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Spatial relation of weed competition and soil fertility in soybean farming

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Abstract

Soybean is one of the main crops in Brazil, with a significant share of national agribusiness exports. Nonetheless, several factors such as weed competition and soil fertility directly affect soybean yield and productivity. This study aimed to analyse the spatial distribution of weeds as a function of soil fertility and soybean yield in farming fields. We carried out the experiment on a farm located in Brejo, Maranhão state, Brazil, through a geostatistical analysis of 60 sampling points on a regular grid of 10.0 m x 50.0 m. At these points, we collected phytosociological information on the weed community, soil fertility, and soybean yield. We performed principal component analysis (PCA) to determine the most responsive variables and to group them. We determined spatial dependence through geostatistical procedures, with the interpretation and adjustment of variogram components. We identified seven weed species, distributed across seven genera and six botanical families, of which 76.78% were eudicotyledons. In the cluster analysis, we grouped monocotyledonous species separately from eudicotyledons as explained by the morphophysiological contrasts between these botanical classes. Soybean yield did not correlate with soil fertility or weeds. These two factors can be considered only as a share of soybean productivity because their individual variations do not directly influence production factors. The efficient management of weeds and soil fertility should result in a more uniform and potencially more soybean yield when other conditioning factors are also effective.

Keywords: *Glycine max* (L.), Merril, Geostatistics, Principal component analysis, Productivity.

Introduction

One of the most important crops worldwide is soybean because the large market that enhances the generation of income and jobs in several countries, notably Brazil. In Brazil in 2020, soybean represented 34.2% of the total exported value, equivalent to US $34.5 billion. Also, Brazil became—with the 2019-2020 harvest—the major global soybean producer, making up 37.4% of world production, followed by the United States (28.7%) and Argentina (14.5%) (IPEA, 2021).

The increase in demand in the international market caused a rapid growth of soybean cultivation in Brazil, which led to the use of areas previously cultivated with other crops and—especially—the expansion of the agricultural frontiers (Freitas; Mendonça, 2016). Stimulated by demand, producers raised investments directed to improve production techniques, resulting in positive effects on productivity, which moved from 2,823 kg ha (hectares)$^{-1}$ in 2006/07 to 3,529 kg ha^{-1} in 2020/2021 harvest (CONAB, 2020).

Soybean was introduced to the South Central Region of Maranhão state in the 1970s. In the 2000s, however, soybeans expanded to the Chapadinha and adjacent microregions and, more recently, were introduced to Caxias microregion (Conte et al., 2018). In Maranhão state, the planted area for 2020/2021 harvest was 1,005.7 thousand ha, with an estimated soybean production of 3,280.6 thousand tons, demonstrating the importance of this crop for the state (CONAB, 2020).

South mesoregion of the Maranhão state highlights as the major soybean producer statewide, whereas the municipality of Balsas has the highest production: around 619,997 tons in the 2019/20 harvest. The eastern mesoregion of the Maranhão state, which included the area investigated in this study, belongs to an expanding frontier with a production of 341,911 tons in the 2019/20 harvest (IBGE, 2020).

Although soybean productivity plays an important socio-economic role, it has experienced significant losses because of several factors, especially weeds and soil fertility. Weeds provide negative impacts estimated in the range of 20 to 30% in the Brazilian productive scenario, which is generally because of competition for water, light, and nutrients, as well as indirect negative effects such as limitations in harvesting operations and reduced grains quality (Mário, 2017; Polles, 2019).

According to Londero et al. (2020), producers have optimised the use of technologies that aim to increase productivity and maximise profitability. Thus, precision agriculture (PA) emerges as an efficient and innovative tool in agricultural guidance and automation systems, phytosanitary management, soil sampling, correction and variable rate fertilization systems, variable rate seeding, yield mapping, and remote sensing.

The most common precision agriculture practice in Brazil nowadays is georeferenced soil sampling, which is used to map the fertility of crop plots. The purpose of this georeferencing is to understand the variability of fertility within a given area and to carry out fertilization more assertively, aiming to better yields (Resende et al., 2004; Soares Filho; Cunha, 2015).

The correlation of soil attributes with weed dynamics and crop yield is still scarce in scientific literature. Some weed species represent a competitive component for resources in the production area and can act as bioindicator organisms. Thus, the infestation of certain weeds could be related to soil fertility or management conditions applied in the area.

