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Multiscale properties of weeds in no-till system

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Abstract: Background: Weeds have high spatial variability and show clustering behavior, with heterogeneity in scales that can be evaluated through multifractal analysis.

Objective: The objective of this study was to evaluate the spatial variability of weeds using multifractal analysis in a no-till area.

Methods: Sampling was conducted at 1,015 sampling points in an experimental plot with a regular grid of 5 × 5 m (2.38 ha) with no tillage. The area was cultivated with triticale (*Triticum secale*), and in the summer of 2011, the area was cultivated with soybean (*Glycine max*). Data were analyzed using descriptive statistics and multifractal analysis using the box-counting method to determine the scaling properties of the variables.

Results: The predominance of *Raphanus raphanistrum* was identified in the winter crop and *Commelina* ssp. during the summer. The singularity spectrum showed greater asymmetry for *Raphanus raphanistrum* and *Commelina* ssp. in relation to the category of other weeds (OW). The degree of multifractality varied throughout the study period, showing the ecological patterns of the studied species. Scale heterogeneity was revealed, with different degrees of multifractality that evidenced the processes of dispersion and colonization of the environment by the different weed species evaluated.

Conclusions: The species *Raphanus raphanistrum* and *Commelina* ssp. showed domains of low measurement values, and OW was the most heterogeneous.

Keywords: Spontaneous Plants; Multifractality; Generalized Dimension; Singularity Spectrum; Spatial Variability

1. Introduction

Weeds compete with agricultural crops for water and nutrients (Booth et al., 2003; Brighenti, Oliveira, 2011; Yamauti et al., 2011), and have high spatial (Schaffrath et al., 2007; Jurado-Expósito et al., 2021) and temporal variability (Chiba et al., 2010; Izquierdo et al., 2020).

In the field, weeds have dispersal and reproduction characteristics that result in zones with greater or lesser concentrations, and are often shown assembling in groups (Schaffrath et al., 2007; Chiba et al., 2010; Brighenti, Oliveira, 2011; Siqueira et al., 2016; Izquierdo et al., 2020; Jurado-Expósito et al., 2021). Therefore, understanding the scale of weed variability in the field allows for localized management, minimized production costs, and sustainable development.

Spatial variability can be assessed using different methodologies, including geostatistical and multifractal analyses. In geostatistical analysis, data are modeled to ascertain the spatial dependence between samples (Vieira, 2000), whereas multifractal analysis evaluates data to understand the complexity and variability in different observation scales (Evertsz, Mandelbrot, 1992).

Multifractal analysis has been used to characterize spatial variability and describe irregularities and structures with a variety of scales (Vidal-Vázquez et al., 2013). According to Kohmoto (1988) and Posadas et al. (2009), multifractal analysis estimates the scaling properties of a set or system using a probability distribution to quantify the uniqueness or irregularity of that system. When the irregularity is equal on all scales, at least statistically, a multifractal system exists (Evertsz, Mandelbrot, 1992). The structure of fractal objects or sets is characterized by an infinite number of dimensions (Hentschel, Procaccia, 1983), which allows for the description of the singularity spectrum (Chhabra, Jensen, 1989). Thus, multifractal analysis describes the structure of a system/object, since the methodology quantifies the spatial distribution of values on the scales (Leiva et al., 2019; Silva, Siqueira, 2020; Siqueira et al., 2022), thereby favoring the understanding of the heterogeneity of the data (Banerjee et al., 2011), which is not characterized by other methods.

The use of multifractal analysis to understand the spatial variability of weeds is still poorly understood; however, this technique has previously been used to determine the variability of soil and plant scales. Vidal-Vázquez et al. (2013), Dafonte et al. (2015), and Siqueira et al. (2018) analyzed the scale patterns and heterogeneity of soil chemical attributes. Posadas et al. (2009) characterized the flow of water in soils through multifractality, while Leiva et al. (2019) determined the multifractality of vertical profiles

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of soil resistance to penetration in different relief units. Silva and Siqueira (2020) and Siqueira et al. (2022) determined the multifractality of invertebrate soil fauna.

Thus, the hypothesis of this study is that weeds have spatial variability in multiple scales and present heterogeneity in scales that are not described by classical methods of spatial analysis. Thus, the objective of this study was to evaluate the spatial variability of weeds using multifractal analysis in a no-till area in Campinas, São Paulo, Brazil.

2. Material and Methods

2.1 Description of the experimental area

The study area was 2.38 ha (140 × 170 m; Figure 1a), and carried out in the Campinas, São Paulo, Brazil (22°53´ S and 47°04´ W, and altitude average of 600 m), with soil classified as dystrophic red latosol (Santos et al., 2018). The region's climate transitions between Cwa (temperate humid climate with dry winters and hot summers) and Cfa (subtropical climate), and the average temperature of the warmest month is greater than or equal to 22° C and the coldest month is less than 18° C. The annual precipitation is 1,462 mm.

