Articles

Spatial dependence of soybean cultivation, in a low-carbon production system, integrated with eucalyptus forest

Dependência espacial da cultura da soja, em sistema de produção de baixa emissão de carbono, integrada com floresta de eucalipto

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ABSTRACT

In a climate change scenario, a producer who decides to invest in a Crop-Forest integration system, instead of investing in conventional production, benefits. The objective the present work, which is a low carbon emission agriculture model, aimed to evaluate the effect of shading and the spatial dependence of soybean crop indices in integration with eucalyptus forest. The design adopted was that of randomized blocks with six replications and treatments composed of different horizontal distances about eucalyptus (30, 34, 38, 42 and 46 m), in two distinct areas, one with the presence of eucalyptus forest in the north and west phase and another one without the presence of eucalyptus in the northern part of the soybean cultivation area. Evaluated the photosynthetically active photons at four different times, the plant stand, plant height, and the vegetation index after 30 and 60 days of germination and finally the mass of a thousand grains and productivity. As a result, all attributes showed spatial dependence, except soybean productivity. As final considerations, the spacing of 34 m between the eucalyptus trees promote less shading. The highest average grain production in the area was found in the presence of eucalyptus on the west and north sides of the cultivation area.

Keywords: Canonical Variables; *Glycine max* (L.) Merrill; Multispectral; Remotely Piloted Aircraft; Vegetation Index

RESUMO

Num cenário de mudanças climáticas, um produtor que decidisse investir em um sistema de integração Lavoura-Floresta, ao invés de investir na produção convencional, se beneficiaria. O presente trabalho, que é um modelo de agricultura de baixa emissão de carbono, teve como objetivo avaliar o efeito do sombreamento e a dependência espacial dos índices da cultura da soja em integração com floresta de eucalipto. O delineamento adotado foi o de blocos ao acaso com seis repetições e tratamentos compostos por diferentes distâncias horizontais sobre eucalipto (30, 34, 38, 42 e 46 m), em duas áreas distintas, uma com presença de eucalipto nas regiões norte e oeste e outra sem a presença do eucalipto na parte norte da área de cultivo da soja. Avaliaram-se os fótons fotossinteticamente ativos em quatro épocas diferentes, o estande de plantas, a altura de plantas e o índice de vegetação após 30 e 60 dias de germinação e por fim a massa de mil grãos e a produtividade. Como resultados, todos atributos apresentaram dependência espacial, exceto produtividade da soja. Como considerações finais, o espaçamento de 34 m entre os eucaliptos promove menor sombreamento. A maior produção média de grãos na área foi encontrada na presença de eucalipto nas laterais oeste e norte da área de cultivo.

Palavras-chave: Variáveis Canônicas; *Glycine max* (L.) Merrill; Multiespectral; Aeronave Pilotada Remotamente; Índice de Vegetação

1 INTRODUCTION

The Low Carbon Emission Agriculture Plan (ABC Plan) is a public policy that already exists in Brazil, which aims to reduce emissions in agriculture and promote the recovery and restoration of vegetation on a large scale. A study by WRI Brasil, by the New Climate Economy initiative, in August 2020, entitled "A new Economy for a new era: elements for building a more efficient and resilient Economy for Brazil" (WRI-Brasil, 2021), shows that sustainable agriculture is a path to the growth of the green economy in Brazil. The actions foreseen in the ABC plan, according to the study, make rural properties more productive, resilient and adapted to climate change (Hellvig; Flores-Sahagun, 2023).

Soy is the most cultivated oilseed in the world (Vieira; Chen, 2021). Soy (*Glycine max* L.) is a vegetable that is part of the legume family (Fabaceae), extremely rich in proteins and can be consumed by both humans and animals.

Eucalyptus is the forest species planted mainly for the energy and cellulose industry, due to its rapid development in relation to other forest species (Pereira *et al.*, 2019)

The integrated cultivation of forests with annual crops brings several benefits to the low-carbon production environment, such as carbon sequestration, minimization of greenhouse gas emissions, cycling and reuse of soil nutrients (Werner *et al*., 2017). The economic and ecological benefits are more significant in integrated low-carbon production systems than in monocultures (Zou *et al*., 2019).

However, trees, depending on their size, can influence the cultivation of annual crops such as soybeans. In this context of forest-culture integration, the issue of the interference of eucalyptus shade in soybean production arises (Caron *et al*., 2018).

The vegetation index (VI) calculated through the reflectance of light at different wavelengths in remote sensing estimates the plant composition of the soil surface, being able to differentiate cultivated fields from forests, areas with exposed soil and rivers and lakes. The estimated VI can be correlated with other information, such as the crop's development stage (Carneiro *et al*., 2019).

The observation of semivariograms and kriging maps, together with the interpretation of data from the plant's productive components, can contribute to finding the reasons for the occurrence of productivity variability, enabling the correction of possible failures and allowing adversities to occur in the next plantings. be reduced (Oliveira *et al*., 2020). Therefore, it is extremely beneficial to seek such information, so that accurate decisions can be made for better management of the crop, not only soybeans, but any other crop that may have specific soil or plant needs (Rodrigues *et al*., 2023).

