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CROP SCIENCE

Weed spatial distribution as a function of soil properties in two distinct environments of the Brazilian semi-arid region

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Abstract: The present study aimed was to evaluate the spatial variability of weed species by means of phytosociological parameters and their correlations with the physical-chemical soil properties, under semiarid climate conditions. Weed phytosociology and soil characterization were carried out in two areas one newly deforested area covering 8.86 ha, and one experimental agricultural area covering 24.7 ha; both in the semi-arid region of Brazil. Weed and soil were sampled by following georeferenced grids in each area. Biomass and the total number of weed individuals, as well as soil properties, were mapped by the ordinary Kriging method. The predominant herbaceous plants in the newly deforested area were *Hexasepalum teres* and *Digitaria insularis*. The weed species that predominated in the agricultural area were *Cyperus rotundus* L., *Euphorbia heterophylla* L. and *Herissantia Crispa* (L.) Brizicky; the latter species outstanding for dry biomass (873.5g). Spatial dependence was observed for the predominant species, except for *Digitaria insularis*. The spatial distribution of these weeds was conditioned by soil K^+ contents in both areas, and by sand content for the experimental agricultural area. Therefore, these two soil attributes resulted key factors for weed infestation in this semi-arid region.

Key words: Geostatistics, mapping, soil properties, weed community.

INTRODUCTION

The presence of undesirable plants in agricultural fields can lead to a wide range of issues, including decreased crop yield. Negative interactions between weeds and crop plants occur as a result of many phenomena, in isolation or in conjunction, from allelospoly (resource competition), to allelopathy (release of chemicals acting on other plants), to allelomediation (weeds harboring organisms that are harmful to crops, such as pest insects and phytopathogens), which are often further aggravated by operational difficulties in the field (Monquero 2014). These undesirable plants, also known as weeds, can be defined as higher plants that interfere with the interests of humans and the environment.

Weed management has become increasingly dependent on herbicides (Kalivas et al. 2012), and the indiscriminate use of these herbicides can generate socio-environmental damages (Chiba et al. 2010). Thus, strategies to improve weed management are essential for modern agriculture. In addition to other information, knowledge of the spatial distribution of weeds is an important prerequisite for successful weed management.

Several studies have shown that the distribution of weeds in agricultural areas is not random, but that it is instead related to spatial dependence (Izquierdo et al. 2009, Jurado-Expósito et al. 2009, Nordmeyer 2009, Chiba et al. 2010, Kalivas et al. 2012, Metcalfe et al. 2016), with such dependence being determined by geostatistics. Geostatistics allows weed mapping, which allows us to understand how weeds are distributed in the area, leading to more efficient management and a deeper understanding of weed ecophysiology.

Diversity of propagation modes, rapid seed production, ease of propagule dispersion, and irregular emergence (seed dormancy) are some of the innate mechanisms behind the success of weeds (Oliveira Júnior et al. 2011) that define the establishment of the weed community. However, environmental conditions are also key factors in the infestation process. Therefore, knowing the spatial distribution of weeds in agricultural fields is not enough; we must also understand the factors that determine this distribution.

Climatic, physiographic factors, and biotic factors determine the occurrence and permanence of weeds in any given environment and time period. Physiographic factors are related to soil and topography, with the edaphic factor having the greatest impact on weed persistence (Fried et al. 2019). Kalivas et al. (2012) confirmed this fact in a cotton field in Greece, in which a spatial correlation between weeds and soil attributes was observed, with clay content having a particularly large impact. Metcalfe et al. (2016) studied the spatial correlation between weeds and soil attributes in the United Kingdom, and verified that clay and soil organic matter content influenced the spatial distribution of *Alopecurus myosuroides*.

Whilst studies have found correlations between the spatial distribution of weeds and soil attributes, there have been few such studies under semi-arid conditions. Understanding the dynamics of infestation in plant communities from different regions and climates enables sustainable and efficient phytosanitary management in accordance with the local conditions, which is preferable to applying methods and information from divergent regions or climates. Therefore, this study aimed to evaluate the spatial distribution of weeds and the correlation between weed special distribution and soil attributes in two areas of the Brazilian semi-arid region.

MATERIALS AND METHODS

Site description

The experiment was carried out in two areas, one of which was newly deforested (ND) and the other was used for agricultural experimentation (AE). Both were located in an experimental farm at Universidade Federal do Vale do São Francisco (UNIVASF), Nilo Coelho irrigated perimeter, Petrolina county, Pernambuco state, in the Brazilian semi-arid zone (Figure 1).

According to Köppen's classification, the local climate is "BSh" (Alvares et al. 2014), meaning that it is semi-arid and has less than 500 mm of rainfall annually, which falls mainly in three to four months of the year, with annual temperatures ranging from 18.7 to 33.6°C. The main meteorological data for the collection periods of the weed sociological survey are shown in Figure 2.

The ND area was originally covered in native vegetation (Caatinga biome), but an 8.86 ha area (9°19'13.652'' S, 40°32'42.131'' W, elev. 388 a.s.l.) was deforested using a tire tractor in 2015. Herbaceous vegetation is now predominant in this area (first spontaneous populations).

The second area (9°19'5.204'' S, 40°33'40.727'' W, elev. 396 m a.s.l.), covering 24.7 ha, is a plant and animal science experimental field belonging to UNIVASF, and is designated as AE (agricultural