Since 1985, the study area was managed by direct seeding with cover crops in the winter and grain in the summer between October and November, and the harvest occurred between February and March. Chemical management for weed control was performed with the application of 1.5 L ha^{-1} of 2.4D + 1 L ha^{-1} of glyphosate in the period prior to the cultivation of winter and summer crops.

2.2 Sampling

In the study area, 1,015 sampling points were demarcated in a regular grid of 5 × 5 m (Figure 1a) for weed sampling on the following dates: 07/16/2010, 08/19/2010, 10/22/2010, 01/26/2011, and 02/17/2011. At the time of sampling, the study area was cultivated with triticale (*Triticum secale* Wittmack) as a winter crop and soybean [*Glycine max* (L.) Merrill] as a summer crop. Weed sampling was performed by casting a circle with a diameter of 1.126 m (1 m^2) randomly and counting and identifying the number of weeds present at each sampling point. Weeds were identified following the procedures described by Lorenzi (2014), and a predominance of *Raphanus raphanistrum* (L.) in winter and *Commelina* ssp. (L.) in summer was observed, as well as other weeds (OW) that showed lower expression levels, including: *Bidens pilosa* L., *Amaranthus deflexus* L., *Ipomoea grandifolia* (Dammer) O'Donell, *Acanthospermum australe* (Loerfl.) Kuntze, *Digitaria insularis* (L.) Fedde, *Euphorbia heterophylla* L. and *Parthenium hysterophorus* L.

2.3 Descriptive statistics and multifractal analysis

Data were analyzed using descriptive statistics to determine mean ($\bar{x}$), variance, standard deviation, coefficient of variation (%), asymmetry, kurtosis, and D (maximum deviation from the normal distribution using the Kolmogorov–Smirnov test, with an error probability of 0.01). The coefficient of variation (CV) was classified according to Warrick and Nielsen (1980) as low (CV < 12%), medium (12% < CV < 60%), or high (CV > 60%).

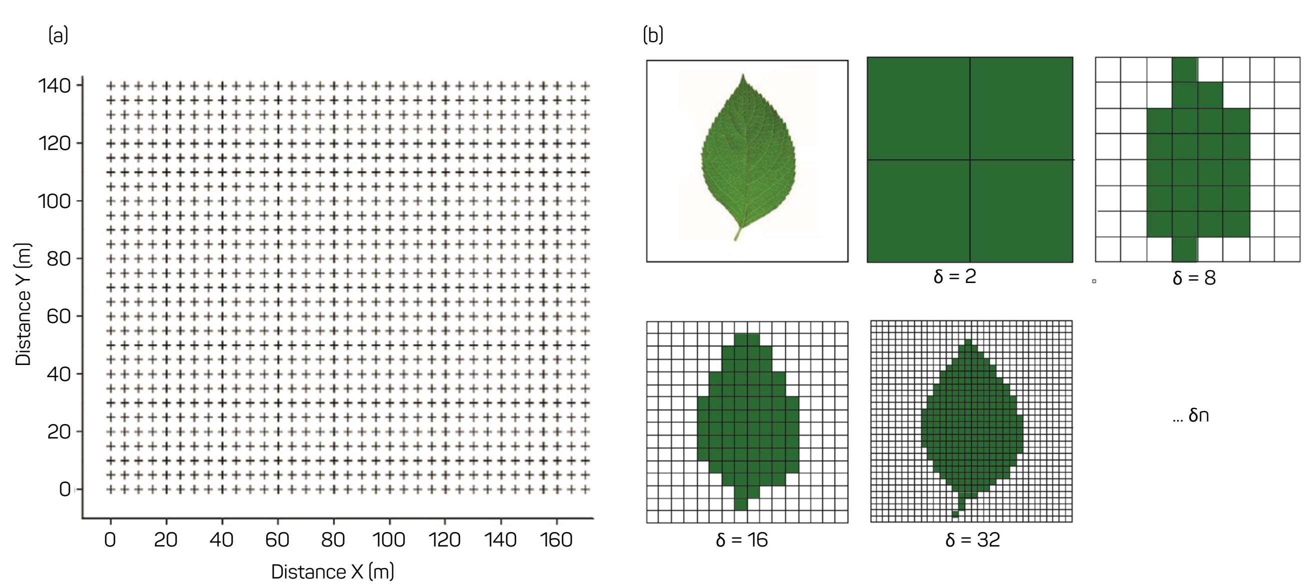

Figure 1 - (a) Sampling scheme (5 x 5 m) of weeds in Campinas, (SP, Brazil), (b) Description of the box counting method for successive segments