Therefore, our hypothesis is that soybean development and production is favored by the presence of eucalyptus forest. Thus, the present work, which is a low carbon emission agriculture model, aimed to evaluate the effect of shading and the spatial dependence of soybean crop indices in integration with eucalyptus forest.

2 MATERIALS AND METHODS

2.1 Experimental Field

The experiment was conducted in area 1 and area 2 (Figure 1) of the Universidade Federal de Mato Grosso do Sul, in the municipality to Chapadão do Sul - MS (18°46'17.9" S; 52°37'25.0" W; 810 a.l.s.). The climate of the region is defined as tropical with a dry season (Aw), according to the Köppen classification, with an average annual temperature of 25°C and average annual precipitation between 1600 to 1800 mm (Souza *et al*., 2022). The rainfall, temperature and relative humidity data observed during soybean cultivation described in Figure 2.

Figure 1 – Satellite image (google Earth) of soybean cultivation sites, with the presence of eucalyptus (A1) and without the presence of eucalyptus (A2)

Source: Authors (2023)

Figure 2 – Monthly averages of temperature and rainfall, which occurred in Chapadão do Sul-MS, Brazil, in the 2018/19 cropping season during the soybean cycle. Source: National Institute of Meteorology (INMET)
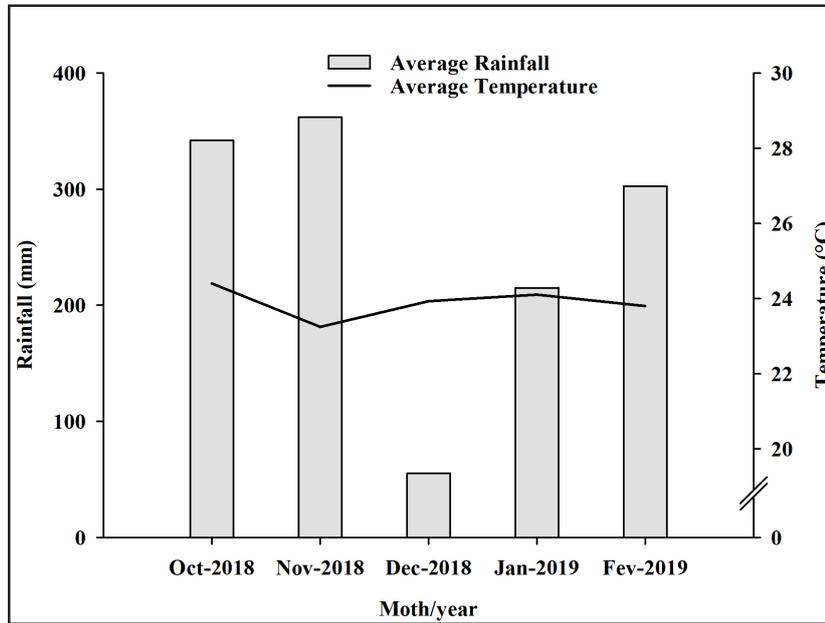
Source: Authors (2023)

The soils of both environment areas were characterized as Rhodic Ferralsol and "Latossolo Vermelho" by the Brazilian survey (Santos *et al.*, 2018). Before starting the experiment, the soil was sampled in the 0-0.20 m layer, with 20 simple samples taken in each area, and then homogenized, thus forming a sample per cultivation area. The samples were taken for analysis in the soil laboratory of the Federal University of the Mato Grosso do Sul, and the chemical properties were analyzed according to the methodology proposed by Teixeira et al (2017) (Table 1).

Table 1 – Chemical and physics description of soil fields

Field	pH[1]	MO	P	H+Al	Al^{3+}	Ca^{2+}	Mg^{2+}	K$^+$	EC	V	Clay	Silt	Sandy
	CaCl$_2$	g dm^{-3}	mg dm^{-3}	------------ cmol$_c$ dm^{-3} ------------------						%	-------g kg^{-3}----------		
A1	4.8	23.2	8.6	3.5	0.02	3.10	1.80	0.29	8.7	59.8	540	50	410
A2	4.3	22.8	12.8	5.7	0.37	2.20	0.40	0.27	8.6	33.5	490	50	460

Source: Authors (2023)

In where: [1]pH= hydrogen potential; [2]S= sum of bases; [3]EC= exchange cation capacity; 4 V= base saturation; [5]OM= organic matter.

2.2 Experiment conduct

The cultivated soybean areas are characterized by their proximity to the planted eucalyptus forest (Figure 2). In environment area A1 is in the coordinates 18º46'16.23" of south latitude located; 52º37'24.27" west longitude. In this area, the eucalyptus forest formed by the 1444 clones AEC (*Eucalyptus grandis* x *E. urophylla*), four years old, with an average height of 17.4 m, with five rows of Eucalyptus on the west side and 11 rows of Eucalyptus on the face north of the soybean area. The plots are arranged concerning the distance from the horizontal (west) and vertical (north) to the peripheral eucalyptus forest. The first plot is 8 m vertically and 12 m horizontally to the Eucalyptus. The other parcels are 4 m away from the beginning (horizontally and vertically), considering the center of the plot until they reach 28 m in width (vertical) and 66 m in length (horizontal).