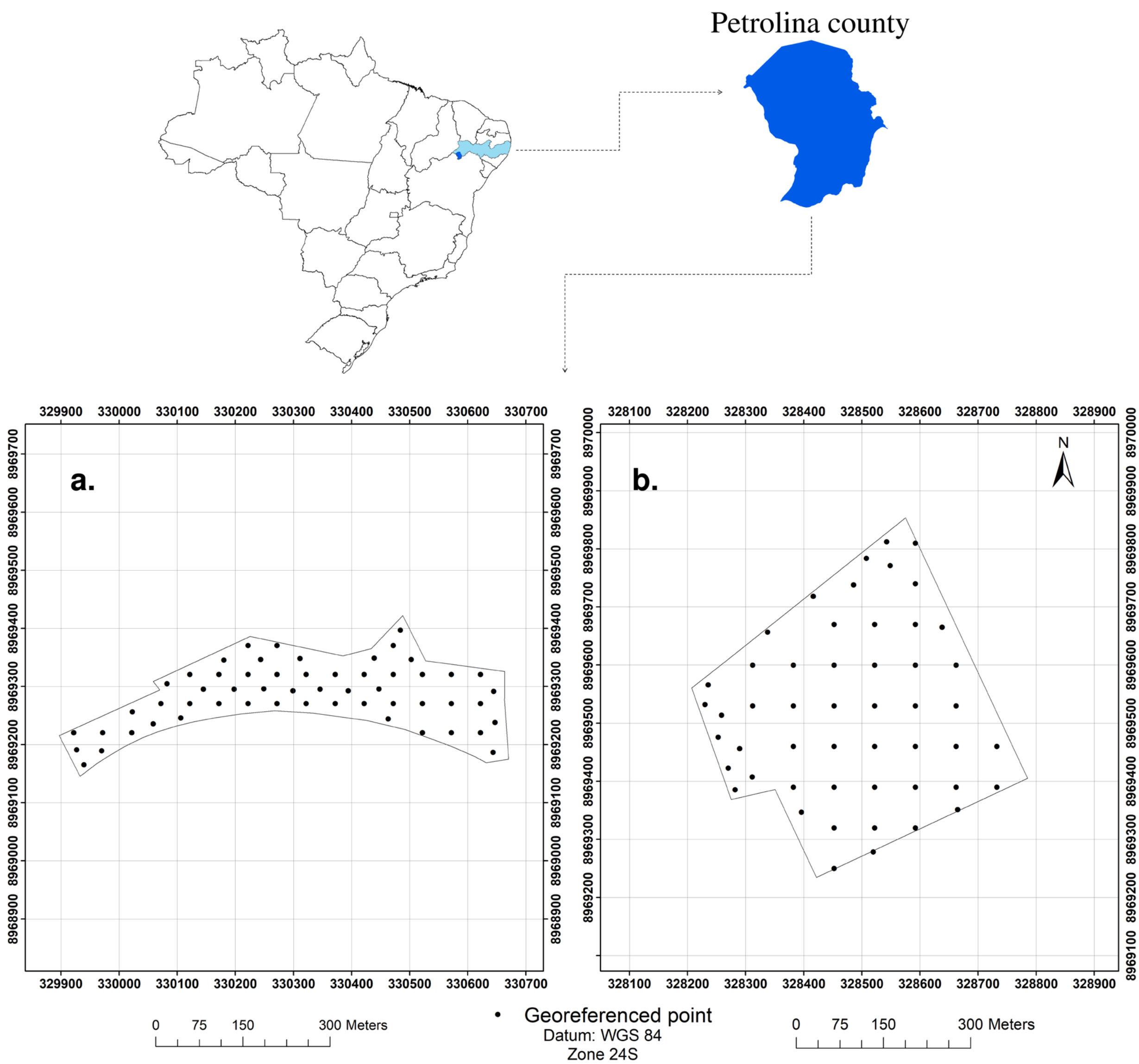

Figure 1. Location of the experimental area and sampling grids for soil collection and phytosociological survey, newly deforested area (a) and agricultural experimentation area (b), Brazil.

experimentation area). The area comprises plantations of fruit orchards (guavas, mango, orange, and acerola trees), grain crops (beans, corn, and soybeans) and forage (elephant grass). The area is irrigated and is subjected to high intensity cultural practices and research activities.

Soil data

Data on the soil attributes of both areas was obtained from a previously undertaken soil survey. In this soil survey, sampling grids obtained using a geographic information system (GIS) were used as a prospecting method. The sampling was guided by a portable GPS receiver (Global Positioning System) with an average error of 3 m. Whilst determining the number of samples for the pedological survey, it was verified that the soil in the ND area was more heterogeneous than the soil in the AE region,

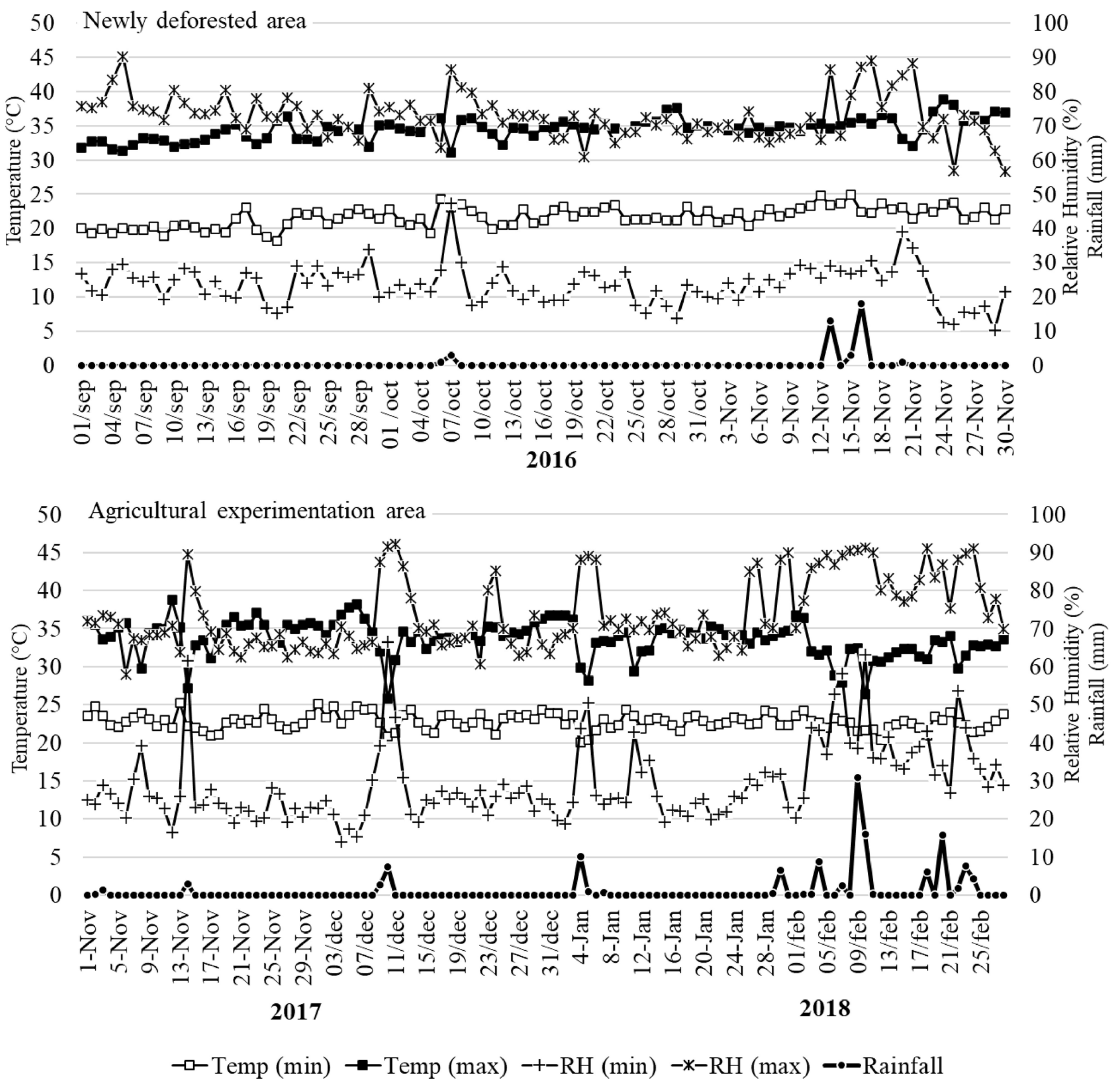

Figure 2. Main meteorological data concerning the collection periods for the weeds sociological survey.

leading to the decision to take 56 samples in the ND area (Figure 1a) and 51 samples in the AE (Figure 1b) area. Soil samples were collected at a depth of 0-0.20 m.

