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DIVERSIDADE, ESTRUTURA E RELAÇÕES DE ESCALA DA FAUNA INVERTEBRADA E DE FISIONOMIAS DE CERRADO

RAIMUNDA ALVES SILVA

São Luís – MA
2021

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Tese de doutorado apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Biodiversidade e Biotecnologia da Rede BIONORTE, na Universidade Federal do Maranhão, como requisito parcial para a obtenção do Título de Doutor em Biodiversidade e Biotecnologia.

Orientador: Prof. Dr. Glécio Machado Siqueira

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Aprovada em ____/_____/_____

Banca Examinadora

____
Prof. Dr. Glécio Machado Siqueira
Universidade Federal do Maranhão - UFMA

____
Prof. Dr. Jorge Dafonte Dafonte
Universidade de Santiago de Compostela - USC

____
Prof. Dr. Osvaldo Guedes Filho
Universidade Federal do Paraná - UFPR

____
Prof. Dr. Ênio Farias de França e Silva
Universidade Federal Rural de Pernambuco - UFRPE

____
Prof. Dr. Daniel de Bortoli Teixeira
Universidade de Marília - UNIMAR

A minha família

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“*Quase todo avanço na arte, gastronomia, medicina, agricultura, engenharia, publicidade, política, educação e design ocorreu quando alguém desafiou as regras e tentou uma nova abordagem*”.

Roger Von Oetch

RESUMO

Os biomas Cerrado (65%) e Amazônia (34%) ocupam a paisagem do Estado do Maranhão (Brasil), e envolvem uma série de ecossistemas que se interligam, favorecendo a formação de diversos ecótonos. Nesse sentido, a paisagem do Maranhão possui elevada variabilidade, e está relacionada a diferentes fatores como: relevo, geologia, geomorfologia, solos, hidrografia, clima. Assim, o objetivo deste trabalho foi avaliar as relações de escala da fauna invertebrada, atributos físicos e químicos do solo em diferentes fisionomias de Cerrado por meio de ferramentas de geoestatística, multifractal e joint multifractal. Os objetivos específicos são: I) Averiguar a abundância da comunidade de Coleoptera do solo nos diferentes sistemas de usos e manejos do solo; II) Avaliar a relação entre a fauna de invertebrados do solo e os atributos físico-químicos do solo em diferentes fisionomias de Cerrado no Parque Estadual do Mirador, Maranhão; III) Determinar as escalas de variabilidade espacial do componente vegetal por meio de análise de geoestatística; IV) Caracterizar as relações de escalas da fauna de invertebrados do solo e da estrutura de vegetação por meio de ferramentas geoestatística, análise multifractal e joint multifractal; V) Caracterizar a variabilidade espacial de atributos físicos, químicos e biológicos do solo em formações savânicas. As amostragens foram realizadas nos municípios de Chapadinha, Mata Roma e no Parque Estadual do Mirador (PEM). O experimento de Mata Roma foi instalado na Fazenda Unha de Gato, sob diferentes sistemas de uso e ocupação do solo no Bioma Cerrado. Em Chapadinha o experimento foi realizado em área de Cerrado do Campus IV da UFMA - Universidade Federal do Maranhão em diferentes fisionomias vegetacionais. No PEM o experimento foi realizado em parcelas experimentais localizadas nas seguintes formações vegetais: Cerrado Denso, Cerrado Típico e Cerrado Ralo. Foram amostrados os seguintes atributos do solo: fauna invertebrada do solo, areia (g kg^{-1}), silte (g kg^{-1}), argila (g kg^{-1}), densidade (Mg dm^{-3}), porosidade total (PT, m^{3}m^{-3}), macroporosidade (m^{3}m^{-3}), microporosidade (m^{3}m^{-3}), conteúdo de carbono orgânico (CO, g dm^{-3}), fósforo (P, g.dm^{-3}), pH ($CaCl_2$), potássio (K, mmol$_c$ dm^{-3}), cálcio (Ca, mmol$_c$ dm^{-3}), magnésio (Mg, mmol$_c$ dm^{-3}) e capacidade de troca catiônica (CTC, mmol$_c$dm^{-3}). nas profundidades de 0-0.05 m, 0.05-0.15 m e 0.15-0.3 m. A fauna invertebrada do solo foi amostrada utilizando armadilhas *pitfall,* e os atributos físicos e químicos foram amostrados utilizando amostras deformadas e indeformadas em anéis volumétricos de 100 cm^3. A vegetação foi amostrada utilizando método de parcelas e subparcelas. Os dados foram analisados por meio da estatística descritiva, estatística multivariada, geoestatística, análise multifractal e joint multifractal. A comunidade de Coleoptera foi influenciada pelo uso e manejo do solo, com maior diversidade para os sistemas florestais. As fisionomias de Cerrado Denso e Cerrado Ralo no município de Chapadinha, apresentaram maior abundância e riqueza, influenciada pela composição dos estratos vegetais. No PEM, a fauna do solo foi relacionada a estrutura do solo (atributos físicos) e aos indicadores de qualidade química do solo (atributos químicos). O Cerrado Ralo apresentou maior heterogeneidade de escalas, enquanto, o Cerrado Denso foi o que demonstrou maior assimetria dos espectros de singularidade.

Palavras-chave: Fauna Edáfica; Grupos Funcionais; Indicadores de Qualidade do Solo; Multifractalidade; Variabilidade Espacial.

ABSTRACT

Cerrado (65%) and Amazon (34%) biomes occupy the landscape of the State of Maranhão (Brazil), and involve a series of interconnected ecosystems, favoring the formation of different ecotones. In this sense, Maranhão landscape displays high variability, which is related to different factors such as: relief, geology, geomorphology, soils, hydrography, climate. Thus, the objective of this work was to evaluate the scale relationships of invertebrate fauna, physical and chemical attributes of soil in different physiognomies of Cerrado by means of geostatistical, multifractal, and joint multifractal tools. The specific objectives were: I) To investigate the abundance of Coleoptera community in soil in different land use and management systems; II) Evaluate the relationship between soil the invertebrate fauna and soil physiochemical attributes in different Cerrado physiognomies in the Parque Estadual do Mirador (PEM), Maranhão; III) Determine the scales of spatial variability of the plant component by means of geostatistical analysis; IV) To characterize the scale relationships of the invertebrate fauna of soil and vegetation structure by means geostatistical tools, multifractal, and joint multifractal analysis; V) Characterize the spatial variability of physical, chemical, and biological attributes of soil in savanna formations. Samplings were carried out in the municipalities of Chapadinha, Mata Roma and in PEM. The in Mata Roma was installed in the Unha de Gato Farm, under different land use and occupation in Cerrado Biome. In Chapadinha, the experiment was carried out in area of Cerrado, belonging UFMA, Campus IV- Federal University of Maranhão, comprising different vegetation types: Dense Cerrado, Typical Cerrado and Sparse Cerrado. In PEM, the experiment was carried out from experimental plots located in the following plant formations: Dense Cerrado, Typical Cerrado and Sparse Cerrado. The following soil attributes were sampled: invertebrate fauna, sand (g kg^{-1}), silt (g kg^{-1}), clay (g kg^{-1}), density (BD, Mg dm^{-3}), total porosity (PT , m^{3}m^{-3}), macroporosity (m^{3}m^{-3}), microporosity (m^{3}m^{-3}), organic carbon content (OC, g dm^{-3}), phosphorus (P, g.dm^{-3}), pH ($CaCl_2$), potassium (K, mmol$_c$ dm^{-3}), calcium (Ca, mmol$_c$ dm^{-3}), magnesium (Mg, mmol$_c$ dm^{-3}) and cation exchange capacity (CEC, mmol$_c$ dm^{-3}) at depths of 0-0.05, 0.05-0.15, and 0.15-0.3 m. The invertebrate fauna of soil was sampled from *pitfall* traps and physical and chemical soil attributes were sampled from deformed and undisturbed samples using volumetric rings of 100 cm^3. The vegetation was sampled using the method of plots and subplots. Data were analyzed using descriptive and multivariate statistics, geoestatistics, multifractal, and joint multifractal analysis. Coleoptera community was influenced by the use and management of soil, with greater diversity for the forest systems. The physiognomies of Dense Cerrado and Sparse Cerrado, in the municipality of Chapadinha, presented greater abundance and richness, influenced by composition of the plant strata. In PEM, soil fauna was related to soil structure (physical attributes) and to indicators of soil chemical quality (chemical attributes). The Sparse Cerrado physiognomy showed the greatest heterogeneity of scales, while Dense Cerrado showed the greatest asymmetry of the singularity spectra.

Keywords: Edaphic Fauna; Functional Groups; Soil Quality Indicators; Multifractality; Spatial Variability.

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1 INTRODUÇÃO

A Savana, em termos de distribuição geográfica ocupa a maior porção entre os trópicos, representando cerca de 50% do continente africano e significativo percentual da América do Sul, Ásia e Oceania (FALEIRO e NETO, 2008). A vegetação é caracterizada pela presença de uma camada contínua de vegetação herbácea e dossel descontínuo de arbustos e árvores, que abrigam elevada riqueza endêmica (OLIVEIRA-FILHO e RATTER, 2002; PARENTE *et al*., 2021). No Brasil, a Savana recebe o nome de "Cerrado", sendo utilizado para conceituar um conjunto de ecossistemas que ocorrem no Brasil Central (EITEN, 1977; RIBEIRO e WALTER, 2008), com diversas fitofisionomias vegetacionais, englobando formações florestais, savânicas e campestres (EITEN, 1977; IBGE, 2012).

As formações florestais do Cerrado são do tipo mata ciliar, mata de galeria, mata seca e cerradão, que apresentam vegetação arbórea com dossel contínuo (RIBEIRO e WALTER, 2008); as formações savânicas englobam as fisionomias de cerrado sentido restrito (cerrado denso, cerrado típico, cerrado ralo e cerrado rupestre), parque de cerrado, palmeiral e vereda, caracterizado por apresentar estrato vegetal arbóreo e arbustivo-herbáceo, sem formação de dossel contínuo (IBGE, 2012); por fim, as formações campestres são do tipo campo sujo, campo rupestre e campo limpo, com presença de arbustos, subarbustos entremeados no estrato herbáceo (RIBEIRO e WALTER, 2008). Dessa maneira, por apresentar elevada heterogeneidade, tanto na flora como na fauna, o cerrado, é considerado como uma área prioritária (*hotspot*) para a conservação da diversidade biológica (LENZA e KLINK, 2006; MYERS *et al*., 2000; MITTERMEIER *et al*., 2011).

Atualmente, o cerrado tem cerca de 56% da vegetação convertida em terras agrícolas (MMA, 2015), e apenas 3% protegida em parques e reservas naturais (FRANÇOSO *et al*., 2015; 2016; 2020). A expansão agrícola sobre esse bioma corresponde a aproximadamente 40% da produção total nacional, sendo responsável por inserir o Brasil no cenário mundial de produtores e exportadores de alimentos (SANO *et al*., 2019).

O estado do Maranhão possui elevada produção de grãos, que segundo a Companhia Nacional de Abastecimento (CONAB) deve alcançar aumento na safra de 2020/21 em 12,2%. Contudo, as vantagens da expansão agrícola no Maranhão não impedem que haja impactos ambientais no Cerrado, principalmente no uso do solo (SILVA JUNIOR *et al*., 2021).

O solo é um sistema multifuncional primordial para a sustentabilidade, resultado da interação dos fatores bióticos e abióticos, sendo a conservação do solo, necessária para garantir a sustentabilidade dos ecossistemas (VEZZANI e MIELNICZUK, 2009). No cerrado, os solos possuem baixa disponibilidade de nutrientes, elevada acidez e concentração de alumínio e baixa disponibilidade de nitrogênio, fósforo e potássio, entre outros elementos essenciais para o crescimento vegetal (KLIN e MACHADO, 2005; MALAVOLTA e MORAES, 2007).

No contexto biológico, solo é um ecossistema que abriga inúmeros organismos invertebrados, responsáveis pelo desempenho de várias funções ecológicas ao ambiente, como a ciclagem de nutrientes (WAGG *et al.*, 2014; BROWN *et al.*, 2015), decomposição e mineralização da matéria orgânica (CARRILLO *et al.*, 2011; ROY *et al.*, 2018), regulação de cadeia trófica (SILVA *et al.*, 2019), modificações na estrutura do solo (OLIVEIRA *et al.*, 2014). Além da participação direta nos serviços ambientais, os invertebrados do solo podem ser utilizados como indicadores de qualidade do solo, respondendo as mudanças no ambiente, principalmente na abundância, riqueza e composição de organismos (ROY *et al.*, 2018; MAGGIOTTO *et al.*, 2020).

A fauna do solo é comumente avaliada pela abundância e riqueza de grupos, porém, ocorre uma lacuna no conhecimento das escalas de distribuição dos organismos do solo (BARDGETT e PUTTEN, 2014), sendo essa informação importante na compreensão da ecologia da fauna edáfica, funcionalidade edáfica em diferentes escalas de observação, além de caracterização espacial dos organismos do solo (GHOLAMI *et al.*, 2017). De maneira, torna-se necessário compreender a fauna edáfica em diferentes escalas de observação espacial, considerando as diversas fisionomias de cerrado presentes no estado do Maranhão.

Assim, as hipóteses desse trabalho são: a) a fauna edáfica é influenciada pelo uso e manejo do solo, que condiciona a abundância, diversidade e riqueza dos grupos de invertebrados do solo nas diferentes formações de Cerrado; b) as formações vegetais de Savana apresentam diferentes escalas de variabilidade espacial; c) abundância e a riqueza de invertebrados do solo tem distribuição e associação em escala multifractal e joint multifractal; d) as ferramentas de geoestatística, análise multifractal e joint multifractal podem caracterizar a variabilidade espacial da fauna de invertebrados do solo em diferentes escalas.

1.1 OBJETIVOS

1.1.1 Geral

- Avaliar a diversidade, estrutura e relações de escala da fauna do solo em diferentes fisionomias de Cerrado por meio de ferramentas de geoestatística, multifractal e joint multifractal no Estado do Maranhão.

1.1.2 Específicos

- Averiguar a abundância da comunidade de Coleoptera do solo nos diferentes sistemas de usos e manejos do solo;
- Avaliar a relação entre a fauna de invertebrados do solo e os atributos físico-químicos do solo em diferentes fisionomias de Cerrado no Parque Estadual do Mirador, Maranhão;
- Determinar as escalas de variabilidade espacial do componente vegetal por meio de análise de geoestatística;
- Caracterizar as relações de escalas da fauna de invertebrados do solo e da estrutura de vegetação por meio de ferramentas geoestatística, análise multifractal e joint multifractal;
- Determinar a variabilidade espacial da fauna edáfica em áreas de savana utilizando ferramentas multifractais e joint multifractais;
- Caracterizar a variabilidade espacial de atributos físicos, químicos e biológicos do solo em formações savânicas.

2 REVISÃO BIBLIOGRÁFICA

2.1 Ecossistemas do Maranhão

O estado do Maranhão contempla aspectos transicionais dos biomas de Cerrado, Caatinga e Amazônia, intercalados com os ecossistemas de campos inundáveis (Baixada Maranhense), ecossistemas costeiros (incluindo a Restinga e as Reentrâncias Maranhense) na porção do litoral e mata de cocais (IBGE, 2011).

O cerrado no Maranhão cobre aproximadamente 65% da extensão territorial do estado (SANO *et al*., 2010), ocorrendo em cerca de 55 municípios (IBGE, 2011), onde 23 desses municípios estão inseridos exclusivamente em domínio de Cerrado (Figura 1a). No Maranhão, o Cerrado apresenta elevada heterogeneidade vegetal, com a presença principalmente de formações savânicas, como cerradão, cerrado sentido restrito (cerrado denso, cerrado típico, cerrado ralo), além de chapadas na porção sul do estado, com predomínio da vegetação arbustivas esparsas e arbustos (EITEN, 1997).

No aspecto de conservação, o cerrado maranhense encontra-se com 12,5% da área associada a unidades de conservação, seja em proteção integral (5,7%) ou em proteção de uso sustentável (6,8%), porém, ainda representa o menor percentual protegido (BRASIL, 2013). É um bioma extremamente rico, que ultimamente, constitui uma fronteira agrícola, principalmente na região Leste e Sul do estado, o que ocasionou a retirada de extensas áreas nativas para o cultivo de soja, milho e eucalipto (SANO *et al*., 2019).

A Caatinga (Figura 1a) é um bioma com vegetação extremamente diversificada, caracterizada por pela presença de estrato arbóreo com galhos retorcidos e raízes profundas (SPINELLI-ARAÚJO *et al*., 2016), definida principalmente, pelo padrão climático, edáfico, topográfico e antrópico (ALVES *et al*., 2009). No estado do Maranhão, a Caatinga abrange cerca de 1,1% do território, localizado na porção leste do estado.

O bioma Amazônico compreende a maior floresta tropical do mundo (ARAÚJO *et al*., 2021); no estado do Maranhão (Figura 1a), está presente em 62 municípios, representando 24,46% do território do estado, sendo inserido na Amazônia Legal (MARTINS e OLIVEIRA, 2011). Possui elevada diversidade biológica, porém, no Maranhão, apresenta menor grau de ocupação de espaço protegido (Unidades de Conservação - UC). Dentre os problemas presentes na Amazônia maranhense, destaca-se a degradação, principalmente em função do desmatamento, queimadas e fragmentação dos ecossistemas, que ocasionam a perda de diversidade.

Dentro do domínio da Amazônia Legal, os campos inundáveis da Baixada Maranhense, constituem ambientes complexos, localizados no extremo norte do estado (Figura 1b). A

Baixada Maranhense é considerada uma Área de Proteção Ambiental (APA), pelo decreto nº 11.900 de junho de 1991, tendo como objetivo disciplinar o uso e ocupação do solo, e a exploração de recursos naturais. A APA da Baixada possui 95.23% da sua extensão em bioma amazônico, com uma interface de ecossistemas que incluem manguezais, babaçuais, campos abertos e inundáveis, lagunas e matas ciliares (ARAÚJO e PINHEIRO, 2013). Devido a esse mosaico fisionômico, tornou-se uma unidade de conservação de extrema importância, uma vez que, é local prioritário para a ocorrência de processos ecológicos (ALMEIDA-FUNO *et al*., 2010). No entanto, não está isenta de problemas ambientais, como criação extensiva (principalmente de bubalino), atividade de pesca e caça predatória e cultivo agrícola (CANTANHEDE *et al*., 2014).

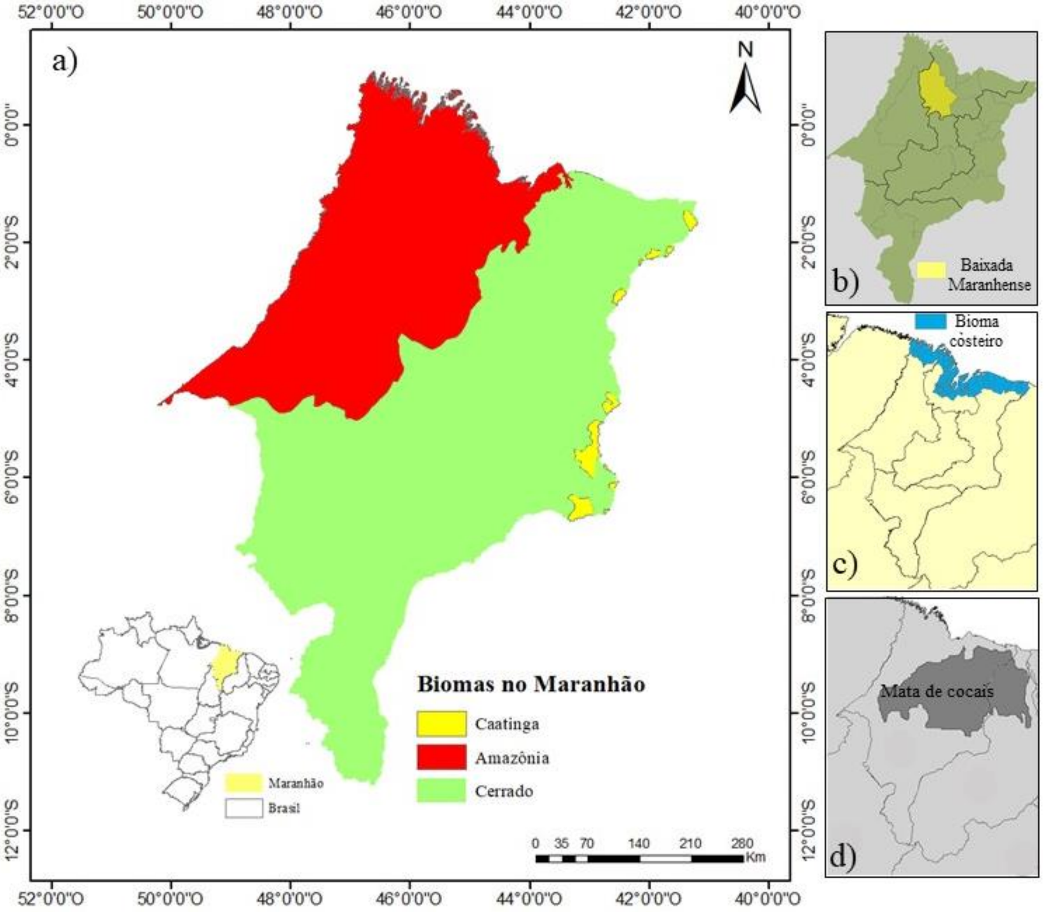

Figura 1 - Distribuição dos biomas e ecossistemas no estado do Maranhão. Fonte adaptada de: IBGE, 2016; 2017 (Figura a, b, c) e Santos-Filho *et al*. (2013 - Figura 1d).

O bioma costeiro é composto de diferentes ecossistemas que abrange áreas ao longo do litoral, constituídos principalmente por restingas, praias, dunas, baías, costões rochosos e manguezais. No estado do Maranhão destacam-se, as restingas e as Reentrâncias Maranhense (Figura 1c), como ambientes importantes para conservação da diversidade biológica.

O ecossistema de Restinga é composto de vegetação herbácea, arbustivo e arbóreo, pertencentes a zona litorânea, caracterizado por extensas faixas de areia e dunas, com uma rica flora e fauna. A costa maranhense (Figura 1c), é considerada a segunda maior do Brasil, sendo dividida em porção oeste (litoral amazônico) e porção leste, pertencente ao litoral nordestino (LIMA e ALMEIDA Jr., 2018). A restinga maranhense possui elevada relevância ecológica, uma vez que a composição vegetal recebe influência dos ecossistemas adjacentes (SERRA *et al*., 2016).

A Área de Proteção Ambiental (APA) das Reentrâncias Maranhenses é uma unidade de conservação (UC) que disciplina o uso e a ocupação do solo, assim como, a exploração de recursos naturais (Secretaria de Estado de Meio Ambiente e Recursos Naturais - SEMA). É um ambiente com elevada produtividade pesqueira e muito importante para a aves migratórias, que a utilizam para pouso e alimentação. Devido a relevância das Reentrâncias Maranhenses, foi inserida como um sítio Ramsar (área de importância internacional em ecologia, botânica, zoologia, limnologia e hidrologia - RIBEIRO *et al*., 2020).

Atualmente, os ecossistemas costeiros sofrem com diversas interferências, como desmatamento, especulação imobiliária e ocupação do solo (SANTOS-FILHO *et al*., 2013), exigindo, assim, a necessidade de conservação desses ambientes.

A mata de cocais (Figura 1d) é um ecossistema denominado de transição entre clima semiárido, equatorial e tropical, com maior predomínio, principalmente no estado do Maranhão (BARRETO *et al*., 2019). Constitui uma vegetação considerada secundária, oriunda da retirada de vegetação nativa (VIVEIROS, 1943), que por apresentar desenvolvimento rápido e com pouca competição (NUNES *et al*., 2012), consegue dominar a paisagem (SANTOS-FILHO *et al*., 2013). A mata de cocais tem uma grande importância histórica, econômica, política e social, principalmente pela atividade extrativista do coco babaçu (PORRO, 2019).

Assim, o Maranhão tem sua diversidade biológica influenciada pelos diversos biomas e ecossistemas presentes, sendo caracterizado como um estado rico e heterogêneo em termos de fauna e flora.

2.2 Fauna invertebrada do solo

O solo é um componente dinâmico e heterogêneo, essencial para manutenção dos ecossistemas (LAVELLE, 2012; BARDGETT e PUTTEN, 2014), constituído por fatores bióticos e abióticos (LAVELLE, 2012), cujos benefícios incluem as propriedades morfológicas, físicas, químicas, mineralógicas e biológicas próprias (DORAN e SARRANTONIO, 1996).

A fauna do solo é composta por organismos que vivem permanentemente no solo, desenvolvem alguma fase no solo, serapilheira ou no interstício solo-serapilheira (AQUINO, 2001; CORREIA e OLIVEIRA, 2000; BARDGETT e PUTTEN, 2014), e desempenham funções relevantes ao ambiente, devido as suas múltiplas interações nos ecossistemas. Para CORREIA (2002) e BARETTA *et al.* (2003) esses organismos são essenciais para a funcionalidade do solo, uma vez que são sensíveis as alterações ambientais, o que viabiliza a sua utilização para aferir a qualidade do solo.

A fauna do solo é geralmente dividida e classificada em grupos para melhor entendimento da diversidade e funcionalidade dos organismos que a compõe. Uma das classificações mais utilizada refere-se as classes de tamanho corporal, que são divididas em microfauna, mesofauna e macrofauna do solo (CORREIA, 2000). Os organismos que compõe a microfauna são principalmente nematoides, rotíferos e protozoários que apresentam tamanho corporal de 4 µm a 100 µm, regulam as populações de fungos e bactérias, influenciando indiretamente a ciclagem de nutrientes no ambiente (AQUINO, 2001). Além disso, os organismos da microfauna, atuam na modificação da estrutura do solo (LAVELLE, 1996), e são presas para outras populações (WARDLE, 1997; CORREIA e OLIVEIRA, 2000).

A mesofauna é composta por organismos ditos reguladores tróficos da microfauna e microflora, com variação no tamanho corporal de 100 µm a 2 mm. São organismos com maior movimentação no solo ou na interface solo-serapilheira, responsáveis pelo controle de outras populações edáficas, se alimentam principalmente de matéria orgânica em decomposição e são atuantes na fragmentação de serapilheira (BROWN *et al*., 2015). Os principais grupos dessa classe são Acari, Collembola, Diplopoda, Chilopoda, Diptera, Diplura e Protura, com maior diversidade e abundância para Acari e Collembola (CORREIA, 2002) importantes na função detritívora.

A macrofauna composta por organismos modificadores de propriedades físicas e químicas do solo, responsáveis pela formação de poros, galerias e túneis (LAVELLE *et al.* 2006; BLOUIN *et al*., 2013; OLIVEIRA *et al*., 2014), atuam na redistribuição de matéria orgânica e fragmentação de resíduos vegetais (CORREIA e OLIVEIRA, 2000). Essa classe abrange invertebrados, com diâmetro corporal superior a 2 mm, composta por organismos fragmentadores de material vegetal, detritívoros, fitófagos, humívoros, xilófagos, predadores e herbívoros (CORREIA, 2002).

Dentro dessa classificação, devido as suas atribuições, maior mobilidade e atuação no interstício do solo, alguns grupos são denominados de “engenheiros do ecossistema”, pois, suas atividades modificam as propriedades físicas e a disponibilidade de recursos (BROWN *et al*., 2001; LAVELLE *et al*., 2006; BLOUIN *et al*., 2013).

Os organismos edáficos se relacionam a qualidade ambiental do solo, como parte ativa e sensíveis às interferências no ambiente (BARETTA *et al*., 2003, e podem ser afetados pela quantidade e qualidade de matéria orgânica (BLOUIN; VRIES *et al.*, 2013; WAGG *et al.*, 2014), temperatura (GONÇALVES, 2017), textura do solo (AYUKE *et al.*, 2011), composição vegetal (MOÇO *et al.*, 2010; KORBOULEWSKY *et al.*, 2016; GHOLAMI *et al.*, 2017; SILVA *et al.*, 2019) e pelas atividades humanas (DOMÍNGUEZ *et al.*, 2010; BEDANO *et al.*, 2016). Assim, esses fatores podem condicionar a abundância, riqueza e a distribuição dos organismos no espaço e no tempo, afetando principalmente as suas funções ecossistêmicas.

2.3 Funções ecossistêmicas

As primeiras observações sobre as interações ecológicas da fauna do solo ocorreram por volta da década de 80 (ANDERSON *et al.*, 1983; PRIMAVESI, 2002), quando foi iniciado os primeiros estudos que relacionavam a fauna edáfica as interações ambientais e consequentemente, as funções ecossistêmicas, tornando as primeiras referências da fauna do solo e dos processos de mineralização (INGHAM *et al.*, 1985) e de decomposição da matéria orgânica (ANDERSON *et al.*, 1983 – Tabela 1).

Para associar a fauna do solo a uma função ecossistêmica, os grupos de invertebrados do solo são agrupados em categorias funcionais (LAVELLE; SPAIN, 2001; SILVA *et al.*, 2013; MAGGIOTTO *et al.*, 2019), que são unidades gerais utilizadas para descrever a comunidade da fauna edáfica relacionando os grupos a uma funcionalidade desempenhada no ambiente (BROWN *et al.*, 2015). Os grupos funcionais podem ser definidos por categorias funcionais similares, morfológicas ou reprodutivas (LAVELLE; GILOT, 1994), que exploram os mesmos recursos no ambiente.

Tabela 1. Distribuição da fauna edáfica em grupos funcionais e serviços ecossistêmicos

CATEGORIA TAXONÔMICA	GRUPO FUNCIONAL	AUTORES
Acari	Decompositores	SILVA et al., 2013
Araneae	Predadores	MOÇO et al., 2005; DOMÍNGUEZ et al., 2010
Blattodea	Fitófagos, onívoros, detritívoros e transformadores de serapilheira	MOÇO et al., 2005.
Blattodea/Isoptera	Fitófagos, detritívoros, geófagos, rizófagos, engenheiros de ecossistemas e transformadores de serapilheira	OLIVEIRA et al., 2014; COUTO et al., 2015; CRISTALDO et al., 2016;
Chilopoda	Predador	KENNING et al., 2017; MAGGIOTTO et al., 2019.
Collembola	Decompositores, catalisadores de nutrientes e saprófagos	BERG et al., 2004; TORDOFF et al., 2008; DOMÍNGUEZ et al., 2010; YANG et al., 2012
Coleoptera	Fitófagos, detritívoros, rizófagos, predadores, parasitas e transformadores de serapilheira	POMPEO et al., 2016; GONÇALVES, 2017; BERNARDES et al., 2020.
Dermaptera	Fitófagos, onívoros, predadores e transformadores de serapilheira	BROWN et al., 2001.
Diplopoda	Detritívoro, transformador de serapilheira	ORGIAZZI et al., 2016.
Diplura	Saprófagos e predadores	SENDRA et al., 2021
Diptera	Transformadores de serapilheira, detritívoros, predadores e parasitas	RAFAEL et al., 2012
Hymenoptera (Formicidae)	Fitófagos, onívoros, detritívoros, rizófagos, engenheiros de ecossistemas e controladores de pragas	SAAD et al., 2017; MARTINS et al., 2018; VICENTE et al., 2018
Neuroptera	Predadores	BROWN et al., 2001.
Oligochaeta	Detritívoros, engenheiros de ecossistemas, transformadores de serapilheira e decompositores	AQUINO, 2001; MOÇO et al., 2010; BERNARD et al., 2012
Opillionida	Predador	BROWN et al., 2001.
Orthoptera	Fitófagos e predadores	SONG et al., 2018
Protura	Decompositores	ORGIAZZI et al., 2016.
Pseudoescorpiones	Predador	ORGIAZZI et al., 2016.
Symphyla	Saprófagos e decompositores	GOLOVATCH e LI, 2020
Thysanoptera	Predadores, saprófagos e herbívoros	MAGGIOTTO et al., 2019.

2.4 Variabilidade espacial e de escala

A variabilidade dos atributos do solo consiste em uma preocupação antiga, sendo resultado das variações e flutuações nas medidas ao longo do espaço (GOOVAERTS, 1994). Para LOGSDON; PERFECT e TARQUIS (2008) cada variável possui uma variabilidade intrínseca que depende da escala de observação, assim, sempre que ocorre o aumento nas variações e flutuações, ocorre também aumento da escala observada.

A distribuição espacial da fauna do solo é controlada por uma diversidade de agentes ambientais que atuam em diferentes escalas espaciais (BARDGETT e PUTTEN, 2014; KORBOULEWSKY *et al.*, 2016), porém, pouco se conhece do padrão de escala que condicionam a fauna edáfica, assim, ferramentas que possibilitam fazer avaliação em diferentes escalas de variabilidade são necessárias. Dessa maneira, a geoestatística e análise multifractal são ferramentas matemáticas, que permitem que uma dada variável possa ser caracterizada no espaço e em diferentes escalas de observação.

2.4.1 Análise geoestatística

A preocupação com a variabilidade do solo remota ao início do século XX, quando foi admitido incertezas no comportamento de variáveis se não fosse considerado a posição espacial da amostragem (WEBSTER, 1985). Assim, surge o termo geoestatística, que se estabeleceu como uma ferramenta que possibilita determinar a variabilidade espacial dos atributos do solo (VIEIRA, 2000).

Os primórdios da geoestatística foram baseadas nas observações de Daniel G. Krige, em 1951, trabalhando com dados de concentração de ouro na África do Sul, Krige não encontrava sentido nas variâncias se não levasse em consideração a posição geométrica das amostras (VIEIRA, 2000). Essas primeiras observações foram a base para mais tarde, Georges Matheron desenvolver a teoria das variáveis regionalizadas. A teoria das variáveis regionalizadas é uma função espacial numérica que varia de um local para outro com uma continuidade aparente e cuja variação não pode ser representada por uma função matemática simples (MATHERON, 1963; MATHERON, 1971).

Diante disso, a geoestatística compreende três hipóteses: a hipótese da estacionariedade de segunda ordem, a hipótese intrínseca e a hipótese de tendência universal ou krigagem (JOURNEL e HUIJBREGTS, 1978; VIEIRA, 2000; VIEIRA *et al.*, 1983). A hipótese da estacionariedade implica na existência de variância finita relacionada aos valores medidos, o que dificilmente é satisfeito, uma vez que não se aplica a fenômenos com capacidade infinita de dispersão (VIEIRA, 2000).

Por sua vez, a hipótese intrínseca é menos restritiva, exigindo apenas a existência e estacionariedade do semivariograma, sem restrição em relação à variância finita, sendo a hipótese mais utilizada (TRANGMAR *et al.*, 1986). A krigagem universal, admite capacidade de dispersão infinita, não possuindo variância finita, com covariância que não pode ser determinada (VIEIRA *et al.*, 1983; VIEIRA, 2000). Sendo o semivariograma a representação gráfica da dependência espacial das variáveis estudadas (Figura 2).

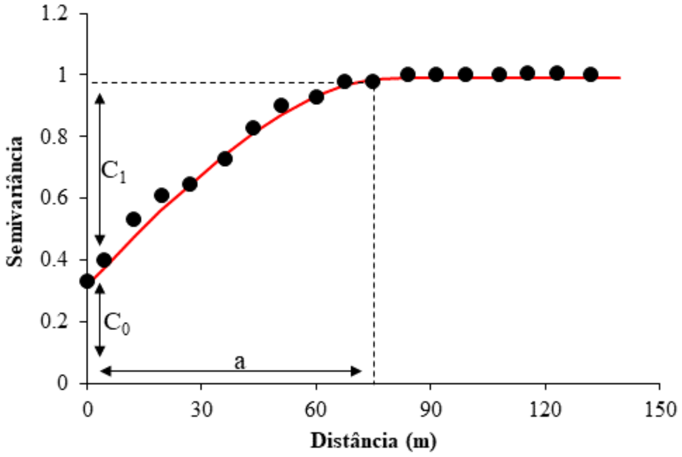

Figura 2 - Semivariograma experimental. C_0: efeito pepita; C_1: variância estrutural; a: alcance (m).

As ferramentas de geoestatística tem sido utilizada para determinação da variabilidade espacial de atributos físicos (VIDAL VÁZQUEZ *et al.*, 2010; VIEIRA *et al.*, 2010; SANTOS *et al.*, 2012; SIQUEIRA *et al.*, 2014; TAVARES *et al.*, 2015; SIQUEIRA *et al.*, 2015; 2016); atributos químicos (CORÁ *et al.*, 2004; GUEDES FILHO *et al.*, 2010; MORALES *et al.*, 2010; DALCHIAVON *et al.*, 2011; MONTANARI *et al.*, 2011; MORALES *et al.*, 2014; OLIVEIRA *et al.*, 2015; BUSS *et al.*, 2019) e atributos biológicos do solo (NEVES *et al.*, 2010; GHOLAMI *et al.*, 2014; SIQUEIRA *et al.*, 2015; 2016; GHOLAMI *et al.*, 2017; SILVA *et al.*, 2018).

Em estudos de atributos biológicos Neves *et al.* (2010) utilizaram a análise geoestatística para avaliar a biodiversidade de reservas naturais no Estado de São Paulo. Siqueira *et al.* (2015) e Siqueira *et al.* (2016) avaliaram a distribuição de plantas daninhas. Gholami *et al.* (2014) determinaram a variabilidade espacial da fauna do solo e de atributos físicos e químicos do solo. Gholami *et al.* (2017) ajustaram modelos geoestatísticos para a diversidade e abundância da macrofauna e espécies arbóreas. Silva *et al.* (2018) estudando a diversidade da fauna edáfica em diferentes usos e manejos do solo, ajustaram modelos geoestatísticos aos índices de diversidade biológica.

2.4.2 Análise multifractal

O uso do fractal ficou conhecido com a publicação do livro “A geometria fractal da natureza” de Benoit B. Mandelbrot, em 1977. Considerado o pai dos fractais, Mandelbrot, afirmava que a geometria se preocupava em estudar as formas regulares e perfeitas dos objetos, porém, na natureza essas formas regulares não são aplicadas, uma vez que os objetos naturais apresentam formas fragmentadas e irregulares que se repetem (MANDELBROT, 1967). Assim, as formas naturais são mais facilmente compreendidas pelos fractais, uma vez que a geometria clássica apresenta limitações.

O termo fractal vem do latim “*fractum*” cuja o verbo significa partido ou quebrado, faz referência as formas fragmentadas, irregulares ou com reentrâncias de um objeto (MANDELBROT,1982). Para tais objetos, a geometria clássica não consegue determinar com precisão as dimensões, sendo necessário uma modelagem que responda a esses elementos (XU *et al*., 1993; XU *et al*., 2001; SUN *et al*., 2006).

Um objeto fractal é definido como um objeto autossimilar que apresenta característica peculiar na escala, dimensão e na complexidade (JORGE *et al*., 2008 - Figura 3). A autossimilaridade desses objetos é classificada em exata, quando objeto apresenta as mesmas estruturas em escalas diferentes, ou aproximada, quando o objeto é apenas semelhante (MANDELBROT, 1982).

Na natureza, as formas são frequentes e seus padrões são repetitivos em diversas escalas (MANDELBROT, 1967), assim, muitos processos biológicos e fenômenos da natureza são caracterizados por estruturas com complexidade na sua definição e que necessitam de determinação matemática considerando as irregularidades das formas (NUNES *et al*., 2006).

Figura 3 - Modelo fractal natural com autossimilaridade.

Dessa maneira, é comum a utilização da geometria euclidiana, para determinação dos objetos, por meio de valor inteiro. Porém, para alguns objetos a dimensão euclidiana não representa as estruturas considerando as diferentes escalas, nesse caso, utiliza-se a dimensão fractal (*D*). Na dimensão fractal, o valor dos objetos é um número fracionário, que considera as irregularidades das estruturas e a ocupação desses objetos no espaço (MANDELBROT, 1982; JORGE *et al*., 2008 - Figura 4).

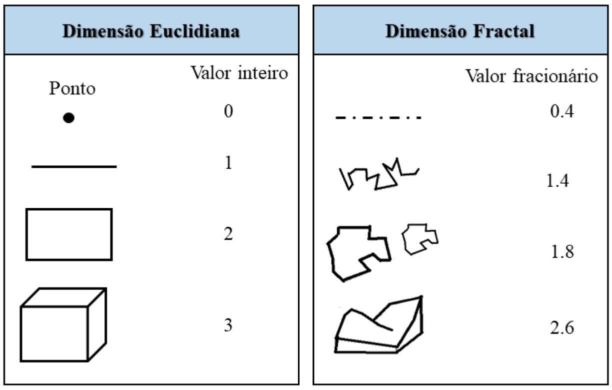

Figura 4 - Diferenças entre os valores de dimensão na geometria euclidiana e na geometria fractal.