In this sense, our objective was to analyse the spatial distribution of weeds as a function of soil fertility and soybean yield in farmer fields.

Results and discussion

Phytosociological survey of weeds

In the phytosociological survey, Table 1 lists 1,417 individual weeds distributed in seven species, seven genera, and six botanical families. The results revealed a higher incidence of eudicotyledons weeds (76.78%), distributed in three botanical families —Euphorbiaceae, Malvaceae, and Molluginaceae — with one species each. Also, we found monocotyledonous species in three botanical families: Commelinaceae, Cyperaceae, and Poaceae. Commelinaceae and Cyperaceae had one species each, whilst Cyperaceae had two weed species.

When investigating the phytosociological indices, particularly the importance value index, we found that the species *Mollugo verticillata* (160.73) was the most relevant in the crop, followed by *Cyperus iria* (57.13), *Commelina benghalensis* (25.56), *Eragrostis maypurensis* (17.33), Sida rhombifolia (14.76), *Chamaesyce hyssopifolia* (14.04), and *Cenchrus echinatus* (10.44), as shown in Fig. 1

The ranking of the degree of importance aligns with the results obtained by Lopes et al. (2020a) when evaluating the weed dissemination bank in an experimental crop located in Chapadinha, Maranhão state, Brazil. Also, our findings corroborate the results of Silva et al. (2021), who performed the phytosociological survey at 21 and 32 days after sowing in a commercial soybean crop in Brejo, Maranhão state. The authors mentioned earlier in this paragraph noticed that the application of S-metolachlor (1,152 g i.a. ha^{-1}) was efficient in the pre-emergence control of weed competition, whose species and cultivation conditions were similar to those identified in the present study.

According to Oliveira and Freitas (2008), the importance value index shows the species that, amongst those found in the weed community, have the greatest potential to cause crop damage. Therefore, the results issue warnings regarding the monitoring and control of the infestation of *Mollugo verticillata* (160.73), *Cyperus iria* (57.13), and *Commelina benghalensis* (25.56).

Notice that some weeds may have less representation in a growing or agricultural season; however, they must be carefully monitored and controlled by the producer to avoid future problems, such as those caused by *Conyza bonariensis*, *Conyza canadenses*, and *Conyza sumatrensis* (buva), and *Digitaria insularis* (capim-amargoso) in the main grain-producing regions, in which these species were initially secondary pests, as point out by Concenço and Grigolli (2014). Other authors, such as Krolikowski et al. (2017), reported difficulties in controlling the species *Commelina benghalensis* L. with glyphosate in post-sowing soybean. This species was recorded in the studied crop although not been listed with the high importance index value.

Concerning the densities of the botanical classes, the eudicot weeds presented greater infestation in the area, reaching 18.13 plants per square meter. By contrast, monocotyledons exhibited 5.48 plants per square meter at 25 DAS, as shown in Fig. 2).

According to Rizzardi and Silva (2014), a necessary strategy involves knowledge of botanical classes, distribution, and phytosociology for defining effective tools for weed suppression. During that study, the density of eudicots increased by *Mollugo verticillata*, which corresponded to 96.05% of the total density. This result implies the need for further studies on the efficient control of this species in pre- and post-emergence in commercial farming.

In scientific literature, diverse studies indicate *Mollugo verticillata* as a species with well adapted to the state of Maranhão, as reported by Corrêa et al. (2015), Lopes et al. (2020b) and Silva et al. (2021). In agreement with Lorenzi (2008), who described *Mollugo verticillata* as a species with short cycles, frequently found the species in the Brazilian northeast region, particularly in annual crops. According to Hereford et al. (2017), on the world stage, this species is important in several continents, especially in the United States, where it occurs on riverbanks, crops, and even desert regions. Due its rapid development cycle, it has significant population growth under favorable conditions, similarly what occurred in the present study.

As for monocotyledonous, *Cyperus iria* caused the highest incidence of individuals per square meter. According to Moreira and Bragança (2011), this species has skillful dissemination, especially via seed. These authors also claimed that although it is a Cyperaceae without rhizome emission for asexual propagation, Cyperus would have structures at its base that allow expressive tillering, making the mechanical control in the crop more difficult.