Soil texture (pipette method), pH (1:1 soil/water mixture), electrical conductivity (EC), potential acidity (H+Al), exchangeable acidity (Al^{3+}), and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were measured in each sample, according to the methodology of Donagema et al. (2011). Sum of basis (SB = Ca^{2+} + Mg^{2+} + K^++ Na^+), cation exchangeable capacity (CEC = SB + H+Al), basis saturation [V% = (SB/CEC) x 100], aluminum saturation [m% = Al^{3+}/Ca^{2+} + Mg^{2+} + K^++ Na^+ +Al^{3+}) x100], and exchangeable sodium percentage (ESP = Na^+/CEC) were also calculated.

The predominant soil in the ND area was Quartzipsamments according to American Classification Soil Taxonomy (Soil Survey Staff 2014). This soil is characterized by its sandy texture, single grain structure, and gentle slope. Regarding the main chemical properties, pH was between 4.9 and 7.9, effective CEC (t) ranged from 1.3 to 3.8, and basis saturation (V%) varied from 19.9 to 81.2. It is important to highlight that 83% of the samples obtained V% values below 60. Aluminum saturation (m%) values ranged from 3.5 to 50.1, and 70% of the samples had aluminum saturation values greater than 10% (Data not shown). Thus, the data showed that the soil in the ND area had very low fertility, low water retention capacity, and a predominance of exchangeable aluminum in soil colloids, which is a toxic element to plants (Echart & Cavalli-Molina 2001).

The soil of the AE area was classified as Ultisol with a cohesive dystrophic horizon, sandy/sandy loam texture, and gentle slope according to American Classification Soil Taxonomy (Soil Survey Staff 2014). The samples presented pH values of between 5.9 and 8.2, the effective CEC (t) ranged from 0.9 to 5.4, and basis saturation varied from 31.9 to 88.9%. For aluminum saturation (m%), values ranged from 0.7 to 22.6. Details on the soil data of the AE can be found in Silva et al. (2017).

Phytosociological survey

The phytosociological survey was carried out following the sample grids defined in Figure 1. This was done so that the soil data and the weeds data had equal sampling intensities. The weed sampling was conducted from September to November 2016 in the ND area and from November 2017 to February 2018 in the EA area. A frame (0.25 m^2) made of PVC (Polyvinyl chloride) was positioned at each sampling grid point according to the inventory square method proposed by Braun-Blanquet (1979), which is frequently used in phytosociological studies.

The plants inside the quadrat were pre-identified, quantified, and collected. The aerial parts of the plants were cut at soil level, were separated by species, and were placed in paper bags before being oven dried with forced air circulation at 70°C for 72 hours (Santos et al. 2016). The plants were then weighed using an analytical balance accurate to 0.001g.

The analysis of the populations of the predominant species was carried out using phytosociological parameters, with the absolute and relative (proportionality of each species in the community) values of frequency (F and Fr), density (D and Dr), abundance (A and Ar), dominance (Do and Dor), and importance index (I and Ir) being calculated using the equations (eq. 1 to 10) proposed in Mueller-Dombois & Ellemberg (1974). The results are presented as relative values.

Frequency (F):

$$F = \frac{\text{number of plots containing the species}}{\text{total number of plots used}} \tag{1}$$

Density (D):

$$D = \frac{\text{total number of individuals per species}}{\text{total area collected}} \tag{2}$$

Abundance (A):

$$A = \frac{\text{total number of individuals per species}}{\text{total number of quadrats containing the species}} \tag{3}$$

Dominance (Do):

$$Do = \frac{\text{total dry biomass of the species}}{\text{total area collected}} \tag{4}$$

Relative Frequency (Fr):

$$Fr = \left(\frac{\text{frequence of the species}}{\text{total frequency of all species}}\right) x100 \tag{5}$$

Relative density (Dr):

$$Dr = \left(\frac{\text{density of the species}}{\text{total density of all species}}\right) x100 \tag{6}$$

Relative abundance (Ar):

$$Ar = \left(\frac{\text{abundance of the species}}{\text{total abundance of all species}}\right) x100 \tag{7}$$

Relative dominance (Dor):

$$Dor = \left(\frac{\text{dominance of the species}}{\text{total dominance of all species}}\right) x100 \tag{8}$$

Importance value index (I):

$$I = Fr + Dr + Dor \tag{9}$$

Relative importance value index (Ir):

$$Ir = \left(\frac{\text{I of the species}}{\text{the sum of I of all species}}\right) \tag{10}$$

In addition, the coefficient of similarity (CS) between the studied areas was calculated according to the equation proposed in Sorensen (1948) (eq.11).

$$CS = \frac{\text{2 x number of species common to both habitats}}{\text{number of species of the A habitat} + \text{number of species of the B habitat}} \tag{11}$$

At the time of sampling, one individual per species was collected and pressed to prepare exsiccates in order to confirm the identification of plants at the species level.

Statistics analysis and mapping

A Pearson correlation matrix was performed between the plant variables (biomass and number of individual weeds predominant in each sampling point) and the soil attributes at a 5% error probability level.

Semivariograms models were used to estimate the spatial dependence among the samples, and to identify whether the variations were systematic or random. Subsequently, models were fitted to represent the spatial behavior of each variable. Spherical, exponential, and Gaussian models were tested for each semivariogram (Zůvala et al. 2016). Cross-validation was used to compare the models and to indicate which model best fitted the data. This method involves consecutively removing data points, interpolating the values from the remaining observations, and comparing the predicted values with the measured values (Sun et al. 2009). The variables that showed trend in the data, that is, the intrinsic hypothesis was not satisfied, were fitted a function to the original data and working with the residuals as described by Vieira et al. (2010).

Based on the relationship between the values of the semivariogram parameters, the nugget effect, and the sill, it is possible to define the degree of spatial dependence of a given attribute. Cambardella et al. (1994) defined a nugget effect of less than or equal to 25% of the sill as strong spatial dependence, a nugget effect of between 25 and 75% of the sill as moderate spatial dependence, and a nugget effect of greater than 75% of the sill as weak spatial dependence.

After the semivariograms were created, the data that demonstrated spatial dependence were interpolated by the ordinary Kriging method, as described in Oliver & Webster (2014).