A dimensão fractal caracteriza os objetos em uma dimensão, ou seja, em um momento estatístico. Para determinação em mais de um momento estatístico, faz-se uso da análise multifractal, que oferece uma caracterização do objeto determinando mais de uma dimensão, sucessivas divisões e diferentes escalas no suporte geométrico (CANIEGO *et al*., 2005; ZELEKE e SI, 2006).

Os valores de dimensões na análise multifractal, são denominados de dimensão generalizada (*Dq*), sendo utilizados como um indicador de heterogeneidade ou homogeneidade dos valores de uma variável dentro do suporte geométrico (ZELEKE e SI, 2006; CANIEGO *et al*., 2006; BISWAS *et al*., 2012; SIQUEIRA *et al*., 2018). Geralmente, os principais momentos utilizados na dimensão generalizada, compreende os intervalos de $q = 0$, $q = 1$ e $q = 2$, que corresponde respectivamente as dimensões D_0, D_1 e D_2 (CANIEGO *et al*., 2006; ZELEKE e SI, 2006). As dimensões generalizadas (D_0, D_1 e D_2) são avaliadas por valores decrescente, denominadas de dimensão de capacidade (D_0), dimensão de entropia ou dimensão de informação (D_1), dimensão de correlação (D_2 - PEITGEN *et al*., 1992; CANIEGO *et al*., 2006).

A D_0 avalia a homogeneidade global ou média dos dados no sistema (POSADAS et al., 2009; BANERJEE *et al*., 2011). Representa um expoente de escala do número de segmentos não vazios no suporte geométrico, não considera a quantidade de massa no sistema, e sim a ocupação desses segmentos por um valor real.

A D_1 fornece informações da heterogeneidade da distribuição dos valores de medida da variável (JORGE *et al*., 2008), uma vez que considera a ocupação nos segmentos, avaliando como a variação nos valores de medidas refletem a heterogeneidade do sistema (PAZ FERREIRO *et al*., 2018). São valores compreendidos no intervalo de $0 < D_1 < 1$, onde valores próximos a 1 caracteriza um sistema uniformemente distribuído em todas as escalas e valores próximos de 0 reflete um subconjunto de escalas (JORGE *et al*., 2008).

A D_2, é uma função de correlação das medidas, computa as correlações contidas em um dado intervalo de tamanho do segmento (DAFONTE DAFONTE *et al*., 2015). Segundo Grassberger e Procaccia (1983), essas dimensões caracterizam a complexidade dos sistemas e a inferência de sistemas multifractais ou não, uma vez que, para que ocorra um sistema multifractal, os valores de dimensão devem seguir a tendência de $D_0 > D_1 > D_2$ (BANERJEE *et al*., 2011; VIDAL VAZQUÉZ *et al*., 2013; SIQUEIRA *et al*., 2018). Porém, para sistemas monofractais os valores de dimensão são representados por uma relação de escala determinada por $D_0 = D_1 = D_2$ (MANDELBROT, 1982; CANIEGO *et al*., 2006).

Dentro da análise multifractal, os gráficos de espectro de singularidade possibilitam avaliar a heterogeneidade de um sistema (DAFONTE DAFONTE *et al*., 2015 – Figura5). O espectro de singularidade expressa a multifractalidade dos subconjuntos de segmentos de tamanho δ, sendo uma função matemática determinada por $f(\alpha)$ em α, que fornece uma escala local ou escala única para o sistema (CANIEGO *et al*., 2005; ZELEKE e SI, 2006; BANERJEE *et al*., 2011; BISWAS *et al*., 2012).

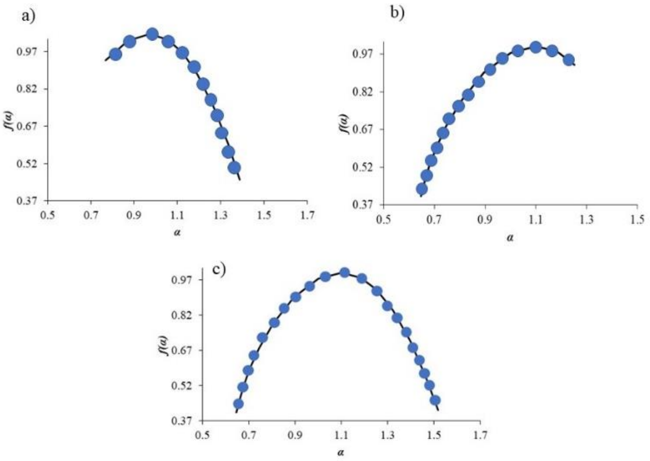

Figura 5 - Espectros de singularidade. a) espectro assimétrico para a direita; b) espectro assimétrico para a esquerda; c) espectro simétrico – sistema uniformemente distruibuido.

Os espectros são gráficos em forma de parábola (Figura 5) que permitem conhecer a concentração nos valores de medidas, mediante a assimetria do ramo do espectro. Dessa maneira, os espectros alongados para direita (Figura 5a) indicam concentração de valores baixos ou extremamente baixos no conjunto de dados (PAZ FERREIRO *et al*., 2018), contrariamente, os espectros alongados para esquerda (Figura 5b) são indicativos de concentração de valores elevados no banco de dados.

Porém, quando ocorre simetria no espectro de singularidade (Figura 5c) os valores são uniformemente distribuídos no suporte geométrico, sem concentração de valor elevado ou baixo no banco de dados, representando a multifractalidade da variável (ZELEKE e SI, 2006; BISWAS *et al*., 2012; YAKIMOV *et al*., 2014; BERTOL *et al*., 2017).

A análise multifractal oferece caracterização de uma única variável por vez, diferente da análise joint multifractal, que permite uma caracterização da distribuição de medidas de duas variáveis no mesmo suporte geométrico (ZELEKE e SI, 2005; BISWAS *et al*., 2012). Desse modo, como conceitua Banerjee *et al*. (2011) a análise joint multifractal representa uma extensão da abordagem multifractal, que determina as multiescalas de duas variáveis, considerando o mesmo suporte geométrico de distribuição das medidas. Assim, um único segmento é dividido em tamanhos menores de δ, e são definidas duas variáveis de probabilidade, $p_i(\delta)$ e $r_i(\delta)$. Essas variáveis determinam as forças de singularidades que são expressas pelos expoentes de singularidade α e β (BANERJEE *et al*. 2011), e que geram os índices de escalas $\alpha(q,t)$ e $\beta(q,t)$, plotados em gráficos de contorno de uma função $f(\alpha, \beta)$ (Figura 6).

Os gráficos de linhas de contorno representam a intensidade da dimensão dos índices de escalas para o par de variáveis, que retrata a distribuição dos valores elevados ou baixos para o banco de dados (ZELEKE e SI, 2005; 2006). Assim, a parte inferior esquerda do gráfico de linhas de contorno exibe a dimensão conjunta dos elevados valores das duas variáveis, enquanto, a parte superior direta representa os baixos valores do conjunto de dados (BISWAS *et al*., 2012).

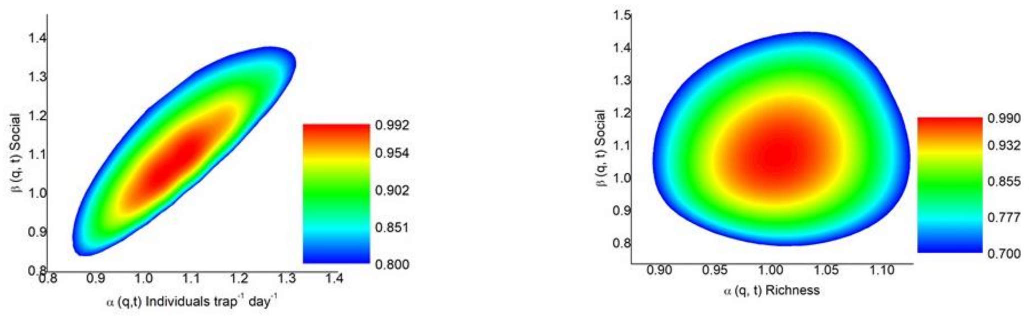
a) b)

Figura 6 - Gráficos de contorno da distribuição joint multifractal com os índices de escalas $\alpha(q,t)$ e $\beta(q,t)$.

Por meio dos gráficos de linhas de contorno é possível verificar a intensidade das correlações das duas variáveis no segmento. Desse modo, gráficos com contornos diagonais representam forte correlação entre os valores dos índices de escalas $\alpha(q,t)$ e $\beta(q,t)$, enquanto, gráficos circulares expressam ausência de associação de valores nas várias escalas (BANERJEE *et al*., 2011 - Figura 6a e 6b).

As fortes correlações obtidas indicam que as relações de escalas entre as duas variáveis são válidas em todas as escalas espaciais (ZELEKE e SI, 2006). Além do mais, a associação de valores entre duas variáveis pode ser expressa positiva ou negativamente. Nesse caso, ocorre associação positiva sempre que as duas variáveis apresentarem elevados valores em um mesmo local (segmento).

Por outra parte, se a primeira variável apresentar elevados valores, e a segunda variável apresentar valores baixos, as correlações serão negativas, e, portanto, a heterogeneidade da primeira variável não reflete a heterogeneidade da segunda variável nas mesmas escalas espaciais (BANERJEE *et al*., 2011; BISWAS *et al*., 2012).

As ferramentas de análise multifractal e joint multifractal vem sendo amplamente utilizada para avaliação da heterogeneidade de escalas de diferentes variáveis do solo (BERTOL *et al*., 2017; PAZ FERREIRO *et al*., 2018; SIQUEIRA *et al*., 2018; SILVA e SIQUEIRA, 2020) pois constituem ferramentas promissoras na avaliação dos atributos físicos, químicos e biológicos.

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CAPÍTULO I - ABUNDANCE AND DIVERSITY OF BEETLES (INSECTA: COLEOPTERA) IN LAND USE AND MANAGEMENT SYSTEMS

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Alana Cristina Cunha Bernardes(1), Osmann Cid Conde Oliveira(1), Raimunda Alves Silva(1), Patrícia Maia Correia Albuquerque(1), José Manuel Macário Rebêlo(1), Jéssica Herzog Viana(2) and Glécio Machado Siqueira(1)*

(1) Universidade Federal do Maranhão, Programa de Pós-Graduação da Rede BIONORTE, São Luís, Maranhão, Brasil.

(2) Universidade do Estado do Pará, Programa de Pós-Graduação em Ciências Ambientais, Belém, Pará, Brasil.

* Corresponding author:
e-mail: gleciosiqueira@hotmail.com

HIGHLIGHTS:

- Soil beetles are affected by management, with reduced ecosystem services.
- Soil arthropod communities (Insecta: Coleoptera) are impacted by soil management.
- Cultivation with soybean presented a high organism rate, with low species diversity.
- Coleoptera was mainly related to soil physical properties.

ABSTRACT: Soil beetles' communities are responsible for many ecosystem services and are very sensitive to environmental changes. Thus, the objective of this study was to evaluate the abundance and diversity of the soil coleoptera fauna under uses and management and also to identify relationships of the beetle community with soil's physical and chemical properties. The soil of the experimental sites is classified as Oxisol (*Latossolo*), and the climate of the region is tropical hot and humid. The experiment involved six experimental plots: corn (CO), soybean (SO), 7-year-old eucalyptus (EI), 4-year-old eucalyptus (EII), preserved Cerrado (PC), and disturbed Cerrado (DC). Soil beetles were sampled at 128 points for each experimental plot, where the soil physical and chemical properties were also measured. The Coleoptera fauna organisms were identified at the family, subfamily, and gender level, and then, the number of individuals per day, richness, Shannon diversity indices, and Pielou evenness were determined. Subsequently, the data were analyzed using multivariate techniques (hierarchical grouping and factor analysis). On total, 750 specimens of beetles were collected, distributed into 9 families, 14 subfamilies, and 27 genera. The most abundant family was Scarabaeidae (11 genera) with the highest occurrence in the areas of preserved Cerrado (147 specimens) and disturbed Cerrado (82 specimens). Cultivation with SO presented the greatest number of trap day individuals (ind trap^{-1} day^{-1} = 0.548); however, the highest diversity was found for areas with preserved Cerrado (20 taxonomic groups) and CO (16 taxonomic groups). Shannon diversity was higher for the corn plot (H' = 3.107), followed by the preserved Cerrado plot (H' = 2.883), and the lowest value was found for the soybean plot (H' = 1.530). The similarity dendrogram grouped the plots into two extracts, demonstrating how the intensity of land use influences the abundance and diversity of beetle fauna. The factor analysis grouped the Coleoptera and the physical and chemical soil properties in two factors: elements related to the state of aggregation and porous system’s elements. The Coleoptera community was influenced by the intensity of land use and the portion with anthropized natural vegetation showed the highest richness, demonstrating that the Coleoptera fauna responds to environmental changes. Edaphic beetles in the different use and management systems were primarily related to soil physical properties, which explain the state of aggregation (pH, altitude, Ca^{2+}, BD, clay, macroporosity, silt, K^{+}, and microporosity) and the porous soil system (sand and total porosity).

Keywords: soil biodiversity, soil properties, soil quality, ecosystem disturbances.

1 INTRODUCTION

The Coleoptera fauna of the soil has high abundance and diversity, being represented by organisms that respond quickly to environmental changes (Silva et al., 2011; Bogoni and Hernández, 2014; Barretto et al., 2019) and can thus be used as an indicator of soil environmental quality. The order Coleoptera represents the most diverse group of the Insect Class, with about 400,000 described species in the world, distributed in 170 families (Segura, 2012). For Brazil, Monné and Costa (2019) shown that only 32,000 species, belonging to 114 families, are described, and few studies have been devoted to the analysis of Coleoptera fauna in land use and management systems.

In this sense, it is necessary to understand the natural diversity of Coleoptera fauna, and how it is influenced by anthropic action. The diversity of the Coleoptera fauna organisms in the natural systems is in dynamic equilibrium (Aquino, 2001,2005), while in the agricultural production systems, we have a diversity associated with land use, influenced by the management, involving colonizing organisms. Depending on the degree of the environmental disturbance, they can become pest insects (Garlet et al., 2015), resulting in increased use of pesticides.

Soil beetles play an important role in nutrient cycling (Hanski and Cambefort, 1991; Nichols et al., 2008; Slade et al., 2011; Portilho et al., 2012), in the physical quality of the soil, with the increase of total soil porosity (Bogoni and Hernández, 2014; Pompeo et al., 2016; Tissiani et al., 2017; Barretto et al., 2019). The abundance of beetles is affected by land use and management (Hanski and Cambefort, 1991; Milhomem et al., 2003), and their occurrence is associated with the amount and quality of plant residues in agricultural production systems, including forest production (Araújo et al., 2004; Price and Young, 2006; Bartelt, 2010; Hernández-Torres, 2018).

Soil beetles also have diverse habits (Brown and Keith, 1991; Ewing and Cline, 2005; Moraes and Köhler, 2011; Santos et al., 2014), with phytophagous species (Louzada, 2008;

Korasaki et al., 2013), detritivores (Araújo et al., 2004), predators (Cividanes and Cividanes, 2008; Cividanes et al., 2009; Triplehorn and Johnson, 2011; Korasaki et al., 2013), fungivores (Louzada, 2008; Korasaki et al., 2013), being their ecological function regulated and/or determined according to the degree of disturbance of the environment, and of environmental characteristics, influencing the diversity and abundance of soil Coleoptera fauna (Gonçalves, 2017).

Therefore, it is necessary to understand how the soil Coleoptera fauna occurs in natural systems and how agricultural and forest production systems influence it. However, it must be considered that the diversity of the Coleoptera fauna is dynamic, and that production systems with lower environmental impact reflect more homogeneous diversity components. However, the magnitude of the biological differences in different land use and management systems, also reflect a complex and dynamic set of interactions in the soil-plant-atmosphere system that make up the natural and agricultural production systems.

Thus, the main hypothesis of this study is that soil use and management influence the coleopteran community; and that the lower the degree of environmental disturbance the greater the abundance and diversity of soil beetles. Our objectives were: a) to evaluate the abundance of the beetle community in land use and management systems; b) to quantify how land use and management influence the diversity of the Coleoptera fauna; c) to relate Coleoptera fauna organisms with physical and chemical properties of the soil.

2 MATERIALS AND METHODS

The experiment was conducted at Fazenda Unha de Gato, municipality of Mata Roma (Maranhão State, Brazil) whose geographical coordinates are: 3° 43’ 36.44” S and 43° 11’ 10.30” O. The climate of the region is hot tropical and humid with rains during summer and autumn and dry winter (Aw), with an average annual temperature of 28.5 °C and an average annual rainfall of 1,500 mm. The soil of the experimental area is an Oxisol (Soil Survey Staff, 2014) and according to Brazilian Soil Taxonomy is a Latossolo Vermelho Amarelo Distrófico típico (Santos et al., 2018), whose main physical and chemical properties are presented in table 1.

Table 1. Average values of soil physical and chemical properties sampled in experimental plots cultivated with soybean (SO), corn (CO), eucalyptus (EI and EII), preserved Cerrado (PC) and disturbed Cerrado (DC)

Area	Clay	Silt	Sand	BD	PT	Micro	Macro	OC	P	pH	K^+	Ca^{2+}	Mg^{2+}	CEC
	--------- g kg^{-1} --------			Mg m^{-3}	-------- m^3 m^{-3} --------			-- g dm^{-3} --		($CaCl_2$)	------- $mmol_c$ dm^{-3} -------			
SO	147.0	106	747.0	1.47	34.9	14.2	20.7	19.0	14.0	5.0	2.4	26.0	5.0	56.4
CO	180.0	100.0	720.0	1.72	35.9	13.2	22.7	22.0	49.0	5.0	0.7	18.0	3.0	46.7
EI	287.0	56.0	657.0	1.32	36.8	15.9	20.9	27.0	10.0	4.7	0.3	14.0	5.0	54.3
EII	202.0	81.0	717.0	0.55	35.8	15.0	20.8	23.0	12.0	4.85	1.35	20	5	55.3
PC	261.0	58.0	681.0	0.97	33.3	15.5	17.8	15.0	7.0	4.1	0.2	2.0	1.0	35.2
DP	256.0	77.0	667.0	1.22	34.1	15.4	18.7	21.0	8.0	4.2	0.5	3.0	3.0	42.5

BD: bulk density; PT: total pososity; Micro: microporosity; Macro: macroporosity; OC: organic carbon; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; CEC (cation exchange capacity). The properties were determined according to the methodology described by Camargo et al. (2009) and van Raij et al. (2001).

Six experimental plots were considered: corn (CO - 103 ha); soybean (SO-113 ha), eucalyptus stage I (E1 - 5.71 ha), eucalyptus stage II (E2 - 5.71 ha), preserved Cerrado (PC - 33.08 ha) and disturbed Cerrado (DC – 20.44 ha). The cultivation of corn (CO - *Zea mays* L.) and soybean (SO - *Glycine max* L.) started in 2007, with the natural vegetation being removed. Since then, the area has been managed under no-tillage system with soybean and corn cultivation in rotation. Eucalyptus plots (EI and EII - *Eucalyptus* ssp.) were planted in 2009 and 2012, respectively; the EI plot has trees of cut age (7 years) and an approximate height of 12 m, with soil cover around 90 % and few weeds; in EII, the trees are approximately 5 m (4 years old), with ground cover of about 70 %, and a high number of weeds and patches of uncovered soil. The natural vegetation in the study area is composed of savannah formations of Brazilian Cerrado Biome, with an upper tree extract composed of different density and height gradients, herbaceous extract and subarbustive, with different floristic composition. The plots with natural vegetation were characterized according to their purpose: PC is maintained as a permanent preservation area without any management; and DC is a natural area being used for cattle grazing in drought years.

Samples were taken on May 1, 2016 in 387 m transepts, containing 128 points and 3 m spacing between points, and the georeferenced sample points using GPS with postprocessed differential correction (DGPS). Deformed and undeformed soil samples were collected at the sampling points to determine the following properties: texture (clay, silt, and sand), bulk density (BD), total porosity (TP), macroporosity (Macro), microporosity (Micro), pH, phosphorus (P), calcium (Ca), Mg (magnesium), potassium (K), cation exchange capacity (CEC), and organic carbon (OC), following the methodology proposed by Camargo et al. (2009) and van Raij et al. (2001) - Table 1.

Soil Coleoptera sampling was performed using pitfall traps with no attractant and 4% formaldehyde solution (Aquino et al., 2001). The pitfall traps remained in the field for seven days and then taken to the laboratory, where the traps were sorted by separating the material from the Coleoptera fauna. After mounting, the specimens were identified to family and subfamily levels using an identification key (Quintero, 2012; Rafael et al., 2012; Cajaíba and Silva, 2015; Lima, 2015) and by comparison with the material previously identified in the Entomological Collection of the Paraense Museum - Emílio Goeldi (MPEG) and the collection of the LABSOLOS - UFMA Soil and Environment Laboratory – Federal University of Maranhão.

From the Coleoptera fauna data of the experimental plots, the number of individuals per day trap (ind trap^{-1} day^{-1}) and the total richness were determined, and the following indices were calculated: Shannon diversity (H') and equitability Pielou (J'). The number of individuals per day trap (ind trap^{-1} day^{-1}) represents the total Coleoptera fauna organisms collected over the seven days of sampling, and the richness was determined by the total number of taxonomic groups identified in each of the experimental plots. Shannon (H') and Pielou (J') indices were determined as described by Magurran (1988).

Multivariate data analysis was performed considering the hierarchical clustering technique and factor analysis using the Statistica 7.0 software. The clustering technique was used to group the Coleoptera data in the experimental plots by joining (tree clustering), from the Euclidean distance, allowing to determine if the subgroups formed had internal similarity or external dissimilarity. Data on Coleoptera fauna and soil physical and chemical properties were analyzed using the factor analysis technique, using the latent dimensions (shared variance), in order to observe the set of relationships between the properties. For factor analysis, the data were selected considering only the properties without collinearity, followed by standardization (null mean and unit variance), and the extracted factors considering the principal component analysis determined from the correlation matrix between the variables, and properties with factor loadings > 0.7 in absolute value are selected (Jeffers, 1978).

3 RESULTS

The Coleoptera community of the study area was represented by 9 families, 14 subfamilies, and 27 genera (Table 2). The family with the highest group diversity was Scarabeidae (11 genera), followed by the family Carabidae which showed great variability, being represented by 4 subfamilies and 8 genera. The other families contributed with a smaller number of taxa (Table 2).

Table 2. Identified Coleoptera families and number of individuals sampled in corn (CO), soybean (SO), eucalyptus (EI and EII), preserved Cerrado (PC), and disturbed Cerrado (DC)

Taxonomic Group	CO	SO	EI	EII	PC	DC
Carabidae Family						
Carabinae Subfamily						
Calosoma spp.	7	51	-	-	-	-
Cicindelinae Subfamily						
Megacephala sp.	3	-	-	-	-	-
Pentacomia sp.	-	-	-	-	1	-
Harpalinae Subfamily						
Poecilus sp.	-	-	-	-	3	-

Selenophorus sp.	6	2	-	1	-	-
Tetragonoderus sp.	9	4	-	-	-	-
Scaritinae Subfamily						
Oxydrepanus sp.	-	-	1	-	-	-
Scarites sp.	2		2	3	10	4
Chrysomelidae Family						
Eumolpinae Subfamily						
Eumolpinae sp.	-	-	1	-	-	-
Allocolaspis sp.	-	-	-	-	-	1
Costalimaita sp.	1	-	-	-	-	-
Galerucinae Subfamily						
Galerucinae sp.	-	-	-	-	1	-
Monomacra sp.	-	-	-	-	1	-
Styrepitrix sp.	-	1	-	-	-	2
Curculionidae Family						
Baridinae Subfamily						
Conoderini sp.	-	-	-	-	1	-
Histeridae Family						
Histerinae Subfamily						
Omalodes sp.	-	-	-	1	-	-
Nitidulidae Family						
Nitidulinae Subfamily						
Stelidota spp.	52	115	8	30	10	9
Ptilidae Family						
Ptilidae sp.	-	-	2	-	-	-
Scarabaeidae Family						
Scarabaeinae Subfamily						
Anomiopus sp.	-	-	-	-	-	1
Atheucus spp.	-	-	-	-	4	-
Canthidium spp.	6	-	3	1	33	4
Canthon spp.	3	1	1	4	20	35
Coprophanaeus sp.	4	1	1	2	4	16
Deltochilum spp.	3	1	28	18	77	18
Dichotomius sp.	27	-	16	-	2	8
Ontherus spp.	1	-	1	-	1	-
Onthophagus sp.	1	-	-	-	-	-
Pseudocanthon sp.	-	-	-	-	1	-
Uroxys spp.	-	-	-	2	5	-

Staphylinidae Family						
Aleocarinae Subfamily						
Aleocarinae sp.	-	-	-	-	3	1
Staphylininae Subfamily						
Philonthina sp.	-	-	-	-	1	-
Xanthopigina sp.	-	-	-	-	3	-
Scydmaeninae Subfamily						
Euconnus sp.	-	-	5	-	-	-
Tenebrionidae Family						
Tenebrioninae Subfamily						
Tenebrionini sp.	15	3	-	-	2	-
Blapstinus sp.	13	5	-	-	-	-
Total of individuals	**153**	**184**	**69**	**62**	**183**	**99**
Total of taxon’s	**16**	**10**	**12**	**9**	**20**	**11**

In total, 750 specimens of beetles were collected, with a predominance of the Scarabaeidae family that contributed 47.2% of the total sample (Figure 1). Following the most abundant families were Nitidulidae (29.86%), Carabidae (14.53%), and Tenebrionidae (5.06%). The remaining families together represented only 3.3% of the total sample. The most abundant genus was *Stelidota* (29.9%), followed by *Deltochilum* (19.3%), *Canthon* (8.5%), *Calosoma* (7.7%), *Dichotomius* (7.1%), and *Canthidium* (6.3%).

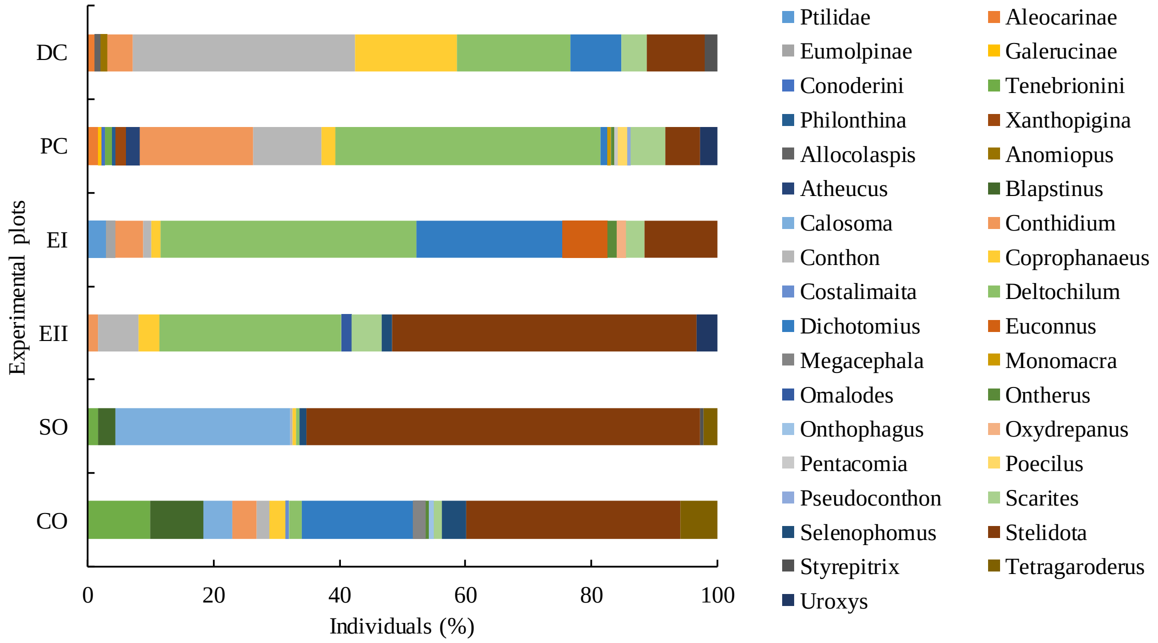

Figure 1. Coleoptera taxa and number of individuals sampled in the treatments: soybean (SO), corn (CO), eucalyptus (EI and EII), preserved Cerrado (PC), and disturbed Cerrado (DC).

The higher richness of Coleoptera taxa was observed in the PC (20 taxa), followed by CO (16), EI (12), DC (11), and SO (10) and EII (9) taxa each. The abundance was higher in the SO (24.5 %), followed by PC (24.4 %), CO (20.4 %), DC (13.2 %), EI (9.2 %), and EII (8.2 %) (Table 2; Figure 1).

Regarding the positivity rate of the traps, it was found that it was higher in the CO plot (45.4% of the coleopteran positive traps), followed by PC (40.8%), SO (36.9%), DC (23.1%), EI (23.1%) and EII (16.9% - Table 3). The cultivation of SO presented the largest number of ind trap^{-1} day^{-1} (0.548 ± 0.714), followed by PC (0.493 ± 0.143), DC (0.471 ± 0.143), EI (0.448 ± 0.143), CO (0.370 ± 1.857), and EII (0.295 ± 0.571), as shown in table 3. The CV values (%) for the number of beetles on traps with individuals was between 28.962% for PC and 501.307% for CO.

The highest value for Shannon diversity was found for CO (3.107), followed by PC (2.883), DC (2.699), EI (2.587), EII (2.099), and SO (1.530). The greater data uniformity, assessed using the Pielou index, was reported for DC (0.780), followed by CO (0.777), EI (0.722), PC (0.667), EII (0.662), and SO (0.460), the least uniform.

Table 3. Biological diversity indices for beetles in the different experimental plots: soybean (SO), corn (CO), eucalyptus (EI and EII), preserved Cerrado (PC) and disturbed Cerrado (DC)

Area	**N**	**Total**	**ind trap^{-1} day^{-1} (± SD)**	**CV** %	**Richness**	**Shannon (H')**	**Pielou (J')**
CO	59(45.4 %)	153	0.370±1.857	501.307	16	3.107	0.777
SO	48(36.9 %)	184	0.548±0.714	130.435	10	1.530	0.460
EI	30(23.1 %)	69	0.448±0.143	31.884	12	2.587	0.722
EII	22(16.9 %)	62	0.295±0.571	193.548	9	2.099	0.662
PC	53(40.8 %)	183	0.493±0.143	28.962	20	2.883	0.667
DC	30(23.1 %)	99	0.471±0.143	30.303	11	2.699	0.780

N: number of points with occurrence of coleoptera and positivity rate of the traps; Total: total of organisms collected; ind arm $^{-1}$ day $^{-1}$: trap individuals^{-1} day $^{-1}$; SD: standard deviation; CV: coefficient of variation (%).

The dendrogram of similarity presented two extracts: the first extract represents 19% of the Euclidean distance, grouping CO, SO, and EII, where CO and SO have greater similarity of the order of 15%; the second extract represents 26% of the Euclidean distance and grouped EI, PC, and DC, where EI and PC present similarity up to 13% (Figure 2).

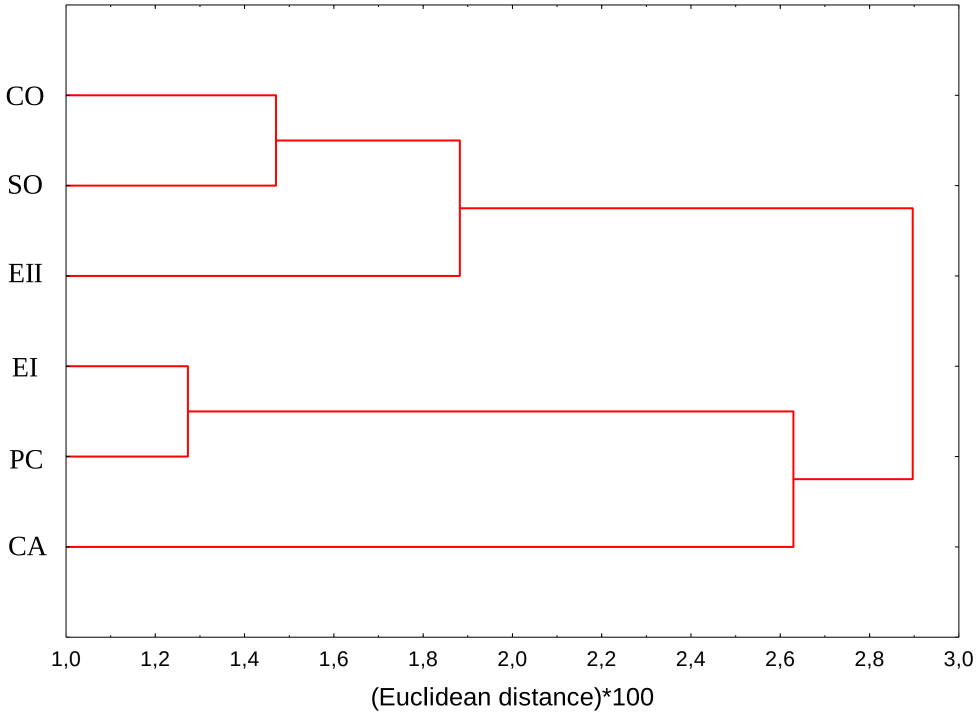

Figure 2. Dendrogram of similarity for beetles in experimental plots [soybean (SO), corn (CO), eucalyptus (EI and EII), preserved Cerrado (PC), and disturbed Cerrado (DC)].

The multivariate factor analysis allowed to group two components that explain 72.15% of the variability of data (Table 4). Factor 1 explained 49.60% of data variability involving 15 properties with factor loadings greater than 0.7: *Blapstinus sp*. (-0.828), *Deltochilum spp*. (0.831), *Scarites* sp. (0.821), *Selenophorus sp.* (-0.822), *Stelidota spp.* (-0.760*), Tetragonoderus sp*. (-0.847), altitude (-0.950), clay (0.842), silt (-0.754), BD (-0.905), microporosity (0.744), macroporosity (-0.843), pH (-0.953), K^+ (-0.745), and Ca^{2+} (-0.949). Factor 2 explained 22.54 % of the variability and grouped three properties: *Dichotomius sp*. (0.737), sand (0.996), and total porosity (-0.777).

Table 4. Analysis of factors (processes) and factor loadings that represent the correlation coefficients between soil attributes and each factor

	Fator 1	**Fator 2**
% of variance	49.60%	22.54%
Cumulative %	49.60%	72.14%
Eigenvalue	13.88	6.31
pH	-0.953*	-0.125
Altitude	-0.950*	0.162
Ca^{2+}	-0.949*	0.164
BD	-0.905*	-0.413
Tetragonoderus sp.	-0.847*	0.434
Clay	0.842*	0.245
Deltochilum spp.	0.831*	0.186
Blapstinus sp.	-0.828*	0.484
Macro	-0.823*	-0.496
Selenophorus sp.	-0.822*	0.517
Scarites sp.	0.821*	0.359
Stelidota spp.	-0.760*	-0.466
Silt	-0.754*	0.597
K^+	-0.745*	0.630
Micro	0.744*	0.222
Sand	-0.039	0.996*
TP	0.150	-0.777*
Dichotomius sp.	-0.457	0.737*
Interpretation	Elements related to the state of aggregation	Porous system elements

* Properties with factor loading significative [>0.7 (Jeffers, 1978)]; Ca: calcium; BD: bulk density; Macro: macroporosity; K: potassium; Micro: microporosity; TP: total porosity.

4 DISCUSSION

The beetle fauna was considered rich, with a wide variety of genera belonging to different families. The predominance of Scarabaeidae confirms the association of this family with forest systems (Nichols et al., 2008; Slade et al., 2011; Portilho et al., 2012; Costa et al., 2014; Pompeo, 2016), where there is continuous input of litter, with diverse composition and quality, resulting in high nutrient cycling rates (Nichols et al., 2008). The higher occurrence of this family is in the PC and DC plots. Scarabids are known to be important in the process of nutrient removal and reintroduction in the soil (Hanski and Cambefort, 1991; Nichols et al., 2008; Slade et al., 2011), as they respond rapidly to environmental changes, making them important indicators for monitoring ecosystems (Silva et al., 2011).

Deltochilum and *Canthon* (Scarabaeidae) genera were more abundant in native vegetation (PC and DC) and eucalyptus plots (EI and EII), showing that use and management systems, with continuous input of organic material, favored the occurrence of these organisms (Pompeo et al., 2016). These genera are sensitive to anthropogenic action under the environment (Halffter and Favila, 1993; Barretto et al., 2019), and their occurrence is related to less disturbed environments (Hanski and Cambefort, 1991; Milhomem et al., 2003; Bogoni and Hernández, 2014), justifying its occurrence in areas with native vegetation (PC and DC). The genera *Canthidium* spp., *Coprophanaeus* sp., *Dichotomius* spp., and *Ontherus* sp. in the experimental plots with CP and DC, presented varied abundance, and according to Lima et al. (2015), these groups are dependent on the availability of environmental resources.

The family Nitidulidae represented by the genus *Stelidota* presented greater abundance for the systems with SO and CO, which is justified by the fact that it is associated with cultivation systems with high input of organic material (Price and Young, 2006; Bartelt, 2010; Hernández-Torres, 2018). This family is composed of detritivorous organisms, and for this reason, they are associated with management systems with a rapid increment of plant residues on the soil surface (Araújo et al., 2004). On the other hand, the genus *Stelidota* has generalist characteristics

(Ewing and Cline, 2005; Moraes and Köhler, 2011; Santos et al., 2014), which, in part, justifies its occurrence in the other portions of this study.

The Carabidae family presented greater abundance in the SO, CO, and PC plots, and for the CO plot, the highest genera richness was described. This family is described as an environmental regulator (Cividanes and Cividanes, 2008; Cividanes et al., 2009; Triplehorn and Johnson, 2011; Korasaki et al., 2013), encompassing predatory species that are often used for biological control of agricultural pests. It is also indicated as a bioindicator of environmental quality due to its ecological fidelity (Brown and Keith, 1991; Quinteiro, 2012), when compared to other families of coleopterans, that are more generalist in relation to the environment.

The Tenebrionidae family occurred in CO and SO systems, distributed in two taxa: *Tenebrionini* sp. and *Blapstinus* sp., being in agreement with the ecological characteristics of the group that has been negatively associated with climate elements such as relative air humidity, and positively with insolation, which in turn results in higher average temperature values (Gonçalves, 2017). Thus, the management systems with higher vegetation cover (EI, EII, PC, and DC) involve systems with shrub and tree extract, having less insolation and higher relative humidity, when compared to the cultivation systems (CO and SO).

The largest abundance of beetles in the experimental plot with SO was due to the genus *Stelidota* that occurred with high frequency. However, Pompeo et al. (2016) studying the diversity of beetles in different land use systems [natural vegetation (Atlantic Forest), eucalyptus reforestation, pasture, crop-livestock integration, and direct tillage with soybean and corn] in southern Brazil, reported greater abundance in areas with native forest related to the family Staphylinidae. Portilho et al. (2012) studying edaphic fauna in different land use systems in central-western Brazil, found the highest abundance for a no-tillage plot, followed by natural vegetation plots [Semideciduous and Cerrado (Brazilian savanna)]. Gonçalves (2017) studying the relationship between soil beetles and climate parameters throughout the year in northeastern

Brazil under natural vegetation (Mata dos Cocais), found the highest abundance for the Scarabaeidae family.

The higher richness of organisms in DC and CO plots is related to food selectivity since in DC, it is used for grazing animals in drought years, making the food availability in this area different. Portilho et al. (2012) describe that Coleoptera fauna benefits from animal excrement in pasture areas, altering the diversity and abundance of coleopteran soil fauna. Price and Young (2006) described that in corn cultivation, Coleoptera benefits from the availability of decaying plant material, favoring mainly organisms with detritivorous habits. Thus, the occurrence of adapted taxa and selective habits related to the quantity and quality of the straw in CO, made this treatment present the highest Shannon diversity value (H' = 3.107). We highlight that the Shannon diversity index (H') quantifies the diversity of an area by the number of species and their relative abundance (Magurran, 1988), demonstrating that in CO, many groups of soil Coleoptera fauna occur and this occurrence is related to the food selectivity of these organisms, resulting in lower Pielou equitability (J' = 0.777). Silva et al. (2018) studying the diversity of soil fauna on different land uses and management also found higher Shannon values related to SO and CO crops. Cajaíba and Silva (2015) studying Coleoptera fauna in an area of the Amazon Rainforest found Shannon values ranging between 2.09 and 2.51 at the edge and inside the forest plot. Lima et al. (2015) studying the Coleoptera fauna under natural vegetation and cultivated field, found Shannon values of 2.54 and 1.62, respectively, demonstrating the decrease in Coleoptera diversity associated with land use and management. Pompeo et al. (2016) described Shannon values of 1.77 for the no-tillage system and 1.28 for natural vegetation for the beetle fauna sampled in southern Brazil.