The genera Cyperus is composed of several species that have great importance as weeds, occurring in different world regions (Pashirzad et al., 2014; Follak et al., 2015). Its control is hampered by morphophysiological characteristics, which generally increase the control costs by requiring specific herbicides (Peripolli et al. 2020).

Principal component analysis

These results make it clear that soybean yield was not selectable for any factor when related to soil fertility or weed infestation, as shown in Table 1. Likewise, Silva et al. (2007) found a low correlation between productivity and soil chemical properties.

According to Resende and Coelho (2017), a higher correlation between isolated factors of production and productivity is rarely found in highly technical crops as the one analysed in this study. Hence, each factor must be considered only as a portion of several factors conditioning crop productivity.

Concerning the analysis of Euclidean distances, we extracted the cluster graph, which showed the formation of two large groups that indicated significant differences between them

Table 1. Identification of weed community in conventional soybean cultivation in Brejo, Maranhao state, Brazil, 2021.

Class	Family	Species
Eudicotyledons	Euphorbiaceae	Chamaesyce hyssopifolia
	Malvaceae	Sida rhombifolia
	Molluginaceae	Mollugo verticillata
Monocotyledonous	Commelinaceae	Commelina benghalensis
	Cyperaceae	Cyperus iria
	Poaceae	Eragrostis maypurensis
	Poaceae	Cenchrus echinatus

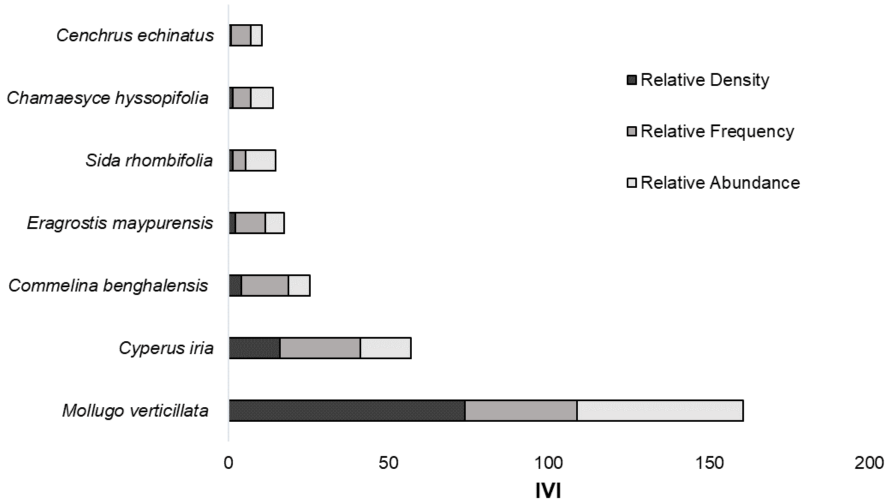

Figure 1. Importance value index of weed species identified in commercial soybean crop at 25 DAS.

Table 2. Pearson correlation coefficients extracted by principal components.

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Yield	-0.319896	-0.098590	0.316013	-0.538606	-0.175402
H+Al	0.897027*	0.050016	-0.002184	0.088385	0.017969
P	0.896703*	0.074769	0.060754	0.067079	-0.121386
OM	0.689443*	0.123215	0.386649	0.062488	-0.055440
V (%)	0.849216*	-0.032464	0.153694	0.115579	0.150254
Mollugo verticillata	0.431292	0.338173	0.577789	-0.024577	0.351484
Chamaesyce hyssopifolia	0.045124	0.785686*	0.151753	0.290880	-0.191277
Sida rhombifolia	0.072865	0.792117*	-0.109623	-0.142231	0.310082
Commelina benghalensis	0.135576	0.078345	0.130342	0.819984*	-0.009008
Cenchrus echinatus	0.062377	-0.104976	0.685400*	0.419994	0.259290
H+Al	0.897027*	0.050016	-0.002184	0.088385	0.017969

Figure 2. Characterization of weed infestation by class of plant species at 25 DAS.

Table 3. Parameters extracted from semivariograms of mean orthogonal coefficients of soil fertility, weeds and soil fertility + weeds.