To confirm the spatial correlations between the plant variables (number of individuals and biomass) and soil attributes, cross-semivariograms were created (Li & Heap 2011).

RESULTS AND DISCUSSION

Analysis of the phytosociological survey

Twenty-one plant species were identified in the ND area (Table I), belonging to eight botanical families. The main families present were: Malvaceae (five species), Poaceae, Cyperaceae, Fabaceae, Amaranthaceae (three species each), Portulacaceae (two species) Rubiaceae, and Lamiaceae (one species each).

The species *Hexasepalum teres* (Rubiaceae) and *Digitaria insularis* (Poaceae) obtained the highest phytosociological parameter values in the NA area. Together, these species represented 65% of the importance value index (IVI), whereas the other species represented 35% collectively, and none of them individually exceeded 8% of the IVI (Table I). Therefore, the results showed a striking predominance of *Hexasepalum teres* and *Digitaria insularis* within the plant community of the ND area.

Hexasepalum teres and *D. insularis* have high reproductive capacities, facilitated dissemination of the propagules, and are highly adapted to the hot and dry climate in the semiarid zone. These characteristics partly explain their predominance. *Hexasepalum teres*, popularly known as "mata-pasto" ("grass-killer"), is a species native to the American continent. It has an annual cycle, is propagated by seeds, and is distributed throughout most of the Brazilian territory, mainly in sandy soils. It is quite aggressive in pastures, hence the name "mata-pasto", but it has also been found in several perennial crop fields (Lorenzi 2008, Flora do Brasil 2018). Varjão et al. (2013) carried out a survey on a preserved Caatinga environment in the semiarid region, and discovered that *H. teres* was also one of the most frequently occurring weeds there. A wide *Hexasepalum teres* distribution was also found by Pereira & Kinoshita (2013) in Mato Grosso do Sul state, Atlantic Forest. This information reveals the adaptive potential of *H. teres*, which can become a problematic weed species in many different environments and climates.

Digitaria insularis, a species commonly known as "capim-amargoso" ("bitter-grass"), is a naturalized herbaceous plant with a perennial cycle that propagates by seeds or vegetatively via short rhizomes (Brighenti 2010). It causes great damage to coffee and citrus crops (Mendonça et al. 2014), and is one of the most problematic weeds in cereal no-tillage fields in southern Brazil. *Digitaria insularis* has several characteristics that enable its aggressiveness, including ease of dispersion by wind due to long bristles on its cariops, and high sprouting capacity that persists after cutting, burning, or herbicide application (Brighenti 2010). Moreover, it produces allelopathic compounds and is a host of the *Puccinia oahuensis* fungus, which causes rust on several plant species (Moreira & Bragança 2011).

Table I. Phytosociological parameters of weed community in a newly deforested area, Petrolina, Pernambuco state, Brazil.

Species	DM	NF	NI	F	D	A	Do	IVI
	- g -			------------------ % ------------------				
Hexasepalum teres (Walter) J. H. Kirkbr	591.36	32	1886	32.65	61.06	20.35	31.54	41.75
Digitaria insularis (L.) Fedde	520.98	22	610	22.45	19.75	9.57	27.78	23.33
Eriope tumidicaulis Harley	152.30	5	304	5.10	9.84	20.99	8.12	7.69
Herissantia crispa L.	155.57	8	24	8.16	0.78	1.04	8.30	5.75
Froelichia humboldtiana (Roem. & Schult.) Seub.	123.43	8	55	8.16	1.78	2.37	6.58	5.51
Chamaecrista nictitans (L.) Moench	120.47	7	65	7.14	2.10	3.21	6.42	5.22
Sida galheirensis Ulbr.	25.12	2	44	2.04	1.42	7.60	1.34	1.60
Sida glaziouvii K. Schum.	34.53	1	3	1.02	0.10	1.04	1.84	0.99
Portulaca grandiflora Hook.	10.15	1	40	1.02	1.29	13.81	0.54	0.95
Digitaria horizontalis Wild.	12.90	1	21	1.02	0.68	7.25	0.69	0.80
Setaria vulpiseta (Lam)	18.17	1	12	1.02	0.39	4.14	0.97	0.79
Stylosanthes viscosa (L.) Sw.	17.22	1	3	1.02	0.10	1.04	0.92	0.68
Portulaca halimoides L.	13.83	1	4	1.02	0.13	1.38	0.74	0.63
Amaranthus viridis L.	11.02	1	6	1.02	0.19	2.07	0.59	0.60
Pavonia cancellata (L.) Cav.	12.18	1	2	1.02	0.06	0.69	0.65	0.58
Walteria spp. *	10.56	1	2	1.02	0.06	0.69	0.56	0.55
Amaranthus deflexus L.	9.97	1	1	1.02	0.03	0.35	0.53	0.53
Cyperus brevifolius (Rottb.) Endl. Ex Hassk.	9.16	1	2	1.02	0.06	0.69	0.49	0.52
Bulbostulis capilaris (L.) C. B. Clarke	9.62	1	1	1.02	0.03	0.35	0.51	0.52
Cyperus rotundus L.	8.23	1	3	1.02	0.10	1.04	0.44	0.52
Macroptilium martii (Benth)	8.35	1	1	1.02	0.03	0.35	0.45	0.50
Total	1812.12	56	3089	100	100	100	100	100

DM: dry matter of shoot; NF: number of frames; NI: number of individuals; F: frequence; D: density; A: abundance; Do: dominance; IVI: importance value index. *unconfirmed species.

The species *Eriope tumidicaulis* Harley (Lamieaceae), *Herissantia crispa* L. (Malvaceae), *Froelichia humboldtiana* (Roem. & Schult.) Seub. (Amaranthaceae), *Chamaecrista nictitans* (L.) Moench (Fabaceae), and *Sida galheirensis* Ulbr. (Fabaceae) can be classified as intermediately important, as these species achieved relative IVI values of between 1 and 8% (Table I). Ind addition, *Eriope tumidicaulis* Harley and *Sida galheirensis* Ulbr. are endemic to Brazil (Flora do Brasil 2018). All abovementioned species are typically found in northeastern Brazil, and are common in the semi-arid region due to their adaptability to local adversities and their ability to form dense populations. They can invade and cause serious problems in annual crops, perennial crops, and pastures. These species have some important characteristics that allow themt to harm crops. For example, *E. tumidicaulis* has the allelopathic ability to inhibit the development of other plants, and *H. crispa* grows in a way that dominates the surrounding vegetation. *Herissantia crispa* L. has also been verified as a host of *Begomovirus* viruses (Assunção et al. 2006). Moreover, *F. humboldtiana* is toxic to and causes primary photosensitization in Equidae species (Pimentel et al. 2007). These characteristics highlight the need to control these plants, even though they are not dominant in the weed community.