Soil use and management influenced the abundance and diversity of soil beetles for the present study, grouping the plots with CO, SO, and EII, according to the similarity dendrogram. Silva et al. (2018) studying the soil fauna in different systems of use and management, found similar results, emphasizing that in addition to the intensity of use, it should be considered the vegetation cover of the plots under study. In this sense, we can explain the grouping between CO and SO considering the temperature and soil moisture in these areas, as reported by Garlet et al. (2015) and Gonçalves (2017). The grouping of EII in the same extract as CO and SO can also be explained by the amount of insolation this plot received, since EII is composed of young eucalyptus plants with 70% vegetation cover.

The similarity dendrogram grouped in a second extract EI, PC, and DC, involving vegetative compositions of natural forests (PC and DC) and eucalyptus forests (EI), with EI comprising a plot of trees larger than 12 m and aged 12 years. The differentiation of DC in this extract is due to the fact that this plot is used as a natural pasture for cattle in drought years. Portilho et al. (2012) report that, in pasture areas, Coleoptera fauna may benefit from animal excrement, resulting in a greater or lesser abundance of organisms. The use of the plot with DC as natural pasture in specific years also favors the development of specific creeping plants, since cattle are selective in their feed, which results in a different creeping plant community, as described by Silva et al. (2018). The greater similarity between EI and PC may be related to the percentage of vegetation cover in these plots (100%). The structure that the forests composes produces a climate of its own, such as the incidence of shade, decreased sun rays due to canopy, vegetation cover and varied organic matter availability, which are fundamental for the stability of beetle communities (Halffter and Favila, 1993; Lima et al., 2015; Barretto et al., 2019).

Factor analysis summarized the various variables into a smaller set of dimensions with minimal information loss, as follows: Factor 1 = elements related to the state of aggregation; and Factor 2 = porous system elements. In Factor 1, the taxa *Tetragonoderus* sp., *Blapstinus* sp., *Selenophorus* sp., *Scarites* sp., and *Stelidota* spp. are the ones that most contributed to explain the set of relations of the Coleoptera fauna with the physical and chemical properties (pH, altitude, Ca^{2+}, BD, clay, macroporosity, Silt, K^{+}, and microporosity). The pH was the property that most explained the presence of soil coleopteran taxa, demonstrating that along the landscape, changes in pH values result in a different coleopteran community, reflecting the occurrence of less abundant groups (*Tetragonoderus* sp., *Deltochilum* spp., *Blapstinus* sp., and *Scarites* sp.) or greater abundance (*Stelidota* spp.). Importantly, factor analysis does not take into account land use and should therefore only be used to identify complex interrelationships between variables. Silva et al. (2018) studying soil edaphic fauna in different soil uses and managements, described that the occurrence of invertebrate soil fauna was mainly explained by the soil Ca content, and that the Coleoptera fauna taxa was the variable that more explained in terms of total variation for the variables under study.

The variables that relate to the soil porous system (Factor 2 - sand, total porosity, and *Dichotomius* sp.) have a clear and expected relationship, since the taxon *Dichotomius* sp. is associated with the disintegration of fecal masses, which are shaped into spheres and transported over the ground and in ground-excavated galleries (Pompeo et al., 2016; Tissiani et al., 2017), thus contributing to the maintenance of the soil total porosity. Lavelle et al. (2006) and Schiavon et al. (2014) describe the importance of soil invertebrate fauna as ecosystem engineers, and responsible for modifying the environment, influencing soil dynamics and the ecosystem. Bogoni and Hernández (2014) and Barretto et al. (2019) also highlight that this taxon is sensitive to changes in the environment and can thus be used as quality indicators, since its populations may indicate the degree of imbalance in agricultural ecosystems.

5 CONCLUSIONS

The Coleoptera community was influenced by soil use and management and benefited from systems with lower environmental impact. Forest systems presented higher specimen abundance when compared to soybean and corn agricultural production systems. The soybean plot presented the highest diversity of taxa, followed by management systems with less soil mobilization (natural and forest systems). However, the highest Shannon diversity (*H'*) and Pielou equitability (*J'*) are described for systems with natural vegetation and eucalyptus, demonstrating how soil use and management interfere with soil Coleoptera fauna. Soil beetles in the different use and management systems were primarily related to soil physical properties, corresponding to the state of aggregation (pH, altitude, Ca^{2+}, BD, clay, macroporosity, silt, K^{+}, and microporosity) and the porous system (sand and total porosity).

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CAPÍTULO II - INVERTEBRATE FAUNA AND PHYSICO-CHEMICAL ATTRIBUTES OF SOIL IN DIFFERENT PHYTOPHYSIONOMIES OF CERRADO[1]

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Raimunda Alves Silva(2)* and Glécio Machado Siqueira(2)

[1]Research developed at Parque Estadual do Mirador, Mirador, MA, Brazil

[2]Universidade Federal do Maranhão. Departamento de Geociências, São Luís, MA, Brazil

* Corresponding author: e-mail: ray-234@hotmail.com

HIGHLIGHTS

Soil fauna is strongly influenced by plant composition.

High levels of organic material favor the presence of edaphic fauna.

Cerrado physiognomies presented different abundances and richness of soil organisms.

ABSTRACT: The edaphic community comprises several organisms that perform ecological functions in the environment, such as litter fragmentation, nutrient cycling, and modifications of soil structure, in addition to acting as food chain regulators. Thus, the objective of this study was to evaluate the composition of the edaphic fauna and the physical and chemical attributes of soil in different physiognomies of Cerrado in the Parque Estadual do Mirador (PEM). The study was carried out in two Cerrado formations (Sparse Cerrado and Typical Cerrado) in PEM, where 100 pitfall traps were installed. The edaphic organisms were screened and identified in terms of orders, suborders, subfamilies, families, abundance, richness, Shannon diversity, and Pielou's equitability. A total of 4,149 individuals were collected from two experimental plots. The plot in the Typical Cerrado showed greater taxonomic richness (25 groups) and greater Shannon diversity (H' = 1.65), while the plot in Sparse Cerrado presented 19 edaphic groups and Shannon diversity equal to H’ = 1.51. The factorial exploration explained 84.43% of the original data from the Sparse Cerrado and 90.84% from the Typical Cerrado. It is concluded that the plot in the Typical Cerrado showed greater differences in terms of richness and abundance due to the more favorable conditions for soil fauna, such as a high content of organic material and greater vegetation cover.

Key words: edaphic organisms, nutrient cycling, chain regulators

Fauna invertebrada e atributos físicos e químicos do solo em diferentes fitofisionomias de Cerrado

RESUMO: A comunidade edáfica é composta por diversos organismos que mantêm interações ecológicas nos ambientes, como fragmentação de serapilheira, ciclagem de nutrientes, modificações na estrutura do solo, além de reguladores de cadeia trófica. Assim, o objetivo deste estudo foi avaliar a composição da fauna invertebrada, os atributos físicos e químicos do solo em diferentes fisionomias de cerrado no Parque Estadual do Mirador (PEM). O estudo foi desenvolvido em duas formações de Cerrado (Cerrado Ralo e Cerrado Típico) no Parque Estadual do Mirador, onde foram instaladas 100 armadilhas pitfall. Os organismos edáficos foram triados, identificados em termos de ordens, subordens, subfamílias e família; a partir disso foram estimados os parâmetros abundância, riqueza, diversidade de Shannon e equitabilidade de Pielou. Um total de 4.149 indivíduos foram coletados nas duas parcelas experimentais. A parcela em Cerrado Típico apresentou maior riqueza taxonômica (25 grupos); e maior diversidade de Shannon (H’ = 1,65), enquanto a parcela em Cerrado Ralo apresentou 19 grupos edáficos e diversidade de Shannon igual a H’ = 1,51. A exploração fatorial explicou 84,43% dos dados originais do Cerrado Ralo e 90,84% dos dados do Cerrado Típico. Conclui-se, que a parcela em Cerrado Típico demonstrou maior diferença em termos de riqueza e abundância, decorrente das condições favoráveis à fauna edáfica como alto teor de matéria orgânica e maior cobertura vegetal.

Palavras-chave: invertebrados do solo, fauna edáfica, diversidade biológica

1 INTRODUCTION

The Cerrado, with high biodiversity and a high degree of endemism, is the second-largest biome in Brazil, covering approximately 22% of the Brazilian territory (Oliveira & Marquis, 2002); however, only 2% of this biome is protected through parks and reserves. In this context, in the State of Maranhão, the Parque Estadual do Mirador (PEM) comprises a Conservation Unit created in 1980 in the Cerrado domain. It contains forest vegetation (Cerradão and Riparian Forest) and savanna (Dense Cerrado, Typical Cerrado, and Sparse Cerrado (Ribeiro & Walter, 2008).

Edaphic organisms are important components of ecosystems, particularly with respect to the modification of the physical and chemical attributes of soil (Martins et al., 2018; Silva et al., 2018). They perform several services in the environment, including the processing of organic matter (Bedano et al., 2016; Franco et al., 2016), nutrient cycling (Wagg et al., 2014), changes in physical structures, in addition to acting in the food chain regulation (Siqueira et al., 2016; Roy et al., 2018).

Thus, physical, chemical, and biological attributes are important for elucidating soil modifications, as the quality of these attributes directly influences the growth and development of vegetation (Franco et al., 2016). Some studies have sought to elucidate the relationship between soil attributes and edaphic fauna. According to Moço et al. (2010), the quality and quantity of organic matter in soil is a key factor in edaphic fauna distribution.

In this sense, the hypothesis for the present study was that the abundance, diversity, and richness of soil fauna in the PEM are conditioned by changes in vegetation. Therefore, this study aimed to evaluate the relationship between soil fauna organisms and soil physicochemical attributes in different physiognomies of Cerrado in the PEM, Maranhão state, Brazil.

2 MATERIAL AND METHODS

The experimental plots were arranged in the Parque Estadual do Mirador (PEM, State of Maranhão, Brazil), which has 766,781 ha and is located under the geographical coordinates: 6° 42' 9.803" S and 44° 42' 54.936" W, and altitude of 432 m (Figure 1A). According to Köppen, the climate of the region is classified as Aw (humid tropical), with annual mean precipitation of 1.183 mm and mean monthly temperature varying between 24 and 32 °C. The natural vegetation of PEM is classified as Cerrado (Ribeiro & Walter, 2008), presenting forest formations (Riparian Forest) and savanna formations (Cerradão, Dense Cerrado, Typical Cerrado, and Sparse Cerrado (Figure 1A). The soil in the PEM is classified as an Oxisol, according to Soil Survey Staff (2014), and is formed from geological formations known as Corda and Sambaíba (Bandeira, 2013).

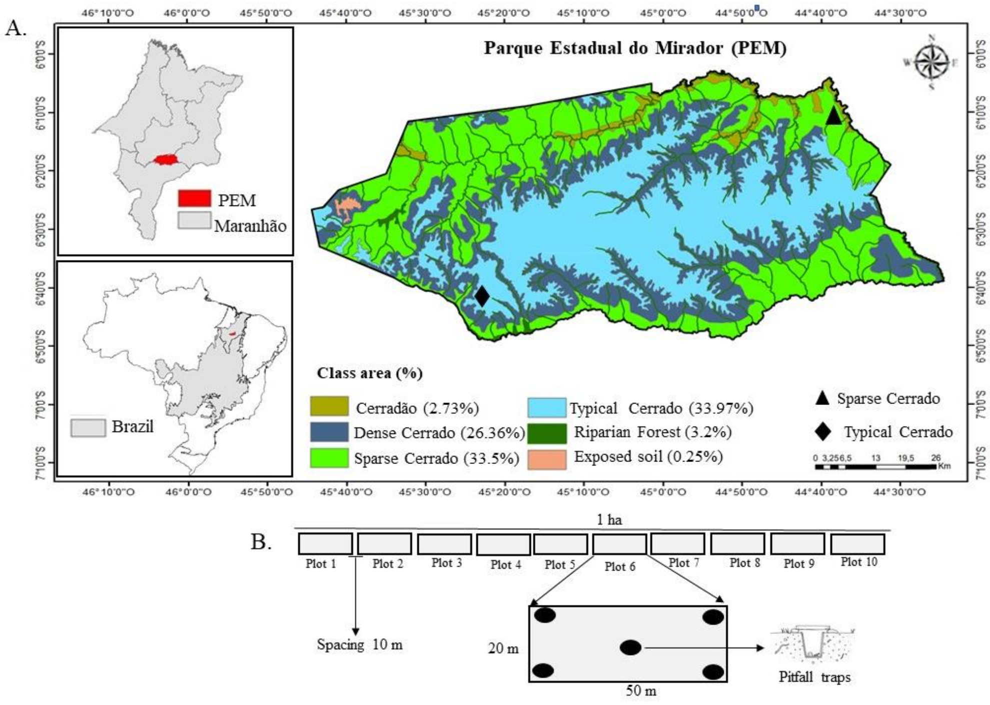


Figure 1. Location of the experimental plots in the Parque Estadual do Mirador, Maranhão, Brazil

On August 21, 2017, sampling was carried out in the two main physiognomies of the Cerrado in the PEM: Sparse Cerrado and Typical Cerrado (Figure 1A), during the dry season, characterized by the absence of precipitation and with a mean temperature of 36 °C. The physiognomy with Sparse Cerrado comprises vegetation with shrub-trees, with a mean height of trees between 2 and 3 m (Ribeiro & Walter, 2008), and the physiognomy of the Typical Cerrado comprises vegetation composed of trees with a mean height of about 3 to 6 m (Ribeiro & Walter, 2008).

In each of the vegetation physiognomies, 10 subplots of 20 × 50 m (1000 m^2) were installed 10 m apart (Figure 1B), from which the following characteristics were determined: soil fauna organisms (abundance, richness, Shannon's diversity, and equitability of Pielou), according to the methodologies of Aquino (2001), physical attributes of soil (texture [sand, silt, and clay], bulk density [BD], total porosity [TP]) according to Camargo et al. (2009); chemical attributes of soil (organic carbon [OC], pH, phosphorus [P], potassium [K], calcium [Ca], magnesium [Mg], the sum of bases [SB], and cation exchange capacity [CEC]), according to van Raij et al. (2001). For vegetation assessment, the number of tree specimens present in each subplot was counted, and the diameter at breast height (DBH) was measured for the shrub-tree layer with a diameter ≥ 0.1.

The soil fauna organisms were sampled using pitfall traps. Five traps were installed in each subplot, totaling 50 traps per Cerrado physiognomy (Figure 1B). The traps remained in the field for seven days, containing a 4% formaldehyde solution to preserve the organisms (Aquino, 2001). Subsequently, the organisms were screened and identified at the level of class, order, suborder, family, and subfamily.

In the present study, the Formicidae family was counted after its separation from the order Hymenoptera, considering evidence that Formicidae organisms participate in multiple environmental interactions and explore several ecological niches (Prado et al., 2019).

After the identification of soil fauna organisms, the following ecological indices were determined: abundance (total number of individuals collected in seven days of sampling), total richness (number of groups present in each plot), and values of Shannon's diversity index and equitability of Pielou, for the two plots under study. Shannon's diversity index was used to quantify the diversity of edaphic fauna in the two physiognomies of Cerrado, considering the number of individuals present in each sample and the relative abundance of groups (Eq. 1).

$$H' = \sum_{i=1}^{N} pi.\log_2 p_i \qquad (1)$$

where:

H' - represents Shannon's diversity;

N - corresponds to the number of individuals belonging to the i species in the sample,

p_i - corresponds to the relative abundance; and,

$\log_2$ - corresponds to the logarithm at base 2.

The Pielou equitability index considers Shannon's diversity and richness present in each sample, enabling the characterization of the uniformity of the sampled area (Eq. 2).

$$U = \frac{H'}{\log_2 S} \qquad (2)$$

where:

U - corresponds to Pielou's equitability;

H’ - corresponds to Shannon’s diversity; and,

$\log_2 S$ - corresponds to the logarithm in base 2 of richness.

The ecological indexes of edaphic fauna (abundance, richness, Shannon diversity, and Pielou equitability), soil physical and chemical attributes, and DBH (m) were subjected to statistical summarization [mean ($\overline{X}$), standard deviation (SD), coefficient of variation (CV%), asymmetry, and kurtosis; the normality of the data was verified by the Kolmogorov-Smirnov test (D-KS, $p < 0.01$)]. The comparison of means was made by t-test, and the intensity of Pearson's linear correlations was classified according to Santos (2007), which were classified as low ($r = \leq 0.5$)

and high (r = ≥ 0.5). Subsequently, the data were subjected to multivariate analysis to obtain the factors that explained the original data and the presentation of factors with factor loadings greater than 0.7 (Jeffers, 1978).

3 RESULTS AND DISCUSSION

A total of 2,258 individuals were identified in the Sparse Cerrado and 1,891 individuals in the Typical Cerrado (Table 1). The highest taxonomic richness was recorded for the Typical Cerrado (25 groups), followed by the Sparse Cerrado with 19 taxonomic groups. The greater diversity of the Typical Cerrado is related to a greater density of trees (Gholami et al., 2017; Sauvadet et al., 2017) and the quantity of food resources (Moço et al., 2010) available in this system, compared to the Sparse Cerrado.

The Shannon diversity index (Table 1) was higher for the Typical Cerrado (H' = 1.65) than for the Sparse Cerrado (H' = 1.51). The Typical Cerrado had the lowest abundance (Table 1); however, the greatest abundance does not mean greater diversity, since this parameter reflects the environment, corroborating the environmental characteristics of the Typical Cerrado, such as microclimate (Kamau et al., 2017), dense arboreal layer, and lower frequency of the herbaceous layer (Ribeiro & Walter, 2008), and the amount of litter (Bedano et al., 2016). Even with environmental differences between the two vegetation physiognomies, the Pielou equitability values were close (U = 0.38 - Typical Cerrado and U = 0.35 - Sparse Cerrado), indicating low variability in the uniformity of groups.

Table 1. Taxonomic groups and soil fauna diversity indexes in two physiognomies within the Parque Estadual do Mirador, Maranhão, Brazil

Taxonomic Grups	Sparse Cerrado		Typical Cerrado	
	Abundance	Numbers individuals/traps (%)	Abundance	Numbers individuals/traps (%)
TAXA CHELICERATA				
Subclass Acari	252	17(34)	116	29(58)
Order Araneae	106	5(10)	51	26(52)
Order Pseudoescorpionida	2	1(2)		
Order Solifugae	23	2(4)	21	11(22)
Family Scorpionidae	2	2(4)	5	5(10)
TAXA MYRIAPODA				
Class Symphyla	6	1(2)	3	2(4)
Class Diplopoda	2	1(2)	42	7(14)
TAXA HEXAPODA				
Order Protura	4	4(8)	4	4(8)
Order Collembola	35	9(18)	235	33(66)
Order Poduromorpha	10	4(8)	21	9(18)
Order Diplura			59	10(20)
Order Zygentoma	4	4(8)	2	2(4)
Order Orthroptera	3	1(2)	3	3(6)
Order Zoraptera			2	2(4)
Suborder Blattaria	132	11(22)	28	14(28)
Suborder Isoptera	10	2(4)	2	2(4)
Order Hemiptera	19	2(4)	5	2(4)
Suborder Sternorrhyncha			2	2(4)
Order Psocoptera			2	1(2)
Order Coleoptera	96	21(42)	99	37(74)
Order Hymenoptera	17	5(10)	23	10(20)
Family Formicidae	1,530	39(78)	1,146	50(100)
Order Lepidoptera	5	1(2)	6	4(8)
Order Strepsiptera			1	1(2)
Order Diptera			13	9(18)
Abundance	2,258		1,891	
Richness	19		25	
Shannon	1.51		1.65	
Pielou	0.35		0.38	

Ecological indices: numbers individuals/traps (%): number of traps with presence of individuals (%); Abundance: number of individuals collected in the sampling period; Richness: number of groups in the sample; Shannon: Shannon's diversity; Pielou: evenness of Pielou

The most abundant groups were Formicidae (1,530 and 1,146 individuals in Sparse Cerrado and Typical Cerrado, respectively); Acari (252 individuals, Sparse Cerrado and 116 individuals, Typical Cerrado); Collembola (35 individuals, Sparse Cerrado and 235 individuals, Typical Cerrado), and Coleoptera (96 individuals, Sparse Cerrado and 99 individuals, Typical Cerrado). The predominance of Formicidae, Acari, Collembola, and Coleoptera in the Cerrado areas was highlighted by Moço et al. (2010), Prado et al. (2019), and Silva et al. (2018).

While ants are described as being responsible for the fragmentation and incorporation of litter into the soil (Silva et al., 2017), mites and springtails are associated with the amount and quality of organic material in the soil (Sauvadet et al., 2017). The Coleoptera, on the other hand, are organisms associated with soil structure and fertility of the soil (Bernardes et al., 2020).

The statistical summary is presented in Table 2. There were statistical differences in the values of abundance of soil fauna ($\overline{X} = 56.450$ for Sparse Cerrado and $\overline{X} = 37.820$ for Typical Cerrado) and average richness ($\overline{X} = 5.640$ for the Typical Cerrado and $\overline{X} = 4.050$ for the Sparse Cerrado) according to the t-test (Table 2). Several organisms interact in the soil environment and support functions, such as litter fragmentation, nutrient cycling, and modification of soil structure, while also acting as food chain regulators. Thus, as shown previously, the diversity and abundance of soil fauna organisms reflect the vegetation composition in Cerrado environments, indicating that fragmentation can lead to loss of diversity and, consequently, to loss of ecosystem services.

The average value of OC was higher for the Typical Cerrado (OC = 11.005 g dm^{-3}) than for Sparse Cerrado (OC = 4.423 g dm^{-3}). The incorporation of OC is influenced by the composition of the vegetation present in the environment and the action of litter fragmenting organisms (Formicidae, Isoptera, and Coleoptera), which provide organic material to the soil (Bedano et al., 2016; Maggiotto et al., 2019). In this sense, the soil fauna is a key element in the dynamics of edaphic properties because it promotes physical and chemical modifications of soil (Ayuke et al., 2009).

Table 2. Summary statistics for the biological, physical, and chemical attributes of soil in the Parque Estadual do Mirador, Maranhão state, Brazil

Sparse Cerrado

	Mean ($\bar{X}$)	Variance	SD	CV (%)	Skew	Kurtosis	D*
Abundance	56.450 A	1585.587	39.819	70.539	1.763	3.678	0.138n
Richness	4.050 B	4.869	2.207	54.485	0.582	0.338	0.134n
Shannon	0.038 A	0.000	0.018	48.690	1.031	1.273	0.109n
Pielou	0.016 A	0.000	0.012	70.111	0.507	0.573	0.098n
Sand (g kg^{-1})	791.788 A	26103.870	161.567	20.405	-1.106	-0.358	0.269Ln
Silt (g kg^{-1})	65.713 B	3468.806	58.897	89.628	0.773	-0.682	0.191n
Clay (g kg^{-1})	142.500 A	12444.872	111.557	78.285	1.174	-0.122	0.281Ln
BD (kg dm^{-3})	1.393 A	0.008	0.089	6.417	-1.166	0.176	0.217n
TP (m^3 m^{-3})	0.421 A	0.002	0.040	9.399	-1.134	-0.267	0.278Ln
OC (g dm^{-3})	4.423 B	9.079	3.013	68.132	1.749	2.532	0.228n
pH (CaCl$_2$)	4.161 A	0.124	0.352	8.472	0.452	0.280	0.134n
P (g dm^{-3})	4.023 A	17.653	4.202	104.451	4.890	27.162	0.317Ln
K (mmol$_c$ dm^{-3})	0.993 A	0.078	0.279	28.062	3.010	13.138	0.204n
Ca (mmol$_c$ dm^{-3})	10.825 A	76.558	8.750	80.829	1.639	2.367	0.282Ln
Mg (mmol$_c$ dm^{-3})	10.417 A	31.013	5.569	53.459	0.487	-0.231	0.125n
SB (mmol$_c$ dm^{-3})	25.349 A	161.066	12.691	50.066	1.011	0.830	0.159n
CEC (mmol$_c$ dm^{-3})	68.458 A	1186.027	34.439	50.307	1.041	0.203	0.171n
DHB (m)	0.577 B	0.157	0.396	68.653	0.803	0.266	0.107n

Typical Cerrado

	Mean ($\bar{X}$)	Variance	SD	CV (%)	Skew	Kurtosis	D*
Abundance	37.820 B	327.008	18.083	47.814	1.204	1.751	0.134n
Richness	5.640 A	4.766	2.183	38.707	0.25	0.153	0.155n
Shannon	0.033 A	0.000	0.011	34.706	0.765	0.515	0.102n
Pielou	0.014 A	0.000	0.005	37.698	0.32	0.596	0.112n
Sand (g kg^{-1})	817.100 A	16242.653	127.447	15.597	-1.314	0.974	0.167n
Silt (g kg^{-1})	125.700 A	6458.622	80.366	63.934	0.967	0.091	0.197n
Clay (g kg^{-1})	57.200 B	4231.786	65.052	113.728	1.607	1.568	0.248Ln
BD (kg dm^{-3})	1.356 A	0.006	0.077	5.706	-0.045	-1.387	0.138n
TP (m^3 m^{-3})	0.412 A	0.002	0.044	10.765	-0.942	-0.389	0.201n
OC (g dm^{-3})	11.005 A	68.541	8.279	75.227	1.273	2.702	0.125n
pH (CaCl$_2$)	3.962 B	0.057	0.239	6.026	-0.656	-0.058	0.159n
P (g dm^{-3})	2.832 B	5.759	2.400	84.741	1.497	0.93	0.236Ln
K (mmol$_c$ dm^{-3})	0.966 A	0.282	0.531	55.006	1.674	2.034	0.295Ln
Ca (mmol$_c$ dm^{-3})	5.700 B	26.418	5.140	90.173	0.363	-1.329	0.186n
Mg (mmol$_c$ dm^{-3})	10.160 A	27.484	5.243	51.6	0.685	-0.725	0.207n
SB (mmol$_c$ dm^{-3})	19.189 B	112.708	10.616	55.325	0.902	-0.538	0.242Ln

CEC (mmol$_c$ dm^{-3})	58.231 B	587.837	24.245	41.637	1.164	1.61	0.149n
DBH (m)	0.611 A	0.051	0.225	54.706	1.405	2.476	0.187n

$\overline{X}$ - Mean; SD - Standard deviation; CV - Coefficient of variation (%); D* - Kolmogorov Smirnov normality test at 0.01; BD - bulk density; TP - total porosity; OC - organic carbonic; P - phosphorus; K - potassium; Ca - calcium; Mg - magnesium; SB - sum of bases; CEC - cation exchange capacity; DBH (m) - diameter at breast height. Means followed by the same letters in the column do not differ by t-test

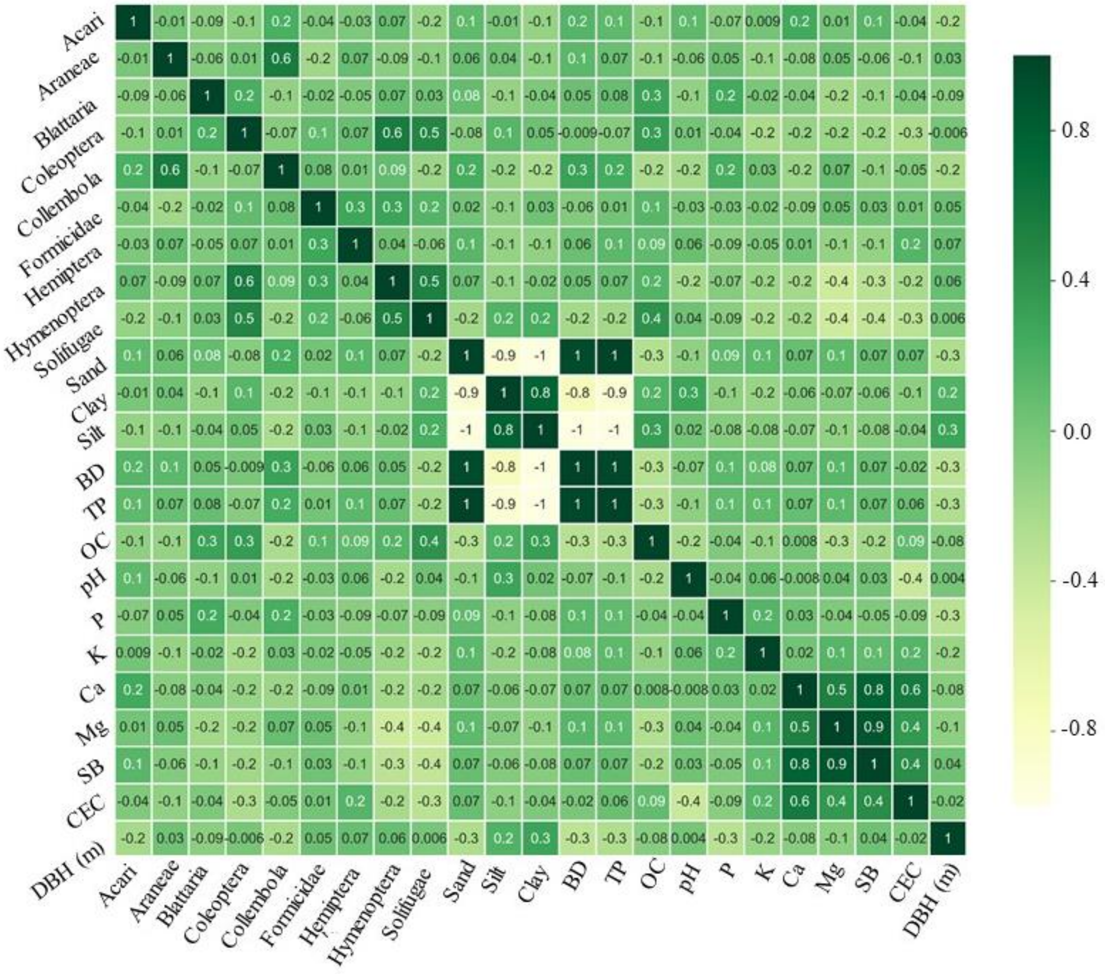
The DBH values showed statistical differentiation, describing the high variability of environments present in the Cerrado biome, as described by Ribeiro & Walter (2008). The statistical differentiation of the Cerrado environments demonstrated the importance of environmental conservation and sustainable land use.

Silt (g kg^{-1}) was the only physical attribute under examination that showed statistical differentiation in the experimental plots installed in the Oxisol of PEM. Regarding chemical attributes, there were statistical differences for pH, P, Ca, SB, and CEC, indicating that the soil in the plot of Typical Cerrado had lower values for these attributes. According to Bandeira (2013), the PEM soils, formed from Corda Formation sediments, have greater variability than the soils formed from the Sambaíba Formation, thus justifying the differences in the mean values of physical and chemical attributes, as well as of CV values (%).

The correlations between the soil fauna organisms and the physical and chemical attributes of soil, as well as the DBH (m), are shown in Figures 2 and 3, where the correlation values were classified according to the classification of Santos (2007).

In the Sparse Cerrado plot (Figure 2), high correlations were found between Solifugae and Hymenoptera (r = 0.53), Collembola versus Araneae (r = 0.56), and Hymenoptera versus Coleoptera (r = 0.57), indicating that two communities of organisms stood out: predators (Solifugae, Hymenoptera, and Araneae), and organic matter shredders (Collembola and Coleoptera). Correlations involving predatory organisms reveal the characteristics that enable them to explore and adapt to the environment.

It is pertinent to highlight that the Solifugae group also showed negative correlations with the soil physical attributes in the Sparse Cerrado: Solifugae versus Sand (*r* = -0.21), Solifugae versus BD (*r* = -0.21), and Solifugae versus TP (*r* = -0.21) demonstrating that this group thrives in environmental situations with high clay content. According to Valdivia et al. (2011), members of the Solifugae have a close relationship with the pedological characteristics of the environment. These characteristics can determine the abundance and distribution of the group because they affect oviposition, soil excavation, and the available food resources.



	Acari	Araneae	Blattaria	Coleoptera	Collembola	Formicidae	Hemiptera	Hymenoptera	Solifugae	Sand	Silt	Clay	BD	TP	OC	pH	P	K	Ca	Mg	SB	CEC	DBH (m)
Acari	1	-0.01	-0.09	-0.1	0.2	-0.04	-0.03	0.07	-0.2	0.1	-0.01	-0.1	0.2	0.1	-0.1	0.1	-0.07	0.009	0.2	0.01	0.1	-0.04	-0.2
Araneae	-0.01	1	-0.06	0.01	0.6	-0.2	0.07	-0.09	-0.1	0.06	0.04	-0.1	0.1	0.07	-0.1	-0.06	0.05	-0.1	-0.08	0.05	-0.06	-0.1	0.03
Blattaria	-0.09	-0.06	1	0.2	-0.1	-0.02	-0.05	0.07	0.03	0.08	-0.1	-0.04	0.05	0.08	0.3	-0.1	0.2	-0.02	-0.04	-0.2	-0.1	-0.04	-0.09
Coleoptera	-0.1	0.01	0.2	1	-0.07	0.1	0.07	0.6	0.5	-0.08	0.1	0.05	-0.009	-0.07	0.3	0.01	-0.04	-0.2	-0.2	-0.2	-0.2	-0.3	-0.006
Collembola	0.2	0.6	-0.1	-0.07	1	0.08	0.01	0.09	-0.2	0.2	-0.2	-0.2	0.3	0.2	-0.2	-0.2	0.2	0.03	-0.2	0.07	-0.1	-0.05	-0.2
Formicidae	-0.04	-0.2	-0.02	0.1	0.08	1	0.3	0.3	0.2	0.02	-0.1	0.03	-0.06	0.01	0.1	-0.03	-0.03	-0.02	-0.09	0.05	0.03	0.01	0.05
Hemiptera	-0.03	0.07	-0.05	0.07	0.01	0.3	1	0.04	-0.06	0.1	-0.1	-0.1	0.06	0.1	0.09	0.06	-0.09	-0.05	0.01	-0.1	-0.1	0.2	0.07
Hymenoptera	0.07	-0.09	0.07	0.6	0.09	0.3	0.04	1	0.5	0.07	-0.1	-0.02	0.05	0.07	0.2	-0.2	-0.07	-0.2	-0.2	-0.4	-0.3	-0.2	0.06
Solifugae	-0.2	-0.1	0.03	0.5	-0.2	0.2	-0.06	0.5	1	-0.2	0.2	0.2	-0.2	-0.2	0.4	0.04	-0.09	-0.2	-0.2	-0.4	-0.4	-0.3	0.006
Sand	0.1	0.06	0.08	-0.08	0.2	0.02	0.1	0.07	-0.2	1	-0.9	-1	1	1	-0.3	-0.1	0.09	0.1	0.07	0.1	0.07	0.07	-0.3
Clay	-0.01	0.04	-0.1	0.1	-0.2	-0.1	-0.1	-0.1	0.2	-0.9	1	0.8	-0.8	-0.9	0.2	0.3	-0.1	-0.2	-0.06	-0.07	-0.06	-0.1	0.2
Silt	-0.1	-0.1	-0.04	0.05	-0.2	0.03	-0.1	-0.02	0.2	-1	0.8	1	-1	-1	0.3	0.02	-0.08	-0.08	-0.07	-0.1	-0.08	-0.04	0.3
BD	0.2	0.1	0.05	-0.009	0.3	-0.06	0.06	0.05	-0.2	1	-0.8	-1	1	1	-0.3	-0.07	0.1	0.08	0.07	0.1	0.07	-0.02	-0.3
TP	0.1	0.07	0.08	-0.07	0.2	0.01	0.1	0.07	-0.2	1	-0.9	-1	1	1	-0.3	-0.1	0.1	0.1	0.07	0.1	0.07	0.06	-0.3
OC	-0.1	-0.1	0.3	0.3	-0.2	0.1	0.09	0.2	0.4	-0.3	0.2	0.3	-0.3	-0.3	1	-0.2	-0.04	-0.1	0.008	-0.3	-0.2	0.09	-0.08
pH	0.1	-0.06	-0.1	0.01	-0.2	-0.03	0.06	-0.2	0.04	-0.1	0.3	0.02	-0.07	-0.1	-0.2	1	-0.04	0.06	-0.008	0.04	0.03	-0.4	0.004
P	-0.07	0.05	0.2	-0.04	0.2	-0.03	-0.09	-0.07	-0.09	0.09	-0.1	-0.08	0.1	0.1	-0.04	-0.04	1	0.2	0.03	-0.04	-0.05	-0.09	-0.3
K	0.009	-0.1	-0.02	-0.2	0.03	-0.02	-0.05	-0.2	-0.2	0.1	-0.2	-0.08	0.08	0.1	-0.1	0.06	0.2	1	0.02	0.1	0.1	0.2	-0.2
Ca	0.2	-0.08	-0.04	-0.2	-0.2	-0.09	0.01	-0.2	-0.2	0.07	-0.06	-0.07	0.07	0.07	0.008	-0.008	0.03	0.02	1	0.5	0.8	0.6	-0.08
Mg	0.01	0.05	-0.2	-0.2	0.07	0.05	-0.1	-0.4	-0.4	0.1	-0.07	-0.1	0.1	0.1	-0.3	0.04	-0.04	0.1	0.5	1	0.9	0.4	-0.1
SB	0.1	-0.06	-0.1	-0.2	-0.1	0.03	-0.1	-0.3	-0.4	0.07	-0.06	-0.08	0.07	0.07	-0.2	0.03	-0.05	0.1	0.8	0.9	1	0.4	0.04
CEC	-0.04	-0.1	-0.04	-0.3	-0.05	0.01	0.2	-0.2	-0.3	0.07	-0.1	-0.04	-0.02	0.06	0.09	-0.4	-0.09	0.2	0.6	0.4	0.4	1	-0.02
DBH (m)	-0.2	0.03	-0.09	-0.006	-0.2	0.05	0.07	0.06	0.006	-0.3	0.2	0.3	-0.3	-0.3	-0.08	0.004	-0.3	-0.2	-0.08	-0.1	0.04	-0.02	1

Figure 2. Correlation matrix for physical, chemical, and biological attributes in Sparse Cerrado in the Parque Estadual do Mirador, Maranhão state, Brazil.

Figure 3 shows the correlations between the soil fauna and the physical and chemical soil properties in the Typical Cerrado. The correlations between the edaphic fauna, the physical and chemical attributes of the soil, and DBH (m) were considered low according to the classification of Santos (2007), except for those between Solifugae and Hymenoptera (r = 0.51), Diptera versus Araneae (r = 0.53), and Myriapoda versus Diplopoda (r = 0.67), which were significant ($r \geq 0.5$) and positive, indicating the growth of food-chain regulatory groups (Solifugae, Araneae, and Diptera) that depend on the abundance of prey organisms (Valdivia et al., 2011).

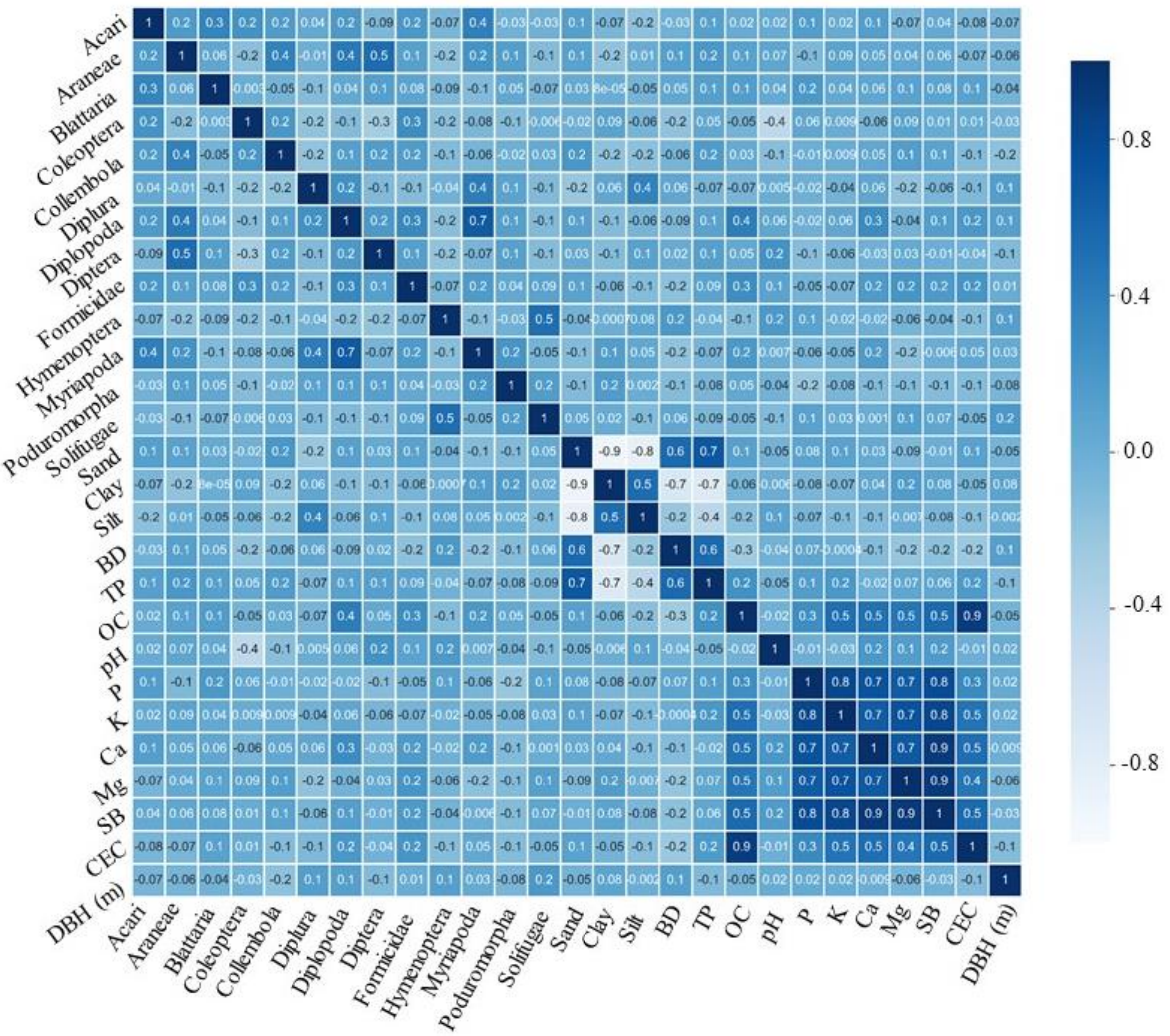


Figure 3. Correlation matrix for physical, chemical, and biological attributes in Typical Cerrado in the Parque Estadual do Mirador, Maranhão state, Brazil.