	Soil fertility	Weeds	Fertility + weeds
SPD	0.99	0.00	0.80
A	20.1	129.06	163.8
C_o	0.00	1.09	0.19
C_i+C_o	0.56	0.00	1.03
Model	Spherical	Linear	Spherical

*SPD = Spatial dependence degree; A = amplitude; C_o = nugget effect; C_i+C_o = threshold.

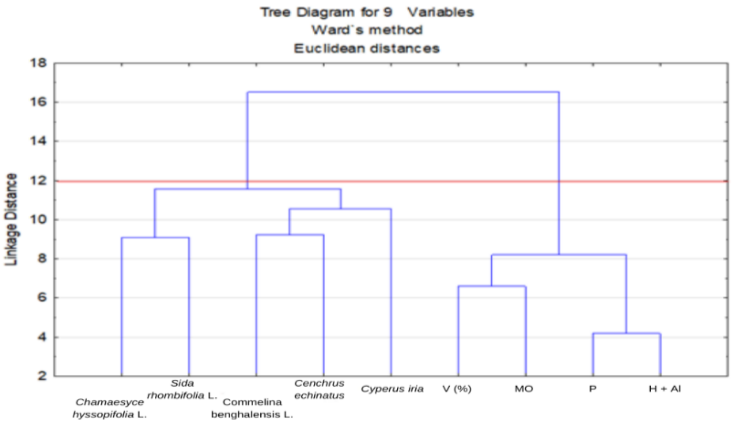

Figure 3. Clusters of weed infestation factors and soil chemical properties in a commercial soybean crop. Fenon line in red color.

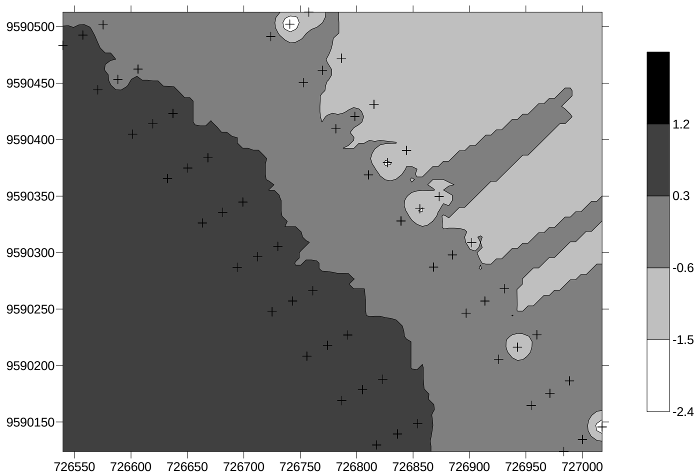

Figure 4. Orthogonal coefficients of soil fertility parameters, extracted from the main factors.

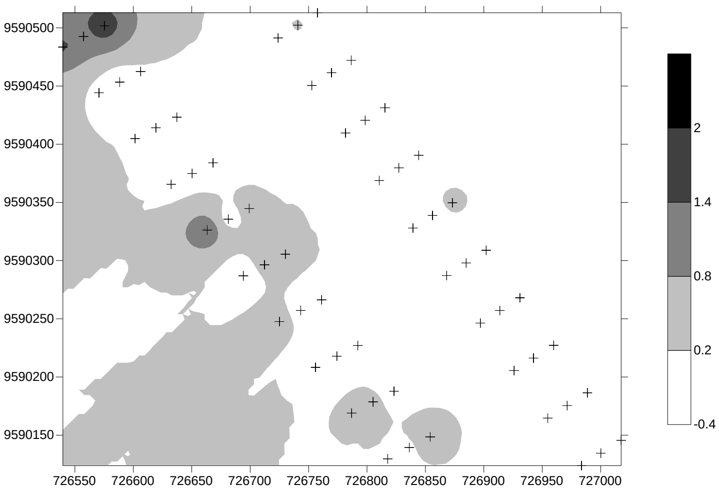

Figure 5. Orthogonal coefficients of weed, extracted from the main factors.