In environment area A2 are in the coordinates 18º46'16.23" of south latitude; 52º37'24.27" West longitude, close to this area, the Eucalyptus (*Eucalyptus grandis* x *E. urophylla*) formed 13 rows on the west side of the experiment area with an average height of 17.50 m, planted in January 2014, with four years old. The first plot is 12 m horizontally to the Eucalyptus. The other parcels are 4 m away from the beginning (horizontally), considering the center of the plot until they reach 46 m in length (horizontal). For both areas, a randomized block design with six replications used. The treatments were composed of the horizontal distance to the Eucalyptus (5 lengths, 30 m, 34 m, 38 m, 42 m, and 46 m), and six repetitions were used in this experiment.

Area 2 the need for soil acidity correction, which was carried to raise of soil to 60% base saturation (levels of Ca^{2+}, Mg^{2+} and K^+ present in the exchange capacity of the soil). The correction of soil acidity was carried out with the external application of 0.4 t ha^{-1} of lime. Limestone has 90.1% reactivity power neutralization, compared to calcium carbonate, and it has CaO: 29%; MgO: 20%. The liming was carried out 60 days before the implementation of the experiment. Sowing of soybeans Brasmax Bônus variety

was carried out mechanically on November 13, 2018, with 13 seeds distributed per meter and a row spacing of 0.45 m. Seeds of soybean were pretreated with fungicide (100 mL ha^{-1}), insecticide (150 mL ha^{-1}), Co and Mo micronutrient (150 mL ha^{-1}) and inoculated with *Bradyrhizobium* sp. (100 mL for 50 kg of seeds).

The planting fertilization consisted of 150 kg ha^{-1} P_2O_5, whose source was mono ammonium phosphate (11% ammonia N and 52% P_2O_5). The delay fertilization was 100 kg ha^{-1} K_2O (60% K_2O), whose source was potassium chloride at 40 days after emergence (DAE). Diseases, pests, and weed control was carried out according to the crop's needs during the experiment in the field.

2.3 Evaluations

The luminous flux (lux m^{-2}) per unit area was measured on December 13, 2018, at 9:00 am (FFF1), 12:00 pm (FFF2), 3:00 pm (FFF3), and 5:00 pm (FFF4), as a Luxmeter (Instrutemp ITLD 270). The luminous flux values were converted into photosynthetic photon flux (FFF) (mmol m^{-2} s^{-1}).

At 30 and 60 days after soybean emergence, the plant stand (PS), plant height (PH), and vegetation index (VI) were evaluated. The PS was measured by counting the number of plants in 2 m in the center of the plot. The PH measured the main trunk of soil surface until the insertion of the last fully expanded leaf in 5 plants of the useful plot of 5 m².

A flyby was performed with the Sensefly eBee RTK, a fixed-wing remotely piloted aircraft (RPA) with autonomous takeoff, flight plan and landing control to collect spectral information on field samples. The image overlap rate in flights was 85% for longitudinal displacement and 70% between passes.

The RPA was equipped with a Parrot Sequoia multispectral sensor. The flight took place at 9:00 am, without clouds and at 100 m altitude, with a spatial resolution of 0.10 m. The aerial survey was carried out using RTK (Real Time Kinematics) technology, which made it possible to position the sensor to collect images with an accuracy of 2.5 cm. Images were mosaicked and orthorectified using Pix4Dmapper.

Radiometric calibration of the sensor was performed with a factory-calibrated reflective surface. The Parrot Sequoia has a brightness sensor that allows you to calibrate the acquired values. The wavelengths (SB) acquired by the sensor were: blue (475 nm, B_475), green (550 nm, G_550), red (660 nm, R_660), Rededge (735 nm, RE_735) and NIR (790 nm, NIR_790).

The attribute values were extracted using 20 sampling points with an area of 0.2 m² randomly positioned in each experimental plot. The ArcGis 10.5 program was used in this process and in generating the attribute table exported to the electronic spreadsheet.

When observing the ripening of stage R_8 soybeans, the following variables were obtained in five plants per plot: the mass of a thousand grains (MTG) (g) and grain yield (YIELD) (kg ha⁻¹), the useful area (1.8 m²) was harvested, standardized for grain moisture of 13%.

2.4 Statistic and Geostatistics

The statistical and canonical variables analysis of the data was performed using the software Rbio (Bhering 2017).

The geostatistical analysis to determine the semivariograms and the interpolation process was performed using the computer program ArcGis 10.5 (ESRI, Rellands, CA, USA). Semivariograms were selected based on the lowest residue of errors (RMSE) by cross-validation. The spatial dependency index (DE) of the semivariogram models was calculated through the percentage of the variance of the nugget effect, as this indicates the variability that cannot be explained and represents the analytical error. The spatial dependence was verified through adjustments of semivariograms considering the inference of natural stationary process, which is estimated by Equation (1):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i-1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{1}$$

where: N (h) - number of observed experimental pairs; Z (xi) and Z (xi + h) separated by a distance h.

The y (h) is the estimated semivariogram. To adjust the mathematical model of the calculated values of y (h), the coefficients of the theoretical model were: nugget effect (C_0), threshold ($C_0 + C_1$), and reach. The classification that considers the following intervals: low spatial dependence for DE <25%, moderate for 25% <DE <75%, and strong for DE> 75% for the degree of the spatial relationship of the attributes studied was analyzed following the same methodology used by Oliveira et al (2020).