Multivariate analysis, through the factorial approach, in the plot of Sparse Cerrado (Table 3), explained 84.43% of the relationships between the variables. Factor 1 explained 66.32%, Factor 2 explained 12.11%, and Factor 3 explained 6.00%. Specifically, Factor 1 grouped variables that indicated the physical, chemical, and biological qualities of soil (pH [0.982], BD

[0.982], TP [0.982], K [0.981], Collembola [0.976], OC [0.945], P [0.982], Coleoptera [0.926], sand [0.905], clay [-0.904], Mg [0.827], silt [-0.820], Blattaria [0.75132], and Araneae [0.748)]). Soil fertility indicators constituted Factor 2, as follows: SB (0.874) and CEC (0.799), while Factor 3 included organisms that explored multiple ecological niches (Formicidae [-0.969]).

The associations of the edaphic groups in Factor 1 are related to a series of interactions between the edaphic fauna and the physical and chemical attributes of soil, establishing a relationship between the organisms responsible for the fragmentation and decomposition processes (Coleoptera, Acari, and Collembola) and trophic relationships (Araneae), corroborating the findings of Bedano et al. (2016) and Roy et al. (2018). On the other hand, the presence of a single group (Formicidae) in Factor 3 was due to the variety of trophic guilds explored by this group (Aquino, 2001), in addition to the intrinsic social behavior of these organisms (Prado et al., 2019).

The factor analysis for the plot of the Typical Cerrado explained 90.84% of the original data (Table 3), distributed in three factors: Factor 1 (65.51%), Factor 2 (18.44%), and Factor 3 (6.89%). Factor 1 was grouped as follows: pH (0.970), BD (0.970), TP (0.969), Araneae (0.966), K (0.964), Blattaria (0.958), Coleoptera (0.943), P (0.929), Acari (0.938), Collembola (0.880), sand (0.854), clay (-0,817), Ca (0.749), and Mg (0.709). Factor 2, mainly comprising SB and CEC, was associated with soil fertility. The Formicidae family was the only factor associated with Factor 3, indicating the complexity of interactions for this group (Prado et al., 2019).

Using multivariate statistics, the biological, physical, and chemical attributes of the soil in both experimental plots were grouped into three coincident factors, which explain the existing processes between the variables in the plots.

Table 3. Factor analysis containing the first three factors with factor loadings of representative correlation coefficients for soil fauna and physical and chemical attributes of soil in the physiognomy of Sparse Cerrado and Typical Cerrado in the Parque Estadual do Mirador, Maranhão state, Brazil

Sparse Cerrado			
Properties	Factor 1	Factor 2	Factor 3
	66.32%	12.11%	6.00%
pH ($CaCl_2$)	0.982	0.102	0.038
BD (kg dm^{-3})	0.982	0.122	0.0236
TP (m^{3} m^{-3})	0.982	0.125	0.0209
K (mmol$_{c}$ dm^{-3})	0.981	0.127	0.023
Collembola	0.976	0.107	0.019
OC (g dm^{-3})	0.945	0.061	-0.066
P (g dm^{-3})	0.942	0.094	0.030
Coleoptera	0.926	-0.017	-0.031
Sand (g kg^{-1})	0.905	0.307	-0.043
Clay (g kg^{-1})	-0.904	-0.343	0.074
Mg (mmol$_{c}$ dm^{-3})	0.827	0.433	0.027
Silt (g kg^{-1})	-0.820	-0.386	0.270
Blattaria	0.751	-0.010	-0.015
Araneae	0.748	-0.024	0.186
SB (mmol$_{c}$ dm^{-3})	0.351	0.786	0.092
CEC (mmol$_{c}$ dm^{-3})	-0.280	0.760	-0.058
Formicidae	0.007	-0.040	-0.969
Interpretation	Elements of physical, chemical, and biological quality of soil	Indicators of soil fertility	Organisms with multiple ecological niches

Typical Cerrado			
Properties	Factor 1	Factor 2	Factor 3
	65.51	18.44	6.89
pH ($CaCl_2$)	0.970	0.158	0.130
BD (kg dm^{-3})	0.970	0.162	0.135
TP (m^{3} m^{-3})	0.969	0.167	0.138
Araneae	0.966	0.151	0.143
K (mmol$_{c}$ dm^{-3})	0.964	0.210	0.118
Blattaria	0.958	0.172	0.147
Coleoptera	0.943	0.130	0.192
P (g dm^{-3})	0.929	0.332	0.023
Acari	0.938	0.153	0.156
Collembola	0.880	0.125	0.137

Sand (g kg^{-1})	0.854	0.414	0.236
Clay (g kg^{-1})	-0.817	-0.331	-0.229
Ca ($mmol_c$ dm^{-3})	0.749	0.588	-0.002
Mg ($mmol_c$ dm^{-3})	0.709	0.608	0.001
SB ($mmol_c$ dm^{-3})	0.280	0.874	-0.160
CEC ($mmol_c$ dm^{-3})	-0.216	0.799	0.361
Formicidae	0.298	0.124	0.815
Interpretation	Elements of physical, chemical, and biological quality of soil	Indicators of soil fertility	Organisms with multiple ecological niches

Notably, regardless of the differences between vegetation types (Sparse Cerrado and Typical Cerrado), because there is no disturbance, the patterns of occurrence of factors and variables remain as subsidiaries in the management process, favoring the development of integrated indicators of quality. Among the soil fauna, ants have a particularly high potential as indicators of environmental quality because they have high diversity and the capacity to explore the environment (Silva et al., 2017; Prado et al., 2019).

In the Typical Cerrado, the taxonomic groups are more uniformly distributed compared to the Sparse Cerrado. Our results demonstrated that the invertebrate fauna in the two physiognomies differed with respect to the values of abundance and richness but with small differences in the magnitude of diversity indices (Shannon and Pielou). This demonstrates how vegetation composition influences the ecology of different taxonomic groups (Gholami et al., 2017; Roy et al., 2018; Silva et al., 2019).

CONCLUSIONS

1. The invertebrate fauna of soil in the Parque Estadual do Mirador (PEM) are associated with soil structure (physical attributes) and with indicators of the chemical quality of soil (chemical attributes).

2. The groups Formicidae, Coleoptera, and Collembola are organisms associated with the chemical quality of the soil in the two physiognomies of Cerrado in PEM.

3. In the PEM physiognomies, the diversity and richness of taxonomic groups are influenced by the plant cover present in the sample area.

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CAPÍTULO III - SPATIAL VARIABILITY OF PLANT FORMATIONS IN SAVANA

Submissão à Revista Ecological Processes

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Raimunda Alves Silva(1)*, Eduardo Bezerra de Almeida Júnior(1) and Glécio Machado Siqueira(1)

(1) Universidade Federal do Maranhão, Programa de Pós-Graduação da Rede BIONORTE, São Luís, Maranhão, Brasil.

[*] Corresponding author: e-mail: ray-234@hotmail.com

Abstract: The Savanna, known in Brazil as Cerrado, comprises a vegetation mosaic distributed in Central Brazil and is considered a *hotspot* for biodiversity. Thus, the objective of this study was to evaluate the structure and spatial variability of vegetation in three plots in Savanna area. The plots were placed in Savanna vegetation (Sparse Cerrado - T1; Typical Cerrado - T2 and Dense Cerrado - T3), using the plots method. A plot of 20 x 500 m (1 ha) was delimited in each area, which was subsequently subdivided into 10 subplots of 20 x 50 m (0.1 ha), where individuals with diameter at breast height (DBH) ≥ 10 cm were sampled. The data were evaluated by descriptive statistics, diameter class and geostatistics tools. Six hundred eighty-four individuals were sampled in T1, 475 in T2 and 453 individuals in T3. There was no statistical difference for Diameter at Breast Height (DBH), analyzed by the Tukey test ($p < 0.05$). For the subplots, the T2 plot showed homogeneity for the mean values of DBH (m), corroborating the coefficient of variation (CV%) of this parameter. The diameter classes showed similar trends for all experimental plots, indicating self-regenerating communities. The spherical model was the one that best fitted the data, with different scales of spatial variability, greater spatial continuity for T3 (a = 210 m), and smaller spatial continuity for the T2 plot (a = 120 m). The scaled semivariograms adjusted to the spherical model showed different degrees of spatial dependence, demonstrating spatial continuity for all sample plots and subplots. The geostatistical tools were efficient to detect the spatial dependence of DBH (m) in the plots and subplots, in the three vegetation formations studied.

Key words: diameter at breast height, vegetation structure, geostatistical.

1 INTRODUCTION

Savanna is a xeromorphic vegetation, which in known as Cerrado Brazil (IBGE, 2012). Originally, the Brazilian Savanna covered an area of approximately 2 million km^2 (Sano et al., 2010), occupying about 22% of the Brazilian territory (Mittermeier et al., 2011; Alencar et al., 2020; Parente et al., 2021). It is considered one of the 25 ecosystems on the planet that present high biological diversity, being considered as a priority area for conservation (Myers et al., 2000). Currently, approximately 50% of the original area of Savanna has been removed or modified by anthropic action (Sano et al., 2007; Soares-Filho et al., 2014; Strassburg et al., 2017), mainly for agricultural use. Since the areas of Savanna comprises a vegetation complex, they are subdivided into four formations: Savanna Forest, Savanna Wooded, Savanna Park and Savanna Grassy-Woody (IBGE, 2012).

In the Brazilian Savanna, the studies about vegetation usually involve floristic and phytosociological surveys that assess the structure of plant community (Mews et al., 2011), providing information that characterizes the distribution and heterogeneity of species across the landscape (Felfili et al., 2002). The diameter at breast height (DBH) is a parameter frequently used to assess the vegetation structure of vegetation, which allows inferring about the state of plant community, describing the balance between mortality rate and recruitment of individuals (Felfili and Silva- Júnior 1988; Gomes et al., 2011; Sumida et al., 2013). In this regard, Felfili et al. (2000) and Assunção and Felfili (2004) consider that the distribution of individuals in diametric classes provides information if a community presents or not a self-regenerative state, information important in the decision-making about conservation aspects. Additionally, when evaluating the plant structure in a woody community in wooded Savanna, by means of the diametric distribution of the individuals, Mews et al. (2011) inferred that there was not the establishment of new individuals, which compensated the mortality rate in the area.

Although the studies about vegetation dynamic, and the studies involving phytosociological and taxonomic aspects are common in areas of Savanna (Felfili and Silva-Júnior, 1988; Araújo et al., 2011; Gomes et al., 2011; Mews et al., 2011), the plant community can also be characterized by the spatial distribution of individuals (Neves et al., 2010), making it possible to evaluate the different scales of spatial variability across the landscape (Gholami et al., 2017). In this sense, geostatistical tools allow the modeling and description of variability and spatial dependence between the attributes sampled in a given space (Cambardella et al., 1994; Vieira, 2000; Vieira et al., 2002), describing the spatial continuity of these attributes (Rosa Filho et al., 2011). Consistent with this, when studying a plant community, Neves et al. (2010) described different scales of spatial variability for the tree, tree and shrub strata, which, according to these authors, was caused by the characteristics of each plant fragment. For Gholami et al. (2017), the spatial variability of tree component can be described with greater or lesser spatial continuity, which is caused by the characteristics of the tree stratum such as density and species coverage.

Therefore, the hypothesis of this study was: that the different vegetal formations of Savannah of Parque Estadual do Mirador present different scales of spatial variability, which can be characterized by means of geostatistical analysis. Thus, the aim of this study was to evaluate the scales of plant component variability in physiognomies of Savannah in Parque Estadual do Mirador, through geostatistical analyses.

2 MATERIAL AND METHODS

2.1 Study area

The study was carried out in the Parque Estadual do Mirador (PEM), located in State of Maranhão, Brazil, in the geographical coordinates: 06°18’51” S and 45° 53’04” W (Figure 1A). PEM is an integral conservation unit with a total area of 766,781 ha, with an Aw type climate (humid tropical), an average annual rainfall of 1.183 mm, and an average temperature ranging from 24 °C (winter) to 32 °C (summer). The natural vegetation in PEM is Savanna, which is known in Brazil as Cerrado (IBGE, 2012), and is subdivided into four vegetation formations: Savanna Forest, Savanna Wooded, Savanna Park and Savanna Grassy-Woody (IBGE, 2012).

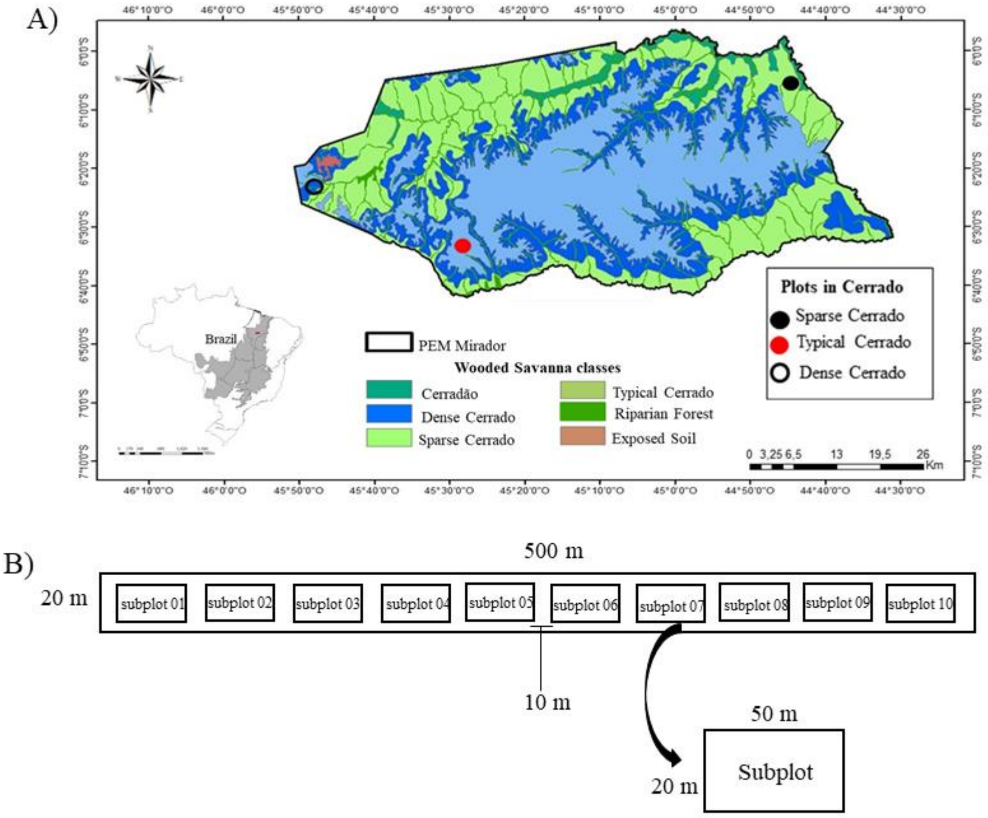


Figure 1. Location of the Parque Estadual do Mirador (PEM), Maranhão, Brazil.

In the present study, three experimental plots were delimited in the period from 07/21/2017 to 07/30/2017, in wooded Savannas that differ by the arboreal size in: Sparse Cerrado (T1), Typical Cerrado (T2), and Dense Cerrado (T3), according to Ribeiro and Walter (2008). T1 corresponds to 33.50% of the total area of PEM (Figure 1A), with sparse vegetation, trees around three meters high, and a three density of 0.396 ha^{-1}. The vegetal formation in T2 represents 33.97% of the PEM area, with a predominance of shrub-tree extract, and three density of 0.467 ha^{-1}. In turn, T3 corresponds to 26.36% of the PEM, with an arboreal size around eight meters high and three density of 1,605 ha^{-1}.

Soil samples were collected from the three experimental plots at depths 0-0.05 m, 0.05-0.15 m and 0.15-0.3 m for physical and chemical characterization. The physical characterization evaluated the fractions [Sand (g kg^{-1}), Silt (g kg^{-1}), Clay (g kg^{-1}), Density (BD, g dm^{-3}) and Total Porosity (TP, m^3 m^{-3})], according to Camargo et al (2009). While the chemical characterization comprised [Organic Carbon (OC, g dm^{-3}), Phosphorus (P, g dm^{-3}), pH (CaCl$_2$), Potassium (K, mmol$_c$ dm^{-3}), Calcium (Ca, mmol$_c$ dm^{-3}), Magnesium (Mg, mmol$_c$ dm^{-3}) and Cation exchange capacity (CEC, mmol$_c$ dm^{-3}), according to van Raij et al. (2001). The results of physical and chemical characterization of soil are shown in table 1.

Table 1: Physical and chemical characterization of the soil from plots in the Parque Estadual do Mirador (PEM), Maranhão, Brazil

Soil	Alt	Depth	Sand	Silt	Clay	BD	TP	OC	P	pH	K	Ca	Mg	CEC
	(m)	(m)	...........g kg^{-1}...........			g dm^{-3}	m^3 m^{-3}	.... g dm^{-3}....		CaCl$_2$	..........mmol$_c$ dm^{-3}..........			
T1 - Sparse Cerrado														
Oxisols	283	0-0.05	820.15	52.85	127.00	1.41	0.42	5.08	6.29	4.09	1.02	10.10	11.30	66.10
		0.05-0.15	845.00	15.00	140	1.41	0.40	3.13	0.8	4.30	0.80	5.00	1.00	20.10
		0.15-0.3	533.00	138.00	329	1.27	0.26	2.14	2.00	3.70	1.20	5.00	7.00	108.80
T2 - Typical Cerrado														
Entisol	432	0-0.05	839.22	41.88	118.88	1.36	0.43	14.20	2.79	3.94	0.79	6.50	8.40	73.19
		0.05-0.15	902.00	19.00	79.00	1.35	0.45	6.70	1.00	4.00	1.10	8.00	2.00	52.70
		0.15-0.3	758.00	13.00	229.00	1.24	0.38	5.86	2.00	4.20	1.20	16.00	10.00	46.60
T3 - Dense Cerrado														
Entisol	411	0-0.05	866.05	37.95	96.00	1.38	0.43	15.86	1.59	3.88	0.84	3.30	9.70	58.64
		0.05-0.15	816.00	155.00	169.00	1.26	0.26	10.20	2.00	4.60	0.90	10.00	9.00	41.50
		0.15-0.3	433.00	140.00	427.00	1.21	0.23	9.40	3.00	3.90	0.70	2.00	8.00	32.80

Alt - Altitude; BD - Bulk density; TP - Total porosity; OC - Organic carbon; P - Phosphorus; K - Potassium; Ca - Calcium; Mg - Magnesium; CEC - Cation exchange capacity

The parameter diameter at breast height [DBH (m)], estimated from the trees present in the experimental plots, were estimated based on the plot's method, according to the methodology of Mueller-Dombois and Ellenberg (1974). For this, the plots of 20 x 500 m (1 ha) were subdivided into 10 subplots of 20 x 50 m (0.1 ha), which were set with a spacing of 10 m (Figure 1B). All shrub-tree individuals with DBH ≥ 10 cm in the plots were measured and georeferenced; from this, the diametric classes were stablished, with an amplitude of 0.4 m (Mueller-Dombois and Ellenberg, 1974; Felfili and Silva-Júnior, 1988).

The individuals found with flowers or fruits at the time of phytosociological sampling were collected, herborized and identified using the Angiosperm Phylogeny Group classification system (APG IV, 2016), totaling 24 species: Anacardiaceae (*Anacardium occidentale* L. and *Tapirira guianensis* Aubl.); Apocynaceae (*Hancornia speciosa* Gomes and *Himatanthus* sp); Caryocaraceae (*Caryocar coriaceum* Wittm.); Chrysobalanaceae (*Hirtella glandulosa* Spreng. and *Hirtella ciliata* Mart. & Zucc.); Combretaceae (*Combretum* sp.); Conaraceae (*Connarus suberosus* Planch.); Dilleniaceae (*Curatella americana* L.); Fabaceae (*Albizia procera* (Roxb) Benth., *Dimorphandra mollis* Benth., *Parkia platycephala* Benth., *Plathymenia reticulata* Benth., *Stryphnodendron coriaceum* Benth., *Tachigali subvelutina* Benth. and *Vatairea macrocarpa* [(Benth. Ducke)]; Melastomataceae (*Mouriri elliptica* Mart.); Myrtaceae (*Eugenia sonderiana* Berg.); Opiliaceae (*Agonandra brasiliensis* Miers ex Benth); Vochysiaceae (*Salvertia convallariodora* A.St.-Hil., *Vochysia gardneri* Warm., *Qualea grandiflora* Mart. and *Qualea parviflora* Mart.).

2.2 Statistical and geostatistical analysis

The following statistical parameters were determined: mean ($\overline{X}$), standard deviation (SD), coefficient of variation (CV%), asymmetry and kurtosis. The normality of data was tested using the Kolmogorov-Smirnov test (D-KS - $p < 0.01$). CV values (%) were classified as low (CV ≤ 12%), median (CV = 12-60%) and high (CV ≥ 60%), according to Warrick and Nielsen (1980). The statistical difference for DBH (m) between plots and subplots were determined by the Tukey test ($p < 0.05$).

The spatial variability of data was assessed with aim of geostatistics tools, considering the assumptions of the intrinsic hypothesis (Journel and Huijbregts, 1978 - Equation 1):

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

(1)

where:

y(h) - is the value of semivariogram estimation for the distance *h*;

x - is the measure of separation of vector *h*;

h - is the distance between measurements;

N(h) - is the number of observations, separated by the distance *h*.

The data were adjusted to a mathematical model (Gaussian, exponential or spherical), by means of cross-validation, considering the values of adjustments corresponding to the parameters of the nugget effect (C_0), structural variation (C_1), and reach (a, m), according to Vieira (2000). Staggered semivariograms were constructed, following the assumptions of Vieira et al (1997), allowing comparing the patterns of spatial variability between variables. Spatial dependence was determined by the spatial dependency index (SDR, %) classified as strong (SDR ≤ 25%), moderate (SDR > 25% to < 75%), and weak (SDR ≥ 75%), according to Cambardella et al. (1994 - Equation 2).

$$SDR = \left(\frac{C_0}{C_0 + C_1}\right) * 100$$

(2)

where:

SDR - is the spatial dependency ratio;

C_0 - is the nugget effect;

C_1 - is the structural variance.

3 RESULTS

A total of 1,612 shrub-tree individuals were sampled in the three physiognomies: 684 ($\overline{X}$ = 0.37A) in T1; 475 ($\overline{X}$ = 0.37A) in T2, and 453 ($\overline{X}$ = 0.37A) in T3; and there was no statistical differentiation by the Tukey test ($p<0.05$ - Table 2). Statistical differentiation was observed for the subplots corresponding to T1 and T3 (subplot 01 - 0.52A; subplot 03 - 0.28B; subplot 08 - 0.33B; subplot 09 - 0.30B; subplot 10 - 0.31B and subplot 30 - 0.66A). The data presented high CV values for the three experimental plots (values > 60%), according to the Warrick and Nielsen classification (1980 - Table 2). However, T2 presented four subplots with median CV values (subplots 11, 13, 15 and 17). While T3 showed two subplots with median CV (subplots 21 and 22). The diameter at breast height data showed lognormal frequency distribution in T1, T2 and T3, based on the Kolmogorov-Smirnov test [D-KS ($p < 0.05$)]. Regarding the subplots, T2 and T3 presented normality of data (Table 2).

Table 2: Descriptive statistics for diameter at breast height (DBH) in physiognomies of Cerrado in the Parque Estadual do Mirador, Maranhão, Brazil

	N		Mean ($\overline{X}$)	Variance	SD	CV (%)	Skew	Kurtosis	D-KS*
			T1 – Sparse Cerrado						
Plot	684	1 ha	0.37A	0.09	0.30	80.35	2.47	8.80	0.181Ln
Subplot 01	42	0.1 ha	0.52A	0.13	0.36	69.05	1.16	1.39	0.144n
Subplot 02	67		0.42AB	0.12	0.35	84.48	2.21	6.03	0.170n
Subplot 03	103		0.28B	0.07	0.26	93.08	2.35	6.09	0.213Ln
Subplot 04	61		0.37AB	0.06	0.24	66.48	1.21	1.09	0.126n
Subplot 05	71		0.37AB	0.08	0.28	76.04	1.73	3.52	0.143n
Subplot 06	68		0.40AB	0.13	0.37	91.68	3.05	11.47	0.206Ln
Subplot 07	59		0.41AB	0.08	0.29	69.93	1.58	2.21	0.153n
Subplot 08	125		0.33B	0.10	0.31	95.02	3.65	18.63	0.203Ln
Subplot 09	76		0.30B	0.05	0.22	73.82	1.98	5.49	0.185Ln
Subplot 10	44		0.31B	0.04	0.20	66.02	1.79	3.69	0.177n
			T2 - Typical Cerrado						
Plot	475	1 ha	0.37A	0.05	0.24	63.88	2.44	9.29	0.153Ln
Subplot 11	47	0.1 ha	0.41A	0.05	0.23	55.88	1.39	2.31	0.202n
Subplot 12	41		0.45A	0.08	0.28	63.37	1.41	1.93	0.186n
Subplot 13	39		0.34A	0.03	0.18	52.72	1.56	3.29	0.118n
Subplot 14	59		0.39A	0.06	0.25	64.81	1.55	2.53	0.158n
Subplot 15	27		0.38A	0.03	0.18	47.50	1.16	1.81	0.170n
Subplot 16	72		0.32A	0.05	0.22	69.42	4.08	23.27	0.182n
Subplot 17	65		0.31A	0.02	0.16	53.57	2.28	8.66	0.126n
Subplot 18	41		0.45A	0.10	0.32	70.65	3.26	14.62	0.218n
Subplot 19	49		0.39A	0.05	0.23	60.76	1.53	2.15	0.179n
Subplot 20	41		0.34A	0.08	0.28	82.28	2.71	9.73	0.231n

T3 - Dense Cerrado									
Plot	453	1 ha	0.37A	0.07	0.26	72.02	2.14	6.75	0.155Ln
Subplot 21	41	0.1 ha	0.29B	0.02	0.16	56.75	1.92	5.27	0.150n
Subplot 22	64		0.29B	0.02	0.16	54.97	1.37	1.85	0.173n
Subplot 23	29		0.35B	0.06	0.26	73.39	1.73	2.08	0.244n
Subplot 24	46		0.32B	0.06	0.24	76.47	1.25	0.87	0.185n
Subplot 25	58		0.41B	0.07	0.28	67.55	2.03	6.52	0.126n
Subplot 26	49		0.34B	0.06	0.25	74.39	1.33	1.28	0.197n
Subplot 27	64		0.39B	0.08	0.29	73.16	1.88	5.15	0.146n
Subplot 28	49		0.39B	0.06	0.24	61.71	1.25	1.14	0.170n
Subplot 29	33		0.27B	0.03	0.18	66.78	1.42	1.43	0.215n
Subplot 30	27		0.66A	0.21	0.46	69.50	1.66	2.09	0.206n

N - Individuals number; ($\bar{X}$) - Mean; SD - Standard deviation; CV (%) - Coefficient of variation; D-KS* - Kolmogorov-Sminorv normality test - 0.01%.

The individuals were distributed in diametric classes from the definition of amplitude of 0.4 m (Figure 2). This occurred in T1 (8 classes of diameter - figure 2A), T2 (7 diameter classes - figure 2D), and T3 (6 diameter classes - figure 2G). Only the histograms with largest number of diameter classes were presented. There was a higher concentration of individuals in the first diametric class (DBH = 0.1-0.4 m - figure 2B, 2C, 2D, 2E, 2F, 2H and 2I) in all plots. However, it is important to highlight that T2 presented the lowest standard deviation value (Table 2), indicating that the system has the least internal variation in relation to DBH in this plot.

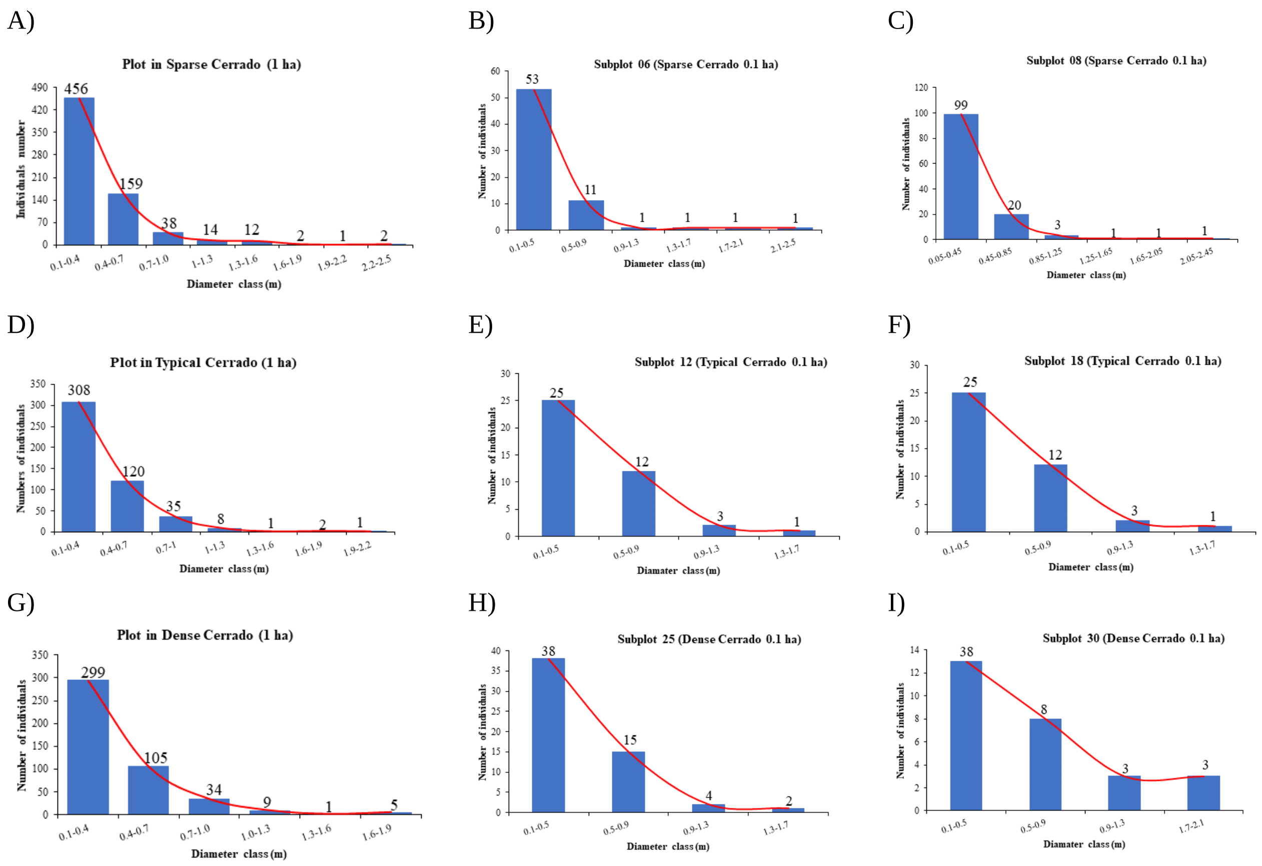


Figure 2. Frequency distribution of diameter classes corresponding to individuals sampled in Cerrado phytophysiognomies in the Parque Estadual do Mirador, MA. A) Plot in T1, B) Subplot 06 in T1, C) Subplot 08 in T1, D) Plot in T2, E) Subplot 12 in T2, F) Subplot 18 in T2, G) Plot in T3, H) Subplot 25 in T3, and I) Subplot 30 in T3.

The spherical model was the one that best characterized the spatial variability for most of the data, in terms of plots and subplots, except the subplot 07 in T1, which fitted the Gaussian model (Table 3). T2 showed 4 subplots with pure nugget effect (PNE - subplot 12, 14, 18 and 19), followed by plot T3 (subplots 22, 23 and 28) and T1 (subplot 05 and 09). Different scales of spatial variability were found, with spatial continuity in T2 (a = 120 m), T1 (a = 130 m), and T3 (a = 210 m). In the subplots, the continuity values were from 8 m to 11 m in T1; from 10 m to 13 m in T2 and from 10 m to 12 m in T3 (Table 3). The spatial dependence was considered low in T2 (SDR = 83.33%), median in T1 (SDR = 61.85%) and T3 (SDR = 62.50%), as shown in table 3. In T1 subplot, SDR values were considered median (SDR = 25-75%) in four subplots, and high (SDR = 0-25%) in four subplots. In T2, three subplots presented median SDR (subplot 11, 13 and 15) and three presented high SDR (subplot 16, 17 and 20). In T3, four subplots showed median SDR (subplot 21, 24, 25 and 29), and three subplots showed high SDR (subplot 26, 27 and 30), as shown in table 3.

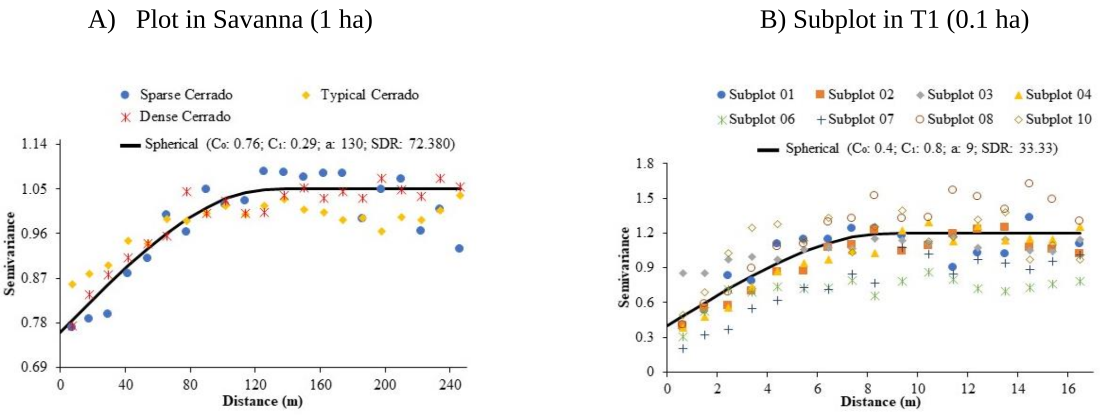
Table 3. Adjustment parameters of semivariograms for plots and subplots in the Parque Estadual do Mirador, Maranhão

		Modelo	C_0	C_1	a (m)	R^2	SDR %
T1 - Sparse Cerrado							
Plot	1 ha	Spherical	0.06	0.03	130	0.99	61.85
Subplot 01	0.1 ha	Spherical	0.03	0.11	8	0.99	21.42
Subplot 02		Spherical	0.04	0.10	10	0.99	28.57
Subplot 03		Spherical	0.06	0.02	9	0.98	73.17
Subplot 04		Spherical	0.02	0.55	11	0.98	26.66
Subplot 05					PNE		
Subplot 06		Spherical	0.03	0.07	8	0.99	30.00
Subplot 07		Gaussian	0.01	0.06	9	0.99	23.17
Subplot 08		Spherical	0.02	0.13	9	0.99	18.23
Subplot 09					PNE		
Subplot 10		Spherical	0.01	0.04	8	0.99	20.00
T2 - Typical Cerrado							
Plot	1 ha	Spherical	0.05	0.01	120	0.99	83.33
Subplot 11	0.1 ha	Spherical	0.04	0.03	10	0.99	53.33
Subplot 12					PNE		
Subplot 13		Spherical	0.01	0.02	13	0.98	36.58
Subplot 14					PNE		
Subplot 15		Spherical	0.01	0.02	12	0.98	25.64
Subplot 16		Spherical	0.01	0.05	11	0.98	14.49
Subplot 17		Spherical	0.01	0.04	12	0.99	20.00
Subplot 18					PNE		
Subplot 19					PNE		
Subplot 20		Spherical	0.01	0.08	11	0.99	17.52
T3 - Dense Cerrado							
Plot	1 ha	Spherical	0.5	0.3	210	0.98	62.50
Subplot 21	0.1 ha	Spherical	0.01	0.03	10	0.98	36.17
Subplot 22					PNE		
Subplot 23					PNE		
Subplot 24		Spherical	0.01	0.03	10	0.99	38.77
Subplot 25		Spherical	0.03	0.05	10	0.98	37.50

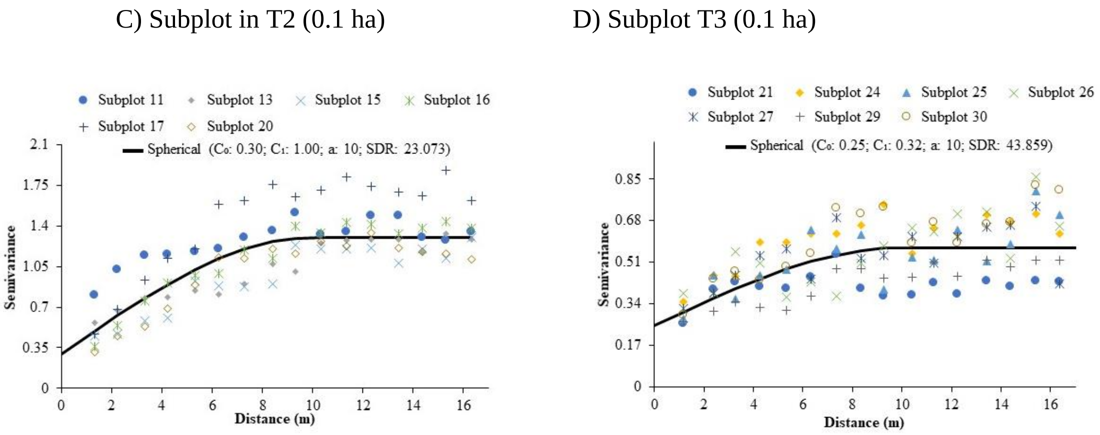
Subplot 26	Spherical	0.01	0.07	10	0.99	16.66
Subplot 27	Spherical	0.04	0.13	11	0.98	23.52
Subplot 28				PNE		
Subplot 29	Spherical	0.01	0.01	12	0.98	34.48
Subplot 30	Spherical	0.01	0.26	10	0.99	3.70

C_0: nugget effect; C_1: structural variance; a (m): range; R^2: determination coefficient; SDR (%): spatial dependence ratio; PNE: pure nugget effect

The scaled semivariograms corresponding to the variables that showed spatial dependence are shown in figure 3. The scaled semivariograms for the T1, T2 and T3 plots were adjusted to the spherical model, with a reach value of 130 m (Figure 3A) and moderate spatial dependence (SDR = 72.38%).


A) Plot in Savanna (1 ha)

B) Subplot in T1 (0.1 ha)


C) Subplot in T2 (0.1 ha)

D) Subplot T3 (0.1 ha)

Figure 3. Scaled semivariograms corresponding to plots and subplots in the Parque Estadual do Mirador, Maranhão. C_0: nugget effect; C_1: structural variance; a (m): range; SDR (%): spatial dependence ratio.

The subplots showed different scales of spatial variability, with ranges ranging from 10 m (in T2 and T3) to 9 m (in T1 - Figure 3B, 3C and 3D). The values of spatial dependence (SDR%) were considered median in the subplots in T1 (SDR = 33.33% - Figure 3B) and in T3 (SDR = 43.85% - figure 3D); in T2, were elevated (SDR = 23.07% - Figure 3C).