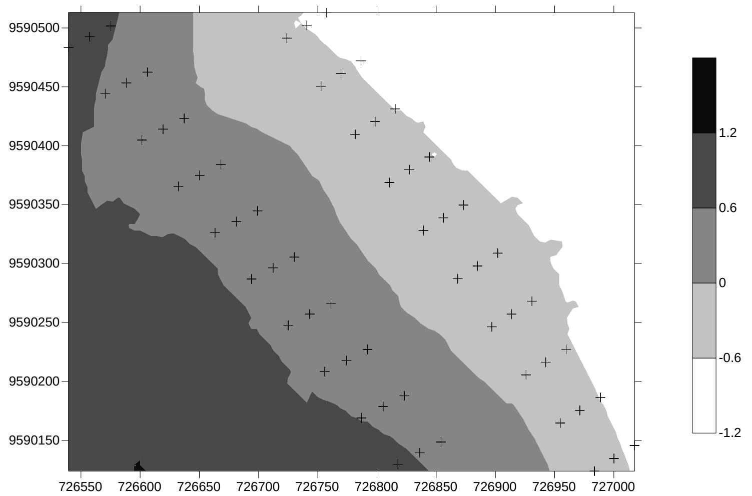

Figura 6. Orthogonal coefficients of soil fertility and weed parameters, extracted from the main factors.

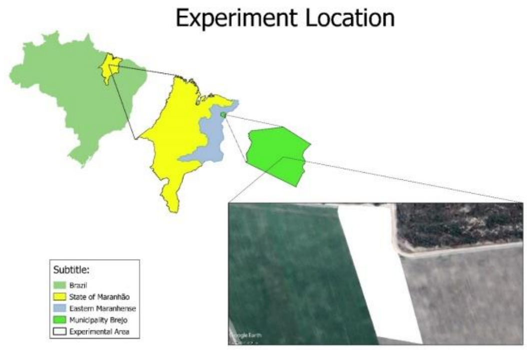

Figure 7. Location of the experimental site and layout of the study area**.**

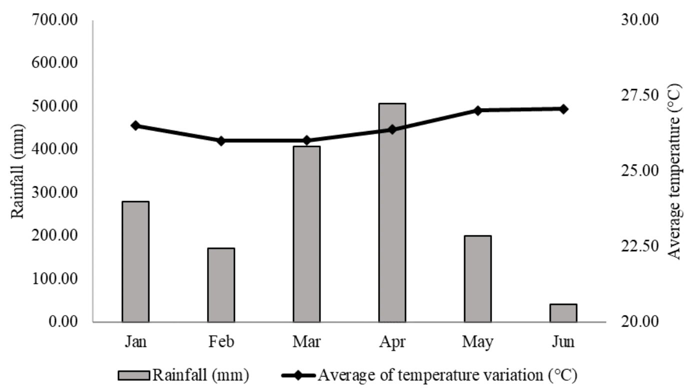

Figure 8. Meteorological indicators of Brejo, Maranhao state, Brazil, from january to june 2021. Source: INMET, 2021**.**

and, therefore, were not correlated. The first group consisted of the infestation factor of *Cenchrus echinatus*, *Chamaesyce hyssopifolia*, *Commelina benghalensis*, *Cyperus iria*, and *Sida rhombifolia*, whilst the second group comprised soil chemical properties, including base saturation (V), soil organic matter (OM), available phosphorous (P), and potential acidity (H + Al), as shown in Fig. 3.

The results suggest that the soil chemical properties do not have a high correlation with the weed community, in contrast to Shiratsuchi et al. (2005) who, assessing the correlation of the spatial distribution of the seed bank and soil fertility attributes, found a grand correlation between the analysed factors. This divergence of results might be related to methodological differences applying during the experiment conduction because in the present investigation, we carried out the phytosociological survey of weeds at 25 DAS in a farmer field, whilst Shiratsuchi et al. (2005) analysed juvenile infestation and under controlled conditions.

The group composed of weeds included a subdivision of species, in which we grouped Monocotyledonous (*Cenchrus echinatus*, *Commelina benghalensis*, and *Cyperus iria*) separately from eudicotyledonous (*Chamaesyce hyssopifolia* L. and *Sida rhombifolia*). According to Ferreira et al. (2013), this distinct grouping could be explained by the botanical and ecophysiological differences between the two classes, whilst the proximity of the clusters could be explained by the natural tendency of weeds to disperse or germinate randomly in the field.