Cyperus rotundus was the most predominant species in the AE area, followed by *Herissantia crispa* and *Euphorbia heterophylla*. These species accounted 70% of the total weed community IVI values (Table II). These three species are native to Brazil and could become problematic species in crop fields, as they show a high degree of aggressiveness and are difficult to control.

Cyperus rotundus (Cyperaceae) is a perennial species, and is considered to be the hardest weed to control in the world due to its excellent capacity for propagation, both by seeds and vegetatively (bulbs and rhizomes). It has high photosynthetic efficiency, mechanisms of dormancy, and high allelopathic potential for many crops. In addition, *C. rotundus* is able to adapt to different environments (mainly anthropic environments with intense soil use, which is the case in the AE area), and there are few efficient herbicides that control the species (Oliveira et al. 2010).

The second most important species in the AE area was *H. crispa*, as found in the ND area, with a relative IVI of 22% (Table II). However, the importance value for *H. crispa* was lower in the AE area (5.7%) than in the ND area. This reveals a greater potential for infestation in intensely anthropized environments, due to the sudden environmental changes that occurred before agricultural production.

Euphorbia heterophylla (Euphorbiaceae) was another predominant weed, and is an infestant species with an annual cycle that is very difficult to control. It occurs quite frequently across the whole of Brazil. *Euphorbia heterophylla* has caused issues in agricultural environments, mainly in large grain crop fields, such as those growing transgenic soybeans, due to its tolerance against glyphosate herbicides (Carvalho et al. 2010). It has the ability to form persistent seed banks (Lorenzi 2008), and this feature explains, in part, its capacity for infestation and aggressiveness.

According to the Sorensen coefficient, the similarity between the areas (ND and AE) was 25%, which can be considered low. Only values greater than 25% can be classified as similar environment (Sarmento et al. 2015). *Hexasepalum teres*, *H. crispa*, *C. rotundus*, *Pavonia cancellata* (Malvaceae), *Cyperus brevifolius* (Cyperaceae), and *Amaranthus deflexus* (Amaranthaceae) were common in both areas. Therefore, these species can be inferred to have greater reaching spatial coverage and environmental adaptability, regardless of the level of infestation, since *P. cancellata*, *C. brevifolius,* and *A deflexus* did not achieve significant IVI values (Tables I and II). The low similarity between the areas is probably due to the large differences in management and soil since, according to Carvalho & Pitelli (1992), similarity is usually related to the distance between the studied areas, soil characteristics, and management practices. The presence of a few common species can be explained by the distance between the areas, which was approximately 1700 m, making their propagation and dispersion possible.

The phytosociological study allowed the herbaceous species with the highest degree of infestation and that therefore dominated the non-occupied space in each area due to its morphophysiological characteristics to be identified. On the other hand, the spatial distribution, as well as the plant vigor of these weed populations, are affected by environmental variables, mainly edaphic factors, which define the degree of interference in the environment and influence the amount of damage to agricultural production.

Table II. Phytosociological parameters of weed community in agricultural experimental area, Petrolina county, Pernambuco state, Brazil.

SPECIES	DM	NF	NI	F	D	A	Do	IVI
	- g -			----------------------- % -----------------------				
Cyperus rotundus L.	325.00	7	3387	8.86	64.47	52.87	13.60	28.98
Herissantia crispa (L.) Brizicky	873.51	22	89	27.85	1.69	0.44	36.55	22.03
Euphorbia heterophylla L.	370.60	9	1386	11.39	26.38	16.83	15.51	17.76
Kallstroemia tribuloides (Mart.) Steud.	157.01	5	53	6.33	1.01	1.16	6.57	4.64
Setaria parviflora (Poir.) Kerguélen	192.10	3	5	3.80	0.10	0.18	8.04	3.98
Macroptilium atropurpureum (Sessé & Moc. Ex DC.) Urb.	63.66	3	16	3.80	0.30	0.58	2.66	2.26
Waltheria rotundifolia Schrank	58.40	3	4	3.80	0.08	0.15	2.44	2.11
Boerhavia difusa L.	39.22	3	19	3.80	0.36	0.69	1.64	1.93
Euphorbia hirta L.	04.10	3	42	3.80	0.80	1.53	0.17	1.59
Tridax procumbens L.	43.40	2	13	2.53	0.25	0.71	1.82	1.53
Pavonia cancellata (L.) Cav.	31.13	2	12	2.53	0.23	0.66	1.30	1.35
Chloris barbata Sw.	32.48	2	5	2.53	0.10	0.27	1.36	1.33
Cyperus brevifolius (Rottb.) Endl. Ex Hassk.	19.90	1	80	1.27	1.52	8.74	0.83	1.21
Trianthema portulacastrum L.	13.80	1	90	1.27	1.71	9.83	0.58	1.19
Conyza bonariensis (L.) Cronquist.	13.70	2	8	2.53	0.15	0.44	0.57	1.09
Cenchrus echinatus L.	35.20	1	12	1.27	0.23	1.31	1.47	0.99
Sidastrum micranthum (A.St.-Hil.) Fryxell	35.60	1	1	1.27	0.02	0.11	1.49	0.92
Hexasepalum teres (W.) J.H. Kirkbr.	17.10	1	3	1.27	0.06	0.33	0.72	0.68
Turnera subulata Sm.	14.10	1	3	1.27	0.06	0.33	0.59	0.64
Waltheria viscosíssima A. St.-Hil.	11.65	1	2	1.27	0.04	0.22	0.49	0.60
Mollugo verticilatta L.	11.20	1	2	1.27	0.04	0.22	0.47	0.59
Acanthospermum hispidum DC.	6.89	1	8	1.27	0.15	0.87	0.29	0.57
Heliotropium indicum L.	9.46	1	2	1.27	0.04	0.22	0.40	0.57
Amaranthus deflexus L.	3.55	1	8	1.27	0.15	0.87	0.15	0.52
Porophyllum ruderale (Jacq.) Cass.	4.70	1	2	1.27	0.04	0.22	0.20	0.50
Euphorbia hyssopifolia L.	2.20	1	2	1.27	0.04	0.22	0.09	0.47
Total	2390	51	5224	100	100	100	100	100

DM: dry matter of shoot; NF: number of frames; NI: number of individuals; F: frequency; D: density; A: abundance; Do: dominance; IVI: importance value index.

Thus, the negative correlation between *H. teres* biomass and K^+ content in the ND area (Table III) could be verified using a Pearson correlation matrix. Similarly, the number of individuals and biomass of the species *C. rotundus* and *E. heterophylla* were also negatively correlated with K^+ content in the AE area (Table III). Studying an agricultural field in Greece, Kalivas et al. (2012) observed a negative correlation between K^+ content and density and uniformity *C. rotundus*. values The same study also reported that the number of *C. rotundus* individuals and *C. rotundus* biomass were also negatively correlated with sand content, while there was a positive correlation between the number of *H. crispa*

Table III. Pearson correlation between weed plant variables and soil attributes in both newly deforested area and agricultural experimentation area in the semiarid region of Brazil.