The multifractal analysis was performed using the software NASS - Non-linear Analysis Scaling System (Posadas and Ferraz, 2019), using the box counting method, which allows for pattern analysis of a geometric support, which is divided into successive segments. Figure 1b illustrates the procedures for segmenting the geometric support (δ), and allowing the description of the number of boxes for each interval (N = 2, 3, 4, 5, 6, 7, ...). Thus, the method considers an infinite number of successive segments for the geometric support (n→∞: Evertsz, Mandelbrot, 1992). Therefore, it is possible to estimate the scaling properties of a fractal set or system to determine the contents of the boxes using a probability distribution, which quantifies the contents and then describes the singularity (α) (Kohmoto, 1988). The probability (P) of heterogeneous systems (Equation 1) is then used to estimate the scale properties for a set of spatial data (Posadas et al., 2009).

$$P_i(\varepsilon) \sim \varepsilon^{\alpha_i} \tag{1}$$

where α_i is the Lipschitz-Hölder exponent, also known as the singularity force that can vary in the interval ($\alpha_{-\infty}$, $\alpha_{+\infty}$), and ε is the scale. Multifractal sets are characterized on the basis of the generalized dimensions (D) of the point of order q in a D_q distribution (Hentschel, Procaccia, 1983), defined by Equation 2:

$$D_q = \lim_{\varepsilon \to 0} \left(\frac{1}{q-1} \frac{\log \mu(q,\varepsilon)}{\log(\varepsilon)} \right) \tag{2}$$

where μ(q,ε) corresponds to the partition function defined by Equation 3, and by replacing q with 0, 1, and 2 in Equation 2, we obtain the capacity dimension (D_0, Equation 4), information dimension (D_1, Equation 5), and correlation dimension (D_2, Equation 6), respectively.

$$\mu(q,\varepsilon) = \sum_{i=1}^{N(\varepsilon)} P_i^q(\varepsilon) \tag{3}$$

$$D_0 = \lim_{\varepsilon \to 0} \frac{\log(N(\varepsilon))}{\log(\varepsilon)} \tag{4}$$

$$D_1 = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N(\varepsilon)} \mu_i(\varepsilon) \log(\mu_i(\varepsilon))}{\log(\varepsilon)} \tag{5}$$

$$D_2 = \lim_{\varepsilon \to 0} \frac{\log(C(\varepsilon))}{\log(\varepsilon)} \tag{6}$$

In multifractal systems, the spectra of dimensions or singularity spectra (q) are defined by Equations 7 and 8 (Chhabra, Jensen, 1989).

$$f(q) = \lim_{\varepsilon \to \infty} \frac{1}{\log(\varepsilon)} \sum_{i=1}^{N(\varepsilon)} \mu_i(q,\varepsilon) \log[\mu_i(q,\varepsilon)] \tag{7}$$

$$\alpha(q) = \lim_{\varepsilon \to \infty} \frac{1}{\log(\varepsilon)} \sum_{i=1}^{N(\varepsilon)} \mu_i(q,\varepsilon) \log[P_i(q,\varepsilon)] \tag{8}$$

Asymmetry (AI) and degree of multifractality (Δ) of the data were determined according to Halsey et al. (1986), considering the values of α and D_q (equation 9 and 10).

$$AI = \frac{\alpha_0 - \alpha_3}{\alpha_{-5} - \alpha_0} \tag{9}$$

$$\Delta = D_{-\infty} - D_{+\infty} \tag{10}$$

AI is the asymmetry of the system, α_0 is the value of f(α) in the range 0, α_3 is the value of f(α) in the interval q = 3, α_{-5} is the value of f(α) in the interval q = -5; and D is the generalized dimension at points q = 3 and q = -5.

3. Results and Discussion

3.1 Statistical analysis

The weeds with the highest density in the study area (Table 1) were *R. raphanistrum* on 10/22/2010 ($\bar{x}$ = 8.85 plants per m^2) and *Commelina* ssp. on 01/26/2011 ($\bar{x}$ = 9.31 plants per m^2). Schappert et al. (2018) described an abundance of *R. raphanistrum* of 3.0 plants per m^2 in their study of weeds, whereas Castro et al. (2021) discovered

Table 1 - Descriptive statistics for the number of weeds in the years 2010 and 2011

Sampling	Weeds	$\bar{x}$	Variance	SD	CV (%)	Skew	Kurtosis	D
07/16/2010	*R. raphanistrum*	7.91	40.14	6.34	80	1.78	4.37	0.10 Ln
	OW	3.79	32.56	5.71	151	5.13	32.21	0.11 Ln
08/19/2010	*R. raphanistrum*	5.84	51.68	7.19	123	3.77	18.18	0.10 Ln
	OW	2.38	4.38	2.09	88	2.31	5.68	0.21 Ln
10/22/2010	*R. raphanistrum*	8.85	105.27	10.26	116	4.05	26.38	0.10 Ln
	OW	41.96	2473.34	49.73	119	3.08	13.97	0.09 Ln
01/26/2011	*Commelina ssp.*	9.31	96.47	9.82	105	2.93	12.28	0.10 Ln
	OW	4.63	111.99	10.58	229	8.03	74.05	0.16 Ln
02/17/2011	*Commelina ssp.*	6.90	37.33	6.11	89	1.95	5.27	0.10 Ln
	OW	4.01	35.25	5.94	148	3.05	9.36	0.15 Ln