Fig. 4 shows a representation of the orthogonal factors of the soil fertility parameters, obtained through sampling and chemical analysis in georeferenced points. We noticed that the variation of the orthogonal coefficients of the fertility parameters ranged from -2.4 to 1.2. Despite the distribution in distinct classes indicated by different colours on the map, slight quantitative variation occurred in the orthogonal coefficients, which indicated uniformity in the management of the area in relation to soil fertility.

Also, this uniformity helped to explain the low correlation evidenced between the soil chemical proprieties and the soybean productivity, because if heterogeneity occurred in the area, the productive yield would probably be affected in terms of significance.

According to Richter et al. (2011), soil management changes several soil properties, such as macro and micronutrient content. Generally, the greatest variability occurs in the physical (particle size and particle density) and chemical (pH, organic carbon content, and cation exchange capacity) characteristics of the soil.

Fig. 5 shows a map of the orthogonal factors of the distribution parameters of the weed infestation, which we sampled with square inventory and extraction of values through principal component analysis.

The results indicated an orthogonal coefficients variation, which we subdivided into five classes, from -0.4 to 2. Class with the highest distribution was the one with amplitude -0.4 to 0.2, followed by the class from 0.2 to 0.8. Other classes appeared only like spots on the map. This analysis found evidence expressing that some weeds are spatially dependent (listed in Table 2), influencing the general distribution of the infestation, which may be associated with differences between the botanical classes, notably regarding ecophysiology, life cycle, forms of perpetuation, and competitive ability in the crop.

Except for the standardised weed coefficients—which showed high random variance (nugget effect), usually denoted because of homogeneity of occurrence—the other fertility coefficients, weed's degree, and soil fertility ratio have a high degree of dependence spatial (listed in Table 2). This behavior was directly in line with previous findings described by Chiba et al. (2010). According to those authors, the variation that occurs in phytosociological studies of weeds in geostatistical patterns is commonly reported in the literature, considering it is a methodology for counting individuals, which can induce heterogeneities regarding the biological characteristics of plant species in terms of crop distribution.

Fig. 6 shows orthogonal factors of the parameters of soil fertility and weeds, obtained through the extraction of the principal component analysis. The map indicates a low correlation between soil fertility and the spatial distribution of weeds in the crop. These results differed from Schaffrath (2009), who studied the spatial variability of soil physical properties and phytosociological indices of weeds in two soil management systems. He detected high spatial dependence of the occurrence of weeds when related to the physical attributes of the soil, which have a significant influence on this correlation. Another factor that may explain these results is the homogeneity of the chemical properties throughout the sample area, similar to those obtained in the present study.

Lousada et al. (2013), in correlation analysis of the chemical properties of the soil, found that some attributes did not show a significant correlation with the density of weeds. According to Otto et al. (2007), this may occur as a result of some weed species being spread throughout the crop, whilst others are concentrated in specific points (dead spots).

Despite differences in the literature regarding the correlation of soil chemical properties with weed infestation, note that some variables would influence the distribution of the weed in the crop—such as physical soil properties, intrinsic sensitivity of each species invasive to soil properties, concepts of biology and ecology of weed species, herbicide application technology, soil management—amongst other aspects of technified production system.

Materials and methods

Study location

We carried out the experiment at a farm field in the municipality of Brejo, in the east mesoregion of Maranhão state, Brazil, with geographic coordinates 3°42'09.1"S and 42°57'36.5"W, and at a local altitude of 103 m (as seen in Fig. 7), between January and June 2021.

The soil of the experimental area was classified as Distrocoeso Yellow argisoil (Dantas et al., 2014). The climate, according to Köppen, is tropical warm and humid, with an average annual temperature of 27ºC and rainfall between 1,600 and 2,000 mm/year. The rainy season occurs between January and June, with an average relative humidity of 76% (Passos et al., 2016).

Fig. 8 shows data about meteorological conditions during the period of the experiment, according to the Brazilian National Institute of Meteorology (Inmet, 2021).

Experiment implementation

We used the conventional cultivar Ansc 89109, with a density of 16 seeds per meter and a spacing of 0.5 m between rows. We treated the seeds with insecticide (thiamethoxam, 350 g i.a. L^{-1}) at a dosage of 0.002 L kg^{-1}, fungicide (20 g i.a. L^{-1} of metalaxyl-M + 150 g i.a. L^{-1} of thiabendazole + 25 g i.a. L^{-1} of fludioxonil) at a dose of 0.002 L kg^{-1}, and insecticide (cyantraniliprole, 600 g i.a. L^{-1}) at a dose of 0.0012 L kg^{-1} of seeds.