3 RESULTS AND DISCUSSIONS

The spatial distribution of soybean cultivation about the eucalyptus forest influenced the FFF, mainly at 4:00 pm (FFF4) (Figure 3A). The highest horizontal distances present the greatest FFF4, in area A1. In area A2, FFF2 was influenced by the more excellent range from Eucalyptus. FFF1 and FFF3 were not dependent on the horizontal distance concerning the forest.

The VIs not showed to the horizontal distance of soybean cultivation to the eucalyptus forest (Figure 3B).

However, there was a distinction between soybean cultivation areas in an low-carbon production system. Area A1 had a strong association with VI1 and area A2 with VI2. VI1 was measured at 30 DAE of soybean, with the shading caused by Eucalyptus, the initial development of the plants was favored, corroborating the vegetation indexes of the analyzed area. The opposite was observed in VI2, measured 60 DAE of soybean, without the presence of Eucalyptus on the north face, the FFF was higher, which favored the development of soybean plants and VIs. However, we cannot say that Eucalyptus will interfere negatively or positively in the event of soybean plants, as both areas had meaningful results, considering the spatial distribution of Eucalyptus to soybean cultivation.

Figure 3 – Canonical variables
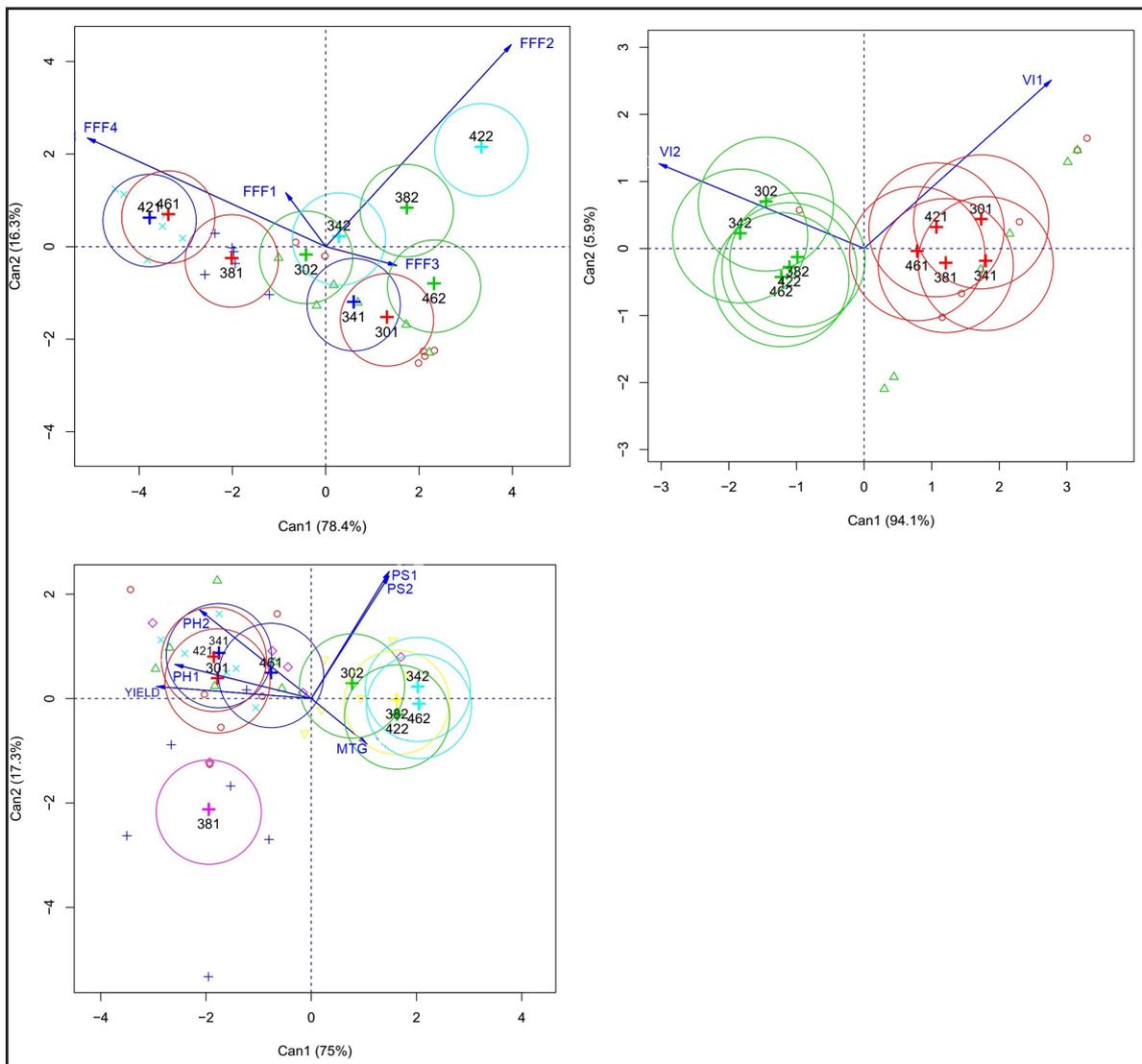
Source: Authors (2023)

