSE. The low yield in the 1st row and in the DSE of 10% of the alley width can be explained by the competition of trees for light, since solar radiation is related to photosynthesis and physiological processes in soybean plants (Nicodemo et al., 2016). Soybean is a C3 plant that presents low solar radiation use efficiency (Tibolla et al., 2019). The limited radiation condition due to the forest component is related to decreases in photosynthesis and plant growth, resulting in low yields (Casaroli et al., 2007; Mantino et al., 2020).

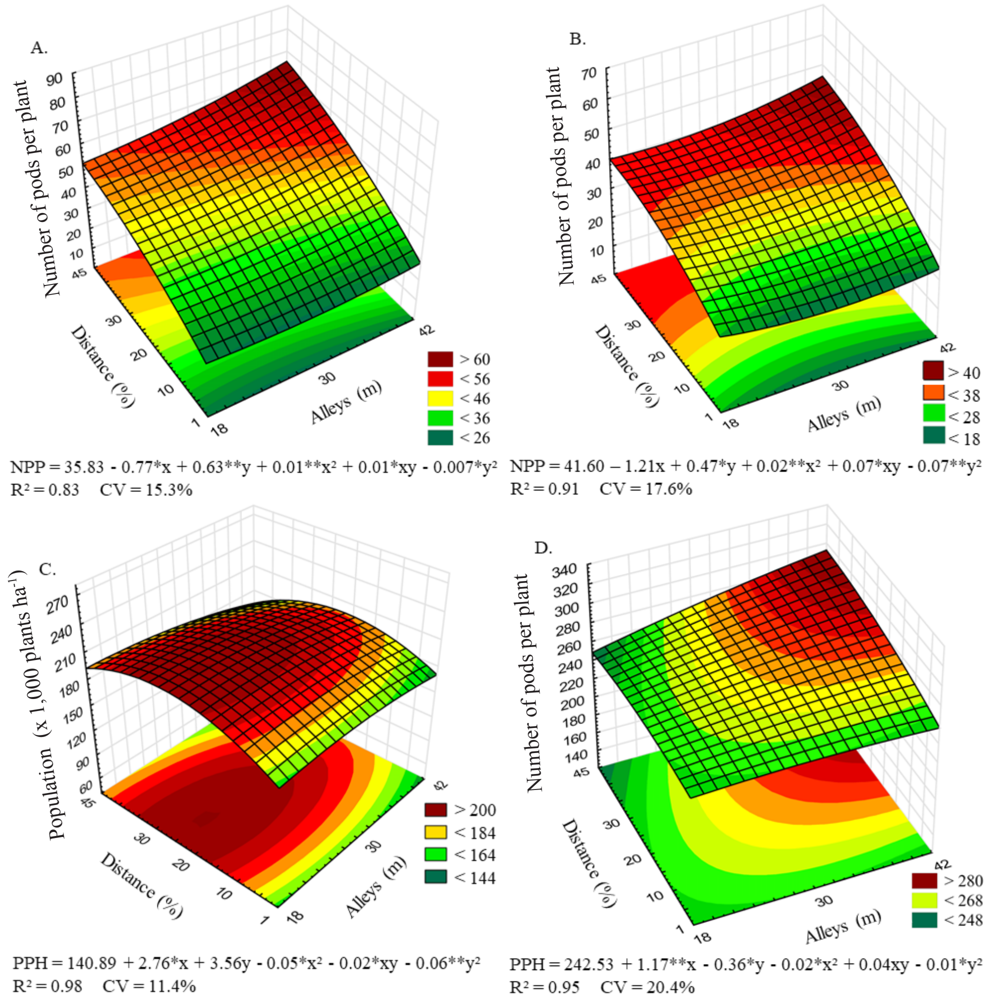
The highest mean grain yields found in the alley widths of 42, 30, and 18 m were 2,894, 2,730 and 2,385 kg ha^{-1}, respectively, considering plants at DSE of 45% of the alley width (Figure 3A). Plants at distances above 20% of the alley width showed lower increases in grain yield per increase in unit of distance, in the alley widths of 30 and 42 m. These plants were subjected to lower competitive and inhibitory effects caused by eucalyptus trees (Mantino et al., 2020), as found by the hyperbolic models fitted to the data (Figure 3A).

The soybean grain yield is lower in areas with higher shading of eucalyptus trees and increases as the DSE is increased; thus, yield losses are caused by low light intensity (Almeida et al., 2014; Werner et al., 2017). Eucalyptus trees have allelopathic effect on soybean plants; the emission of inhibitory secondary metabolites to the interspersed crops generates a gradient from the source plant, with decreasing inhibitory effect as the DSE is increased (Abdelmigid & Morsi, 2018).

The proximity of soybean plants to the forest component resulted in lower plant height in the 1st row of all alley widths evaluated (Figure 3B). The highest plant height in the 1st row and at DSE of 45% of the alley width were found in soybean plants in the alley width of 18 m (65.3 and 86.5 cm, respectively). The low availability of photosynthetic radiation caused by the arboreal component in the smallest alley width caused etiolation of the stem and increase plant height (Almeida et al., 2014).

The alley widths of 30 and 42 m showed increases in plant height up to the DSE of 20% of the alley width, which stabilized at DSE above 20% of the alley width, as shown by the models for this soybean plant growth attribute, with higher plant height in the alley width of 42 m (Figure 3B).