4 DISCUSSION

The occurrence of greater abundance of shrub-tree individuals in T1 plot (684 individuals) reflects the presence of individuals with smaller diameters (between 0.1-0.4 m), which according to Mendes et al. (2012) are the individuals that occur predominantly in areas such T1. Ribeiro and Walter (2008) described that the Sparse Cerrado is characterized by individuals with shorter and sparse size, smaller canopy and vegetation cover, aspects confirmed in the present study. The presence of 475 individuals in T2 indicates that it is an intermediate formation between T1 and T3, where occurs individuals common to both environments (IBGE, 2012).

There was less abundance of individuals (453 individuals) in T3, justified by the occurrence of trees with larger size, which provide greater shading, thus preventing the development of lower strata (Ribeiro and Walter, 2008). Although there are particularities in each plant formation, other factors can affect the abundance and distribution of plant species in Cerrado, such as altitude (Maracahipes et al., 2011), soil type (Mendes et al., 2012), climate (Peixoto et al., 2020) and degree of human exploitation (Rios et al 2018).

There was no statistical differentiation by the Tukey test ($p < 0.05$) for the mean values of DBH between the plant formations (Table 2), however, there was statistical differentiation for this parameter in the subplots in T1 and T3, showing heterogeneity for these formations (Table 2). The homogeneity of DBH values in T2 is possibly caused by the specific characteristic of this area, where occurs the presence of shrub and tree individuals common in T1 and T3 (Ribeiro and Walter, 2008; IBGE, 2012), corroborating the lower CV value (%).

The high CV values corresponding to the subplots in T1 (Table 2), describe the greater heterogeneity of DBH values in this plot, since there are also greater variations in the number of individuals between the sub-plots. On the other hand, the presence of median CV values for the subplots in T2 and T3 is indicative of the low variation of DBH within these subplots, compared to T1 (Table 2).

The distribution of DBH in diametric classes showed that there is a greater number of individuals with diameters between 0.1-0.4 m, suggesting the same trend for all plant formations. The greater number of individuals allocated to the first classes describes that the plant community presents an inverted “J” trend, indicating a balance between the recruitment rate and mortality in the community (Maracahipes et al., 2011). Inverted “J” trend is commonly described in preserved communities, where mortality and recruitment rates are stabilized (Vale et al., 2009; Santos et al., 2017), thus, young individuals replace adults in the population balancing the plant community (Oliveira and Ratter, 2002). The distribution pattern observed in this study was registered by Araújo et al. (2011), Gama et al. (2018) and Lima et al. (2020) in studies in Savana, indicating continuous recruitment and self-regeneration in the communities.

The presence of individuals with largest diameters was recorded from T3 (DBH = 1.6-1.9 m), whereas in T1, only 2 individuals had DBH = 2.2-2.4 m. Although there are structural differences between the Cerrado physiognomies, these differences are more pronounced in areas such as T1 and T3 (Oliveira and Ratter, 2002; Ribeiro and Walter, 2008), compared to areas such as T2. The different levels of shading, caused by the density of individuals in plant formation, which can define the succession of species in the landscape, is another factor that differentiates areas such as T1 and T3 (Pinheiro and Durigan, 2012).

The spherical model was the one that best described the spatial variability of vegetation in the experimental plots (Table 3). The highest range value corresponded to T3 (a = 210 m), followed by T1 (a = 130 m), and T2 (a = 120 m), thus evidencing the existence of different ranges of variability space for the tree component (Vieira, 2000). When studying the structure of a vegetation, Neves et al. (2010) described the occurrence of greater spatial continuity for the tree strata, compared to the lower strata (herbaceous and shrub). When studying a tree vegetation, Gholami et al. (2017) described the spatial continuity over long distances (a = 3110 m), possibly caused by the specific characteristics of elements present in the sampling area (topography, edaphic properties, and climate), which are components that define the spatial scale gradient of tree strata. Different range values were observed in the subplots (Table 3), and the variations between the range values were from 8 m to 11 m for the sub plots in T1; from 11 m to 13 m in T2, and from 10 to 12 m in T3, indicating that DBH along had different ranges of variability along the plots, mainly in areas such as T1 (Neves et al., 2010). The range values are indicative of the maximum distance at which a variable is spatially correlated and is an important parameter in the assessments involving geostatistics tools (Vieira, 2000; Machado et al., 2007).

The spatial dependency ratio indicated low spatial dependence in T2 plot (SDR = 83.33%), corroborating the lower range value observed in this physiognomy, while in T1 and T3 the SDR was considered median, according to Cambardella et al. (1994). As to the subplots, in the vegetation formations, the spatial dependence values ranged from high (SDR ≤ 25%) to moderate (SDR = 25 - 75%), according to Cambardella et al. (1994), indicating that the spatial dependence vary according to the vegetable composition present in the area of study. Thus, according to Cambardella et al. (1994), the strong spatial dependence may reflect the intrinsic characteristics of a variable, while the spatial dependence considered as median may be an indication of less variability of the data.

The scaled semivariograms adjusted for the vegetation formations (Figure 3A), showed moderate spatial dependence (SDR = 72.38%). However, for the scaled semivariograms of subplots, there was high spatial dependence in T2 (Figure 3C), and median spatial dependence in T1 and T3 (Figure 3B and 3D). According to Vieira et al. (1997), the scaled semivariograms allows grouping different values of semi variance, considering the same distance. Thus, it is possible to infer that the DBH trend in the physiognomies is more homogeneous, corroborating the individual SDR values (Table 3). The use of geostatistics tools made it possible to describe the spatial variability of vegetation, indicating the occurrence of variations in DBH, corroborating with Ribeiro and Walter (2008). The class intervals of diameters described communities with balanced recruitment and mortality rate, reflecting the balance in plant community (Vale et al., 2009; Mendes et al., 2012; Santos et al., 2017).

The use of geostatistics tools made it possible to show that DBH in physiognomies and subplots have different scales of spatial variability, according to Vieira et al. (2000), with a lower spatial continuity value in T2, a portion with greater homogeneity. The geostatistical analysis described the community structure in the present study, constituting a tool promising for evaluating the spatial trend of plant strata.

5 CONCLUSION

It was evidenced that T2 presents a homogeneous system for DBH compared to T1 and T3 plots, which are more heterogeneous systems. Savana's physiognomies showed different scales of spatial variability, conditioned by the pattern of plant distribution present in the plots, demonstrating median spatial dependence in T1 and T3, with plant formations with greater differentiation in DBH. In T2, the largest number of subplots without detection of spatial variability was caused by the spacing used between arboreal individuals. The vegetation structure in the Parque Estadual do Mirador showed a self-regenerating pattern, with a concentration of DBH values in the smallest class interval (0.1-0.4 m), indicating the occurrence of a balanced replacement of adult individuals.

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CAPÍTULO IV -SCALE RELATIONSHIPS OF SOIL ARTHROPODS AND VEGETATION STRUCTURE OF CERRADO PHYTOPHYSIOGNOMIES

Submetido - Revista Brasileira de Ciência do Solo

Raimunda Alves Silva(1)* and Glécio Machado Siqueira(1)

(1) Universidade Federal do Maranhão, Programa de Pós-Graduação da Rede BIONORTE, São Luís, Maranhão, Brasil.

* Corresponding author: e-mail: ray-234@hotmail.com

ABSTRACT: Soil fauna is an important component for soil maintenance, and can be influenced by several environmental and anthropic factors. The objective of this study was to assess the soil fauna by mean of geostatistical and multifractal tools in Cerrado physiognomy. The experimental plots were set in the areas with Dense Cerrado (T1), Typical Cerrado (T2) and Sparse Cerrado (T3), where the edaphic fauna was collected in 128 points, through pitfall traps and the vegetation evaluated in sub-plots of 9 m^2. The data were evaluated by descriptive statistics, geostatistics, multifractal analysis and joint multifractal. All variables adjusted to a geostatistical model, except for the plants between Arborescent (T1), Abundance of arthropods and Arboreal (T2), which showed a pure nugget effect. The variables showed different degrees of multifractality, demonstrated by the singularity spectrum. The contour graphs of joint multifractal dimension showed circular lines with high values of joint correlation for the correlations of Arthropod Richness *versus* Abundance of plant strata ($R = -0.498$ - $p < 0.01$), Arthropod Richness *versus* Herbaceous ($R = 0.323$ - $p < 0.01$) and Arthropod Richness *versus* Arboreal ($R = 0.451$ - $p < 0.01$) at T1. In T2, the multifractal joint dimension presented diagonal lines in ellipse and low correlation value for Arthropod Richness *versus* Arthropod Abundance ($R = -0.092$ - $p < 0.05$). In T3, the graphs were in ellipse and circular with negative correlation values for Arthropod Richness *versus* Abundance of plant strata ($R = - 0.365$ - $p < 0.01$). The multifractal tools characterized variables in different scales satisfactorily.

Keywords: Soil fauna, Arthropods, Cerrado, Multifractal.

1 INTRODUCTION

The invertebrate soil biota is composed of different groups of arthropods that contribute to the maintenance of several ecosystem services, namely: nutrient cycling (Bityutskii et al., 2016; Roy et al., 2018), formation of pore and galleries and improvement of soil structure (Moço et al., 2010), incorporation of organic material and biomass (Bardgett and Putten, 2014; Bedano et al., 2016), mineralization and humidification of organic matter (Bityutskii et al., 2016), pest control (Marichal et al., 2014), and bioindicators of environmental quality (Bardgett and Putten, 2014).

In view of the importance of invertebrate fauna soil for ecosystems, it is necessary that its characterization be carried out considering the different scales of spatial variability throughout the landscape. Thus, the use of geostatistics and multifractal analysis allows the assessment of edaphic fauna at different scales of spatial variability. Geostatistics evaluates the spatial variability and dependence between samples distributed in space (Vieira, 2000), and the multifractal analysis allows the understanding of spatial distribution of measurements in compartments in a system (Chhabra and Jensen, 1989; Caniego et al., 2006; Zeleke and Si, 2006).

Studying the spatial distribution of tree species and soil arthropods Gholami et al. (2017), described that soil fauna was influenced by vegetation at different scales of spatial variability. Silva et al. (2018) studying the spatial variability of soil fauna in different land use and occupation systems, described that the spatial variability of soil fauna was influenced by the type of vegetation cover. On the other hand, Neves et al. (2010) studying the scales of spatial variability of plant fragments, showed that the tree, arborescent and herbaceous extracts have different scales of spatial distribution resulting from the ecological processes of plant colonization in the environment.

The multifractal analysis is applied to characterize data sets at different moments of statistical order (Caniego et al., 2006; Banerjee et al., 2011; Biswas et al., 2012), considering different scales for a system, offering a characterization of heterogeneity or homogeneity (Halsey et al., 1986; Bertol et al., 2017; Siqueira et al., 2018). Multifractual analysis has already been used to characterize, on a simple scale, physical and chemical attributes (Caniego et al., 2006; Biswas et al., 2012; Bertol et al., 2017; Siqueira et al., 2018) and biological attributes (Gelashvily et al., 2008; Yakimov et al., 2014; Silva et al., 2020).

On the other hand, the joint multifractal analysis allows to characterize variables on a joint scale of a system, generating the singularity indices α (t, q) and β (q, t), which provides information on the association of high and low values for pairs of variables (Biswas et al., 2012; Bertol et al., 2017), information important for understanding the heterogeneity of variables at different scales (Banerjee et al., 2011; Siqueira et al., 2018). However, there are no studies considering the relationships in joint scale between invertebrate fauna and vegetation structure. Thus, it is necessary to elucidate the different scales of variability of the invertebrate fauna of the soil and of different vegetation formations to characterize the scales of spatial variability.

Thus, the hypotheses of this study are: a) the spatial variability of the invertebrate fauna of soil is influenced by changes in the landscape that condition the occurrence of different vegetation formations; b) the tools of geostatistics, multifractal and joint multifractal analysis can characterize spatial variability at different scales. Therefore, the objective of this study was to characterize the relationships of scales of the invertebrate fauna of soil and of vegetation structures by means of geostatistical tools, multifractal analysis and joint multifractal.

2 MATERIAL AND METHODS

2.1 Study location

The experimental plots are located in the municipality of Chapadinha (Maranhão, Brazil), under the geographical coordinates 3º 73’ 34.68’’S and 43º 32’ 03.12’’ W, in three different vegetation types of Cerrado (Fig. 1). The region's climate is classified as tropical hot and humid

(Aw), with average annual temperature varying between 27 and 30 ºC, and the average annual precipitation between 1,400 to 1,600 mm. The soil of the study area is classified as Oxisol (Soil Survey Staff, 2014), which main physical and chemical attributes in the layers 0-0.2 m, determined according to EMBRAPA (2017), are shown in table 1.

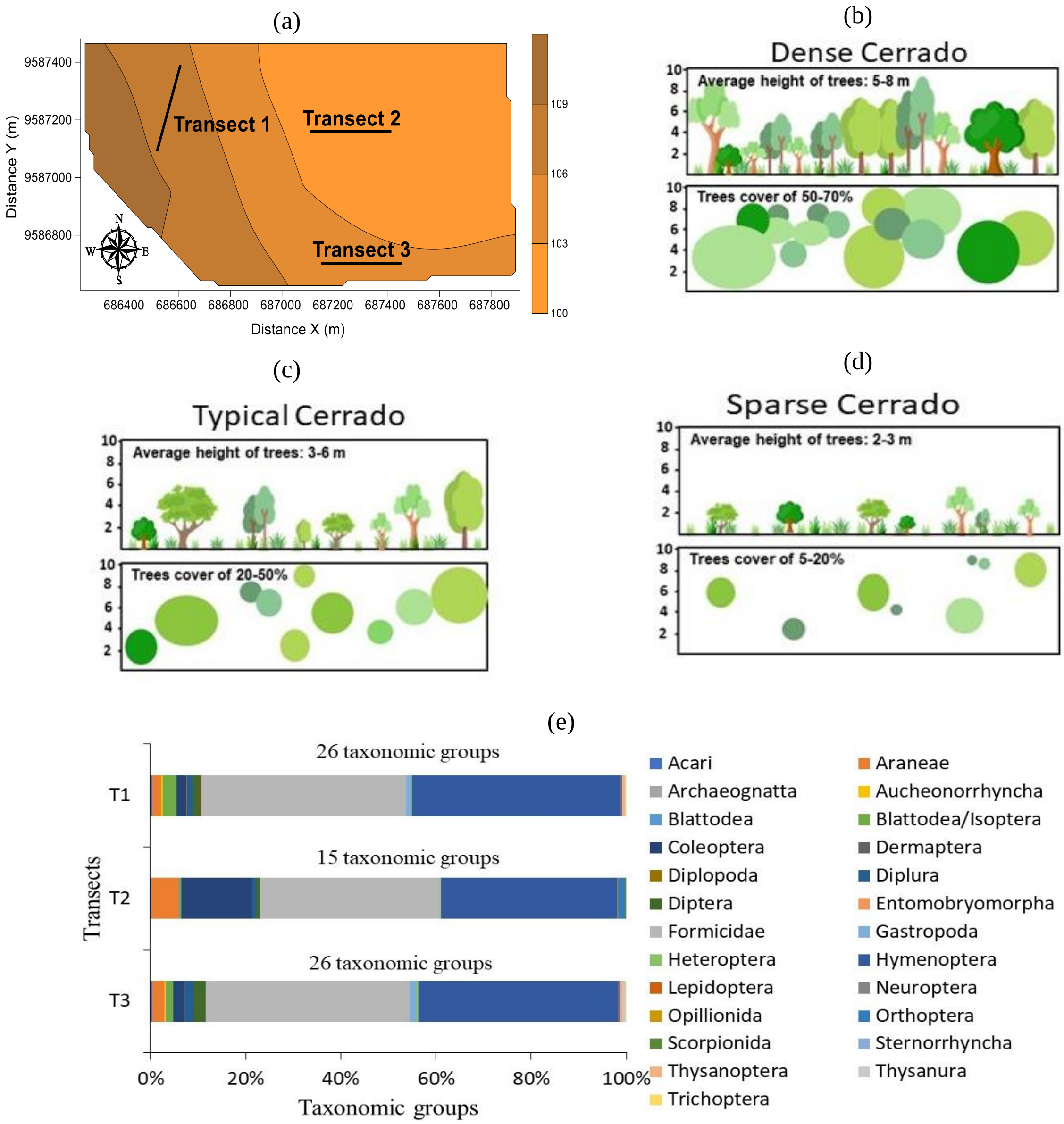

Figure 1. Topographic map and location of experimental plots (a); vegetation formations of Cerrado and tree cover profile: Dense Cerrado (b), Typical Cerrado (c) and Sparse Cerrado (d); and abundance of the taxonomic groups of invertebrate fauna of soil (e).

Table 1. Physical and chemical characterization of the superficial layer soil (0-0.2 m) in the experimental plots located in the municipality of Chapadinha (Maranhão, Brazil)

	Clay	Silt	Sand	OC	pH	P	K^+	Ca^{2+}	Mg^{2+}	SB	CEC	V%
	----------- % -----------			g dm^{-3}	($CaCl_2$)	mg dm^{-3}	------------ $mmol_c$ dm^{-3} ------------					
Transect 1 (T1)	80	60	860	20	4.3	2	2.1	9	7	21.8	52.0	42.0
Transect 2 (T2)	160	60	780	12	4.3	5	3.7	6	4	19.8	48.4	40.9
Transect 3 (T3)	140	60	800	20	4.5	13	2.5	13	4	19.5	47.5	41.1

OC: organic carbon; P: phosphorus; K^+: potassium; Ca^{2+}: calcium; Mg^{2+}: magnesium; SB: sum of bases; CEC: cation exchange capacity; V%: base saturation.

Sampling was carried out on November 14, 2014, in three transects (T1, T2 and T3) installed in an area with Cerrado vegetation. The attributes of the edaphic fauna (Abundance and Richness of arthropods) and the vegetation structure of the Cerrado (Abundance of plant strata, number of herbaceous, arborescent, arboreal plants and average diameter of tree plants (DAP 1.3 m) were sampled over three transects containing 128 sampling points, with 3 m spacing between points, totaling 381 m.

The transects were allocated to different vegetation formations of Cerrado, classified according to Ribeiro and Walter (2008): Dense Cerrado (T1 - Fig. 1c), Typical Cerrado (T2 - Fig. 1d) and Sparse Cerrado (T3 - Fig. 1e). The edaphic fauna was sampled using *pitfall traps*, according to Aquino (2001), and the traps, containing 200 mL of 4% formaldehyde solution (Aquino, 2001), remained in the field for a period of seven days. After this period, the content of the traps was packed in airtight containers for subsequent sorting and identification of the organisms at the level of order, family, and subfamily (Rafael et al., 2012).

For the present study, 26 taxonomic groups were identified, where T1 and T3 had 26 taxa and T2 had 15 taxonomic groups (Fig. 1b). From the taxonomic groups, the abundance and richness of arthropods was determined for each of the sample points. The vegetation structure was evaluated in sub-plots of 9 m^2, using the sampling point of the invertebrate fauna of soil as a centroid, allowing the determination of the number of plants < 0.5 m (herbaceous stratum), the number of plants between 0.5-1.3 m (arborescent stratum), and the number of plants > 1.3

m (tree stratum), where the average diameter of tree plants (tree stratum) was also determined, according to Neves et al. (2010).

2.2 Descriptive statistics and scale analysis

The main statistical moments were determined for the attributes under study: mean, standard deviation, coefficient of variation (%), asymmetry and kurtosis; the normality of the data was assessed by the Kolmogorov-Smirnov test (D-KS - $p < 0.01$). The Tukey test was used to compare the means of variables in the experimental plots, considering the significance of $p < 0.01$.

The scale analysis for the variables was performed by geostatistics (Vieira et al., 1997; Vieira, 2000), multifractal analysis (Hentschel and Procaccia, 1983; Halsey et al., 1986; Siqueira et al., 2018; Silva et al., 2020), joint and multifractal (Zeleke and Si, 2006; Biswas et al., 2012; Siqueira et al., 2018).

The characterization of spatial variability of data along the transect was made based on geostatistics, as described by Vieira (2000), and considering the stationarity of the intrinsic hypothesis (Vieira, 2000) according to equation 1:

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

Eq. 1

where: $y\ (h)$ corresponds to the semi variogram estimated for the distance h; x corresponds to the position measure; h corresponds to the distance between measurements; $N\ (h)$ corresponds to the number of observations, separated by the distance h. The semi variograms were adjusted to a mathematical model, considering the nugget effect (C_0), the structural variance (C_1) and the range (a), following the procedures described by Vieira (2000).

The experimental semi variogram was adjusted by cross-validation, using the methods of ordinary least squares, and weighted least squares, where the best fit was chosen according to the "jack-knifing" technique. The spatial dependency index (SDR, %) for the variables was calculated, considering $[C_0 / (C_0 + C_1)] * 100$, according to Cambardella et al. (1994), in which the special dependence is classified as strong (≤ 25%), moderate (between 25 and 75%) and weak (≥ 75). Subsequently, staggered semi variograms were constructed for the variables that showed spatial dependence in each of the experimental plots, according to Vieira et al. (1997 - Equation 2):

$$y(h)_{sc} = \frac{y(h)}{Var_{(z)}}$$

Eq. 2

where:

$y(h)_{sc}$ corresponds to the scaled semi variogram;

$y(h)$ corresponds to the original semi variogram;

$\mathrm{Var}_{(z)}$ corresponds to the data variance.

The data multifractality was determined by the method of the moment, where the partition function was generated (Halsey et al. 1986); and the generalized dimension (D_q - Hentschel and Procaccia, 1983); and the spectrum of singularity of function of $f(\alpha)$ versus α (Chhabra and Jensen, 1989) was generated by the direct method. The data were evaluated in intervals of 2.0, and statistical moments of $-10 \leq q \leq +10$.

The total length of transect was divided into segments (equation 3), and converted into a function of normalized mass $p_i(\delta)$ or $\mu_i(\delta)$, which describes the contribution of a segment or subintervals of size δ to the total mass (Equation 4).

$$\chi(q, \delta) = \sum_{i=1}^{n(\delta)} [p_i(\delta)]^q$$

Eq. 3

$$p_i\ (\delta) = \varphi_i\ (\delta) / \sum_{i=1}^{n(\delta)} \varphi_i\ (\delta)$$

Eq. 4

Where:

n(δ) is the number of segments with size *δ*, which statistical moments q are defined for $-\infty < q < +\infty$;

φi corresponds to measurement value in the *i*th segment in scale *δ*; $\sum_1^{n(\delta)} \varphi_i\ (\delta)$ represents the total mass of transect.

The generalized dimension was obtained for the moments of $q = 0$, $q = 1$, $q = 2$ (Equation 5 and Equation 6), observing when $q \neq 1$ and q = 1, which makes D_1 indeterminate, when is necessary to use the rule of l' Hôpital, which was not the case in the present study.

$$D_q = \frac{1}{q-1} \lim_{\delta \to 0} \frac{\log[\chi(q,\delta)]}{\log \delta} = \frac{\tau(q)}{q-1}, \text{para } q \neq 1$$

Eq. 5

$$D_1 = \lim_{\delta \to 0} \frac{\sum_{i=1}^{n(\delta)} \mu_i\ (\delta) \log \chi(q,\delta)]}{\log \delta}, \text{para } q \neq 1$$

Eq. 6

The singularity spectra were obtained through the function of *f(α)* versus *α*, which generates a parable for multifractal variables, and a linear function for monofractal data (Equation 7 and Equation 8).

$$\alpha(\mathrm{q}) \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta) \log[\mu_i(\delta)]}{\log\ (\delta)}$$

Eq. 7

$$f(\alpha(q)) = \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta) \log\ [\mu_i(\mathrm{q},\delta)]}{\log\ (\delta)}$$

Eq. 8

The degree of multifractality (Δ - Equation 9) and the asymmetry of the singularity spectrum (Δ - Equation 10) were determined following the procedures described by Halsey et al. (1986):

$$\Delta = D_{-\infty} - D_{\infty}$$

Eq. 9

$$A = \frac{\alpha_0 - \alpha_{min}}{\alpha_{max} - \alpha_0}$$

Eq. 10

For assessing the association of values by the joint multifractal analysis, the transect was divided into segments of size δ and the partitions were determined on the scales of measures of p and r, which are partitioned into δ and defined as p_i ((δ) and $r_i(\delta)$ (Banerjee et al., 2011; Biswas et al., 2012 - Equation 11).

$$\mu_i(q,t,\delta) = \frac{[p_i(\delta)]^q\,[r_i(\delta)]^t}{\sum_{i=1}^{n(\varepsilon)}[p_i\,(\delta)]^q[r_i(\delta)]^t}$$

Eq. 11

where q and t correspond to real numbers that represent the orders of the moment; and δ correspond to the scale. The scale exponents of function of $f(\alpha, \beta)$ determine the singularity indices $\alpha(q, t)$ and $\beta(q, t)$ in relation to the μ_i measure (Zeleke and Si, 2006; Biswas et al., 2012; Bertol et al., 2017), Equation 12, Equation 13 and Equation 14.

$$\alpha(q,t) = \lim_{\varepsilon \longrightarrow 0} \frac{\sum_{i=1}^{n(\varepsilon)}[\mu_i(q,t,\delta).\log p_i(\delta)]}{\log \delta}$$

Eq. 12

$$\beta(q,t) = \lim_{\varepsilon \longrightarrow 0} \frac{\sum_{i=1}^{n(\varepsilon)}[\mu_i(q,t,\delta).\log r_i(\delta)]}{\log \delta}$$

Eq. 13

$$f(\alpha,\beta) = \lim_{\varepsilon \longrightarrow 0} \frac{\sum_{i=1}^{n(\varepsilon)}[\mu_i(q,t,\varepsilon).\log\,(q,t,\varepsilon)]}{\log \varepsilon}$$

Eq. 14

The indexes of joint multifractal scale [$\alpha(q, t)$ and $\beta(q, t)$] were subjected to Pearson's linear correlation in order to determine the association on the joint scale under ($p < 0.01$ and $p < 0.05$. In addition, the relationship between the pairs of variables were studied using Pearson's linear correlation, which allowed evaluating the single association between the variables.

3 RESULTS

A total of 7,428 individuals were collected (3,456 in T1; 1,629 in T2 and 2,343 in T3 - Table 2), and there was statistical difference for T1 (Tukey, $p < 0.01$), in relation to T2 and T3. Regarding the average Richness of arthropods, the Tukey test demonstrated statistical differences for all treatments (T1: 5.781A, T2: 4.726B and T3: 2.867C). The Abundance of plants in T1 and T2 did not show statistical differentiation (34.992A plants in T1 and 32.852A plants in T2), while T3 differed from the other treatments (25.219B plants). Arthropod richness and plant attributes showed median coefficient of variation (CV, %), and arthropod abundance showed high CV for T1, T2 and T3 (Table 2), according to the Warrick and Nielsen (1980) classification.

Table 2. Descriptive statistics of soil fauna and phytosociological parameters in Cerrado areas

	T1 – Dense Cerrado						
	Sum	Mean	SD	CV %	Skew	Kurtosis	D*
Arthropod abundance	3,456	27.000A	22.722	84.155	1.439	2.084	0.137n
Arthropod richness	---	5.781A	2.416	41.806	0.475	0.999	0.167Ln
Abundance of plant strata	4.479	34.992A	18.205	52.025	1.276	2.770	0.121n
Herbaceous	1.346	10.516A	6.926	65.863	1.311	2.154	0.154Ln
Arborescent	1.142	8.922A	10.071	112.881	7.671	74.435	0.216Ln
Arboreal	1.991	15.555A	9.948	63.953	1.031	1.437	0.123n
DBH	408.950	3.220A	2.219	68.914	2.393	7.332	0.226Ln
	T2 – Typical Cerrado						
	Sum	Mean	SD	CV %	Skew	Kurtosis	D*
Arthropod abundance	1,629	12.727B	10.838	85.160	1.610	3.367	0.165Ln
Arthropod richness	---	4.726B	2.589	54.781	0.409	0.630	0.122n
Abundance of plant strata	4.205	32.852A	10.764	32.765	0.527	-0.147	0.104n
Herbaceous	1.200	9.375A	4.631	49.400	0.657	0.022	0.101n
Arborescent	1.240	9.688A	4.543	46.899	1.090	1.858	0.144Ln

Arboreal	1.765	13.789A	8.438	61.197	0.845	-0.004	0.123n
DBH	467	3.652A	1.577	43.178	2.572	13.615	0.140n
T3 – Sparse Cerrado							
	Sum	Mean	SD	CV %	Skew	Kurtosis	D*
Arthropod abundance	2,343	18.305B	18.837	102.910	1.384	2.303	0.166Ln
Arthropod richness	---	2.867C	1.949	67.999	0.526	0.436	0.145Ln
Abundance of plant strata	3.228	25.219B	8.800	34.893	0.474	0.952	0.094n
Herbaceous	1.254	9.797A	5.095	52.006	0.902	1.151	0.114n
Arborescent	930	7.266A	3.959	54.495	1.372	3.948	0.120n
Arboreal	1.044	8.156B	3.881	47.583	0.543	0.311	0.086n
DBH	402	3.142A	1.538	48.962	1.483	2.939	0.177Ln

SD: standard deviation; CV%: coefficient of variation; *D: Kolmogorov Smirnov normality test at (0.01). Means followed by the same letters in the column did not differ by the Tukey test ($p < 0.01$).

The spherical model was the one that best adjusted to the variables under study (Table 3), and the Gaussian model was adjusted in T1 for the Abundance of arthropods and abundance of tree plants, and in T2 for DBH (1.3 m). The Arborescent (T1), Abundance of arthropod and Abundance of arboreal plants (T2) showed pure nugget effect. The reach values (a, m) demonstrated that the variables had a greater spatial dependence scale in T1 and T3 (average of 97.5 m for T1 and 77.14 m for T3), while in T2 the variables had lower values.

The degree of spatial dependence (SDR,%) described by Cambardella et al. (1994), demonstrated that most of the variables had median SDR values (25-75%), except for the Abundance of arthropods in T1 (SDR = 77.27%), Arthropod richness in T1 (SDR = 74.07%), DBH 1.3 m in T1 (SDR = 71.42%), Arthropod richness in T2 (SDR = 75.00%), Arborescent plants in T2 (SDR = 76.92%), Herbaceous plants in T3 (SDR = 72.58%), and plants between Arborescent in T3 (SDR = 71.42%).

Table 3. Geostatistical parameters of soil fauna and phytosociological aspects in Cerrado areas

Parameters	Model	C_0	C_1	a (m)	SDR (%)
T1 – Dense Cerrado					
Log Arthropod abundance	Gaussian	1.70	0.50	100	77.27
Log Arthropod richness	Spherical	0.20	0.08	70	74.07
Log Abundance of plant strata	Spherical	0.30	0.25	80	54.54
Log Herbaceous	Spherical	0.60	0.53	115	53.09
Log Arborescent	Pure nugget effect				
Log Arboreal	Gaussian	1.09	0.70	110	60.89
Log DBH	Spherical	0.50	0.20	110	71.42
				$\bar{X}$ = 97.50	$\bar{X}$ = 65.21
T2 – Typical Cerrado					
Log Arthropod abundance	Pure nugget effect				
Log Arthropod richness	Spherical	0.30	0.10	83	75.00
Log Abundance of plant strata	Spherical	0.18	0.08	65	69.23
Log Herbaceous	Spherical	0.42	0.21	70	66.66
Log Arborescent	Spherical	0.40	0.12	70	76.92
Log Arboreal	Pure nugget effect				
Log DBH	Gaussian	0.21	0.16	80	56.75
				$\bar{X}$ = 73.60	$\bar{X}$ = 68.91
T3 – Sparse Cerrado					
Log Arthropod bundance	Spherical	1.70	0.90	110	65.38
Log Arthropod richness	Spherical	0.25	0.16	80	60.97
Log Abundance of plant strata	Spherical	0.23	0.16	60	57.50
Log Herbaceous	Spherical	0.45	0.17	80	72.58
Log Arborescent	Spherical	0.50	0.20	70	71.42
Log Arboreal	Spherical	0.40	0.27	60	59.70
Log DBH	Spherical	0.30	0.17	80	63.82
				$\bar{X}$ = 77.14	$\bar{X}$ = 64.48

C_0: nugget efect; C_1: structural variance; a: range (m); SDR (%): spatial dependency ratio; $\bar{X}$: average

The scaled semivariogram (Figure 2a, 2c and 2e) was adjusted for the set of variables that showed spatial dependence, where the values ranged between 60 m (T3) and 90 m (T1). The variables in T1 and T3 showed moderate spatial dependence (SDR = 25-75%), while T2 presented low spatial dependence (SDR = 75.92%), according to the SDR classification proposed by Cambardella et al. (1994).

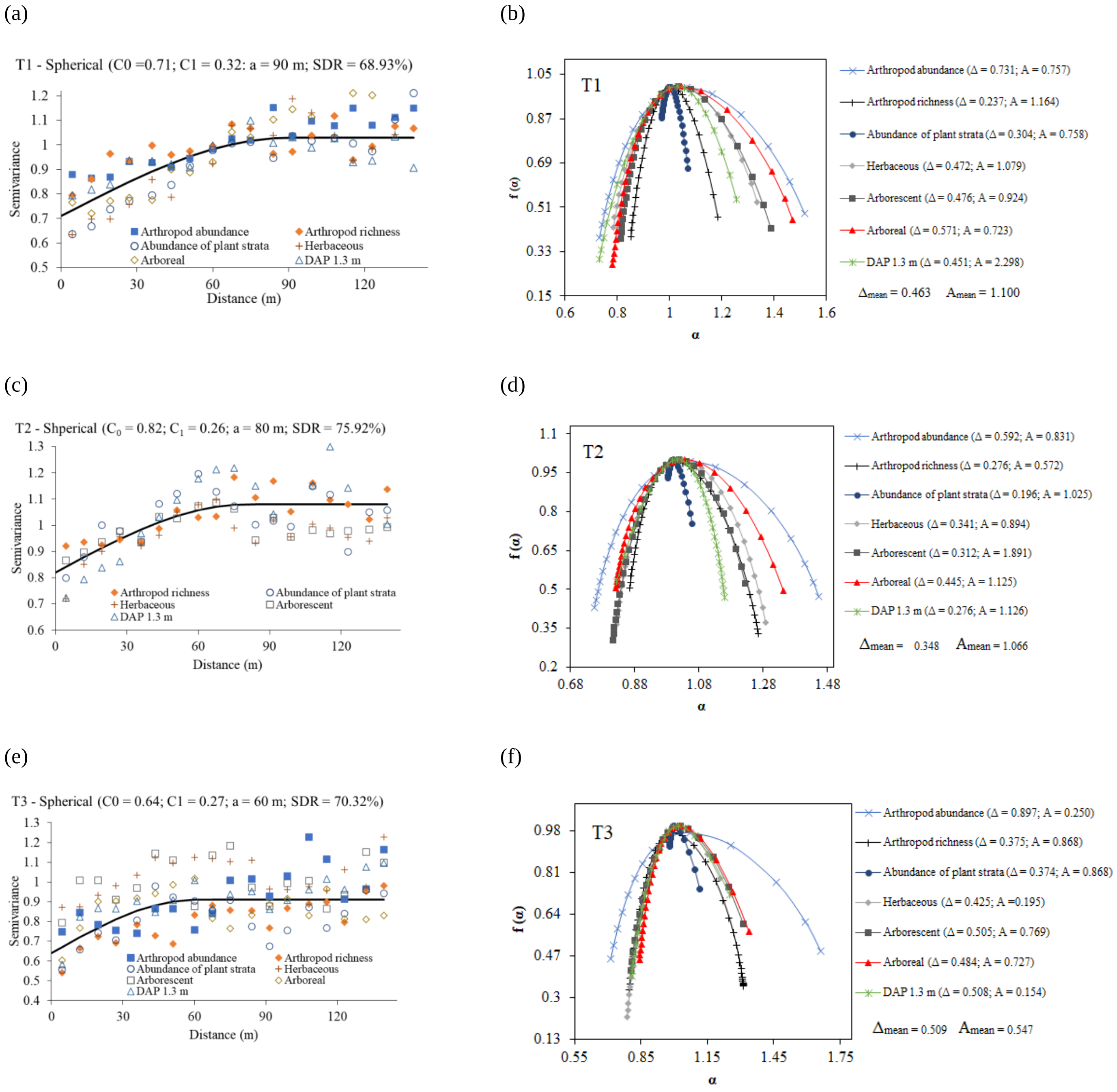

Figure 2. Singularity spectra of soil fauna and phytosociological parameters in the areas of Cerrado areas. a) multifractality and asymmetry at T1; b) multifractality and asymmetry in T2; c) multifractality and asymmetry in T3; d) singularity spectrum in T1; e) singularity spectrum in T2; and f) spectrum of singularity in T3. Δ = multifractality and A = asymmetry.

The multifractal analysis was determined considering the total length of transects (381 m), and the successive divisions for the segment (2^k), with an interval from k = 0 to k = 7, for the moments of order q ($-10 < q < 10$) in scales of 0.5, with adjustment of determination coefficient (R^2) > 0.90.

All variables showed multifractal behavior, which was assessed using the singularity spectrum (Figures 2b, 2d and 2f), with different degrees of multifractality (Δ) and asymmetry (A). The degree of multifractality at T1 was lower for Arthropod richness (Δ = 0.237) and higher for Arthropod abundance (Δ = 0.731 - Figure 2b); in T2, the lowest value for the degree of multifractality was described for the Abundance of plant strata (Δ = 0.196), and the highest degree was described for the Abundance of arthropods (Δ = 0.592 - Figure 2d); in T3, the lowest value for the degree of multifractality was found for the Abundance of plant strata (Δ = 0.374), and the highest value was for the Abundance of arthropods (Δ = 0.897 - Figure 2f). The lowest asymmetry value was described for DBH (1.3 m) in T3 (Δ = 0.154), and the highest asymmetry value was reported for the DBH (1.3 m) at T1 (A = 2.298). In general, T3 and T2 showed the least asymmetry for the set of pairs of variables (Δ = 0.525 and Δ = 1.066, respectively), while T1 presented the highest average asymmetry for the variables (Δ = 1.100).

The graphs of joint multifractal distribution were obtained using the function of $f(\alpha, \beta)$ and are shown in Figure 3, where only those graphs showing Pearson's correlation on a multifractal joint scale are displayed. The singularity indexes of $f(\alpha, \beta)$ are presented on the horizontal [α (q, t)] and on the vertical axis [β (q, t)]. The contour plots for the dimension joint multifractal in T1 that showed significant Pearson correlation values for the joint scale were Arthropod richness *versus* Abundance of plant strata (R = -0.498 - $p < 0.01$ - Figure 3a), Arthropod richness *versus* Herbaceous (R = 0.323 - $p < 0.01$ - Figure 3b), Arthropod richness *versus* Arboreal (R = 0.451 - $p < 0.01$ - Figure 3c), and Abundance of plant strata *versus* Arthropod richness (R = -0.246 - $p < 0.01$ – Figure 3d).

In T2, the contour plot for the multifractal joint dimension showed diagonal ellipse lines for Arthropod richness *versus* Arthropod abundance (R = -0.092 - $p < 0.05$ - Figure 3e), Arthropod richness *versus* Herbaceous (R = 0.203 - $p < 0.01$ - Figure 3f) and Arthropod richness *versus*

Arborescent (R = -0.080, p < 0.05 - Figure 3g). For T3, Arthropod richness *versus* Arthropod abundance (R = 0.289, p < 0.01 - Figure 3h), Arthropod richness *versus* Abundance plant strata (R = - 0.365 - p < 0.01 - Figure 3i), Arthropod richness *versus* Arborescent (R = -0.156 - p < 0.01 - Figure 3j) and Arthropod richness *versus* Herbaceous (R = 0.343 - p < 0.01 - Figure 3l) showed significant correlation for the joint $f(\alpha, \beta)$ scales.