In where: A - photosynthetic photon flow - FFF at different times in 13 December 2018, FFF1: 9:00 am., FFF2: 12:00 am., FFF3: 3:00 pm., FFF4: 5:00 pm; B - VI1: vegetation index at 30 days of planting, and VI2: vegetation index at 60 days of planting; C - PH1: plant height at 30 days of planting, PH2: plant height at 60 days of planting; PS1: stand of plant at 30 days of planting; PS2: stand of plant at 60 days of planting; MTG: thousand grain mass and yield of soybean in fields shaded by Eucalyptus; Horizontal distances from the Eucalyptus forest in different areas [A1 (301: 30 m, 341: 34 m, 381: 38 m, 421: 42 m, 461: 46 m) and A2 (302: 30 m, 342: 34 m, 382: 38 m, 422: 42 m, 462: 46 m)].

Analyzing the canonical variables was found that the most influential associations occurred observed in area A1 (Figure 3). Thus, geostatistical analyzes were explored for the data obtained from area A1. Variables VIs, FFF1, FFF2, FFF3, and FFF4, showed substantial dependence space. However, the PH2 and MTG showed low spatial

dependence, and yield of soybean did not show spatial dependence, for cultivation to the eucalyptus forest (Table 2).

Table 2 – Parameter of the semivariogram for variable VI in the soybean crop under shading conditions

Variables	Model	Nugget Effect (Co)	Contribution (Co+C)	Scope (m)	ED* (%)	Cross-validation RMSE**
VI	Gaussian	8.6E-6	3.8E-5	16.2	77.4	1.08
FFF1	Exponential	0.0	3.2E3	7.7	100.0	0.99
FFF2	Gaussian	1.2E-1	1.3E2	6.4	99.9	1.06
FFF3	Spherical	0.0	1.3E5	9.8	100.00	0.85
FFF4	Gaussian	1.6	1.9E2	56.7	99.9	1.23
PH	Gaussian	3.8E1	5.2E1	17.3	26.9	0.96
MTG	Exponential	1.2E3	1.8E3	15.8	33.3	1.11
YIELD	Pure nugget effect					

Source: Authors (2023)

In where: VI: vegetation index, photosynthetic photon flow - FFF at different times FFF1: 9:00 am., FFF2: 12:00 am., FFF3: 3:00 pm., FFF4: 5:00 pm; PH: plant height; MTG: thousand grain mass; YIELD: yield of soybean in fields shaded by Eucalyptus. *ED: Spatial Dependence Dependência espacial [1-(C/Co+C)]. **RMSE: standard deviation of errors.

The methodology of using sensors in an autonomous vehicle proved to be efficient for estimating soybean development parameters and correlating VIs as a function of production environments (Figure 3). VIs were estimated by sensors embedded in an remotely piloted aircraft, unlike remote sensing that uses satellite images to estimate soybean biomass in monoculture (Sakamoto, 2020), and low-carbon production systems concerning the production environment (Souza *et al*., 2020).

The other evaluations of FFF's performed at different times on the same day, not showed coherence with the presence of the eucalyptus forest on the northwest side of soybean cultivation, showing high variation in the observed of date in the function of the time of observation (Figure 4A, 4B, 4C and 4D). FFF4, evaluated at 17:00, showed higher values when the soybeans were grown farther from the eucalyptus forest (Figure 4D), showing the effect of afternoon shading in area A1.