Variables	r-value	p-value
	Newly deforested area	
Biomass (DIQTE) x K^+ content	- 0.291	0.029
	Agricultural experimentation area	
Number of Individuals (CYPRO) x sand content	- 0.276	0.050
Biomass (CYPRO) x sand content	- 0.373	0.007
Number of Individuals (ABUCR) x sand content	0.318	0.023
Number of Individuals (EPHHL)x Na^+ content	0.365	0.008
Biomass (EPHHL) x Na^+ content	0.389	0.005
Number of Individuals (CYPRO) x K^+ content	- 0.432	0.002
Biomass (CYPRO) x K^+ content	- 0.410	0.003
Number of Individuals (EPHHL) x K^+ content	- 0.470	0.001
Biomass (EPHHL) x K^+ content	- 0.439	0.001
Number of Individuals (ABUCR) x Al^{3+} content	0.383	0.005

CYPRO = ***Cyperus rotundus*****; ABUCR =** ***Herissantia crispa*****; EPHHL =** ***Euphorbia heterophylla*****; DIQTE =** ***Hexasepalum teres*****.**

individuals and sand content. The number of *E. heterophylla* individuals and *E. heterophylla* biomass were positively correlated with Na^+ content, and a positive correlation was also observed between the number of *H. crispa* individuals and Al^{+3} content (Table III).

In the ND area, only *H. teres* showed spatial dependence for the biomass data (Table IV), and an exponential model was fitted. Since Pearson's analysis (Table III) indicated a negative correlation between *H. teres* biomass and the K^+ content, spatial analysis of this nutrient was performed. This analysis verified that K^+ content showed spatial dependence, and an exponential model was also fitted (Table IV).

Based on a visual analysis of the maps (Figure 3), it was found that, in general, the regions with the largest *H. teres* biomasses had the lowest K^+ values, as indicated by the correlation results (Table III). However, it was not possible to fit a cross-semivariogram between these two variables, since cross-semivariograms that present the series of points in more than one quadrant are considered an indefinite spatial correlation (Camargo et al. 2008).

In the AE area, spatial dependence was observed for the numbers of individuals and for the biomass of the three predominant species (Table IV). The models fitted to the semivariograms of all species (number of individuals and biomass) were spherical, except for the number of *H. crispa* individuals and biomass of *E. heterophylla*, for which exponential models were fitted. A similar result was observed by Kalivas et al. (2012) in a cotton field in Greece, where the density data of *C. rotundus* were fitted to a spherical model. Chiba et al. (2010) also verified that the models that fitted their weed data were spherical and exponential in a no-tillage field in São Paulo state, Brazil.

Based on the degree of spatial dependence classification suggested by Cambardella et al. (1994), the biomasses of *C. rotundus*, *H. crispa,* and *E. heterophylla*, and the number of *E. heterophylla* individuals, showed strong spatial dependence ($[C_o / C + C_o] \times 100 < 25\%$), whereas the other variables showed moderate spatial dependence. Kalivas et al. (2012) also reported moderate spatial dependence for weed variables. This index can be an indication of map quality since the greater the degree of

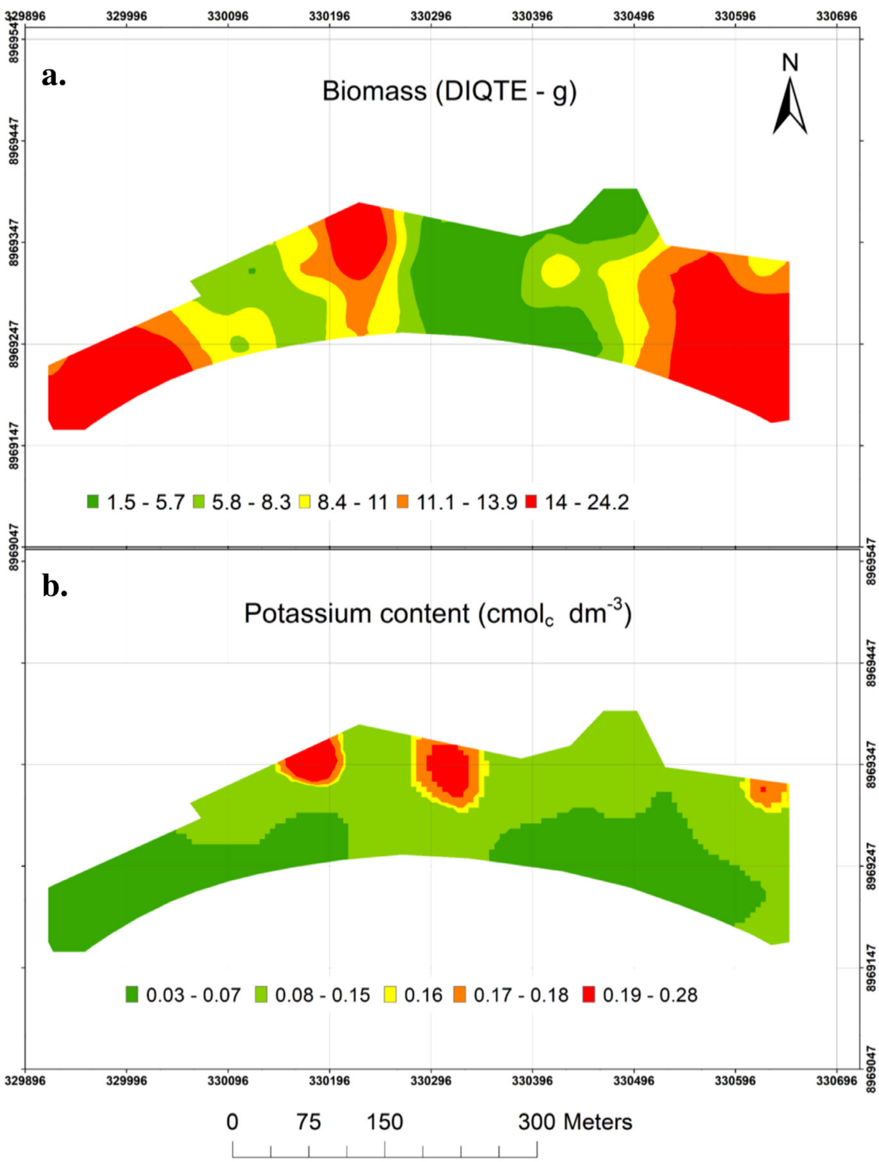

Figure 3. Biomass maps of *Hexasepalum teres* (a) and soil potassium content (b) in a newly deforested area in the semiarid region of Brazil.

spatial dependence, the lower the nugget effect (error) and, consequently, the smaller the error in estimating the maps interpolated using the Kriging method.