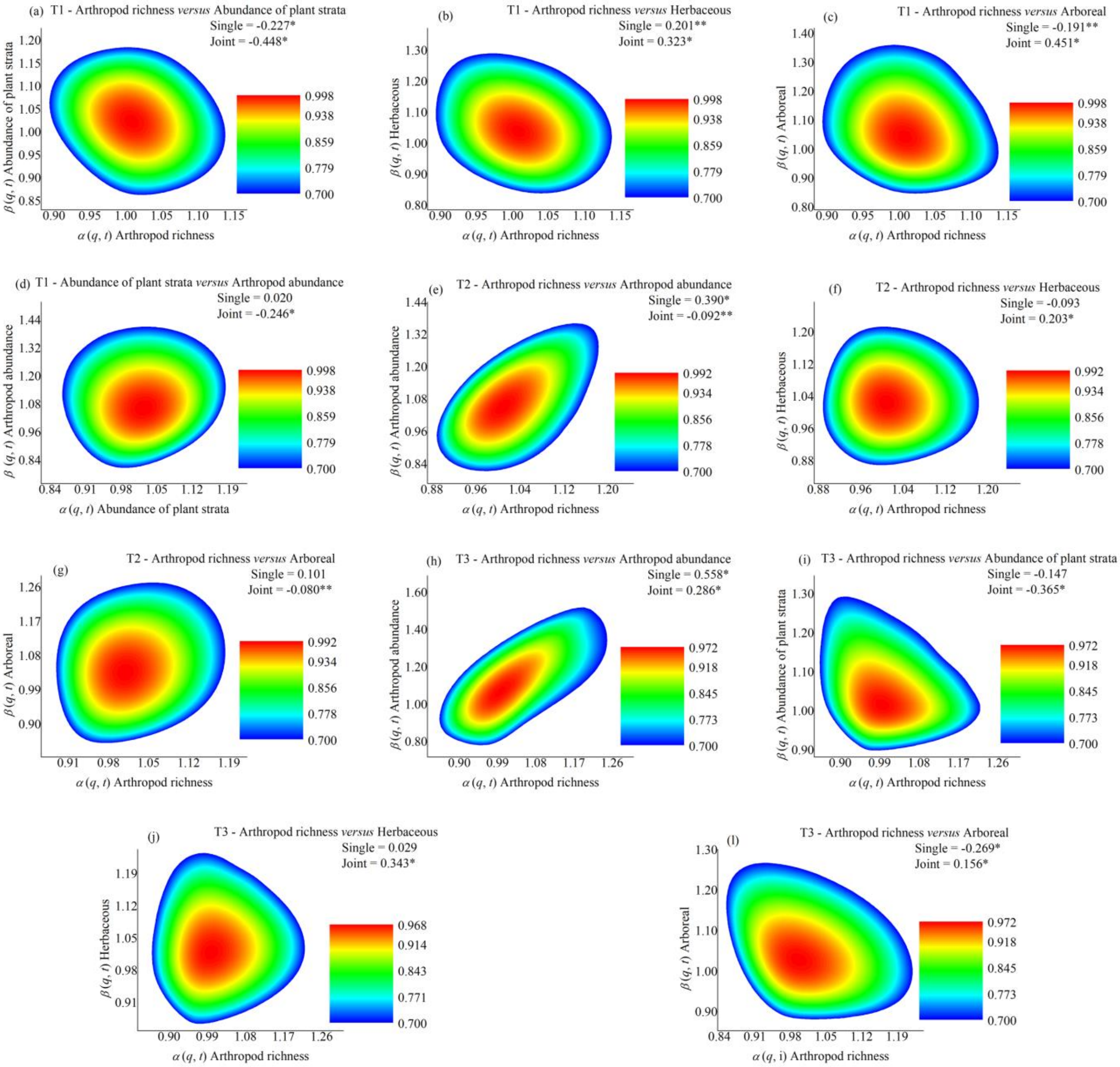

Figure 3. Joint multifractal distribution for soil fauna and vegetation attributes in T1, T2 and T3. Pearson's correlation at the significance of $p < 0.01$ and $p < 0.05$ on a simple and joint multifractal scale. * $p < 0.01$ and ** $p < 0.05$.

4 DISCUSSION

In the present study, we observed that the arthropod average richness (Table 2) was influenced by the vegetation composition, describing that there was a decrease for the average arthropod richness with the decrease in tree cover in the plots (T3 < T2 < T1), corroborating the studies by Korboulewsky et al. (2016), Gholami et al. (2017) and Silva et al. (2018). In this sense, the composition of vegetation cover influences the invertebrate fauna of soil, since it influences the availability of food resources (Moço et al., 2010; Marichal et al., 2014), provides better conditions in terms of physical and chemical attributes of the soil (Korboulewsky et al., 2016), and favor the development of favorable microclimates for the invertebrate fauna of soil (Bardgett and Putten, 2014).

Studying the vegetation cover of Cerrado fragments using geostatistics tools, Neves et al. (2010) described that the tree strata (plants of 0.5-1.3 m and DBH > 1.3 m), described by means of the reach values, presented greater spatial continuity than the herbaceous strata (plants < 0.5 m), thus describing the existence of different ranges of variability for the vegetation cover. In this sense, the invertebrate fauna of soil assumed a similar behavior in the landscape. The highest values of reach (a, m - Table 3) were described for the plot with Dense Cerrado (T1), followed by the plot with Sparse Cerrado (T3), and Typical Cerrado (T2), showing the existence of different scales of spatial variability for the variables under study.

According to Gholami et al. (2017), the spatial structure of soil fauna occurs in scales of variability, which reflect the gradient of vegetation cover. Thus, the spatial variability of vegetation influenced the diversity of edaphic communities. The better performance of T3 in relation to T2 for the range values (a, m), is justifiable, considering that 26 taxonomic groups were identified in T3 and that 15 taxonomic groups were identified in T2. The greater richness in T3 compared to T2, was due to a lower amount of tree plants in this first, with a greater dynamic of competition between plant strata, resulting in a greater availability of food, compared to T2, where the tree strata is more abundant, corroborating the studies of Moço et al. (2010); Bardgett and Putten (2014); Marichal et al. (2014); Bedano et al. (2016) and Roy et al. (2018).

Our results showed that the spherical model was adjusted to 15 variables, the Gaussian model was adjusted to 3 variables and another 3 variables showed pure nugget effect (Log arborescent in T1, Log arthropod abundance in T2 and Arboreal log in T2). The presence of a pure nugget effect indicates that arborescent plants in T1, arthropod abundance in T2 and arboreal in T2 had scales of variability less than the spacing used in this study, and according to Vieira (2000) represent variables with high spatial variability.

The scaled semivariogram (Figures 2a, 2c and 2e) demonstrated that there was different scales of variability between the plots, where the adjusted scaled semivariogram in T1 had the highest range value (a = 90 m), followed by T2 (a = 80 m), and T3 (a = 60 m). According to Vieira et al. (1997), the staggered semivariogram allows grouping and comparing different variables on the same scale, thus allowing to verify how the staggered semivariance pairs oscillate upon the increasing of the distance. In this sense, it appears that T1, T2 and T3 showed moderate spatial dependence between the samples, according to Cambardella et al. (1994). However, it is worth highlighting that although T3 had a smaller range than T2, there was a greater spatial dependence between the samples for the simple semivariogram as shown by the mean values of SDR (64.48% - Table 3) and for the scaled semivariogram (SDR_{mean} = 70.32% - Figures 2a, 2c and 2e).

The multifractal spectrum constructed for the *Dq* moment interval (q = 10 and q = -10) expressed different degrees of multifractality (Δ) and asymmetry (A), reflecting moderate heterogeneity (Figures 2b, 2d and 2f). The abundance of arthropods in T1, T2 and in T3 showed different degrees of multifractality (Δ), where T3 was the most heterogeneous portion for the values of measures along the geometric support (Δ = 0.897). On the other hand, T2 showed the lowest degree of multifractality for the abundance of arthropods (Δ = 0.592 - Figure 2d), indicating that there was less heterogeneity in the values of measures along the transect. In this case, it appears that T1 and T3 had the lowest values of average multifractality ($\Delta = 0.463$ and $\Delta = 0.348$, respectively) for the variables under study, as they were more homogeneous environmental systems. Additionally, each of them had its own particularity, where there was a predominance of the tree layer in T1, and a dominance of the herbaceous layer in T3, corroborating Ribeiro and Walter (2008). In this way, we show that the multifractal scales of the singularity spectrum reflected heterogeneity or homogeneity of the different vegetation formations, something also reported by Silva and Siqueira (2020).

In general, the mean values of asymmetry (Fig. 2b, 2d and 2f) for the variables under study represented high value domains along the geometric support (Figure 2), describing that there was heterogeneity in the different measurement scales, one since the branches of the spectra were elongated to the left, with concentration of measurement values $f(\alpha)$. According to Bertol et al. (2017), and Siqueira et al. (2018), the asymmetry of the branches of the singularity spectrum to the right or to the left provides important information on the degree of heterogeneity and domains of measurement of the scales of a system. The singularity spectrum for the Abundance of plant strata showed similar behavior for the three plots studied, however, it appears that there was a variability in the scales associated with low measurement values distributed along the geometric support. Regarding the arthropod richness, it appears that T2 and T3 showed singularity spectra elongated to the right, describing the domain of low measurement values distributed over the transects (Zeleke and Si, 2006; Yakimov et al., 2014).

The graphs of the joint multifractal spectrum [$f(\alpha, \beta)$ - Figure 3] are represented by contour lines that express the scale relationship of the distribution of values between two variables (Zeleke and Si, 2006; Banerjee et al., 2011; Biswas et al., 2012), in which the association of high values is represented in the lower left part, while in the upper right part the association is of low values (Zeleke and Si, 2006). Thus, pie charts indicate that there is no association in the scales of variables distribution, while charts tending to an ellipse present an association of positive or negative values in the scales of variables distribution (Biswas et al., 2012), and in the present study are shown only the graphs that showed statistical significance ($p < 0.01$ and $p < 0.05$) on the joint multifractal scale. The graph of the joint multifractal distribution for Arthropod richness *versus* Arthropod Abundance in T2 ($R = -0.092$ - $p < 0.05$ - Figure 3e) and for Arthropod richness *versus* Arthropod Abundance in T3 ($R = 0.286$ - $p < 0.01$ - Figure 3h) presented ellipse contour lines, describing that there is an association in the joint distribution scales for high and low values of $f(\alpha, \beta)$ (Banerjee et al., 2011; Biswas et al., 2012; Siqueira et al., 2018). The other graphs have contour lines with circular distribution, demonstrating that there is no joint multifractal associations in the distribution scales.

The use geostatistics tools, multifractal and joint multifractal analysis allowed to show that the attributes of the invertebrate fauna of soil and the vegetation composition, presented different scales of variability. The geostatistical analysis described that the variables have similar scales of variability when considering the particularities of each phytophysiognomy of Cerrado, and in particular, the transect 2 (Typical Cerrado), was the one that presented the least spatial continuity among the samples, describing a certain heterogeneity of the data. According to Ribeiro and Walter (2008) the Typical Cerrado is an intermediate environment to the Dense Cerrado and the Sparse Cerrado, thus justifying the less spatial continuity between the samples.

The most homogeneous environments, T1 with a predominance of tree species and T3 with a predominance of herbaceous species, showed the greatest spatial continuity among the samples. The multifractal analysis proved itself important for the describing the scales of spatial variability along the geometric support, characterizing systems with greater or lesser multifractality, and above all, indicating the presence of high or low measurement values along the transects. In this sense, the multifractal analysis shows, through the singularity spectrum, a description of the variability scales, consisting of a promising strategy in application such as the study of biological variables.

Thus, the left branch of the singularity spectrum represents the domain and concentration of high measurement values, representing the abundance and dominance of organisms, while the right branch of the singularity spectrum is associated with the domain and concentration of low measurement values that represent the distribution of rare species, and according to Gelashvily et al. (2008), these associations correspond to the multifractal dimensions (D_0, D_1 and D_2). On the other hand, the joint multifractal analysis described the magnitude of the relationships of the joint scales [$f(\alpha, \beta)$], allowing to ascertain whether the measurement values of the pairs of variables have spatial association in the geometric support, thus being an important tool for environmental studies, as it allows investigating the variables with potential of predicting other variables, as described by Siqueira et al. (2018).

5 CONCLUSION

The fauna of soil was influenced to a greater or lesser extent by the composition of plant strata, and the plot with Typical Cerrado (T2) showed the least diversity and abundance of groups of invertebrate fauna of soil. The plots with Dense Cerrado (T1) and Sparse Cerrado (T3) showed the greatest spatial dependence between samples, indicating that the scales of spatial variability are influenced by the homogeneity of the tree strata in T1 and the homogeneity of the herbaceous strata in T3.

The multifractal analysis showed that the plot with Sparse Cerrado (T3) was the system with greatest heterogeneity of measurement along the geometric support; while the greatest asymmetry of the singularity spectrum was described for the plot with Dense Cerrado (T1), indicating the concentration of high measurement values in the different scales. The use of geostatistics and multifractal analysis tools allowed characterizing the scale relationships between the variables, however, the joint multifractal analysis did not detect high correlations between the joint scales for the pairs of variables of the invertebrate fauna of soil and the plant strata.

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CAPÍTULO V - MULTIFRACTAL AND JOINT ANALYSIS OF SOIL ARTHROPOD DIVERSITY IN SAVANA

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Raimunda Alves Silva$^{(1)*}$ and Glécio Machado Siqueira$^{(1)}$

$^{(1)}$ Universidade Federal do Maranhão, Programa de Pós-Graduação da Rede BIONORTE, São Luís, Maranhão, Brasil.

* Corresponding author: e-mail: gleciosiqueira@hotmail.com

Abstract The aim of this study was characterizing the spatial variability of the soil fauna from multifractal and joint multifractal analysis in savanna areas. The soil fauna was collected by pitfall traps in two savanna formations, in two transects with 128 points. The organisms were identified and classified into functional groups (Microphages, Pollinators, Predators and Social), than Ind.trap^{-1}.day^{-1} (number of individuals per day in the sample) and Richness were determined. The data were analyzed by means of multifractal and joint multifractal analysis, and the scale indexes $f(\alpha,\beta)$ were generated for the singularity indexes of $\alpha(q,t)$ and $\beta(q,t)$, considering Ind. trap^{-1}.day^{-1} and Richness as predictive variables. A total of 3,456 and 1,629 individuals were collected from T1 and T2, respectively. Richness in T1 and T2 had the best fit for the partition function with a value of $R^2 = 0.999$; and the lowest adjustment value corresponded to Ind.trap^{-1}.day^{-1} in T1 and T2 ($R^2 = 0.980$, $R^2 = 0.972$, respectively). The data group Pollinator (D_{-10}-D_{10} = 0.936) in T1, and for Social (D_{-10}-D_{10} = 0.620) in T2, reflecting more heterogeneous systems. The multifractal joint dimension showed a high correlation between Ind.trap^{-1}.day^{-1} and the functional groups (Pollinators, Predators and Social) in T1, demonstrating how the phytophysiognomy of this experimental plot (Dense Savanna) favors the presence of these organisms and reflects the spatial correspondence of the measurement values along the geometric support. The abundance of organisms (Ind.trap^{-1}.day^{-1}) and Richness were promising variables to represent the set of relationships with the functional groups of the invertebrate fauna of soil. In general, multifractal analysis using abundance and Richness can assist in decision-making focused on conservation of savanna areas.

Keywords: Multifractal dimension, Multifractal joint dimension, Soil invertebrates, Spatial variability of scales, Oxisols

1 INTRODUCTION

In Brazil, savanna areas cover 22% of the national territory (Eiten, 1977, IBGE, 2012), corresponding to an area of 2,036,448 km^2 (MMA, 2020). Brazilian savanna comprises different ecotones, including forest formations, typical savannas and savanna fields (Ribeiro and Walter, 2008), representing an important hotspot of biological diversity (Myers et al., 2000). These ecotones have high abundance of endemic species, and in recent years have suffered exceptional habitat loss (MMA, 2020), related to the expansion of agricultural frontiers in this region.

According to Pompermaier et al. (2020), 56% of savanna areas in Brazil have already been converted to agricultural use, impacting soil biota organisms. Soil fauna comprises a diversity of organisms that occupy different trophic levels (Roy et al., 2018), and are responsible for decomposition (Aubert et al., 2003; Bernardes et al., 2020), nutrient cycling (Martins et al., 2018; Silva et al., 2019) and soil structure (Bernardes et al., 2020).

Soil organisms can be grouped according to their functionality (Silva et al., 2013), into organisms related to the process of decomposition and fragmentation of biological material in the soil-litter system (Aubert et al., 2003; Maggiotto et al., 2019); organisms closely linked to interaction with plants, using it to obtain its resources and also making resources available for other interactions (Roy et al., 2018); organisms that regulate populations through prey-predator dynamics, occupying higher trophic levels (Silva et al., 2013); in addition to organisms with aggregate behavior, which actively act in soil aggregation (Bernardes et al., 2020), both in physical and chemical aspects, among other important features for the soil system.

Given the importance of soil organisms, the decrease in soil biota affects the multifunctionality of ecosystems (Wagg et al., 2014), presenting greater spatial variability in the landscape (Gholami et al., 2017), affected positively or negatively by the use and coverage soil (Silva et al., 2019; Bernardes et al., 2020). Thus, soil fauna organisms should be studied at different spatial scales, allowing the description and understanding of the functionality as well as the dynamics of the communities of organisms that make up the soil system.

As described by Goovaerts (1998), the variability is composed by variations and fluctuations of measures in the landscape. Logsdon et al. (2008), reported that the intrinsic variability of a variable depends on the observation scale, and that the variations and fluctuations of measures increase upon the increase of the observation scale. For this reason, it is necessary to know the variability of measurement values at different scales.

In this sense, fractal theory (Zeleke and Si, 2005; 2006; Caniego et al., 2006; Biswas et al., 2012; Siqueira et al., 2018) is an important tool for quantifying and characterizing spatial variability at different scales, allowing the understanding of spatial heterogeneity (Biswas et al., 2012), regardless of the observation scale (Saravia et al., 2012). On the other hand, the multifractal methodology considers heterogeneity at multiple scales (Vidal Vázquez et al., 2010; Biswas et al., 2012; Dafonte Dafonte et al., 2015), characterizing the spatial distribution of a variable, at different times of a statistical order (Peitgen et al., 1992; Caniego et al., 2006). This allow to identify the magnitude of the measurement values of a variable (Biswas et al., 2012), and thus provides information about the heterogeneity of the variable in successive scales (Halsey et al., 1986; Vidal Vázquez et al., 2013).

Multifractal methodology has been used in soil science mainly to understand physical attributes (Paz Ferreiro et al., 2010; Vidal Vázquez et al., 2010; Bertol et al., 2017) and chemical aspects (Caniego et al., 2006; Biswas et al., 2012; Dafonte Dafonte et al., 2015; Paz Ferreiro et al., 2018; Siqueira et al., 2018). However, there is a knowledge gap about the scale variability for soil biological attributes. Evaluating the multifractality of biological communities in a meadow, Yakimov et al. (2014) described that the species richness had different degrees of scale heterogeneity, which was influenced by the sample size. Studying the species richness using multifract models, Yakimov et al. (2018) described that the systems were influenced by the diversity and abundance of the species, describing differences in the degrees of heterogeneity or multifractality for the systems.

Characterizing the invertebrate fauna in different systems of use and occupation, Silva and Siqueira (2020) found that the degree of heterogeneity or multifractality of the systems was influenced by the decrease in species richness in systems with greater use and management of the soil, also observing greater or lesser asymmetry and heterogeneity in the distribution of scales. In this sense, more studies involving the multifractal methodology are needed, which might elucidating the diversity and spatial variability of the invertebrate fauna of soil at different scales, including the joint multifractal analysis.

Multifractal joint analysis allows the joint characterization of different variables (Zeleke and Si, 2006; Banerjee et al., 2011; Biswas et al., 2012; Bertol et al., 2017; Siqueira et al., 2018). This is possible because joint multifractal joint analysis provides information about the association of measurement values of two variables in a geometric support, considering spatial or temporal scale (Siqueira et al., 2018), where $\alpha(q,t)$ and $\beta(q,t)$ singularity indices are generated, for the measured values (Banerjee et al., 2011; Biswas et al., 2012). The joint multifractal distribution has already been used to characterize patterns of spatial variability of physical and chemical attributes of soil (Zeleke and Si, 2005; 2006; Bertol et al., 2017; Siqueira et al., 2018) and for parameters related to the yield of crops (Kravchenko et al., 2000; Banerjee et al., 2011).

In general, it is necessary understanding the soil fauna in the multiple spheres and interactions, as well as the parameters used to characterize it. Species richness is the most common metric for measuring diversity in a community or area of interest, as it directly quantifies the groups in the sample, providing a measured value to the database (Magurran, 2011), not attributing entropy to the system (Salat et al., 2017), and considering with equal importance the set of abundant and rare species present in the community (Magurran, 2011). Coupled with species richness, the abundance of organisms constitutes, in principle, the first inference about a biological community, where it is possible to characterize the various organisms in the aspects of composition and distribution in a community (Silva et al., 2013).

Furthermore, soil fauna can be characterized in functional categories, through the functionality of groups, interactions exercised in the environment and services provided (Roy et al., 2018; Maggioto et al., 2019). It is worth mentioning that, in addition to the intrinsic variability of the invertebrate fauna of soil, other processes interfere in these metric patterns, such as anthropic interference, use, management and occupation of soil (Siqueira et al., 2014; Martins et al., 2018; Silva et al., 2018; Bernardes et al., 2020).

Many studies have been concerned with understanding the interactions of soil fauna, mainly through richness and abundance (Gholami et al., 2017; Martins et al., 2018; Silva et al., 2018; Silva et al., 2019; Bernardes et al., 2020), however little has been said about the soil fauna determining its spatial variability by multifractal methods, thus, we tried to answer the following hypotheses: (1) the Richness and abundance of soil invertebrates has distribution and association in multifractal scale and multifractal joint; (2) the complexity of the functional groups of the soil fauna can present different degrees of multifractality. Thus, the aim of this study was to characterize the spatial variability of soil invertebrate fauna in savanna areas, through the Richness, abundance and functionality of the soil fauna, using multifractal and joint multifractal tools.

2 MATERIAL AND METHODS

2.1 Area of study

The study area covers 107.92 ha, and is located in the municipality of Chapadinha (State of Maranhão, Brazil), whose geographic coordinates are: 3º 73’34.68’’S and 43º 32’03.12’’ W (Fig. 1). The area natural vegetation is characterized as savanna, and in Brazil, it comprises different phytophysiognomies known as Cerrado (IBGE, 2012). According to Ribeiro and Walter (2008), these phytophysiognomies comprises formations such as: savanna forest, typical savanna and savanna fields.

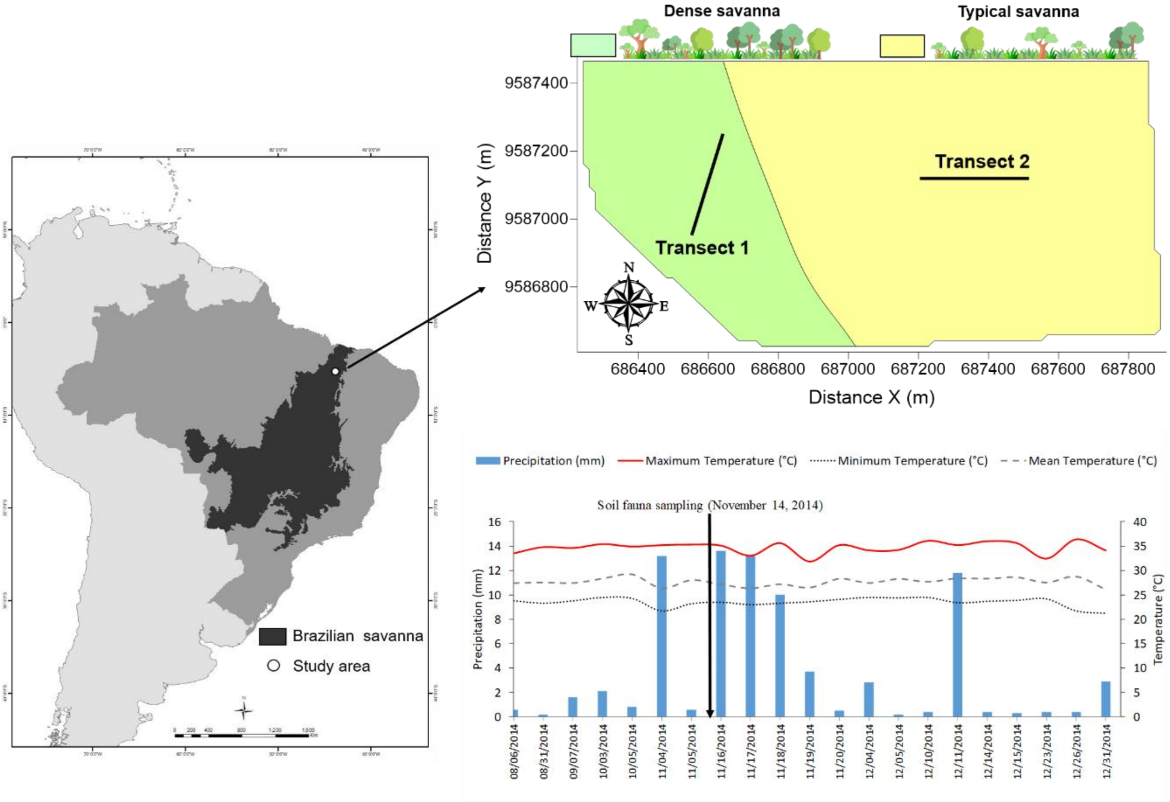

Fig. 1. Location map of the study area, vegetation formations (dense savanna and typical savanna) for the transects 1 and 2, and meteorological parameters during the sampling period.

The climate is tropical hot and humid (Aw), with two well-defined seasons, a rainy season from December to May, and a dry season from June to November, with average temperature ranging between 27 and 30 ºC, and average annual precipitation of 1,600 mm (Silva et al., 2019). The relief of the region is smooth undulating, with an average altitude of 100 m, and the soil was classified as Oxisol (Soil Survey Staff, 2014), whose main physical and chemical characteristics were determined according to EMBRAPA (2017), and are shown in Table 1.

Table 1 Physical and chemical characterization of the superficial layer of soil (0-0.2 m) in the experimental plots, located in the municipality of Chapadinha (Maranhão, Brazil)

	Clay	Silt	Sand	OC	pH	P	K	Ca	Mg	SB	CEC	V%
	----------- % --------			g dm^{-3}	(CaCl$_2$)	mg dm^{-3}	------------ mmol$_c$ dm^{-3} --------					
Transect 1 (T1)	80	60	860	20	4.3	2	2.1	9	7	21.8	52.0	42.0
Transect 2 (T2)	160	60	780	12	4.3	5	3.7	6	4	19.8	48.4	40.9

OC: organic carbon; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; SB: sum of bases; CEC: cation exchange capacity; V%= base saturation.

2.2 Biological Diversity

The biological diversity was sampled over two transects with 128 points, installed in an area with savanna (Fig. 1). Transect 1 (T1) was installed in an area with dense savanna vegetation (T1), with 1.605 trees ha^{-1}, and abundant bush/undergrowth; transect 2 (T2) represented the typical savanna with predominance of undergrowth and sparse trees (0.467 trees ha^{-1}). Sampling of the invertebrate fauna of soil was carried out on 2014/11/14, in the transition period between the dry and rainy seasons. One hundred and twenty-eight pitfall traps were installed in the two experimental plots (T1 and T2), with a 3 m of spacing between traps, and a total length of transects of 381 m.

Each trap remained in the field for seven days, containing 4% formaldehyde solution for the conservation of organisms (Aquino, 2001; Siqueira et al., 2014; Silva et al., 2018). In a laboratory, soil arthropods were screened and identified at the level of order, suborder, family, subfamilies and immature organisms-larvae (Aquino, 2001; Rafael et al., 2012; Roy et al., 2018). The Formicidae family was removed from the order Hymenoptera due to the ecological relationships established by ants in the environment, such as aggregate behavior and diversity of trophic guilds. For T1 there was no capture of organisms for points 27 and 64, and for T2 there was no capture of organisms for points 8, 14, 15, 62, 126 and 127.

Using invertebrate soil fauna data, we determined the abundance of organisms for the period in which the traps remained in the field (Ind.trap^{-1}.day^{-1}), the richness of taxonomic groups present in each of the sample points (Richness). The relative Abundance refers to the number of organisms at each point divided by the total number of individuals in the sample of the transect.

The soil organisms were also grouped according to their functionality in the environment, following the methodology of Silva et al. (2013) and Maggiotto et al. (2019): Microphages (Acari, Archaeognatta, Aucheonorrhyncha, Blattodea, Dermaptera, Diplopoda, Entomobryomorpha, Gastropoda, Coleoptera larva, Formicidae larva, Trichoptera and Zygentoma); Pollinators (Hymenoptera and Lepidoptera); Predators (Araneae, Coleoptera, Diplura, Diptera, Diptera Larva, Neuroptera, Opillionida, Orthroptera and Scorpionida); Social (Formicidae and Isoptera) and Others (Heteroptera, Sternorrhyncha and Thysanoptera). The functional groups were classified according to the data set in each transect and represent real values of individuals at the sample points.

2.3 Descriptive statistical

The main statistical moments determined for the data under study were: mean, coefficient of variation (CV, %), asymmetry, kurtosis and the maximum deviation in relation to the normal distribution (D-KS) using the Kolmogorov-Smirnov test, at the error probability of 0.01.

2.4 Multifractal analysis

The number of samples along the transect was defined considering that the geometric support (L = 381 m) represented successive segments of size 2^k, thus allowing the geometric support to be divided into segments with known size, and that each segment was filled by samples decomposed from the total number of sample points at k = 0 to k = 7 (Halsey et al., 1986; Peitgen et al., 1992; Vidal Vázquez et al., 2013). In this way, successive partition functions generated for the segments in stages (k = 1, 2, 3 ...), were considered on a scale δ, to a segment of number, $N(\delta) = 2^k$ of characteristic length for $\delta = L \times 2^{-k}$.

The multifractal properties of the soil fauna attributes were converted into a mass distribution for the segments, considering the values for the biological attributes at the sampling points as representative, within a radius of 3 m around the sampling point. The normalized mass function $p_i\,(\delta)$ ou $\mu_i\,(\delta)$, is a variable that describes the contribution of a segment or subintervals of size δ to the total mass (Equation 1).

$$p_i\,(\delta) = \varphi_i\,(\delta) / \sum_{i=1}^{n(\delta)} \varphi_i\,(\delta) \tag{1}$$

where:

φ_i correspond to the value of the measurement in the $i^{\text{-th}}$ scale segment δ;

n (δ) corresponds the number of segments with size δ, which covers the sample space;

The $\chi(q,\delta)$ partition function was estimated using the moment method (Evertsz and Mandelbrot, 1992), according to equation 2.

$$\chi(q,\delta) = \sum_{i=1}^{n(\delta)} [p_i(\delta)]^q \tag{2}$$

where:

$n\ (\delta)$ corresponds to the number of segments with size δ, whose statistical moments q are defined for $-\infty < q < +\infty$. In this case, when shown graphically in relation to the size of the box, the partition function has the scale property expressed by equation 3.

$$\chi(q,\delta) \propto \delta^{-\tau(q)} \tag{3}$$

where:

$\tau_{(q)}$ corresponds to a nonlinear function of q, known as a mass exponent function.

The $\tau_{(q)}$ function is obtained from a graph $\chi(q,\delta)$ versus δ for the different values of q. When measurements are multifractal, a non-linear function $\tau_{(q)}$ is adjusted, and for monofractal measurements, a linear function $\tau_{(q)}$ occurs.

The generalized dimension *Dq* or Rényi dimension of the *q* order, *Dq* (Hentschel and Procaccia, 1983), was estimated by the moment method (Evertsz and Mandelbrot, 1992 - equation 4), for q ≠ 1. When $q = 1$, D_1 becomes undetermined, due to the denominator value be zero. For this particular case, when q = 1, *Dq* is obtained by the l'Hôpital rule according to equation 5.

$$D_q = \frac{1}{q-1}\lim_{\delta\to 0}\frac{\log[\chi(q,\delta)]}{log\,\delta} = \frac{\tau(q)}{q-1}, \text{para } q \neq 1$$

(4)

$$D_1 = \lim_{\delta\to 0}\frac{\sum_{i=1}^{n(\delta)} \mu_i\,(\delta)\log\chi(q,\delta)]}{\log\delta}, \text{para } q \neq 1$$

(5)

Thus, for generalized dimensions, *Dq* for $q = 0$, $q = 1$ and $q = 2$, respectively named capacity dimension (D_0), Shannon entropy or entropy dimension (D_1), and correlation dimension (D_2). In continuity, the scale functions can be calculated by the Legendre transformation, using: $f\,(\alpha) = q\,(\alpha q) - \tau_{(q)}$ *e* $\alpha_q = d\,\tau_{(q)}/d_q$. In practice, the Legendre transformation has several disadvantages such as higher error in the estimation of $f\,(\alpha)$ and α in negative moments. In this case, the direct method of Chhabra and Jensen (1989) is used more frequently. For the use of Chhabra and Jensen (1989) it is necessary to use the modified partition function $\chi\ (q,\ \delta)$, where the normalized generating function is obtained in $\mu_i\,(q,\ \delta)$ and defined by equation 6:

$$\mu_i(q,t) = \mu_i^q(\delta)/\sum_1^{n(\delta)} \mu_i^q(\delta)$$

(6)

The singularity spectrum is represented by a graph of $f\,(\alpha)$ versus α, having a parable shape, for multifractal (heterogeneous) systems. In a homogeneous monofractal system, the graphical representation of *f (α)* versus α, has a spectrum reduced to a point (Siqueira et al., 2018). For multifractal spectra, the heterogeneity of the scale and the parable amplitude are evaluated, which are estimated by equations 7 and 8.

$$\alpha(\mathrm{q}) \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta)\log[\mu_i(\delta)]}{\log(\delta)} \tag{7}$$

$$f(\alpha(q)) = \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta)\log[\mu_i(\mathrm{q},\delta)]}{\log(\delta)} \tag{8}$$

For this study, the generalized dimension spectrum, *Dq* was calculated for the statistical moments $-10 \leq q \leq +10$ at 2.0 lag increments, with determination coefficients, $R^2 \geq 0.90$.

The analysis of the joint partition functions was performed for the total length (L = 381 m), which was divided into boxes of size *δ,* where the partitions are obtained (Bertol et al., 2017). Joint analysis is a tool used to characterize two variables at various scales of measurement in *p* and *r*, which are partitioned into *δ.* These variables (*p* and r) are defined as $p_i(\delta)$ and $r_i(\delta)$, and their exponents are related to *α* and *β*, maintaining the ratio of $p_i(\delta) \propto \delta^{\alpha}$ and $r_i(\delta) \propto \delta^{\beta}$, with normalized partition function, $\mu_i(q,t,\delta)$, where the joint distribution function $p_i(\delta)$ and $r_i(\delta)$, is calculated according to equation 9.

$$\mu_i(q,t,\delta) = \frac{[p_i(\delta)]^q\,[r_i(\delta)]^t}{\sum_{i=1}^{n(\varepsilon)}[p_i(\delta)]^q[r_i(\delta)]^t} \tag{9}$$

Where: *q* and *t* correspond to real numbers that represent the moment orders, and *δ* is the scale. Based on the contribution of intervals for each segment, the singularity indexes *α (q,t) and β (q,t)* were calculated in relation to the µi measure (equation 10 and 11 - Zeleke and Si, 2006).

2.5 Joint multifractal analysis

This allowed obtaining the dimension of the joint, *f (α,β)*, for the set in which *α (q,t)* and *β (q,t)* represent the average of the measure's singularity under study (Biswas et al., 2012), equation 12.

$$\alpha(q,t) = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{n(\varepsilon)} [\mu_i(q,t,\delta). \log p_i(\delta)]}{\log \delta} \tag{10}$$

$$\beta(q,t) = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{n(\varepsilon)} [\mu_i(q,t,\delta). \log r_i(\delta)]}{\log \delta} \tag{11}$$

$$f(\alpha,\beta) = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{n(\varepsilon)} [\mu_i(q,t,\varepsilon). \log\,(q,t,\varepsilon)]}{\log \varepsilon} \tag{12}$$

The graphs of multifractal spectra are constructed using the function $f(\alpha,\beta)$ in $\alpha(q,t)$ and $\beta(q,t)$, which describe the distribution of the intensity levels of a variable in contrast to another analyzed variable (Bertol et al., 2017).

The relationship between the biological variables under study was assessed by Pearson's linear correlation, at different levels of significance ($P < 0.01$ and $P < 0.05$), which throughout this study we will be called simple correlation. Pearson's linear correlation was also used to assess the singularity indexes $\alpha(q,t)$ and $\beta(q,t)$, which were obtained by means of the joint multifractal analysis, at the significance of $P < 0.01$ and $P < 0.05$ for the biological variables that from now on will be termed joint correlation.

3 RESULTS AND DISCUSSION

3.1 Taxonomic Groups and Functional groups

A total of 3,456 individuals were collected at T1, distributed in 26 taxonomic groups; and 1,629 individuals in T2, distributed in 15 taxonomic groups (Table 2). Silva et al. (2019)

studying the soil fauna in an area with preserved and anthropized savanna, identified 2,384 and 1,777 individuals, distributed in 15 and 11 taxonomic groups, respectively. Characterizing the soil macro fauna in agroforestry systems in a savanna area, Martins et al. (2018), identified 1,993 specimens, distributed in 27 taxonomic groups. Studying the epigeal soil fauna in a savanna area, Souza et al. (2017) identified 454 individuals distributed in 13 taxonomic groups.

The collected organisms were grouped according to their functionality in Microphages, Pollinators, Predators, Social and Others (Table 2). The Social functional groups (1,576 and 614 individuals, in T1 and T2 respectively) and Pollinators (1,518 and 605 individuals, in T1 and T2 respectively) were the most abundant. Social organisms (Isoptera and Fomicidae) showed a positivity rate of 94.53% of the organisms collected in T1 and 85.15% in T2, where almost all organisms being represented by Formicidae.

The high abundance of Formicidae in savanna areas have been reported in previous studies (Martins et al., 2018; Silva et al., 2018; Silva et al., 2019; Vicente et al., 2018). Pollinating organisms are represented by the taxonomic groups Hymenoptera and Lepidoptera, with a positivity rate greater than 85.93%. Hymenoptera order was the most abundant in T1 (1,517 individuals), followed by the family Formicidae (1,479 individuals), while in T2, the family Formicidae was the most abundant (607 individuals), followed by the order Hymenoptera, with 605 individuals (Table 2). The separation of the Formicidae family from the order Hymenoptera, was carried out considering the aggregated behavior of ants (Vicente et al., 2018), and their diversified ecological habits (Costa-Milanez et al., 2014), in relation to the order Hymenoptera, which in most cases are winged.

Predatory organisms (Araneae, Coleoptera, Diplura, Diptera, Diptera Larva, Neuroptera, Opillionida, Orthroptera, Scorpionida) occurred in 66.40% (T1) and 69.53% (T2) of the traps, and their occurrence along the transect is related to different environmental factors, and above all, the availability of food resources, as described by Silva et al. (2013). The functional group Microphages (Acari, Archaeognatta, Aucheonorrhyncha, Blattodea, Dermaptera, Diplopoda, Entomobryomorpha, Gastropoda, Coleoptera larva, Formicidae larva, Trichoptera and Zygentoma) were sampled in 8.59% of the traps in T2, and 28.90% of the traps in T1.

Table 2. Taxonomic groups, number of individuals, relative abundance and percentage of soil fauna in savanna transects

Taxonomic grups	Transect 1			Transect 2		
	Abundance	N	%	Abundance	N	%
FILO MOLLUSCA						
Class Gastropoda	33	3 (2.34)	0.95	-	-	-
FILO ARTHROPODA						
SUBFILO MYRIAPODA						
Class Diplopoda	3	3 (2.34)	0.09	-	-	-
SUBFILO CHELICERATA						
Class Arachnida						
Order Acari	14	14 (10.93)	0.41	4	4 (3.12)	0.25
Order Araneae	64	44 (34.37)	1.85	95	45 (35.15)	5.83
Order Opillionida	-	-	-	2	2 (1.56)	0.12
Order Scorpionida	-	-	-	5	3 (2.34)	0.31
SUBFILO HEXAPODA						
Order Entomobryomorpha	1	1 (0.78)	0.03	-	-	-
Order Diplura	44	22 (17.18)	1.27	16	4 (3.12)	0.98
Class Insecta						
Order Archaeognatha	1	1 (0.78)	0.03	-	-	-
Order Zygentoma	9	6 (4.68)	0.26	-	-	-
Order Orthoptera	6	6 (4.68)	0.17	23	15 (11.71)	1.41
Order Dermaptera	4	4 (3.12)	0.12	-	-	-
Order Isoptera	97	9 (7.03)	2.81	7	5 (3.90)	0.43
Order Blattaria	4	4 (3.12)	0.12	1	1 (0.78)	0.06
Order Hemiptera						
Suborder Aucheonorrhyncha	8	7 (5.46)	0.23	-	-	-
Suborder Heteroptera	9	6 (4.68)	0.26	2	2 (1.56)	0.12
Suborder Sternorrhyncha	4	2 (1.56)	0.12	-	-	-
Order Thysanoptera	13	2 (1.56)	0.38	-	-	-
Order Coleoptera	69	37 (28.90)	2.00	239	53 (41.40)	14.67
Order Neuroptera	1	1 (0.78)	0.03	-	-	-
Order Hymenoptera	1,517	116 (90.62)	43.89	605	108 (84.37)	37.14
Family Formicidae	1,479	116 (90.62)	42.80	607	95 (74.21)	37.26
Order Trichoptera	6	4 (3.12)	0.17	-	-	-
Order Lepidoptera	1	1 (0.78)	0.03	-	-	-
Order Diptera	27	6 (4.68)	0.78	12	6 (4.68)	0.74

Imature organisms						
Larva Coleoptera	2	2 (1.56)	0.06	1	1 (0.78)	0.06
Larva Diptera	32	5 (3.90)	0.93	-	-	-
Larva Formicidae	8	6 (4.68)	0.23	10	6 (4.68)	0.61
Functional groups						
Microphages	93	37 (28.90)	-	16	11 (8.59)	-
Pollinators	1,518	116 (90.62)	-	605	110 (85.93)	-
Predators	243	85 (66.40)	-	392	89 (69.53)	-
Social	1,576	121 (94.53)	-	614	109 (85.15)	-
Others	26	20 (15.62)		2	2 (1.57)	
Total	3,456	-	100%	1,629	-	100%
Richness	26	-	-	15	-	-
Number of points with individual	126*	-	-	122**	-	-

% = Relative abundance; N = Number of points with occurrence of individuals and the rate of sample positivity (%). * In T1, no individual were collected from the points 27 and 64. In T2, no individual were collected from the points 8, 14, 15, 62, 126 and 127.