Figure 4 – Spatial dependence of photosynthetic photon flow - FFF at different times in 13 December 2018, A - FFF1: 9:00 am., B - FFF2: 12:00 am., C - FFF3: 3:00 pm., and D - FFF4: 5:00 pm; soybean in area A1 shaded by eucalyptus
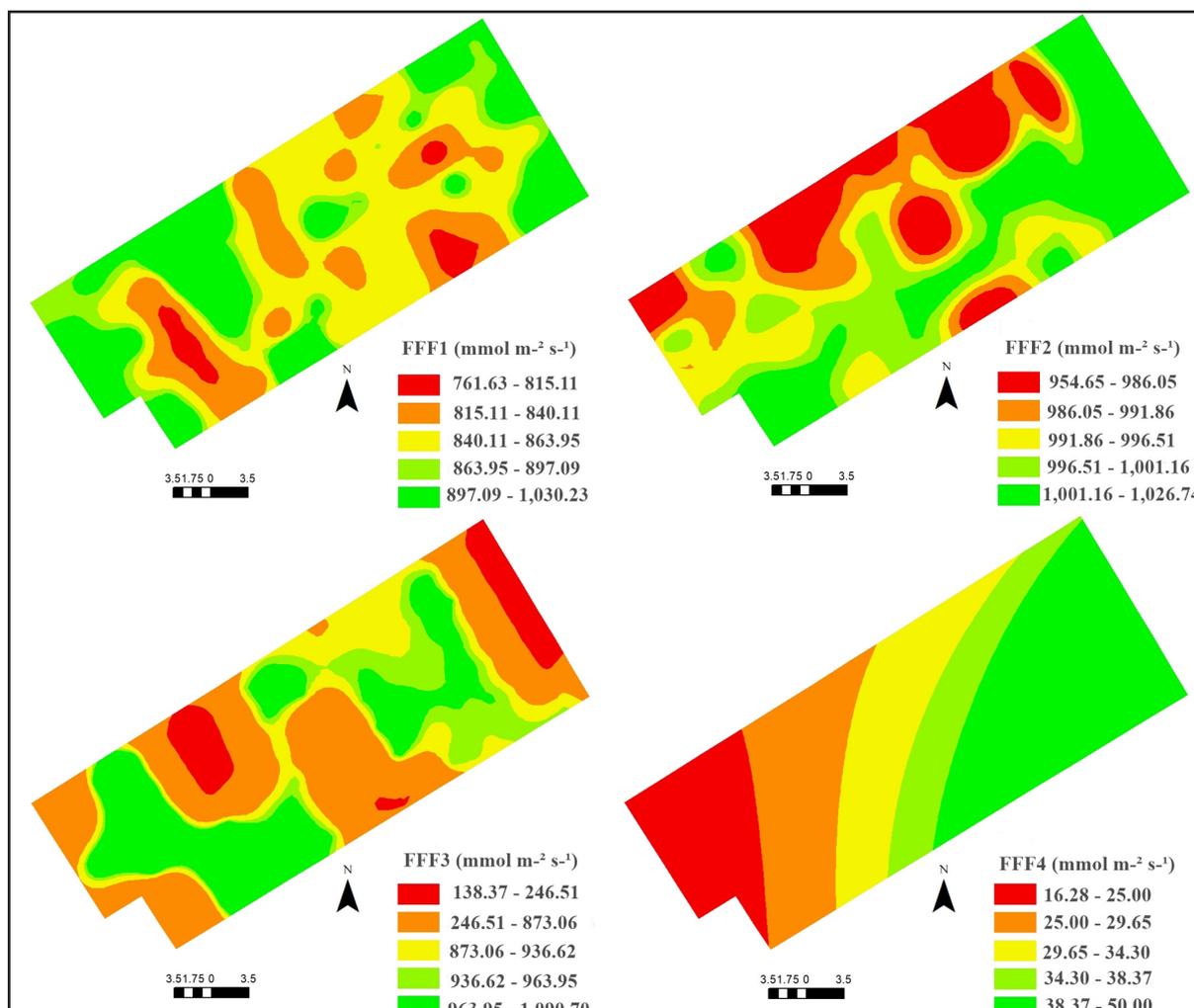
Source: Authors (2023)

The parameters FFF's, PH's, VIs, and MTG, showed spatial dependence concerning the distance from the eucalyptus forest. The closer to the eucalyptus trees, the smaller was FFF4, VI2, and PH2 of soybean cultivation area A1. Given these observations, recommended growing soybeans at 34 m to the east and 12 m to the south of the eucalyptus forest with trees above 17 m in height, to obtain the best soybean yield. In this way, soybean yield is higher in central areas among eucalyptus rows in low-carbon production systems (Werner *et al*., 2017).

Werner *et al.* (2017) observed that the highest yields of soybeans were obtained in the central part of the cultivation area between eucalyptus rows. Still, in the present study, soybeans obtained the best FFF4, PH2, and IV2 from 34 m from the eucalyptus forest. Soybean yield did not show spatial dependence due to the distance from the eucalyptus forest.

An important feature of integrated crop-forest (CLI) systems is the creation of a microclimate in the area where it is implemented (Souza Rangel *et al.*, 2020) for soybean culture, favoring its initial growing and yield. An average of 7% raised Peng *et al.* (2015) report that the presence of trees in soybean cultivation increased the relative humidity of the air, the water content in the soil decreased by an average of 31%, the ambient temperature dropped by 1.2°C, generating a microclimate that the soybean yield. Bonini *et al.* (2018) relate collapse of ecosystem carbon stocks due to forest conversion to soybean plantations at the Amazon-Cerrado transition.

The maps obtained through data interpolation and through the kriging method are of paramount importance for precision agriculture, and they are subsequently analyzed so that new samplings can be planned, bringing greater economic viability, according to spatial variability of the values of each attribute, whether soil or plant (Oliveira *et al.*, 2020; Rodrigues *et al.*, 2023). This information corroborates the present study, in that the integration of soybeans with the eucalyptus forest, well planned, with adequate spacing, reflects on the success of the enterprise.

The soybean plots close to the Eucalyptus showed low VI2 (Figure 5A) at the time of flowering. The soybean PH2 was smaller closer to the Eucalyptus (Figure 5B). MTG was higher in specific locations in area A1, not consistent with the distance from the Eucalyptus (Figure 5C), the same occurred with yield (Figure 5D), both soybean variables can be considered without exclusive dependence about the distance to the Eucalyptus.