Response surface models were used to evaluate the effects of the interaction between alley widths and DSE on the plant population per hectare and number of pods per plant (Figure 4).



NPP = 35.83 - 0.77*x + 0.63**y + 0.01**x² + 0.01*xy - 0.007*y²
R^2 = 0.83 CV = 15.3%

NPP = 41.60 – 1.21x + 0.47*y + 0.02**x² + 0.07*xy - 0.07**y²
R^2 = 0.91 CV = 17.6%

PPH = 140.89 + 2.76*x + 3.56y - 0.05*x² - 0.02*xy - 0.06**y²
R^2 = 0.98 CV = 11.4%

PPH = 242.53 + 1.17**x - 0.36*y - 0.02*x² + 0.04xy - 0.01*y²
R^2 = 0.95 CV = 20.4%

* - Significant by the F test at p ≤ 0.05; ** - Significant by the F test at p ≤ 0.01

Figure 4. Response surface models for number of pods per plants (NPP) in the 2016-2017 (A) and 2017-2018 (B) agricultural years, and plant population per hectare (PPH) in the 2016-2017 (C) and 2017-2018 (D) agricultural years of soybean plants grown in crop-livestock-forest integration systems

Plant population in the smallest alley widths and DSE were larger in the 2016-2017 (Figure 4C) than in the 2017-2018 agricultural year (Figure 4D). The mean plant population per hectare in the 2016-2017 agricultural year was greater in the alley widths of 18 and 30 m (199.375 and 198.194 plants ha^{-1}, respectively), with a decrease of 9.3% (16.944 plants ha^{-1}) for the DSE of 42 m (Figure 4C). The greatest DSE in the alley widths of 18 and 30 m resulted in larger plant population. The alley widths evaluated in the 2016-2017 agricultural year presented no differences in plant population in the 1st row, except for the alley width of 42 m.

In the 2017-2018 agricultural year, the plant population decreased from the 1st row to the DSE of 45% of the alley width, in the alley width of 18 m. In the alley width of 42 m, the plant population increased from the 1st row to the DSE of 45% of the alley width (Figure 4D). The largest plant population was found in the largest alley width, from the DSE of 30% up to the DSE of 45% of the alley width (289,497 plants ha^{-1}) (Figure 4D).

The highest number of pods per plant were found for plants in the highest alley widths and DSE, for both agricultural years (Figure 4A and Figure 4B). The highest number of pods per plant found in the greatest DSE in the alley width of 42 m (Figure 4B) was reached in all alley widths in the 2016-2017 agricultural year by plants in all DSE, except the 1st row (Figure 4A).

The number of pods per plant in the 1st row in all alley widths were similar. The number of pods per plant varied from 27.0 in the 1st row to 49.3 in the greatest DSE evaluated, in both agricultural years (Figure 4). This variation can be due to the shading effect caused by the forest component and the soil quality near the eucalyptus (Assis et al., 2015; Feitosa et al., 2019; Mantino et al., 2020).

The increase in alley width did not result in significant increases in number of pods per plant up to the DSE of 20% of the alley width; above this distance, the alley widths of 30 and 42 m presented higher results for this variable, and the alley width of 42 m at DSE of 45% of the alley width presented the highest numbers of pods per plant.

The smallest alley widths and the eucalyptus tree size can reduce solar radiation incidence (Almeida et al., 2014), affecting the production and transport of photoassimilates, decreasing the number of ramifications and internodes, stem stretching, and pod fixation (Mauad et al., 2010). Soybean plants are tolerant to adversities, but require adequate edaphoclimatic conditions, including solar radiation to reach high yields (Câmara, 2009; Mantino et al., 2020).

Soybean plants can adjust their production components according to variations in plant density to maintain their production under an appropriate source–sink relationship in response to different environmental resource conditions (Büchling et al., 2017). Increases in plant population cause competition for photosynthetic radiation, stem etiolation, and decreases in the number of ramifications (Almeida et al., 2014), leading to low flower bud fixation rate and number of pods per plant (Vaz Bisneta, 2015).

The highest number of pods per plant was found in the 2016-2017 agricultural year. The greatest increases and absolute values of plant population were found in the alley width of 42 m in the 2017-2018 agricultural year (Figure 4D); however, it presented the lowest number of pods per plant.

A large plant population decreases the number of pods per plant due to decreases in plant ramifications caused by competition for solar radiation and lower availability of photoassimilates (Mauad et al., 2010). Although soybean plants show high morphological plasticity (Büchling et al., 2017), i.e., capacity to adapt and adjust production components according to the available area and resources for their growth and development, changes in plant population can affect grain yield (Balbinot Junior et al., 2018).

Conclusions

1. Soybean plants in crop-livestock-forest integration systems with 5-year-old forest component present higher grain yields when grown in alleys with widths of 30 m or more.

2. The proximity of soybean plants to the eucalyptus results in decreases in grain yield, plant height, first pod insertion height, plant population, and number of pods per plant.

3. The growth of soybean crops in alleys of 18 m between 4-row tree sets of 5-year-old eucalyptus trees is not recommended for the southwestern region of the Brazilian Amazon biome.

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