The greater occurrence of Microphages in T1, is justified by the diversity of vegetation strata in this plot compared to T2. Our results corroborate with Silva et al. (2013) and Maggiotto et al. (2019) who also reported greater diversity of microphages, related to environments with greater quantity and diversity of food resources. Organisms without defined environmental functionality, here called as Others are represented by Heteroptera, Sternorrhyncha and Thysanoptera, and in general, their positivity is associated with T1, confirming that environmental diversity favors the richness of soil invertebrate fauna organisms (Silva et al., 2019).

For the Coleoptera order, 239 individuals were identified, representing 14.67% of the sample population in T2, and 69 individuals (2%) in T1 (Table 2), demonstrating that the abundance of beetles is influenced by vegetation cover. In a study of soil fauna in a savanna area, Martins et al. (2018) identified 350 organisms that represented 17.56% of the total of individuals. Bernardes et al. (2020) registered 282 beetles in a savanna area, distributed in 20 taxa. Characterizing the soil fauna in savanna transition areas, Santos et al. (2017) sampled 141 coleoptera, which represented 2.05% of the total collected individuals. Evaluating the population fluctuation of coleoptera in savannah area, Gonçalves (2017) collected 2,123 beetles, representing an average of 176.91 organisms per month.

For the Isoptera group, 97 individuals were identified in T1, and 7 individuals in T2 (Table 2). Oliveira et al. (2013) identified 115 individuals (Isoptera) in areas with typical savanna formation and savanna fields, describing that the presence of this group was associated with the presence of litter. The lower abundance of certain organisms such as Archaeognatta, Entomobryomorpha and Neuroptera is related to the content of organic matter (Roy et al., 2018). According to Rafael et al. (2012), this also might be related to the absence of predators, benefiting invertebrate fauna organisms such as Lepidoptera and Blattodea, which are active, winged and synanthropic organisms.

Twenty-seven adult dipterans and 32 larvae were collected in T1, and 12 adult dipterans for T2. The occurrence of dipterans adult and at larval stage in the present study is justified by the content of organic matter (20 g dm^{-3} and 12 g dm^{-3}, for T1 and T2, respectively - Table 1), and according to Kaneda et al. (2013) are organisms that benefit from decomposing organic matter.

On the other hand, Moço et al. (2010) studying soil soil fauna and its relationship with physical and chemical attributes of the soil, showed that the clay content is one of the determining factors for the occurrence of certain groups. Bedano et al. (2016) described that the soil fauna is also influenced by the sand content of the soil, benefiting mainly social organisms, thus justifying the higher occurrence of the Formicidae family in T1 (sand = 86%), compared to T2 (sand = 78%). Bernardes et al. (2020) studying the Coleoptera fauna showed that the occurrence of Coleoptera in the experimental plots was influenced to a greater or lesser extent by the clay and sand content of the soil.

3.2 Descriptive statistics

The mean values for Ind.trap^{-1}.day^{-1} and Richness indices in T1 were 3.850 and 5.990, and in T2 were 1.810 and 5.630, respectively (Table 3). Studying soil macrofauna in riparian forest, Gholami et al. (2017), found average abundance values of 39.60 individuals/m^2 and average

Richness of 1.40, describing that invertebrate fauna organisms were associated with the type of vegetation cover. This corroborates the results fund in the present study, which describe that the type of vegetation cover influenced the average abundance of individuals. According to Marichal et al. (2014) systems with greater vegetation cover, favor the formation of microclimate and supply of food resources for soil fauna.

Social organisms were the functional group with highest average occurrence (12.313 in T1 and 4.796 in T2), followed by Pollinators (11.859 in T1 and 4.726 in T2), Predators (1.898 in T1 and 3.062), Microphages (0.727 in T1 and 0.125 in T2) and Others (0.203 in T1 and 0.015 in T2). The highest occurrence of social organisms, represented mainly by the family Formicidae, occurs due to a high variety of guilds, different ecological niches (Moreira et al., 2010), aggregate behavior (Vicente et al., 2018) and with different eating habits (Costa-Milanez et al., 2014).

Regarding pollinating organisms (Hymenoptera and Lepidoptera), their occurrence for the present study was not expected, since these organisms are winged, and according to Correia and Oliveira (2000) their occurrence in ground-level traps is justified by the use of formaldehyde, which in addition to functioning as a preservative agent, for this specific group also acts as attractive. It is important to highlight that, for the functional group Pollinators, the order Hymenoptera was the one that most contributed to the rate of positivity (Table 2).

Predator organisms are represented in this study mainly by the Araneae group, and according to Bedano et al. (2016) have as their main function the biological regulation through the prey-predator dynamics. The microphages showed a higher mean at T1 compared to T2, and as previously discussed, such behavior is a direct result of the quantity and availability of organic carbon in these plots, corroborating with Silva et al. (2013) and Maggiotto et al. (2019). The Others group had the lowest mean value associated with T2 (Mean = 0.015), indicating that this environment is less diverse compared to T1. It is worth mentioning that, in this case, the spatial variability of these organisms is high, and the experimental design used in this study is not effective for understanding organisms whose ecological function is little known (Silva et al., 2013).

Table 3. Descriptive statistics of the diversity indexes of soil fauna in two transects in the Savanna Biome

T1					
Parameters	Mean	CV (%)	Skewness	Kurtosis	D-KS*
Ind.trap^{-1}.day^{-1}	3.850	84.150	1.430	2.084	0.137n
Richness	5.990	38.510	0.710	1.490	0.202Ln
Microphages	0.727	298.017	5.848	39.161	0.368Ln
Pollinators	11.859	126.656	2.804	11.168	0.215Ln
Predators	1.898	151.281	2.609	7.079	0.286Ln
Social	12.313	95.745	2.254	8.125	0.173Ln
Others	0.203	328.00	5.988	39.256	0.369Ln
T2					
	Mean	CV (%)	Skewness	Kurtosis	D-KS*
Ind.trap^{-1}.day^{-1}	1.810	85.150	1.610	3.360	0.165Ln
Richness	5.630	46.510	0.110	0.500	0.167Ln
Microphages	0.125	155.032	3.441	15.174	0.259Ln
Pollinators	4.726	342.544	3.808	15.100	0.521Ln
Predators	3.062	95.060	2.164	5.255	0.247Ln
Social	4.796	109.636	2.393	7.296	0.228Ln
Others	0.015	399.200	4.200	7.540	0.332Ln

Ind.trap^{-1}.day^{-1}: Individuals trap^{-1} day^{-1}, CV%: Coefficient of variation; Ln: Lognormal; D-KS*: Kolmogorov-Sminorv normality test - 0.01%.

The Kolmogorov-Smirnov test (D-KS, $P < 0.01$), demonstrated that all attributes under study had a lognormal frequency distribution (Ln), except Ind.trap^{-1}.day^{-1} in T1, which showed a normal frequency distribution. Although it is important characterizing the frequency distribution of organisms along the transects in order to ascertain the normality of the data, this is not a requirement for multifractal analysis; multifractal analysis only requires that the data present the distribution of values in successive segments and that they obey a power law, as reported by Mandelbrot (1982).

3.3 Multifractal analysis

The multifractal analysis was carried out considering the total length of transects (381 m), with a partition function, $\chi(q,\delta)$ (Fig. 2) built for the successive segments of 2^k in k = 0 to k = 7, and moments of order $-10 < q < 10$ (Peitgen et al., 1992), with an interval for 2.0 scales. For both transects, seven variables were evaluated by means of multifractal analysis, however, it was evidenced that in T1, five variables presented multifractality (Ind.trap^{-1}.day^{-1}, Richness, Pollinators, Predators and Social), and for T2, three variables showed multifractality (Ind.trap^{-1}.day^{-1}, Richness and Social).

In this sense, it is possible to see that the invertebrate fauna of soil had different degrees of heterogeneity for the experimental plots. The greater description of multifractal patterns for T1, is due to a greater spatial distribution of the measured values for these variables in the transect and in the partitions. Silva and Siqueira (2020) studying the invertebrate fauna in different land use and management systems, described that the scale variability of the abundance and Richness of the organisms reflects the environment, in terms of disturbance and conservation. In this way, the occurrence of greater multifractality for T1, in relation to T2, describes how the diversity of the environment in T1 benefits the arthropod fauna community in this plot, showing systems with greater complexity and spatial continuity of the measurement values.

The partition functions with the highest coefficient of determination (R^2 - Fig. 2) corresponded to the Richness in T1 and T2 ($R^2 = 0.999$, Fig. 2a and 2b). The Richness describes that there is homogeneity of taxonomic groups through the transects, with no clear relationship between abundance, corroborating (Saravia et al., 2012). On the other hand, the occurrence of lower values of R^2 for Ind.trap^{-1}.day^{-1} in T1 and T2 (T2: $R^2 = 0.972$ - Fig. 2d and T1: $R^2 = 0.980$ - Fig. 2c), described that the internal structure of the system for the abundance of organisms is heterogeneous, as shown by the positivity rate (Table 2).

In general terms, the partition function is indicative of the scale structure, which can be monofractal (single scale) or multifractal (multiple scale) (Zeleke and Si, 2006; Vidal Vázquez et al., 2013; Bertol et al., 2017; Siqueira et al., 2018;). Thus, the results found in this study demonstrated that the attributes under study are distributed on a multiple scale, to a greater or lesser degree of multifractality (Saravia et al., 2012; Salat et al., 2017; Silva and Siqueira, 2020).

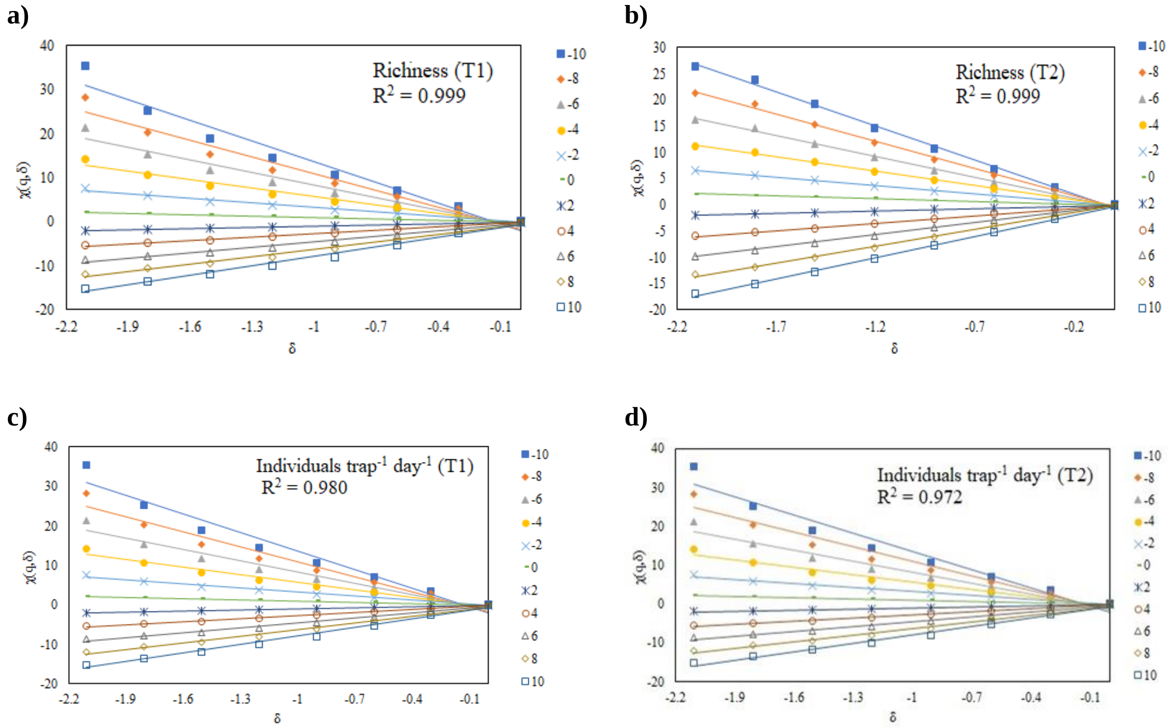

Fig. 2. Partition function for the indexes of soil fauna. Richness in T1 (a) and in T2 (b), individuals trap^{-1} day^{-1} in T1 (c) and in T2 (d).

We highlight that the presence of a better fit for Richness in relation to Ind.trap^{-1}.day^{-1}, occurs because the distribution of the values of measures of Richness are uniformly distributed throughout the geometric support and in the partitions, with low variability between the measured values, while for Ind.trap^{-1}.day^{-1} there is a greater variation between the measured values, resulting in a partition function with less adjustment (T2: $R^2 = 0.972$ and T1: $R^2 = 0.980$ - Fig. 2d and 2c).

The generalized dimensions *Dq* or Rényi dimension (Peitgen et al., 1992; Hentschel and Procaccia, 1983) are presented in Table 4, and were estimated by the moment method, according to Evertsz and Mandelbrot (1992). Capacity dimension (D_0) provides global or average information of the system, indicating that the segments have a mass value, that is, it represents the exponent of scale for the segments, computing the presence or absence of values through the sampling points.

The lowest value of D_0 (Table 4) for the plots was described for the functional group Predators (D_0 = 0.936±0.024 in T1) and Social (D_0 = 0.976±0.009 in T2), and the highest value was described for Ind.trap^{-1}.day^{-1} (D_0 = 0.997±0.001 in T1 and D_0 = 0.991±0.003 in T2), followed by Richness (D_0 = 0.996±0.002 in T1 and D_0 = 0.990±0.003 in T2). According to Banerjee et al. (2011) and Vidal Vázquez et al. (2013) D_0 values equal to 1, indicate that all sample points are associated to a numerical value, whereas values < 1 represent the absence of a numerical value at one or more points throughout the segment of the partition function.

Therefore, the highest values of D_0 for Ind.trap^{-1}.day^{-1} followed by Richness, describe that there are few points without measurement values in all the geometric support, and consequently, in the partitions. The occurrence of lower values of D_0 for the functional groups, describes the absence of measurement values in the geometric support, indicating that the variability of the functional groups in the geometric support is influenced by the greater or lesser environmental complexity in T1 and T2.

According to Gelashvily et al. (2008) the generalized dimensions reflect the structural heterogeneity of the biological community, where the greatest differences are described by the abundance of organisms and richness of species that make up the sample. In this sense, D_0 in T1 represents a system with greater structural heterogeneity, with a greater number of measurements along the geometric support (N = 126 points with measurement values), while T2 has a greater number of points without associated measurements (N = 122 points with measurement values).

The lowest value for the information dimension (D_1) at T1 was described for Predators (D_1 = 0.930±0.020), and at T2 for Ind.trap^{-1}.day^{-1} (D_1 = 0.940±0.014), and the highest values of D_1 described for Richness in T1 and T2 (D_1 = 0.984±0.004 and D_1 = 0.974±0.005, respectively). The information of dimension (D_1) is related to Shannon's entropy information and quantifies the degree of disorder present in a distribution, and it must be in the range $0 < D_1 < 1$. In this way, when the D_1 value is close to 1, the system is uniformly distributed across all scales, while values lower than 1 describe a subset of scales with concentrated irregularities (Posadas et al., 2009; Vidal Vázquez et al., 2013).

The greater uniformity of the distribution of values in the scales for Richness describes systems uniformly distributed in T1 and T2, with partitions occupied by measurement values with low variation between the measurement values present in the partitions; while the less uniformity in the scales for Predators and Ind.trap^{-1}.day^{-1} reflects that there is heterogeneity of the measures of values in the partitions. Our results demonstrate that Richness and spatially is little influenced by the heterogeneity of the abundance of organisms (Ind.trap^{-1}.day^{-1}), since, Richness is the result of a series of environmental relationships (Gholami et al., 2017) and the complexity of the soil invertebrate fauna community (Roy et al., 2018).

The dimension of D_2 is mathematically associated with the correlation function and computes the correlation of measures contained between the intervals (Posadas et al., 2009). According to Grassberger and Procaccia (1983), it is a measure that describes how closely the segments are correlated, and represents the complexity of the systems. Thus, we might infer that the attributes under study represent complex systems, not necessarily stating that they are multifractal systems, as there is a trend, which can be confirmed if $D_0 > D_1 > D_2$, as described by Banerjee et al. (2011), Vidal Vazquéz et al. (2013), Dafonte Dafonte al. (2015) and Siqueira et al. (2018). However, when the dimensions are represented by $D_0 = D_1 = D_2$, the system is characterized as a monofractal, that is, the structure of the system is self-similar (Mandelbrot, 1982; Caniego et al., 2006), and when the dimensions are represented by $D_0 \approx D_1 \approx D_2$, the systems have certain homogeneity.

The difference between D_{-10}-D_{10} was lower for Richness in T1 and T2 (D_{-10}-D_{10} = 0.204 e D_{-10}-D_{10} = 0.276); and the highest values of D_{-10}-D_{10} were described for Pollinators in T1 (D_{-10}-D_{10} = 0.936), and for the Social group in T2 (D_{-10}-D_{10} = 0.620). The values of D_{-10}-D_{10} are often used to determine the degree of multifractality of the system scale (Caniego et al., 2006; Paz Ferreiro et al., 2010; Dafonte Dafonte et al., 2015). Thus, the biological attributes of soil under study differ in spatial distribution, representing different degrees of heterogeneity. It is necessary to consider that the variability of soil fauna results from the interaction of factors in the environment, such as the interaction of climatic and edaphic (Silva and Siqueira, 2020), as well as from the interaction of physic and chemical factors (Bedano et al., 2016), occurrence of ecological niches (Wagg et al., 2014; Roy et al., 2018).

Thus, the interference of these factors can contribute to a greater or lesser degree of heterogeneity in the soil community. In this sense, our results demonstrate that the spatial distribution of Richness in the geometric support has low variability compared to the other parameters under study. We also emphasize that the high variability of the data for the functional groups, in general reflects the data heterogeneity, especially with regard to the abundance of organisms (Ind.trap^{-1}.day^{-1}), which in both transects had high variability (CV = 84.150% in T1 and 85.154% in T2).

Table 4 Multifractal parameters obtained for partition function, generalized dimension (D_{10}, D_0, D_1, D_2 and D_{-10}) and singularity spectrum (q_+, q_-, α_0, α_{min}, α_{max}) of soil fauna

Variables		D_{-10}	D_0	D_1	D_2	D_{10}	D_{-10}-D_{10}	q_+	q_-	α_0	α_{-10}	α_{10}	$\Delta\alpha_L$	$\Delta\alpha_R$
T1	Ind.trap^{-1}.day^{-1}	1.489±0.086	0.997±0.001	0.940±0.012	0.898±0.019	0.758±0.032	0.731	6	-2	1.066±0.026	1.460±0.183	0.724±0.072	0.342	-0.394
	Richness	1.106±0.025	0.996±0.002	0.984±0.004	0.973±0.006	0.902±0.016	0.204	10	0	1.007±0.003	1.125±0.058	0.864±0.014	0.143	-0.118
	Pollinators	1.585±0.101	0.985±0.006	0.975±0.005	0.826±0.032	0.649±0.052	0.936	2	0	1.110±0.021	1.111±0.021	0.771±0.084	0.339	-0.001
	Predators	1.174±0.089	0.936±0.024	0.930±0.020	0.754±0.018	0.610±0.019	0.564	4	-2	1.024±0.064	1.171±0.145	0.599±0.040	0.425	-0.147
	Social	1.496±0.084	0.990±0.003	0.980±0.002	0.876±0.024	0.709±0.053	0.787	2	0	1.071±0.023	1.172±0.023	0.830±0.065	0.342	-0.101
T2	Ind.trap^{-1}.day^{-1}	1.378±0.077	0.991±0.003	0.940±0.014	0.902±0.021	0.787±0.041	0.591	8	-10	1.052±0.020	1.409±0.178	0.772±0.088	0.280	-0.347
	Richness	1.180±0.027	0.990±0.003	0.974±0.005	0.961±0.006	0.904±0.017	0.276	10	-4	1.008±0.007	1.213±0.068	0.875±0.046	0.133	-0.205
	Social	1.328±0.056	0.976±0.009	0.960±0.003	0.854±0.029	0.708±0.048	0.620	2	-2	1.046±0.012	1.319±0.109	0.804±0.074	0.515	-0.273

Ind.trap^{-1}.day^{-1}: Individuals trap^{-1} day^{-1}

The singularity spectra (α_0, α_{-10}, α_{10}, $\Delta_{\alpha L}$, $\Delta_{\alpha R}$ - Table 4 and Fig. 3) demonstrated that the scale properties for the data represented multifractal systems. The systems asymmetry was evaluated considering: $\Delta_{\alpha L}$ (α_0-α_{10}) and $\Delta_{\alpha R}$ (α_0-α_{-10}). The Hölder exponent (α_0) is a parameter that quantifies the average degree of mass density of the measure, obtained from the statistical distribution of the singularity spectrum (Paz Ferreiro et al., 2010), while α_{-10} describes the minimum value for the function *f(α)* versus α function of the singularity spectrum, and α_{10} represents the maximum value of *f(α)* versus α function for the singularity spectrum.

The functional groups Predator and Social showed a singularity spectrum with an elongated branch to the left ($\Delta_{\alpha L} = 0.425$ and $\Delta_{\alpha L} = 0.515$ in T1 and T2, respectively), and the abundance of organisms (Ind.trap^{-1}.day^{-1}) presented a spectrum of singularity with elongated branch to the right ($\Delta_{\alpha R}$) in T1 ($\Delta_{\alpha R} = -0.394$) and in T2 ($\Delta_{\alpha R} = -0.347$).

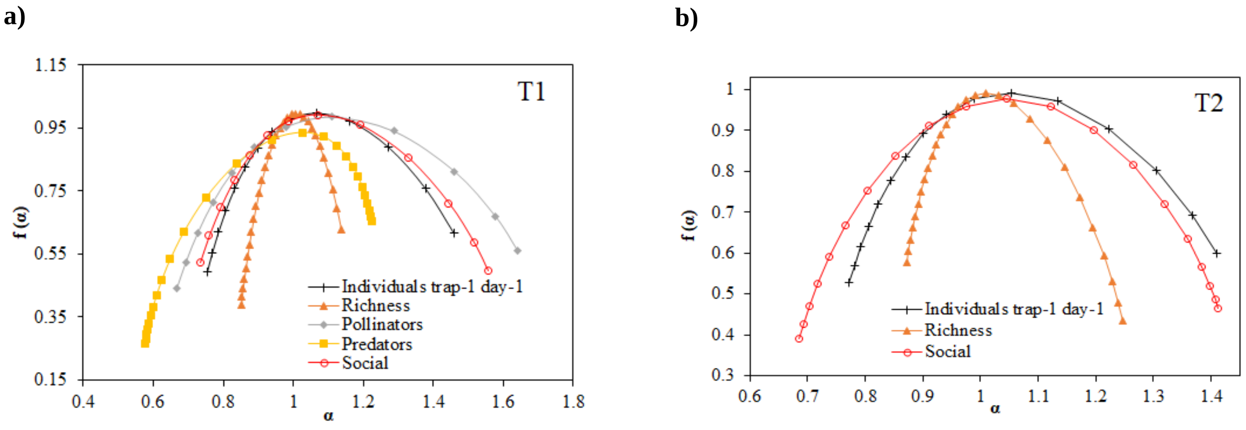

Fig. 3. Spectrum of singularity of soil fauna. Individuals trap^{-1}day^{-1}, Richness, Pollinators, Predators and Social in T1 (a), and Individuals trap^{-1}day^{-1}, Richness and Social in T2 (b).

As previously discussed, the variability of Ind.trap^{-1}.day^{-1} has a direct association with the functional groups of soil fauna along the transect. In this case, the singularity spectrum for Ind.trap$_{-1}$.day^{-1} represents a system with a greater variety of high singularity exponent values, which are associated with low concentrations of measured values, thus justifying the reverse behavior for Social Organisms (Table 4 and Fig. 3a and 3b), which has asymmetrical branches and elongated to the left, and the high measures of Ind.trap^{-1}.day^{-1} are associated.

The singularity spectrum for Richness showed that there is a concentration of high singularity exponents in T1 and T2 (Figure 3a and 3b), however, there is asymmetry of the branches to the left in T1 and to the right in T2. Thus, the spectrum of uniqueness for Richness reflected the complexity of the environment, and the differentiation for the asymmetry of branches in T1 and T2, represents the characteristics of vegetation formation for each of the experimental plots. There is a greater diversity of vegetation strata in T1, thus influencing the composition and abundance of soil fauna in this treatment, corroborating the studies by Aubert et al. (2003), Sereda et al. (2012) and Gholami et al. (2017).

3.4 Joint multifractal analysis

The graphs for the joint multifractal distribution (Fig. 4 and 5), obtained from the joint dimensions of $f(\alpha,\beta)$, in which the singularity indexes $\alpha(q,t)$ and $\beta(q,t)$ are presented on the horizontal and vertical axes, respectively. The scale indexes [$\alpha(q,t)$ and $\beta(q,t)$] for the biological attributes under study, were evaluated considering the linear (simple) correlation and the joint correlations, by Pearson's correlation, with significance of $P < 0.01$ and $P < 0.05$. The joint multifractal analysis was performed considering Ind.trap^{-1}.day^{-1} and Richness as fixed variables on the [$\alpha(q,t)$] axis in order to assess the association with the functional groups of soil fauna on [$\beta(q,t)$].

The results of the joint multifractal analysis (Fig. 4 and 5) showed that the attributes under study had different degrees of association between the scale indexes $\alpha(q,t)$ and $\beta(q,t)$ in T1 and T2. The graphs of the joint multifractal spectrum [$f(\alpha,\beta)$] were represented by contour lines in relation to the distribution of high or low values, with the lower left part representing high values of $\alpha(q,t)$ and $\beta(q,t)$, and the upper right representing low values of $\alpha(q,t)$ and $\beta(q,t)$ (Zeleke and Si, 2006). This represents a diagonal graph, with ellipse and narrow/close lines, showing strong correlation between values (Biswas et al., 2012). It is also important to describe that circular contour lines indicate that there was no association between the joint dimension of scales, representing more rounded graphics (Fig. 4 and 5).

The contour plot of the joint dimension for Ind.trap^{-1}.day^{-1} *versus* Richness at T1 (Fig. 4a), showed a single correlation of R = -0.105 (P <0.01) and a joint correlation of R = 0.095 (P < 0.05). In general, the graph describes circular contour lines, indicating that the joint scales [$\alpha(q,t)$ and $\beta(q,t)$] do not have a well-defined correlation, especially for the high measurement values of $\alpha(q,t)$ and $\beta(q,t)$. Ind.trap^{-1}.day^{-1} *versus* Richness in T2 (Fig. 4e), described a single correlation of R = 0.396 (P <0.05) and a joint correlation of R = -0.150 (P <0.01).

The results demonstrate that there is a strong correlation in the scales $\alpha(q,t)$ and $\beta(q,t)$ for these variables. In this case, it is important to describe that the contour lines have diagonal distribution and with elliptical lines, indicating a high correlation in the joint scales (Biswas et al., 2012). The presence of a higher joint correlation for Ind.trap^{-1}.day^{-1} *versus* Richness in T2, compared to T1, is justified by the greater uniformity and symmetry of the singularity spectrum for these variables, according to the initial multifractal analysis (Table 4 and Fig. 3). This demonstrates how the type of vegetation cover affects the scales of variability of the invertebrate fauna of soil, corroborating with Silva and Siqueira (2020).

The multifractal joint dimensions for Ind.trap^{-1}.day^{-1} *versus* Pollinators (Fig. 4b) in T1, Ind.trap^{-1}.day^{-1} *versus* Social (Fig. 4d) in T1 and Ind.trap^{-1}.day $^{-1}$ *versus* Social (Fig. 4f) in T2 presented graphs with diagonal contour lines, and in ellipse, describing a high relationship for the distribution of the scales of $\alpha(q,t)$ and $\beta(q,t)$, resulting in high values of joint correlation: Ind.trap^{-1}.day^{-1} *versus* Pollinators (R = 0.299, P < 0.01) at T1, Ind.trap^{-1}.day^{-1} *versus* Social (R = -0.305, P < 0.01) at T1 and Ind.trap^{-1}.day^{-1} *versus* Social in T2 (R = -0.598, P < 0.01). The high correlation in the joint scales for the abundance of organisms (Ind.trap^{-1}.day^{-1}) and for the functional groups (Pollinators and Social) reflects that there is a spatial correspondence for the measurement values of these variables along the geometric support, thus, there is a correlation in single and joint scales. The abundance of organisms presented itself as a variable with the potential to predict the pollinating and social functional groups, however, it must be kept in mind that abundance does not directly reflect biological diversity (Maguram, 2011).

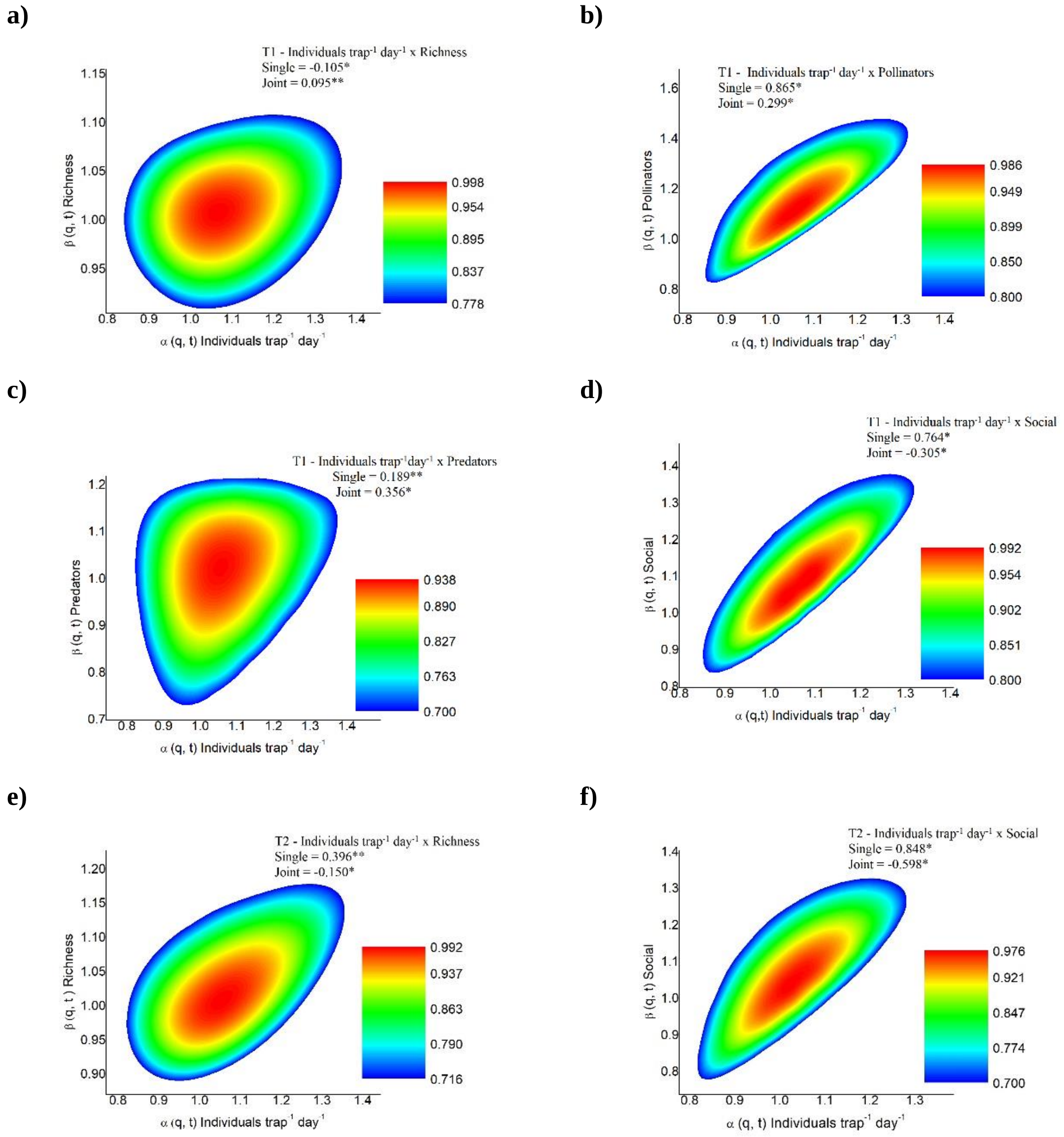

Fig. 4. Joint multifractal distribution in T1 for individual trap^{-1} day^{-1} (horizontal axis) versus taxonomic groups (vertical axis): Richness (a), Pollinators (b), Predators (c) and Social (d) in T1; and Social (f) in T2, with Pearson's correlation coefficient on a joint scale of $\alpha(q,t)$ and $\beta(q,t)$ and simple scale. * significance value P < 0.01 and ** significance value P < 0.05.

The graphs of contour lines of the joint dimension of T1 and T2 for Richness *versus* Functional groups (Ind.trap^{-1}.day^{-1}, Pollinators, Predators and Social) are shown in Figure 5. In general, the graphs of the joint dimension using Richness as a predictor variable (Fig. 5), showed slightly lower correlation values compared to the joint correlation values using Ind.trap^{-1}.day^{-1} as a predictor variable (Fig. 4). This fact is justified, since Richness has less variability along the geometric support and in the scales, while the abundance of organisms (Ind.trap^{-1}.day^{-1}) represents a system with greater heterogeneity.

The multifractal spectra of the of joint distributions in T1 for Richness *versus* Ind.trap^{-1}.day^{-1} (Fig. 5a) presented weak correlation, presenting graphs with circular contour lines, with different values of joint correlation: 0.095 significant a $P < 0.05$. The contour plots for the multifractal joint association of Richness *versus* Pollinators (Fig. 5b - $R = 0.205$, $P < 0.01$), Richness *versus* Social (Fig. 5d - $R = 0.137$, $P < 0.05$) in T1 and Richness versus Socia in T2 (Fig. 5f - $R = 0.035$, not significant) presented circular lines, confirming the low correlation for the scales $\alpha(q,t)$ and $\beta(q,t)$.

It is important to highlight that the presence of low joint correlation for these pairs of variables is a direct result of the intrinsic variability of each system. Richness comprises a system with low heterogeneity for the values of measures along the transect, with 126 measures for T1 and 122 measures for T2, thus ensuring that all joint partitions are filled with values. However, the data from the functional groups Pollinators (T1) and Social (T1 and T2), have a high heterogeneity of measures, and with variable partitions filling in the geometric support and related to the positivity rate of these groups (Table 2). In this sense, despite the low values of joint correlation for these variables, it is possible to affirm that there are associations on multiple scales (Biswas et al., 2012).

The joint correlation for Ind.trap^{-1}.day^{-1} *versus* Predators (Fig. 4c) and Richness *versus* Predators (Fig. 5c) was 0.356 ($P > 0.01$) and 0.749 ($P > 0.01$) for T1. It appears that Richness *versus* Predators has a better association on multiple scales, than Ind.trap^{-1}.day^{-1} *versus* Predators. This fact was already expected since the values of Richness measures have less variation in geometric support and scales compared to Ind.trap^{-1}.day^{-1}.

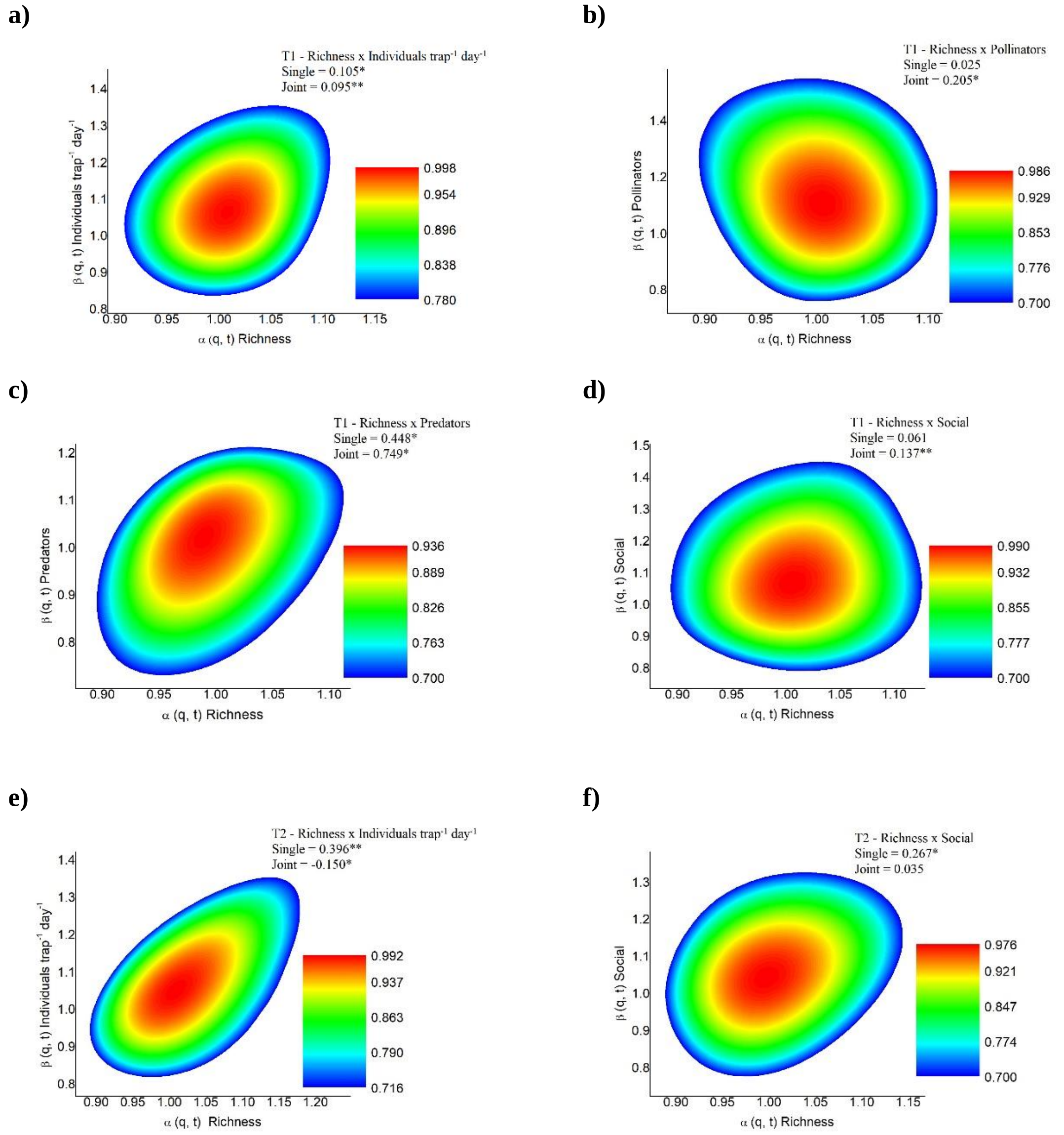

Fig. 5. Joint multifractal distribution in T1 for Richness (horizontal axis) versus taxonomic groups (vertical axis): individuals trap^{-1} day^{-1} (a) and Social (b) in T2, with Pearson's correlation coefficient on a joint scale of *α(q,t)* and *β(q,t)* and simple scale. * significance value P < 0.01 and ** significance value P < 0.05.

The multifractal joint analysis allowed describing that the attributes under study showed association for the scale indexes *α(q,t)* and *β(q,t)* with greater or lesser value of joint correlation. The use of Ind.trap^{-1}.day^{-1} and Richness as predictor variables for functional groups (Pollinators, Predators and Social), indicated that functional groups with greater abundance (Pollinators and Social) and greater distribution along the geometric support showed a better association with Ind.trap^{-1}.day^{-1}; and Richness showed a high association with Predators, related to T1, and in T2, predatory organisms did not show multifractality.

Thus, the results demonstrate that the portion with vegetation formation of dense savanna type (T1), presented greater multifractality for the variables under study, related to the availability of food resources, corroborating with Silva et al. (2013); Costa-Milanez et al. (2014); Marichal et al. (2014); Gholami et al. (2017) and Martins et al. (2018). On the other hand, the presence of social organisms in T1 and T2, whose multifractality of data was evidenced in this study, confirms the capacity of these organisms to explore the environment, a direct result of the high diversity of guilds (Moreira et al., 2010) and of their aggregate behavior (Vicente et al., 2018).