Figure 5 – Spatial dependence of the A - HP: high plant, B - VI: vegetable index in December 2018, C - MTG: thousand grain mass and D - yield of the soybean in area A1 field shaded by eucalyptus
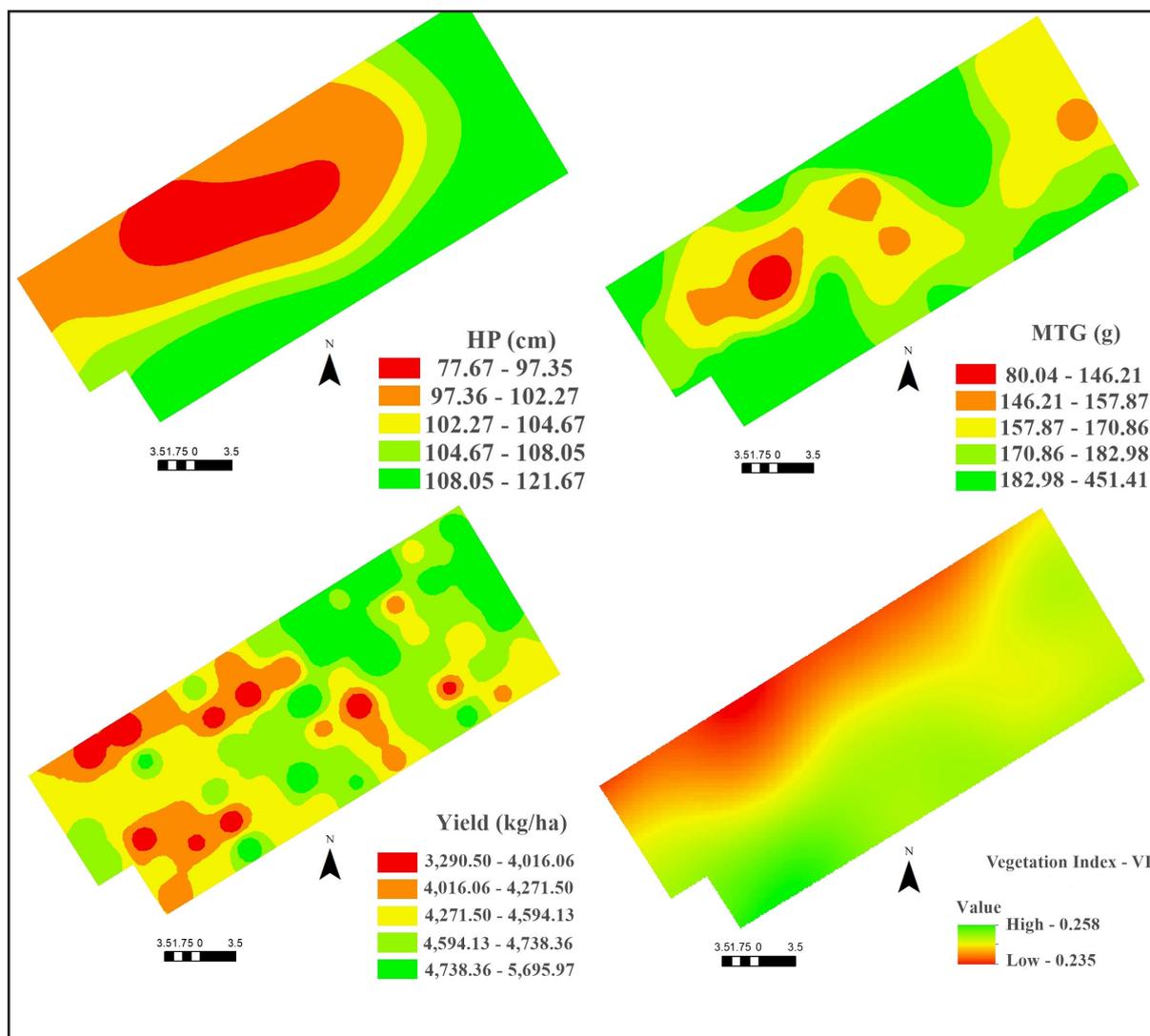
Source: Authors (2023)

PH1 was higher in area A1, as well as the yield of soybeans, compared to area A2. However, due to the shading of the cultivation area A1 promoted the lower FFF4, PH2, and VI2 of soybean. Soybean cultivated in the presence of trees shows a reduction in liquid photosynthesis (LP), development, and production of grain (Peng *et al*., 2015).

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Table 3 presents development data and yield parameters for soybean cultivated in the two different areas of the study. PH1 and PH2 were higher in area A1 (Table 3). While the PS was better in area A2, these observations were possibly influenced by the presence of the Eucalyptus forest, promoting a microclimate for soybean culture in the most shaded area. The microclimate of area A1 favored the production of soybeans, compared to area A2. The Vi's were also different due to the soybean cultivation environment.