Based on the correlation analysis (Table III), spatial analyses of K^+, Na^+, Al^{3+}, and sand were performed. Spherical models were fitted for K^+ and sand content, as they were classified as strong spatial dependence. No spatial dependence was observed for the Na^+ and Al^{3+} variables.

The maps of the number of individuals and plant biomasses indicate that the largest infestations of *C. rotundus* and *E. heterophylla* are present in the upper region of the area (Figures 4a, b, e and f), whereas *H. crispa* is concentrated in the lower region of the area and in a small part of the upper right region (Figures 4c and d).

Although visual comparisons between the maps are important in understanding how abiotic factors (soil attributes) determine the spatial distribution of weeds in the AE area, analyzing the cross-semivariograms allows confirmation of these relationships, and also quantifies the spatial

Table IV. Variogram model parameters of weed plant and soil attributes in both newly deforested area and agricultural experiment area in the semiarid region of Brazil.

Variable	Model	C_o	Sill (C_o+C)	Range (m)	$[C_o/C+C_o]$x100
	Newly deforested area				
Biomass (DIQTE)	Exp.	63.9	127.9	218	50
K^+ content	Exp.	0.00075	0.00428	162	18
	Agricultural experimentation area				
Individuals (CYPRO)	Sph.	15900	42440	138	38
Biomass (CYPRO)	Sph.	54.11	350	125	16
Individuals (ABUCR)	Exp.	3.2101	8.5816	276	37
Biomass (ABUCR)	Sph.	45.44	759.70	140	6
Individuals (EPHHL)	Sph.	1410	5743	144	25
Biomass (EPHHL)	Exp.	115	546.4	230	21
K^+ content	Sph.	0.0019	0.0093	134	20
Sand content*	Sph.	29	885.7	131	3

DIQTE = *Hexasepalum teres*; CYPRO = *Cyperus rotundus*; ABUCR = *Herissantia crispa*; EPHHL = *Euphorbia heterophylla*; C_o = Nugget Effect; Exp. = Exponential model; Sph.= Spherical model; *semivariogram fitted using the residuals from the trend surface.

correlation through range values. All visual similarities observed between the plant variable (number of individuals and biomass) maps and the soil attribute (K^+ and sand content) maps were confirmed by the cross-semivariogram analysis (Figure 5).

Observing the range values of the cross-semivariograms (Figure 5), the strongest negative spatial correlation between plant variables (number of individuals and biomass) and soil variables was found for sand content, which varied from 318 to 441 m. Similar results were obtained by Kalivas et al. (2012), which found that the greatest negative spatial correlation was between weed density and soil sand content. Also, Metcalfe et al. (2016) reported a positive spatial correlation between the number of *Alopecurus myosuroidese* individuals and soil clay content. In agreement with Kalivas et al. (2012), this can be explained due to low water retention in sandy soils. This factor is very important in semi-arid regions, since rainfall is scarce and soils with higher water retention are fundamental for plant establishment and development. This hypothesis can be strengthened when taking into account the results of Schaffrath et al. (2015), which found a positive special correlation between weed biomass and soil microporosity in an agricultural field in Paraná state under a conventional soil management system using a cross-semivariogram. This is because soils with higher microporosity generally have higher clay content and, consequently, higher water retention.

A strong negative spatial correlation was also observed between K^+ and *C. rotundus* and *E. heterophylla*, with values ranging from 164 to 266 m. K^+ is an essential plant nutrient and makes up around 1% of the dry matter of plants. This element is the cofactor in more than 40 enzymes and is the main cation involved in turgor and cellular electroneutrality, making it a fundamental element in osmotic regulation and membrane permeability (Taiz et al. 2017).

The negative correlation between K^+ content and *H. teres* in the ND area, and between K^+ content and *C. rotundus* and *E. heterophyllana* in the AE, is unlikely to be directly related to the nutrient, since it is also fundamental for these weeds. Instead, these negative correlations are probably