R. raphanistrum - *Raphanus raphanistrum* L.; *Commelina ssp.* - *Commelina ssp.* L.; OW – Other weeds; $\bar{x}$ - mean; SD - Standard deviation; CV - Coefficient of variation (%); D - Kolmogorov-Smirnov test of normality (p < 0.01).

that for weeds in agricultural production areas of southern Brazil, *Commelina benghalensis* had an average density of 15.2 plants per m^2 in a no-tillage system.

In the present study, OW were identified with lower occurrence winter and summer crops: *B. pilosa, A. deflexus, I. grandifolia, A. australe, D. insularis, E. heterophylla*, and *P. hysterophorus* distributed in the area in clusters and with regular occurrence, with the smallest number of OW described on 08/19/2010 and the largest on 10/22/2010. According to Booth et al. (2003) and Brighenti and Oliveira (2011), weeds have a high capacity for reproducing viable seeds and special adaptations for dissemination, which justifies their occurrence in clusters, as described by Schaffrath et al. (2007), Chiba et al. (2010), and Jurado-Expósito et al. (2021). Weeds are also associated with the cropping system adopted in the field (Izquierdo et al., 2020).

The lowest and highest coefficients of variation (%, Table 1) were described for *R. raphanistrum* on 07/16/2010 (CV = 80%) and 08/19/2010 (CV = 123%), respectively. The highest CV value (%) for OW was reported on 01/26/2011 (CV = 229%), and the lowest was found for the data from 08/19/2010 (CV = 88%). According to the classification by Warrick and Nielsen (1980), the CV percentages in this study were classified as high (CV > 60%). Chiba et al. (2010) reported that high CV values for weeds reveal that their distribution in the field is heterogeneous. Thus, the occurrence of a lognormal frequency distribution (Ln) for the data was expected, as verified by the Kolmogorov-Smirnov test (D – Table 1) and the asymmetry and kurtosis values.

3.2 Multifractal analysis

The multifractality of the weed data in the study period was determined considering points of order q (-5 < q < 3), evaluated on a scale of 0.1, and the multifractal parameters are shown in Table 2. In monofractal systems, the dimensions are equal ($D_0 = D_1 = D_2$) (Dafonte et al., 2015); however, for multifractal systems the dimensions must follow the relationship $D_0 > D_1 > D_2$ (Chhabra, Jensen, 1989; Banerjee et al., 2011; Vidal-Vázquez et al., 2013; Siqueira et al., 2018; Leiva et al., 2019; Silva, Siqueira, 2020); therefore, data on weed species (*R. raphanistrum, Commelina* ssp. and OW) follow the relationship $D_0 > D_1 > D_2$ (Table 2), indicating a multifractal behavior.

The lowest and highest values of D_0 (Table 2) were described for OW on 10/22/2010 (D_0 = 1.972) and 08/19/2010 (D_0 = 1.677). The capacity dimension (D_0) describes a global view of the system (Leiva et al., 2019; Siqueira et al., 2022), allowing us to verify how the scales are filled by the measurement values. Variations in D_0 values for *R. raphanistrum, Commelina* ssp., and OW on the sampling dates showed that the scales were filled with measurement values, indicating that the difference in D_0 values for the species under study reflects their ecology (Booth et al., 2003; Brighenti, Oliveira, 2011), mainly with regard to the aggregated distribution (Cheam, Code, 1995; Schaffrath et al., 2007; Chiba et al., 2010; Siqueira et al., 2016; Pereira et al., 2018; Izquierdo et al., 2020; Sousa et al., 2020; Jurado-Expósito et al., 2021). The D_1 dimension is related to the entropy information and quantifies the degree of disorder in the system. Thus, D_1 values close to 2 indicate systems with uniform distribution (Posadas et al., 2009), while D_1 values close to 1 represent subsets, with irregularities in the distribution of measurement values (Posadas et al., 2009; Leiva et al., 2019; Silva, Siqueira, 2020; Siqueira et al., 2022). Here, the values of D_1 varied between 1.866 and 1.666 (Table 2), indicating a tendency toward uniformity in the distribution of the scales in the study area. The D_2 dimension calculates the correlation of the measurements contained in a box of size ε (Hentschel, Procaccia, 1983); thus, it is possible to state that for each of the evaluated dates, there was a correlation in the spatial distribution of the measurements.