For weed management in the whole area, we carried out pre-planting desiccation of weeds 15 days before sowing, through the application of glyphosate (2,477.1 g i.a. ha^{-1}) + 2, 4-D (1,476 g i.a. ha^{-1}). One day after sowing (DAS), we performed pre-emergence control with diclosulam (35 g i.a. ha^{-1}+ imazethapyr (164.8 g i.a. ha^{-1}). At 28 DAS, we did post-emergence spraying with clethodim (108 g i.a. ha^{-1}). We carried out the sprayings with a uniport Jacto® sprayer, model 2500 star, with a capacity of 2,500 L, equipped with a 28 m bar with 56 nozzles, spaced 0.5 m apart.

Variables analysed by geostatistical tools

We executed weed monitoring through a phytosociological survey, with the aid of square inventory with dimensions of 1.0 mx 1.0 m, in a regular sampling grid (10.0 mx 50.0 m), in a total of 60 georeferenced samples in a commercial plot, at 25 DAS. Weed identification occurred by morphological comparison of individuals of each species, according to Lorenzi (2008). By identification and quantification, we estimated phytosociological indices based on the following formulas:

$$\text{Density} = \frac{\text{Total number of individuals of species}}{\text{Total number of square meters sampled}}$$

$$\text{Relative Density} = \frac{\text{Species density} \times 100}{\text{Total species density}}$$

$$\text{Frequency} = \frac{\text{number of squares where the species was found}}{\text{Total number of squares obtained in the area}}$$

$$\text{Relative Frequency} = \frac{\text{Species frequency} \times 100}{\text{Total species frequency}}$$

$$\text{Abundance} = \frac{\text{Total number of individuals of species}}{\text{Total number of squares where the species was found}}$$

$$\text{Relative Abundance} = \frac{\text{Species abundance} \times 100}{\text{Total species abundance}}$$

Importance value index (IVI) = Relative Density + Relative Abundance + Relative Frequency

We characterised soil fertility by chemical attributes initially through sampling at a depth of 0-20 cm in a regular sampling grid of 10.0 mx 50.0 m, in 60 georeferenced points, located 10 cm in front of the plant sampling point weeds, whose survey was previously carried out with square inventory (1.0 mx 1.0 m), at 25 DAS. After soil collection, we shade-dried the samples in a sieved in a 2.0 mm mesh, packed in plastic bags, and sent to the Soil Laboratory of the Federal University of Tocantins, Campus de Araguaína. We evaluated the values: Hydrogen + Aluminum (H+Al), Phosphorus (P), Organic Matter (OM), and Base Saturation (V%).

To perform the yield analysis, we sampled soybean plants at 60 georeferenced points at 115 DAS. By using the following formula, we transformed the estimated results into kg ha^{-1}:

$$\frac{(\text{Plants per hectare}) \times (\text{Pods per plant}) \times (\text{Seeds per pod}) \times (\text{Weight of a thousand grains})}{60{,}000}$$

Statistical methods

Afterward, we performed a principal component analysis. From the determination of the most responsive variables, we grouped the new variables by a transformation of soil chemical variables by using the non-hierarchical fuzzy k-means method.

We applied analysis of variance (ANOVA) for variables soil chemical, weed population density, and productivity amongst the different management units generated by the grouping to verify differences between the means. We used Tukey's Honest Significant Difference test (HSD) to compare treatment means for different-sized samples. To express spatial dependence by the principles of geostatistics, we used a GS+ 5.1 software to interpret and adjust variogram components, made from the cases extracted in the grouping.

Conclusion

We identified seven weed species that were distributed across seven genera and six botanical families, of which 76.78% were eudicotyledons. In the cluster analysis, monocotyledonous species were grouped separately from eudicotyledons, as explained by the morphophysiological contrasts between these botanical classes.

Soybean yield did not correlate with soil fertility or weeds. These two factors can be considered only as a share of soybean productivity because their individual variations do not directly influence production factors. The efficient management of weeds and soil fertility should result in a more uniform and potent soybean yield when other conditioning factors are also effective.

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