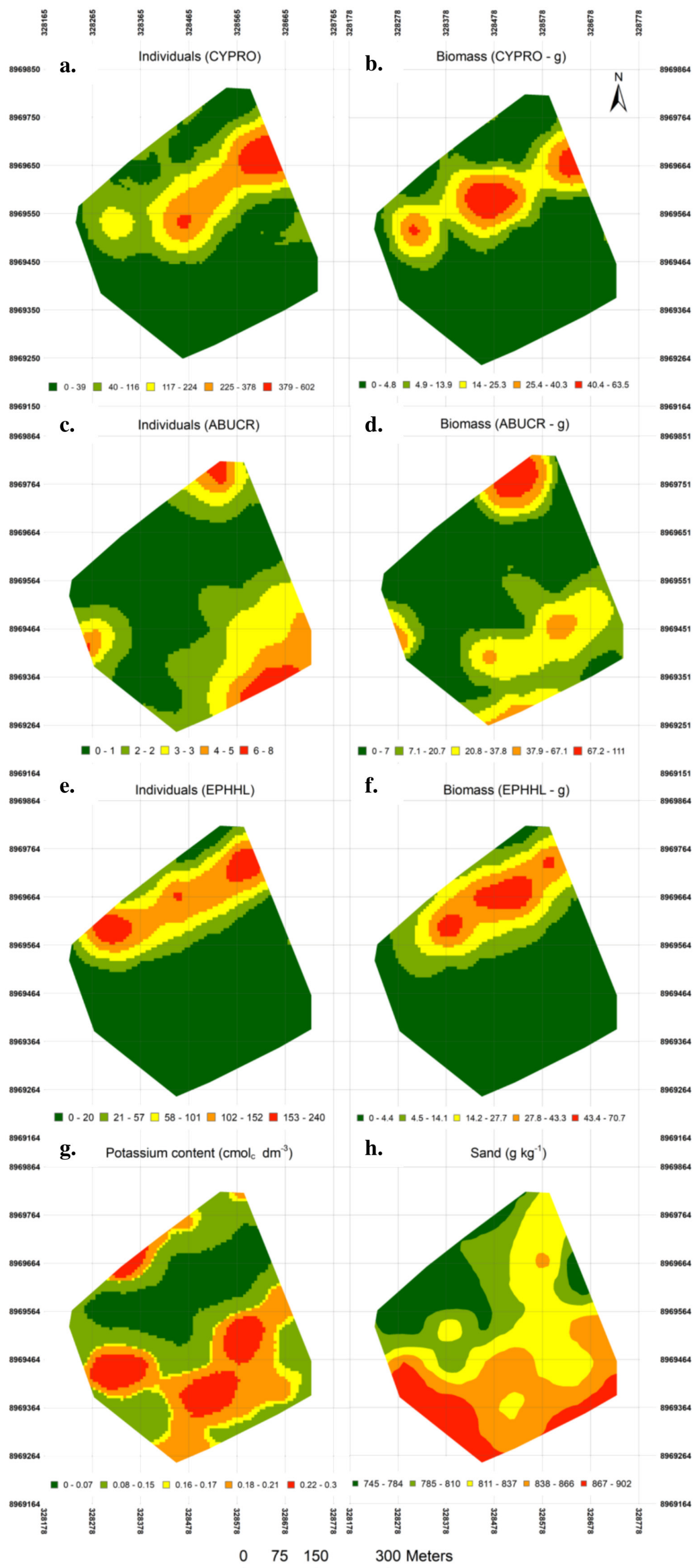

Figure 4. Individual numbers and biomass maps of *Cyperus rotundus* (CYPRO) (a, b), *Herissantia crispa* (ABUCR) (c, d), and *Euphorbia heterophylla* (EPHHL) (e, f), and soil potassium (g) and sand content (h) in an agricultural experimentation area in the semiarid region of Brazil.

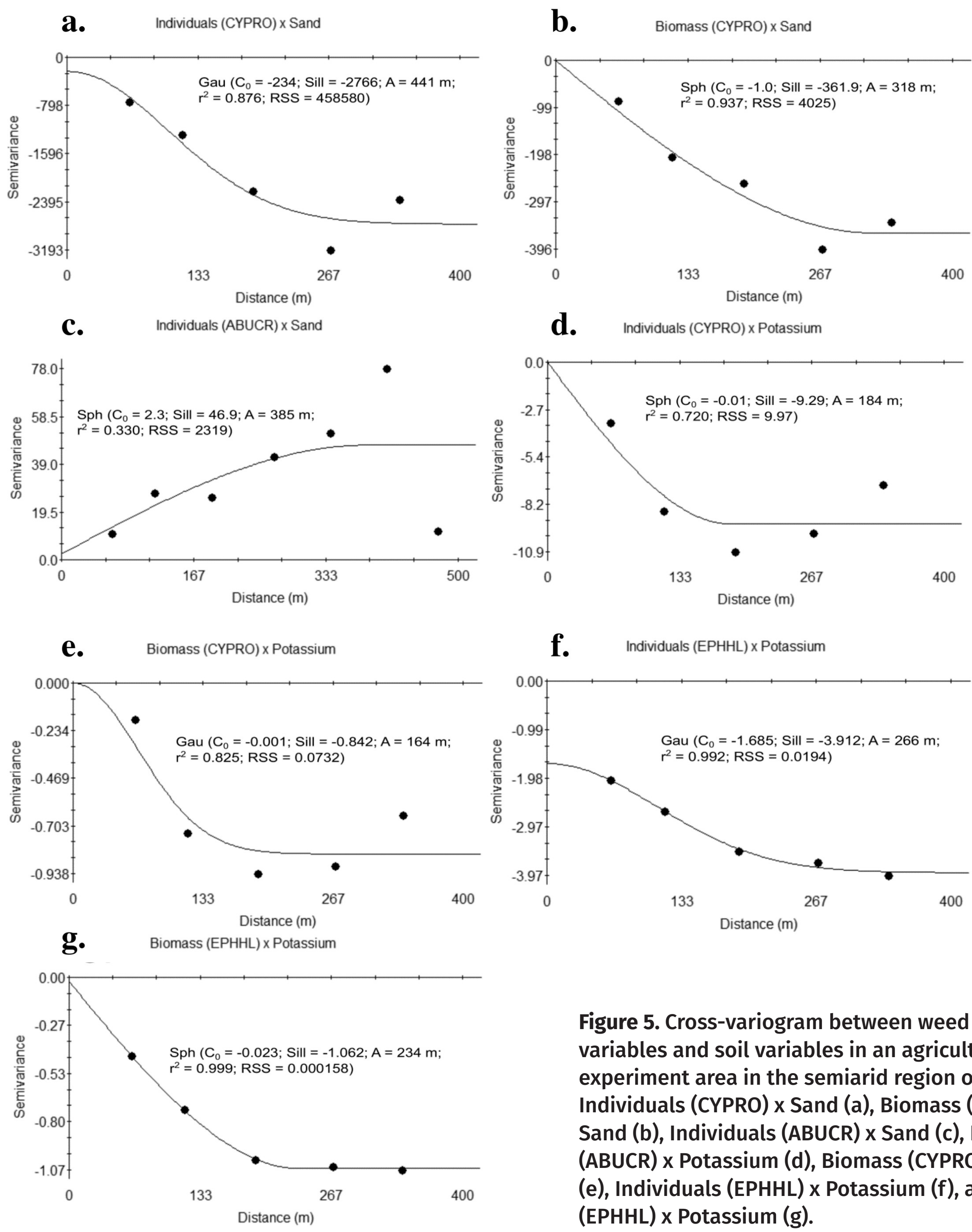

Figure 5. Cross-variogram between weed plant variables and soil variables in an agricultural experiment area in the semiarid region of Brazil. Individuals (CYPRO) x Sand (a), Biomass (CYPRO) x Sand (b), Individuals (ABUCR) x Sand (c), Individuals (ABUCR) x Potassium (d), Biomass (CYPRO) x Potassium (e), Individuals (EPHHL) x Potassium (f), and Biomass (EPHHL) x Potassium (g).

caused by the fact that K^+ availability in the regions where these species dominate is classified as very low (0.0 - 0.07 $cmol_c\ dm^{-3}$) to low (0.08-0.15 $cmol_c\ dm^{-3}$) according to the Raij et al. (1997) availability classification for crops in Brazil (green colors in figures 3B and 4G). Thus, in regions with low K^+ availability, cultivated plants may be deficient and become more susceptible to competition, causing weeds to infest the region with greater aggression. This result agrees with Tilman's classic theory of competition between plants, which suggests that competing plants require fewer resources for their complete development, allowing them to survive in unfavorable environments (Agostinetto et al. 2008). Therefore, fertilization management in crop fields in the semi-arid zone is essential when aiming to control weeds. In particular, K fertilization should occur to promote adequate levels of this nutrient for the crops.

The results of this study confirm the hypothesis that weed distribution is dependent to soil attributes, both in areas with consolidated agricultural activity (AE) and in areas in the initial stages of land use (ND). Therefore, the information obtained in this work enhances our understanding of the dynamics of weed infestation, contributing to the adoption of more efficient and sustainable control strategies.

CONCLUSIONS

Spatial dependence was only found in the predominant species, which were *Hexasepalum teres, Cyperus rotundus*, *Herissantia crispa,* and *Euphorbia heterophylla*. The spatial distribution of these weeds was conditioned by K^+ content in both areas (newly deforested and agricultural experimentation area), and by sand content in the agricultural experimentation area only.

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