The highest values of the Hölder exponent (α_0) were identified for OW on 10/22/2010 (2.131), *R. raphanistrum*

Table 2 - Multifractal parameters for weeds identified in the study area

Sampling	Weeds	q_-	q_+	α_{-5}	α_3	α_0	AI	Δ	D_0	D_1	D_2
07/16/2010	*R. raphanistrum*	-5	3	2.297	1.726	2.019	1.050	0.383	1.944	1.866	1.806
	OW	-5	3	2.320	1.658	1.935	0.715	0.497	1.801	1.708	1.676
08/19/2010	*R. raphanistrum*	-5	3	2.369	1.673	2.029	1.049	0.507	1.896	1.774	1.716
	OW	-5	3	1.936	1.650	1.689	0.155	0.151	1.677	1.666	1.656
10/22/2010	*R. raphanistrum*	-5	3	2.402	1.676	2.089	1.321	0.535	1.941	1.797	1.727
	OW	-5	3	2.493	1.724	2.131	1.122	0.576	1.972	1.831	1.770
01/26/2011	*Commelina ssp.*	-5	3	2.338	1.710	2.039	1.097	0.434	1.947	1.851	1.783
	OW	-5	3	2.026	1.687	1.774	0.342	0.219	1.739	1.711	1.696
02/17/2011	*Commelina ssp.*	-5	3	2.278	1.716	2.010	1.095	0.394	1.923	1.837	1.779
	OW	-5	3	2.158	1.690	1.806	0.328	0.318	1.748	1.709	1.695

R. raphanistrum - *Raphanus raphanistrum* L.; *Commelina ssp.* - *Commelina ssp.* L.; OW - Other weeds; α_{-5}, α_3, α_0, are the spectra of singularities for the moments q = -5, q = 3 and q = 0; AI - Asymmetry; Δ - degree of multifractality; D_0 – Capacity dimension; D_1 – Information dimension; D_2 – Correlation dimension.

on 10/22/2010 (2.089), and *Commelina* ssp. on 01/26/2011 (2.131). The Hölder exponent (α_0) characterizes the multifractal scale of the system (Silva, Siqueira, 2020); therefore, there is an increasing trend over the period studied for *R. raphanistrum* and *Commelina* ssp. However, for the OW, the pattern was not repeated, with the lowest value described for OW on 08/19/2020 (α_0 = 1.650) and the highest for 10/22/2020 (α_0 = 2.131).

The lowest and highest asymmetry values (AI, Table 2) were described for OW on 08/19/2010 (AI = 0.155) and *R. raphanistrum* on 10/22/2010 (AI = 1.321), respectively. Asymmetry (AI) is an indicator of the heterogeneity of the system (Silva, Siqueira, 2020), which can assume positive or negative values. Positive asymmetry indicates an association in scales related to low measurement values, and negative asymmetry indicates an association in high measurement value scales (Vidal-Vázquez et al., 2013). The asymmetry values found indicate greater heterogeneity for *R. raphanistrum* than for *Commelina* ssp. (Table 2). The asymmetry of OW (Table 2) varied throughout the study period, without showing any increasing or decreasing pattern; however, the data demonstrated the dominance of *R. raphanistrum* and *Commelina* ssp. over the OW occurring in the study area, indicating ecological processes of dominance and distribution of weeds in the scales.

The highest and lowest degrees of multifractality ($\Delta = D_{-5} - D_3$; Table 2) were described for OW on 10/22/2010 (Δ = 0.576) and 08/19/2010 (Δ = 0.151), respectively. The degree of multifractality identifies systems with greater or lesser heterogeneity (Vidal-Vázquez et al., 2013; Dafonte et al., 2015; Siqueira et al., 2018). The multifractality of OW tended to increase during the winter (triticale) and summer (soybean), indicating an increase in complexity during the crop cycles. *R. raphanistrum* showed an increase in heterogeneity throughout the crop cycle of triticale, while *Commelina* ssp. lost complexity throughout the soybean cycle. The increase in complexity of *R. raphanistrum* and loss of complexity for *Commelina* ssp. are justified by the environmental interactions of these weed species. For *R. raphanistrum,* competition for resources in the environment escalates with the increase in the triticale canopy (Yamauti et al., 2011), thereby increasing its complexity, as evaluated by the degree of multifractality (Δ). However, the population dynamics of *Commelina* ssp. diminished as the soybean crop developed, thereby losing complexity (Δ).