Table 3 – Development an yield parameters of sobean grown in two different areas

Field	HD (m)	HP1	PS1	HP2	PS2	MTG	YIED	IV1	IV2
		cm	Plant m^{-1}	cm	Plant m^{-1}	g	kg ha^{-1}		
	30	32.75	10.83	101.14	10.83	151.19	4393.98	0.58	0.9
	34	32.58	11.67	108.94	11.67	169.63	4300.57	0.56	0.9
Area A1	38	30.78	8.17	95.95	8.00	173.73	4281.65	0.55	0.9
	42	31.97	11.67	106.45	11.67	164.27	4533.71	0.56	0.9
	46	28.99	11.50	96.94	11.50	144.14	4211.9	0.54	0.9
Means		31.41A	10.77B	101.88A	10.73B	160.59	4344.36A	0.56A	0.9B
	30	27.64	12.00	97.61	12.00	181.06	3297.12	0.51	0.91
	34	25.58	12.17	91.22	12.17	168.78	2713	0.48	0.91
Area A2	38	25.86	11.50	91.92	11.50	165.16	2821.31	0.49	0.91
	42	26.58	12.17	92.55	12.17	215.59	3121.2	0.49	0.91
	46	26.28	12.33	90.75	12.33	200.92	2845.8	0.48	0.91
Means		26.39B	12.03A	92.81B	12.03A	186.3	2959.69B	0.49B	0.91A
CV%		10.76	13.64	7.57	13.76	19.53	16.95	13.00	0.44

Source: Authors (2023)

In where: 1.HD: Horizontal distances; 2. HP1: Hight plant at 30 days of planting; 3. PS1: Stand of plant at 30 days of planting; 4. HP2: Hight plant at 60 days of planting; 5. PS2: Stand of plant at 60 days of planting; 6. MTG: thousand grain mass; 7.VI1: vegetation index at 30 days of planting; 8. VI2: vegetation index at 60 days of planting in fields shaded by *Eucalyptus*. 9. CV: Coefficient of variation; Means followed by the same uppercase letter in the column does not differ from each other by the Scott-Knott test (P < 0.05).

Regarding PH1, area A1 showed a higher average, differing from area A2, similar to PH2 (Table 3). PS1 obtained a better standard in area A2, varying from area A1, as

well as for PS2. The soybean Yield was better in area A1, differing from area A2. VI1 was better in area A1, changing from area A2, while VI2 showed better results, diverging from area A1, as observed in the canonical analysis (Figure 3).

For area A1, the FFF4 was 46m higher, but it does not differ from the 42m distance, the 30m length showed the lowest result. In area A2, the FFF4 was already the greatest in the shortest horizontal distances, 30m was the best result not differing from 34m, 46m was the lowest result not changing from 42 and 38m; comparing the averages of the two areas, area A1 showed a higher standard, differing from area A2.

The continuity of evaluations throughout the growth cycle of the trees are necessary to determine the spatial and temporal magnitude of their effects on grain crops and forage plants and to generate technical subsidies for the optimization of the combination of the different components of the ILPF allied to the evaluation economy of the system (Farias Neto et al., 2019).

Wen et al. (2020) and Cassel et al. (2021) when evaluating the rejuvenation of growth and development of soybean plants through light shading stress, suggest that light shading, 43% reduction in light intensity, is beneficial to crops. However, Cheng et al. (2022) the shading is an important factor, which leads to yield loss of soybean, especially in areas with low solar radiation. Given this observation, together with the soybean production results in area A1 (Table 3), it is evident that the soybean plant was not able to adapt to a shaded environment. However, the plants were favored by the presence of the eucalyptus forest (Caron et al., 2018).

The FFF4 in soybean cultivation was influenced in area A1 by the presence of Eucalyptus, obtaining lower values closer to the Eucalyptus. Although, in area A2, this influence may be due to the presence of clouds since the shading would not promote a higher incidence of light due to the horizontal distance.

Conventional low-carbon production systems have rows of Eucalyptus at known distances, and the cultivation of annual crops in between rows only allows cultivation over the first few years, after which it is necessary to plant forage and will enable the

grazing of animals (Werner *et al*., 2017). However, many farmers are not ranchers, which makes it challenging to implement low-carbon production systems and manage them. Caron et al (2018), describe that soybean produced less than 1000 kg ha^{-1}, with the presence of forest species, *E. urophylla* x *E. grandis* e *P. dubium*, by the effect due to the shading close to the trees due to the geographical distribution of the crops.

The proposed soybean cultivation neighborhood to the eucalyptus forest already implanted, and with more than 17 m in height, indicate a principle that the geographic distribution of the eucalyptus forest with the soybean cultivation area can be varied. The unexpected increase in soybean productivity in area A1 proves that the low-carbon production system brings productive and environmental benefits, necessary for the sustainability of the agricultural system. Low-carbon production systems can increase soil carbon sequestration and mitigate climate change (Bonini *et al*., 2018).

In a climate change scenario, a producer who decides to invest in a Crop-Forest integration system, instead of investing in conventional production, would benefit from increased air humidity and water availability on its property; improvement in soil fertility and reduction of erosion; reduction in the frequency of cold waves, heat waves, droughts and natural disasters; in addition to increased productivity and income (Hellvig; Flores-Sahagun, 2023).

4 CONCLUSIONS

Cultivation at distances less than 34 m to the east and 12 m to the south of the eucalyptus forest decreases the photosynthetic photon flow, vegetation index, and plant height at 60 days of planting of soybeans due to shade.

Thousand grain mass and yield of soybean do not have spatial dependence with the distance from the shadow by eucalyptus forest.

The shadow to the eucalyptus forest favors the yield of soybeans, depending on the cultivated distance.

The analysis of the influence of the shade of forests in the cultivation of grains and cereals should be extended to the sustainable use of in a low-carbon production system.

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