The generalized dimension graph for weeds in the study area with positive (q = 0 to q = 3) and negative (q = 0 to q = -5) points are shown in Figure 2. According to Posadas et al. (2009) and Leiva et al. (2019), the generalized dimension graph describes the spatial variability of the

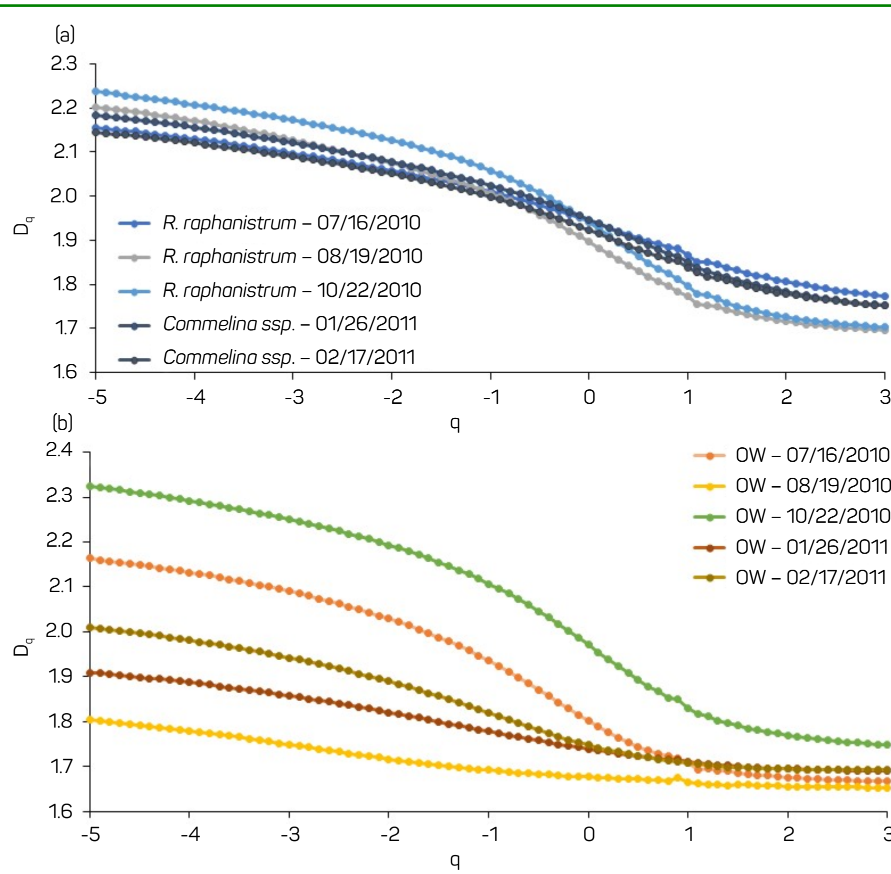

Figure 2 - Generalized dimension graph (D_q) for the number of weeds identified in triticale and soybean crops under no-tillage: (a) *R. raphanistrum* and *Commelina* ssp. and (b) OW – Other weeds

value measurements, characterizing the heterogeneity of the system. The generalized dimension graph (Figure 2a) shows that D_q is a decreasing function of q, shaped like a sigma curve, indicating that there is variability in the low and high measurement values of the studied weeds. For the OW category (Figure 2b), it appears that for the negative points (q = 0 to q = -5), there is a greater degree of heterogeneity in the scales compared to the positive points (q = 0 to q = 3), demonstrating that the dynamics of weeds in this category have high variability in the study period.

The singularity spectrum plots for *R. raphanistrum* and *Commelina* ssp. (Figure 3a) exhibit descending and concave parabolas, and according to Dafonte et al. (2015) and Silva and Siqueira (2020), this format confirms the multifractality of the data. The singularity spectra for *R. raphanistrum* and *Commelina* ssp. show positive asymmetry (right branch), indicating that in the study area and on the different sampling dates, low values of measurements occurred. Information regarding the heterogeneity and complexity of *R. raphanistrum* and *Commelina* ssp. has potential for weed management, because our results describe greater heterogeneity and are associated with low measurement values, indicating that these scales can be used to determine the degree of infestation. It is noteworthy that the singularity spectra for *R. raphanistrum* and *Commelina* ssp. (Figure 3a) show similarity in the distribution behavior of the scales in the branches, with the greatest difference being described for *R. raphanistrum* on 10/22/2010 (AI = 1.321; Table 2) at the end of the triticale crop cycle.

The singularity spectrum for OW (Figure 3b) is asymmetrical to the right, indicating the domain of low measurement values in the study area, but with a lower degree of multifractality (Δ) and asymmetry, when compared to *R. raphanistrum* and *Commelina* ssp. (Table 2 and Figure 2). We emphasize that the multifractality of OW in winter and in summer expressed by the singularity spectrum indicates that, during the study period, OW presented high variability in the distribution of scales, corroborating the complex of interactions that this category of study plants represents (*Bidens pilosa* L., *Amaranthus deflexus* L., *Ipomoea grandifolia* (Dammer) O'Donell, *Acanthospermum australe* (Loerfl.) Kuntze, *Digitaria insularis* (L.) Fedde, *Euphorbia heterophylla* L., and *Parthenium hysterophorus* L.). The differences in the singularity spectrum for OW in the study period describe the dynamics of the dispersal and colonization processes of the

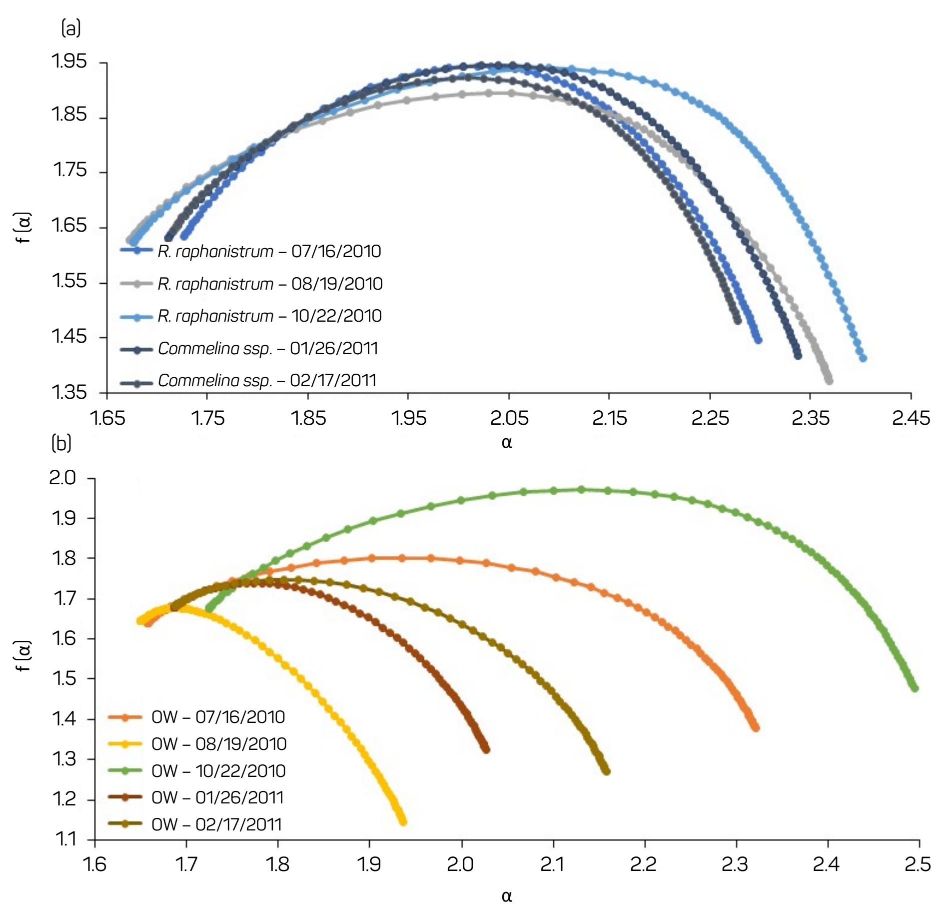

Figure 3 - Singularity spectrum for the number of weeds identified in triticale and soybean crops under no-tillage: (a) *R. raphanistrum* and *Commelina* ssp.; (b) OW – Other weeds

environment (Booth et al., 2003; Brighenti, Oliveira, 2011) by the species grouped in this category, the dominance of *R. raphanistrum* and *Commelina* ssp., and the competition with triticale and soybean crops for environmental resources.

3.3 Ecology and weed management

The prevalence and dominance of *R. raphanistrum* (L.) throughout winter crops and of *Commelina* ssp. (L.) in summer crops is a response to characteristics of species ecology. According to Lorenzi (2014) and Pereira et al. (2018), the species *R. raphanistrum* (L.) has a high capacity for the production of viable seeds and is a common spontaneous plant for winter crops. Cheam and Code (1995) report that the occurrence of *R. raphanistrum* (L.), even if at low populational densities, can compromise the productivity of winter crops. As for *Commelina* ssp. (L.), Brighenti and Oliveira (2011) describe the species as being resistant to chemical management with glyphosate, and, according to Sousa et al. (2020), its control is hindered due to the low efficiency of mechanical methods since its rapid reproduction occurs vegetatively or through seeds. Hence, during the present research period, the species with the most significant expression presented different reproductive and occupational strategies, resulting in high spatial variability and variability scale.

Consequently, multifractal analysis has a significant potential for describing species ecology in the field of agricultural production. The D_0, D_1 and D_2 (Table 2) values are indicators of richness, entropy, and evenness, respectively, allowing one to understand the diversity, complexity, and heterogeneity dynamics of weed ecology within the study area, and should follow the $D_0 > D_1 > D_2$ relation (Chhabra, Jensen, 1989; Banerjee et al., 2011; Vidal-Vázquez et al., 2013; Siqueira et al., 2018; Leiva et al. 2019; Silva, Siqueira, 2020; Siqueira et al., 2022). Thus, it is essential we understand that the focus of multifractal analysis is the description of variable complexity, which will lead to the understanding of weed ecology dynamics.

The singularity spectrum (Figures 3 and 4), in its turn, describes weed dynamics and complexity in the research area in terms of spatial and scale variability. Based on the singularity spectrum, it is possible to attain the characterization of asymmetry (AI), multifractality (Δ) and variability scale distribution. Negative or positive asymmetry (AI) allows the description of possible dominance of high or low measurement values, respectively. With this, weed management strategies can be identified on a scale never considered before. The complexity of the system, or the complexity of the ecological dynamics of weed species, is assessed by the degree of multifractality (Δ). Systems with a greater complexity express heterogeneous weed species dynamics, while homogenous systems represent low species diversity and weed phenological homogeneity in the field. Therefore, multifractal analysis is a promising tool for weed management, the development of new control indicators, and localized input application for the practice of precision agriculture.

Within the area of new research perspectives, we point out the use of multifractal analysis for localized identification of weed species in embedded systems, considering species leaf architecture at different stages of vegetative development. The use of the multifractal methodology should also be highly considered for weed management with the use of drone images, where the ecological relations among species can be understood, as well as the dominance in variability scales for commercial crops.

4. Conclusions

Raphanus raphanistrum L. was the dominant weed in winter cultivation, whereas *Commelina* ssp. L. was dominant in summer cultivation. Different degrees of multifractality were observed for the weeds, and the OW

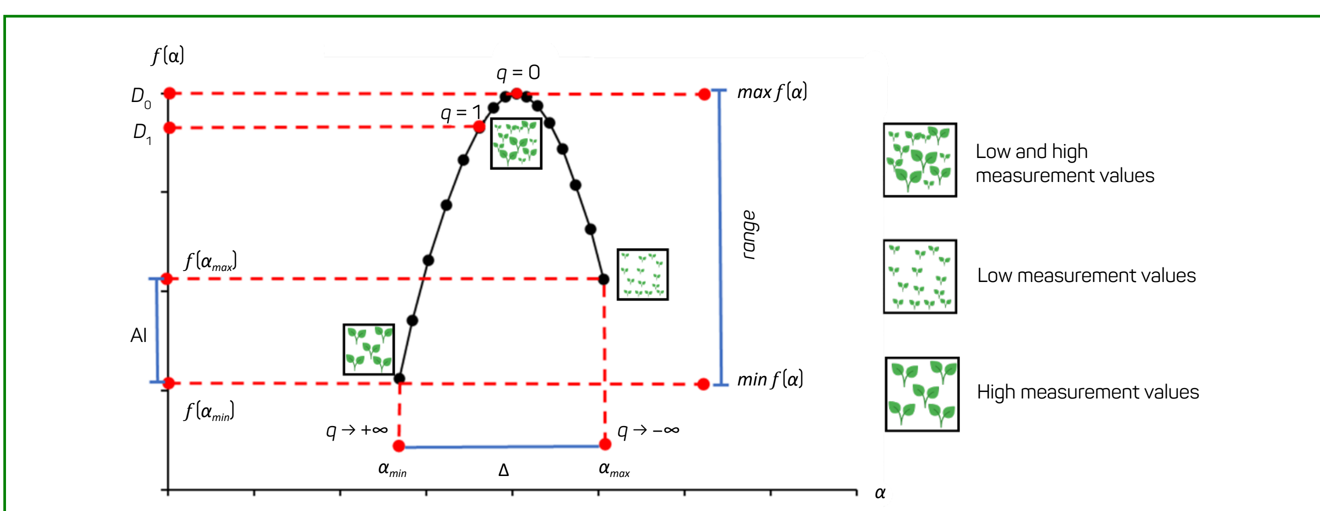

Figure 4 - Interpretation of the multifractal singularity spectrum

category was the most heterogeneous. During the study period, *Raphanus raphanistrum* L. and *Commelina* ssp. L. showed less asymmetry of the branches of the singularity spectrum than OW, indicating the dominance of low measurement values. Therefore, multifractal analysis can be a promising tool for understanding the spatial dynamics of weed distribution.

Author's contributions

All authors read and agreed to the published version of the manuscript. GSM: Conceptualization of the manuscript and development of the methodology, data collection and curation, project administration, supervision. DMS and GSM: data analysis, writing, review and editing. DMS, JFM, RNB, and GSM: data interpretation, writing the original draft of the manuscript.

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Conflict of Interest

The authors have no conflicts of interest to declare regarding the research.

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