It is important to highlight that Richness and abundance (Ind.trap^{-1}.day^{-1}) represent the invertebrate fauna of the soil, thus describing the spatial variability of the different biological communities, as well as their interactions. Studying the multifractality of Richness and abundance of small mammals Gelashvily et al. (2008) described that the study of these variables by multifractal analysis, reflects the structural heterogeneity of a community, which in most studies is evaluated by different indexes of diversity. In this way, the results demonstrate that the invertebrate fauna of soil has differences in structural heterogeneity that mainly represent the degree of disturbance, availability of food resources (Costa-Milanez et al. (2014); Marichal et al. (2014), and the predominance and/or dominance of some groups (Magurram, 2011; Silva et al., 2019).

Our results corroborate the importance of studying and understanding the heterogeneity of the invertebrate fauna of soil by multifractal analysis. In this sense, further studies are needed to ascertain how biological diversity is represented by means of multifractal parameters. The results showed that the biological diversity of the invertebrate fauna can be assessed using the generalized multifractal dimensions, amplitude, and the asymmetry of the singularity spectrum.

In this sense, the methodological application of multifractal analysis for the knowledge and understanding of the structural heterogeneity of the communities of the invertebrate fauna groups of the soil, presented itself as a promising tool, since it is possible to evaluate a set of biological-environment interactions, based on the Richness and abundance of organisms. On the other hand, the effective use of multifractal analysis to understand the biological diversity of the soil requires a sampling effort, which in turn is influenced by variations in the landscape, the size of the experimental plot, the spatial distribution of fragments with natural vegetation and the degree of disturbance.

We emphasize that when evaluating biological data by multifractal tools it is interesting to take into account the intrinsic behavior of the variable under study, in this case, we choose variables that do not present entropy or little entropy to the system (Salat et al., 2017), because depending on the variable, some parameters can be favored (Magurran, 2011).

The present study made use of the Richness of organisms, as it understands that this evaluation includes both rare and abundant species, in turn, the use of abundance (Ind.trap^{-1}.day^{-1}) is also necessary, as this is an elementary parameter for biological characterization, providing the first information about the community, such as group dominance and inferences about the spatial distribution of organisms in the area. Finally, we highlight that the study of the spatial variability of soil invertebrates allows decision making, supporting conservationist actions, considering Richness and abundance, key parameters for assessing environments.

4 CONCLUSIONS

The invertebrate fauna of soil presented different degrees of multifractality, related to the complexity of the type of savanna formation. The multifractal analysis described that the vegetation composition for the formation of typical savanna (T2) presents less heterogeneity of the measures of scale than the dense savanna (T1). The experimental plot T1 presented better conditions for soil fauna, reflecting greater availability of food resources, greater dynamics among individuals in the soil community, resulting in greater abundance and Richness.

The high scale ratio of Richness with functional group Predators in T1, demonstrated that the variation in abundance of this functional group influences the values of Richness, which are homogeneous throughout the landscape. Ind.trap^{-1}.day^{-1} as a predictor variable, was the one that best described the heterogeneity of value relationships in the multifractal joint distribution for the functional groups (Pollinators, Predators and Social). The joint multifractal analysis proved to be an important tool for understanding the variability of soil invertebrate fauna, and the associations of the variability scales for the variables under study.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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CAPÍTULO VI - PROPRIEDADES MULTIFRACTAIS DE ATRIBUTOS BIOLÓGICOS, FÍSICOS E QUÍMICOS DO SOLO

Submissão à Revista Brasileira de Ciência do Solo

Raimunda Alves Silva(1)* and Glécio Machado Siqueira(1)

(1) Universidade Federal do Maranhão, Programa de Pós-Graduação da Rede BIONORTE, São Luís, Maranhão, Brasil.

[*] Corresponding author: e-mail: ray-234@hotmail.com

HIGHLIGHTS

Foram encontrados diferentes graus de multifractalidade

A fauna edáfica apresentou multifractalidade relacionada ao gradiente vegetal

Os atributos físicos e químicos do solo possuem relação nas escalas

A análise multifractal descreveu as relações de escala para as variáveis

RESUMO: O solo é um sistema dinâmico, resultado da ação dos fatores formação (material de origem, clima, organismo e relevo), que condicionam a variabilidade dos atributos biológicos, físicos e químicos. Assim, objetivo deste trabalho foi avaliar a multifractalidade de atributos biológicos, físicos e químicos do solo. Os atributos do solo foram amostrados em duas parcelas experimentais alocadas em formação de Cerrado (Cerrado Ralo - T1 e Cerrado Típico - T2) no Parque Estadual do Mirador (PEM) estado do Maranhão. Em cada parcela foi amostrada a fauna do solo e os atributos físicos [areia, argila, silte, densidade absoluta (BD), porosidade total (PT), macroporosidade e microporosidade] e atributos químicos [conteúdo de carbono orgânico (CO), pH, fósforo (P), Potássio (K), cálcio (Ca), magnésio (Mg), soma de bases (SB) e capacidade de troca catiônica (CTC)] nas profundidades de 0.0-0.05 m; 0.05-0.15 m e 0.15-0.3 m. Os dados foram submetidos a análise estatística (média, variância, desvio padrão, CV % e teste de normalidade Kolmogorov-sminorv à 0.01 de probabilidade), e análise multifractal considerando o método direto e o método do momento. O Cerrado Típico foi o que apresentou maior riqueza taxonômica (25 grupos), enquanto, o Cerrado tipo registrou 19 grupos taxonômicos. Houve diferenciação estatística para os atributos biológicos, com exceção do grupo de funcional de Predadores. Para os atributos físicos e químicos do solo, houve diferenciação estatística entre os tratamentos e nas profundidades estudadas. Dentre os atributos biológicos, o grupo de Predadores apresentou maior multifractalidade em T1 e T2 (Δ = 0.64 e Δ = 0.33, respectivamente), enquanto, Social, foi o grupo com menor grau de multifractalidade (Δ = 0.09 e Δ = 0.06). Os atributos físicos e químicos do solo apresentaram diferentes graus multifractalidade e assimetria. Na camada de 0.0-0.05 m e 0.05-0.15 m, o silte e Ca foram as variáveis com maior multifractalidade, enquanto, na camada de 0.15-0.3 m, o CO e Ca apresentaram maior multifractalidade. Os espectros de singularidade [$f(\alpha)$ versus α] para as variáveis biológicas e atributos físicos e químicos demonstraram comportamento multifractal, com assimetria dos ramos (esquerdo e direito) entre as parcelas e profundidades, influenciados material de origem, tipo de solo e formas do relevo.

Palavras-chave: Fauna edáfica, variabilidade espacial, multifractalidade

1. INTRODUCÃO

O solo é um sistema dinâmico, fundamental para a sustentabilidade dos ecossistemas (Roy et al., 2018), e é resultado dos fatores de formação: material de origem, clima, organismos e relevo (Bandeira, 2013; Santos et al., 2018). Na paisagem, os atributos do solo possuem elevada variabilidade natural, e a determinação de parâmetros de qualidade ambiental deve considerar a variabilidade dos atributos biológicos, físicos e químicos do solo.

Dentre os atributos biológicos, temos a fauna do solo que é um importante indicador ambiental (Roy et al., 2018), e possui relação com a porosidade do solo (Silva et al., 2017), estabilidade de agregados (Gholami et al., 2017), fragmentação e incorporação do material orgânico (Correia e Oliveira., 2000; Silva et al., 2017; Nunes et al., 2019) e ciclagem de nutrientes (Correia e Oliveira, 2000; Rafael et al., 2012). Os atributos físicos e químicos também são importantes indicadores de qualidade, e são resultado do intemperismo (Vidal Vázquez et al., 2013; Santos et al., 2018), com variabilidade associada aos compartimentos da paisagem.

Nesse sentido, o uso de ferramentas de análise multifractal permite entender as escalas de variabilidade espacial para os comportamentos da paisagem (Leiva et al., 2021). Banerjee et al. (2011) estudando relações de escala na paisagem, descreveram que as variáveis são altamente heterogêneas e dependentes da escala. Na análise multifractal, as escalas de variabilidade são caracterizadas em diferentes momentos (Halsey et al., 1986; Evertsz e Mandelbrot, 1992), permitindo a descrição da heterogeneidade dos sistemas (Vidal Vázquez et al., 2013; Wilson et al., 2015).

A aplicação de análise multifractal para o estudo de atributos físicos e químicos do solo já é conhecida, porém, pouco se conhece sobre a multifractalidade da fauna edáfica do solo. Para os atributos físicos, Posadas et al. (2009) aplicaram a teoria multifractal para entendimento do sistema poroso do solo; Vidal Vázquez et al. (2013) e Siqueira et al. (2018) estudaram parâmetros texturais do solo por meio de análise multifractal; Wilson et al. (2015) e Leiva et al. (2019) aplicaram ferramentas multifractais para o estudo da resistência do solo à penetração em perfis verticais; Bertol et al. (2017) utilizaram a análise multifractal para o estudo das perdas de solo e água. Para os atributos químicos, Dafonte Dafonte et al. (2015) utilizaram a análise multifractal para estudo dos atributos químicos do solo; Vidal Vázquez et al. (2013) estudaram a heterogeneidade de escala de atributos químicos do solo em dois transectos perpendiculares; Marinho et al. (2017) empregaram ferramentas de análise multifractal para o entendimento da distribuição espacial do conteúdo de carbono orgânico em profundidade; Siqueira et al. (2018) descreveram a multifractalidade dos atributos químicos em um transecto cultivado com cana-de-açúcar; Silva e Siqueira (2020) utilizaram análise multifractal para o estudo da diversidade da fauna edáfica do solo.

Diante do exposto, o presente estudo tem como hipótese que: a) os atributos biológicos, físicos e químicos do solo possuem padrões de escalonamento e estrutura de heterogeneidade na paisagem. Assim, o objetivo deste trabalho foi avaliar a multifractalidade de atributos biológicos, físicos e químicos do solo.

2. MATERIAL E MÉTODOS

O estudo foi conduzido no Parque Estadual do Mirador – PEM com 766.781 ha, no Estado do Maranhão, Brasil (6° 42' 9,803" S e 44° 42' 54,936" W - Figura 1). O clima é classificado como Aw (tropical e úmido), com precipitação média anual de 1,183 mm e temperatura média anual de 24 ºC e 32 ºC. As classes de solos predominantes no PEM são Argissolos Vermelhos-Amarelos, Latossolos Amarelos Distróficos, Neossolos Quatzarênicos Órticos e Neossolos Litólicos Distróficos de acordo com a classificação de Santos et al. (2018), e no Soil Survey Staff (2014) são classificados como Ultisol, Oxisols, Psamment e Entisols, respectivamente (Figura 1a). As unidades geológicas do PEM compreendem as formações Corda e Sambaíba, pertencentes ao grupo Balsas, sendo que a formação Corda ocorre nas partes altas (chapadas), e a formação Sambaída está associada as feições baixas do terreno (Bandeira, 2013 - Figura 1c).

A vegetação no PEM (Figura 1b) compreende formações savânicas, que no Brasil correspondem ao Bioma Cerrado (IBGE, 2012). O Cerrado engloba diferentes tipos de formações vegetacionais, sendo que no PEM ocorrem formações florestais (Cerradão, Mata ciliar e Mata de Galeria), formações savânicas (Cerrado Denso, Cerrado Típico, Cerrado Ralo, Parque de Cerrado, Palmeiral e Vereda) e formações campestres (Campo Sujo, Campo Rupestre e Campo Limpo - Ribeiro e Walter, 2008). De maneira geral, na paisagem do PEM ocorrem principalmente Cerrado Ralo (33,50%) e Cerrado Típico (33,97%) onde foram instaladas as parcelas experimentais (Figura 1b).

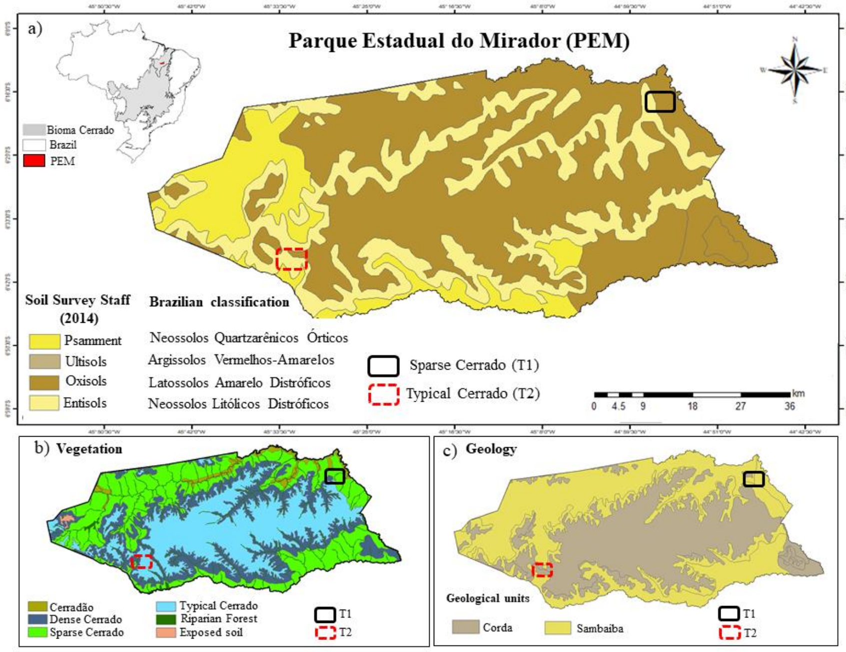


Figura 1. Mapa de localização do Parque Estadual do Mirador, Maranhão (Brasil)

Nas parcelas experimentais (Figura 1) foram amostrados atributos biológicos, físicos e químicos em agosto de 2017, sendo: T1 alocado em vegetação do tipo Cerrado Ralo (IBGE, 2012), com altitude média de 308 m, com predominância de Latossolo Amarelo Distrófico, pertencente a formação geológica Sambaíba; e T2 foi instalado em Cerrado Típico (IBGE, 2012), com altitude média de 432 m, e predomínio de Neossolo Litólico Distrófico originado a partir da unidade geológica Corda (Figura 1).

Em cada parcela foi instalado um transecto com 128 pontos amostrais, com distância de 3 m entre os pontos, e comprimento total de 381 m. A fauna invertebrada foi amostra utilizando pitfall traps, que permaneceram em campo por um período de sete dias, contendo solução de formaldeído à 4% para conservação dos organismos (Aquino, 2001), sendo triados e identificados à nível de ordens e família (Rafael et al., 2012). A partir da triagem dos organismos da fauna invertebrada foi determinada a abundância de organismos (número de indivíduos por ponto e para a parcela), riqueza (número de grupos taxonômicos por ponto e para a parcela) e grupos funcionais: Micrófagos (1.093 indivíduos); Predadores (331 indivíduos); Social (2.688 indivíduos) e Outros (39 indivíduos), seguindo os procedimentos de Roy et al. (2018).

Os atributos físicos e químicos do solo foram coletados nas camadas de 0.0-0.05 m, 0.05-0.15 m e 0.15-0.3 m de profundidade, em amostras de solo indeformadas que foram analisadas conforme Camargo et al. (2009 - atributos físicos) e Raij et al. (2001 - atributos químicos), permitindo a determinação dos seguintes atributos: areia (g kg^{-1}), argila (g kg^{-1}), silte (g kg^{-1}), densidade absoluta (BD - Mg m^{-3}), macroporosidade (m^3 m^{-3}), microporosidade (m^3 m^{-3}), porosidade total (PT - m^3 m^3), carbono orgânico (CO, g dm^{-3}), pH em solução de $CaCl_2$, fósforo (P, mg dm^{-3}), potássio (K, $mmol_c$ dm^{-3}), cálcio (Ca, $mmol_c$ dm^{-3}), magnésio (Mg, $mmol_c$ dm^{-3}), somas de bases (SB) e capacidade de troca catiônica (CTC, $mmol_c$ dm^{-3}).

Os dados foram avaliados inicialmente por meio da estatística descritiva [média ($\overline{X}$), variância, desvio padrão (SD), coeficiente de variação (CV %), assimetria, curtose e D-KS (desvio máximo em relação à distribuição normal por meio do teste de Kolmogorov-Smirnov com probabilidade de erro de 0.01)], e teste de significância das médias dos atributos (T) com probabilidade de 0.05.

A análise multifractal foi utilizada para determinação da heterogeneidade do conjunto de dados, utilizando o método do momento (Halsey et al., 1986; Evertsz e Mandelbrot 1992) e o método direto (Chhabra e Jensen, 1989). Assim, o comprimento total do transecto ($\delta = 381$ m) foi dividido em sucessivos segmentos de 2^k (k = 1, 2, 3...) para obtenção das divisões da função de partição (Evertsz e Mandelbrot 1992; Vidal Vázquez et al., 2013), valores da dimensão generalizada (D - Hentschel e Procaccia, 1983) e espectro de singularidade da função de $f(\alpha)$ versus α, conforme Chhabra e Jensen (1989). Inicialmente, o comprimento do transecto foi convertido em uma função de massa normalizada $p_i(\delta)$ ou $\mu_i(\delta)$, para cada segmento (subintervalo) compreendido no tamanho δ (equação 2).

$$\chi(q,\delta) = \sum_{i=1}^{n(\delta)} [p_i(\delta)]^q \tag{1}$$

$$p_i\,(\delta) = \varphi_i\,(\delta) / \sum_{i=1}^{n(\delta)} \varphi_i\,(\delta) \tag{2}$$

onde:

$n(\delta)$ é o número de segmentos com tamanho δ, com momentos de q para $-\infty < q < +\infty$; φ_i é o valor da medida no *i-ésimo* segmento da escala δ; $\sum_1^{n(\delta)} \varphi_i\,(\delta)$ representa a massa total de cada transecto.

A determinação dos valores de dimensão generalizada ou dimensão de Rényi (Dq) foram obtidos por meio do método do momento para quando $q \neq 1$ (equação 3 - Halsey et al., 1986), e nos casos de $q = 1$, pela regra de l'Hôpital (equação 4). Foram avaliados os valores de Dq nos momentos de $q = 0$, $q = 1$ e $q = 2$, denominadas respectivamente de dimensão de capacidade (D_0), entropia de Shannon ou dimensão de informação (D_1) e dimensão de correlação (D_2).

$$D_q = \frac{1}{q-1} \lim_{\delta \to 0} \frac{\log[\chi(q,\delta)]}{\log \delta} = \frac{\tau(q)}{q-1}, \text{para } q \neq 1 \tag{3}$$

$$D_1 = \lim_{\delta \to 0} \frac{\sum_{i=1}^{n(\delta)} \mu_i\,(\delta) \log \chi(q,\delta)]}{\log \delta}, \text{para } q = 1 \tag{4}$$

Os espectros de singularidade avaliados pela função de $f(\alpha)$ versus α foram determinados pelo método direto (Chhabra e Jensen, 1989). Os sistemas multifractais (heterogêneos) foram representados por uma parábola, enquanto, para sistemas monofractais (homogêneos) a relação de $f(\alpha)$ versus α é uma função linear (Siqueira et al., 2018 - equação 5 e 6).

$$\alpha(\mathrm{q}) \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta) \log[\mu_i(\delta)]}{\log\,(\delta)} \tag{5}$$

$$f(\alpha(q)) = \propto \frac{\sum_{i=1}^{n(\delta)} \mu_i(q,\delta) \log\left[\mu_i(q,\delta)\right]}{\log(\delta)} \tag{6}$$

A multifractalidade dos dados foi determinada pela diferença entre a dimensão generalizada ($\Delta = D_{-\infty} - D_{\infty}$) e o índice de assimetria (IA) definidos por: $AI = (\Delta\alpha_L - \Delta\alpha_R) / (\Delta\alpha_L + \Delta\alpha_R)$, sendo $\Delta\alpha_L = (\alpha_0 - \alpha_{min})$ e $\Delta\alpha_R = (\alpha_{max} - \alpha_0)$, denominados de lado esquerdo e direito, respectivamente. No presente estudo, a análise multifractal foi calculada nos momentos estatísticos de $q = -5$ a $q = +5$, em intervalos de 0.5, considerando os ajustes superiores à 0.9.

3. RESULTADOS

A parcela experimental T1 apresentou a maior abundância de organismos (2.258 indivíduos), com riqueza de 19 grupos, e em T2, a abundância foi de 1.891 indivíduos e riqueza de 25 grupos (Tabela 1). Houve diferenciação estatística pelo teste T ($p < 0.05$ - Tabela 1), para os valores de média da Abundância ($\overline{X}$ = 56.45A em T1 e $\overline{X}$ = 35.82B em T2), Riqueza ($\overline{X}$ = 4.05B em T1 e $\overline{X}$ = 5.64A em T2), Micrófagos ($\overline{X}$ = 13.40A em T1 e $\overline{X}$ = 11.10B em T2), Social ($\overline{X}$ = 38.50A em T1 e $\overline{X}$ = 22.96B em T2) e Outros ($\overline{X}$ = 0.65A em T1 e $\overline{X}$ = 0.26B em T2 - Tabela 1), sendo que Predadores não apresentou diferenças estatísticas entre os tratamentos ($\overline{X}$ = 3.90A em T1 e $\overline{X}$ = 3.50B em T2).

Os atributos físicos e químicos do solo (Tabela 2) apresentaram diferenças estatística em T1 e T2 de maneira distinta para cada uma das camadas do solo estudadas, sendo que na camada de 0.0-0.05 m foi evidenciado diferenças para argila, silte, CO, Ca, Mg e CTC. Na camada de 0.05-0.15 m houve diferenças para silte, CO e CTC; e na camada de 0.15-0.30 m foram encontradas diferenças para silte, CO, Ca, Mg e CTC.

Os valores de CV (%) foram classificados conforme Warrick e Nielsen (1980), e os atributos biológicos apresentaram de maneira geral valores de CV elevados (> 60%), e apenas a Riqueza em T1, Abundância em T2, Riqueza em T2 e Social em T2 apresentaram valores medianos de CV (12-60%). Os atributos físicos e químicos do solo nas parcelas experimentais demonstraram que em T2 as variáveis possuem maior variabilidade do que em T1, sobretudo para os atributos químicos do solo (Tabela 2).

Tabela 1. Estatística descritiva para os atributos biológicos do solo nas fisionomias de Cerrado Ralo (T1) e Cerrado Típico (T2) no Parque Estadual do Mirador, Maranhão (Brasil)

	Number (N)	Mean	Variance	SD	CV (%)	Skew	Kurtosis	DS*
				Sparse Cerrado - T1				
Abundance	2,258	56.45A	1527.12	39.07	69.22	0.54	0.21	0.054n
Richness	19	4.05B	4.86	2.20	54.48	-0.30	-0.48	0.093n
Microphages	536	13.40A	343.01	18.52	138.21	1.02	0.14	0.226Ln
Predators	156	3.90A	150.75	12.27	314.83	2.79	8.15	0.226Ln
Social	1,540	38.50A	1147.23	33.85	87.97	0.88	-0.41	0.214Ln
Others	26	0.65A	1.72	1.31	201.79	0.87	-0.23	0.126Ln
				Typical Cerrado - T2				
Abundance	1,891	35.82B	327.00	18.08	47.81	2.67	1.43	0.169Ln
Richness	25	5.64A	4.76	2.18	38.70	-1.41	-0.08	0.102n
Microphages	557	11.10B	64.50	8.03	72.35	6.96	2.60	0.289Ln
Predators	175	3.50A	16.74	4.09	116.91	0.37	-1.29	0.226Ln
Social	1,148	22.96B	184.97	13.60	59.23	7.72	2.23	0.194Ln
Others	13	0.26B	0.60	0.77	299.03	-0.22	0.96	0.168Ln

N: number of individuals or groups; SD: standard deviation; CV: coefficient of variation; DS: Kolmogorov Smirnov normality test at 0.01. Means followed by the same letters in the column do not differ by the T test ($p < 0.05$).

Tabela 2. Estatística descritiva para os atributos físicos e químicos nas fisionomias de Cerrado Ralo (T1) e Cerrado Típico (T2) no Parque Estadual do Mirador, Maranhão (Brasil)

	Mean	Variance	SD	CV (%)	Skew	Kurtosis	DS
			Sparse Cerrado - T1				
			0.0-0.05 m				
^{1}Sand	802.04A	1823.05	42.69	5.32	0.79	-0.65	0.236Ln
^{1}Clay	139.61A	587.21	24.23	17.35	-0.39	-1.65	0.23Ln
^{1}Silt	59.65A	379.29	19.47	32.64	-1.74	2.18	0.23Ln
^{1}Bulk Density (BD)	1.40A	0.00	0.02	1.57	0.42	-1.46	0.183Ln
^{1}Macroporosity	0.17A	0.00	0.009	5.29	0.88	-0.45	0.230Ln
^{1}Microporosity	0.25A	0.00	0.001	0.40	0.44	-1.43	0.187Ln
^{1}Total Porosity (TP)	0.42A	0.00	0.01	2.38	0.82	-0.62	0.225Ln
^{2}Organic Carbon (OC)	4.33B	0.54	0.74	17.09	-0.64	-0.24	0.098n
^{2}pH	4.20A	0.01	0.09	2.14	0.85	-0.05	0.132Ln
^{2}P	3.32A	0.19	0.44	13.25	-1.41	0.95	0.189Ln
^{2}K	0.95A	0.00	0.02	2.10	-0.57	-0.97	0.144Ln
^{2}Ca	8.93A	2.34	1.53	17.13	-0.66	0.37	0.117Ln

[2]Mg	9.61A	0.56	0.75	7.80	-0.05	-0.83	0.090n
[2]SB	22.26A	3.94	1.98	8.89	-0.89	0.94	0.14Ln
[2]Cationic Exchange Capacity (CEC)	58.32B	41.62	6.45	11.05	-1.12	1.23	0.176Ln
0.05-0.15 m							
[1]Sand	796.66A	3705.54	60.87	7.64	-1.18	0.77	0.140Ln
[1]Clay	160.69A	4722.69	68.72	42.76	1.54	1.45	0.204Ln
[1]Silt	42.64A	217.32	14.74	34.56	0.03	-0.44	0.134n
[1]Bulk Density (BD)	1.37A	0.00	0.04	2.91	-1.77	2.11	0.246Ln
[1]Macroporosity	0.16A	0.00	0.01	6.25	-1.18	0.77	0.139n
[1]Microporosity	0.23A	0.00	0.01	4.34	-1.184	0.779	0.140Ln
[1]Total Porosity (TP)	0.40A	0.001	0.03	7.5	-1.183	0.777	0.140Ln
[2]Organic Carbon (OC)	6.90A	1.35	1.16	16.81	0.75	-0.80	0.194Ln
[2]pH	3.96A	0.00	0.04	1.01	0.26	-1.28	0.121n
[2]P	2.62A	0.02	0.15	5.72	0.37	-1.01	0.135n
[2]K	0.92A	0.00	0.07	7.60	-1.07	0.21	0.156Ln
[2]Ca	4.84A	0.77	0.87	17.97	-1.92	3.10	0.306Ln
[2]Mg	7.35A	0.28	0.53	7.21	0.17	-1.79	0.249Ln
[2]SB	15.65A	0.68	0.82	5.23	-0.62	1.15	0.214Ln
[2]Cationic Exchange Capacity (CEC)	46.92B	40.53	6.36	13.55	-0.26	-0.39	0.050n
0.15-0.3 m							
[1]Sand	783.71A	5375.87	73.32	9.35	-0.71	-0.62	0.138n
[1]Clay	145.06A	1934.40	43.98	30.31	0.89	-0.31	0.156Ln
[1]Silt	71.22A	877.85	29.62	41.58	0.42	-1.01	0.116n
[1]Bulk Density (BD)	1.41A	0.00	0.03	2.12	-0.93	-0.26	0.165Ln
[1]Macroporosity	0.16A	0.00	0.01	6.25	-0.71	-0.62	0.138n
[1]Microporosity	0.23A	0.00	0.02	8.69	-0.71	-0.62	0.138n
[1]Total Porosity (TP)	0.39A	0.00	0.03	7.69	-0.71	-0.62	0.138n
[2]Organic Carbon (OC)	4.68A	5.59	2.36	50.42	0.31	-1.05	0.122n
[2]pH	4.07A	0.00	0.06	1.47	-1.06	1.45	0.162Ln
[2]P	2.21A	0.02	0.15	6.78	-1.28	0.94	0.229Ln
[2]K	0.96A	0.00	0.02	2.08	-0.62	-0.50	0.106n
[2]Ca	2.75B	1.00	1.00	36.36	-1.37	0.87	0.216Ln
[2]Mg	7.08B	0.40	0.63	8.88	-0.02	-1.53	0.178Ln
[2]SB	13.29A	0.33	0.58	4.36	-0.74	1.76	0.237Ln
[2]Cationic Exchange Capacity (CEC)	45.77B	20.91	4.57	9.98	-0.13	-0.42	0.048n
Cerrado Typical - T2							
0.0-0.05 m							
[1]Sand	859.41A	671.57	25.91	3.01	2.35	1.77	0.348Ln
[1]Clay	106.65B	316.70	17.79	16.68	0.71	-0.60	0.132Ln
[1]Silt	33.92B	197.95	14.07	41.47	0.50	-0.05	0.114Ln
[1]Bulk Density (BD)	1.36A	0.00	0.04	2.94	0.74	0.23	0.216Ln
[1]Macroporosity	0.17A	0.00	0.007	4.11	1.48	1.53	0.256Ln
[1]Microporosity	0.25A	0.00	0.003	1.20	0.75	0.28	0.224Ln
[1]Total Porosity (TP)	0.42A	0.00	0.01	2.38	1.78	1.70	0.286Ln

[2]Organic Carbon (OC)	15.60A	58.36	7.64	48.97	0.78	0.78	0.163Ln
[2]pH	3.95A	0.01	0.09	2.27	-1.44	0.34	0.143Ln
[2]P	2.65A	0.62	0.79	29.81	2.93	1.75	0.298Ln
[2]K	0.96B	0.06	0.24	25.00	-0.11	0.06	0.148Ln
[2]Ca	5.36A	6.86	2.62	48.88	0.04	0.45	0.124n
[2]Mg	11.56A	10.11	3.18	27.50	0.74	1.24	0.171Ln
[2]SB	20.24A	38.31	6.19	30.58	0.16	0.97	0.147Ln
[2]Cationic Exchange Capacity (CEC)	75.07B	486.21	22.05	29.37	1.33	1.41	0.226Ln
0.05-0.15 m							
[1]Sand	818.86A	1656.03	40.69	4.96	0.81	1.30	0.214Ln
[1]Clay	140.96A	1667.58	40.83	28.96	-0.95	-0.58	0.219Ln
[1]Silt	40.17B	330.63	18.18	45.25	-0.12	1.12	0.331Ln
[1]Bulk Density (BD)	1.38A	0.00	0.04	2.89	-1.02	0.56	0.243Ln
[1]Macroporosity	0.17A	0.00	0.009	5.29	0.83	1.30	0.213Ln
[1]Microporosity	0.24A	0.00	0.01	4.16	0.82	1.30	0.214Ln
[1]Total Porosity (TP)	0.41A	0.00	0.02	4.87	0.83	1.30	0.214Ln
[2]Organic Carbon (OC)	6.53B	2.74	1.65	25.26	-1.33	-0.49	0.304Ln
[2]pH	4.00A	0.00	0.04	1.00	-1.35	0.01	0.125n
[2]P	1.73B	0.12	0.35	20.23	0.96	1.08	0.237Ln
[2]K	0.94B	0.00	0.03	3.19	0.24	0.96	0.170Ln
[2]Ca	4.23B	0.62	0.79	18.67	-0.26	-0.01	0.098n
[2]Mg	7.12B	4.43	2.10	29.49	-0.22	-0.44	0.125n
[2]SB	15.14B	2.62	1.61	10.63	1.21	-1.12	0.244Ln
[2]Cationic Exchange Capacity (CEC)	65.22A	52.31	7.23	11.08	-1.14	-0.66	0.202Ln
0.15-0.3 m							
[1]Sand	830.37A	3776.10	61.452	7.40	-0.00	-1.32	0.260Ln
[1]Clay	144.28A	2669.73	51.66	35.80	0.33	-0.81	0.222Ln
[1]Silt	25.33B	162.23	12.73	50.28	-0.05	-1.32	0.196Ln
[1]Bulk Density (BD)	1.41A	0.00	0.03	2.79	-0.32	-0.83	0.223Ln
[1]Macroporosity	0.17A	0.00	0.01	7.38	-0.002	-1.32	0.260Ln
[1]Microporosity	0.24A	0.00	0.01	7.41	-0.002	-1.32	0.260Ln
[1]Total Porosity (TP)	0.41A	0.00	0.03	7.40	-0.002	-1.32	0.260Ln
[2]Organic Carbon (OC)	2.41B	0.13	0.36	15.08	-0.04	-1.50	0.152Ln
[2]pH	4.05A	0.00	0.07	1.97	-2.08	4.68	0.255Ln
[2]P	2.14A	0.04	0.22	10.40	0.49	0.42	0.201Ln
[2]K	1.04A	0.01	0.10	10.18	-0.41	-0.04	0.080n
[2]Ca	3.94A	1.43	1.19	30.40	-0.66	-0.75	0.185Ln
[2]Mg	7.48A	3.36	1.83	24.50	-0.40	-0.38	0.128Ln
[2]SB	14.85A	5.04	2.24	15.10	0.39	-1.35	0.234Ln
[2]Cationic Exchange Capacity (CEC)	86.47A	715.68	26.75	30.93	0.06	-1.11	0.225Ln

P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; SB: sum bases; SD: standard deviation; CV: coefficient of variation; DS: Kolmogorov Smirnov normality test at 0.01. The properties were determined according to the methodology described by [1]Camargo et al. (2009) and [2]Raij et al. (2001). Means followed by the same letters in the column do not differ by the T test ($p < 0.05$).

A multifractalidade foi determinada em segmentos de 2^k, com intervalos de $k = 0$ a $k = 7$, e em momentos de ordem q ($-5 < q < 5$), avaliados em escala de 0.5, sendo a função de partição ajustada com valores de coeficientes de determinação > 0.9, confirmando que a distribuição das escalas avaliadas dos atributos biológicos, físicos e químicos obedecem a uma lei de potência.

Todas as variáveis apresentaram comportamento multifractal (Tabela 3 e 4), com diferentes graus de multifractalidade (Δ) e índice de assimetria (AI), avaliados por meio da dimensão generalizada (Dq) e do espectro de singularidade [$f(\alpha)$ versus α].

Para os atributos biológicos os maiores valores de Δ (Tabela 3) foram descritos para Predadores em T1 e T2 ($\Delta = 0.64$ e $\Delta = 0.33$, respectivamente). Para os atributos físicos e químicos (Tabela 4) na camada de 0.0-0.05 m a maior multifractalidade foi descrita para o silte ($\Delta = 1.12$ em T1) e para o Ca ($\Delta = 1.21$ em T2); na camada de 0.05-0.15 m a maior multifractalidade ocorre para Ca ($\Delta = 0.29$ em T2) e silte ($\Delta = 1.17$ em T1), e na camada de 0.15-0.3 m para CO em T2 ($\Delta = 0.70$) e Ca ($\Delta = 1.56$ em T1).

Tabela 3. Dimensão generalizada para os atributos biológicos do solo no Cerrado Ralo (T1) e Cerrado Típico (T2) no Parque Estadual do Mirador, Maranhão (Brasil)

Sparse Cerrado - T1										
	Δ	D_{-5}	D_0	D_1	D_2	α_0	α_{-5}	α_5	D_5	AI
Abundance	0.12	1.05±0.00	1.00±0.00	0.98±0.00	0.97±0.00	1.11±0.03	1.01±0.02	0.87±0.01	0.93±0.04	-2.40
Richness	0.19	1.13±0.02	1.00±0.00	0.98±0.00	0.97±0.00	1.26±0.07	1.01±0.05	0.90±0.02	0.94±0.08	-1.44
Microphages	0.55	1.36±0.02	1.00±0.00	0.94±0.00	0.90±0.00	1.56±0.08	1.05±0.04	0.72±0.03	0.80±0.07	-1.65
Predators	0.64	1.34±0.02	1.00±0.00	0.89±0.01	0.81±0.03	1.51±0.07	1.10±0.04	0.64±0.10	0.70±0.05	-2.12
Social	0.09	1.04±0.00	1.00±0.00	0.98±0.00	0.97±0.00	1.07±0.02	1.01±0.03	0.91±0.02	0.94±0.08	-2.67
Others	0.59	1.46±0.05	1.00±0.00	0.94±0.01	0.91±0.02	1.70±0.14	1.08±0.00	0.82±0.06	0.86±0.08	-1.42
Typical Cerrado - T2										
Abundance	0.07	1.01±0.00	1.00±0.00	0.99±0.00	0.97±0.01	1.00±0.00	1.01±0.04	0.90±0.05	0.94±0.01	10.00
Richness	0.07	1.01±0.00	1.00±0.00	0.99±0.00	0.93±0.01	1.00±0.00	1.01±0.05	0.90±0.05	0.93±0.01	10.00
Microphages	0.14	1.03±0.00	1.00±0.00	0.99±0.00	0.97±0.01	1.00±0.01	1.05±0.06	0.84±0.03	0.89±0.01	3.20
Predators	0.33	1.25±0.03	1.00±0.00	0.98±0.00	0.97±0.01	1.01±0.06	1.36±0.07	0.89±0.05	0.91±0.01	0.34
Social	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.01±0.02	0.92±0.05	0.94±0.01	8.00
Others	0.32	1.16±0.03	1.00±0.00	0.97±0.00	0.95±0.06	1.02±0.06	1.17±0.00	0.80±0.04	0.84±0.01	1.47

D_0: capacity dimension; D_1: entropy dimension; D_2: correlation dimension; Δ: multifractality; A: asymmetric

O índice de assimetria (AI - Tabela 3) para os atributos biológicos evidenciou sistemas heterogêneos, sendo que em T1 as variáveis biológicas possuem assimetria com valores negativos, indicando que existem domínio de valores baixos de medidas; e em T2, a assimetria é positiva indicando predomínio de valores de medidas elevados.

Os valores de dimensão generalizada (D_q - Tabela 3 e 4) para os atributos biológicos, físicos e químicos descrevem sistemas multifractais, pois foi evidenciada tendência de $D_0 > D_1 > D_2$. Os atributos físicos e químicos do solo (Tabela 4) apresentaram de maneira geral valores de assimetria (AI) positivos, indicando domínio de valores elevados de medidas.

Tabela 4. Dimensão generalizada (D_q) para os atributos físicos e químicos do solo no Cerrado Ralo (T1) e no Cerrado Típico no Parque Estadual do Mirador, Maranhão (Brasil)

Sparse Cerrado - T1										
	Δ	D_{-5}	D_0	D_1	D_2	α_0	α_{-5}	α_5	D_5	AI
0.0-0.05 m										
Sand	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.01±0.02	1.01±0.00	0.91±0.05	0.93±0.01	0.00
Clay	0.10	1.02±0.00	1.00±0.00	0.99±0.00	0.98±0.01	1.04±0.22	1.04±0.01	0.89±0.05	0.92±0.01	0.00
Silt	1.12	2.04±0.19	1.00±0.00	0.98±0.01	0.97±0.02	1.03±0.05	1.07±0.05	0.88±0.04	0.91±0.01	3.75
BD	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.91±0.0	0.93±0.08	9.00
Macro	0.07	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.01±0.02	1.01±0.00	0.90±0.05	0.93±0.01	0.00
Micro	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.91±0.05	0.94±0.01	9.00
TP	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.01±0.00	0.91±0.05	0.94±0.01	9.00
OC	0.12	1.05±0.00	1.00±0.00	0.99±0.00	0.90±0.00	1.10±0.02	1.04±0.00	0.89±0.05	0.92±0.01	-3.50
pH	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.01	1.01±0.00	0.91±0.05	0.94±0.01	9.00
P	0.10	1.03±0.00	1.00±0.00	0.99±0.00	0.92±0.00	1.08±0.08	1.03±0.00	0.90±0.05	0.93±0.01	-3.60
K	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.91±0.05	0.94±0.01	9.00
Ca	0.14	1.05±0.00	1.00±0.00	0.99±0.00	0.98±0.00	1.11±0.23	1.04±0.00	0.89±0.04	0.91±0.01	-3.14
Mg	0.06	1.01±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.02±0.03	1.02±0.00	0.92±0.05	0.94±0.01	0.00
SB	0.08	1.01±0.00	1.00±0.00	0.99±0.00	0.93±0.00	1.03±0.06	1.02±0.00	0.90±0.05	0.93±0.01	-13.00
CEC	0.09	1.02±0.00	1.00±0.00	0.99±0.00	0.93±0.00	1.06±0.12	1.02±0.00	0.91±0.05	0.93±0.01	-3.75
0.05-0.15 m										
Sand	0.08	1.01±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.01±0.02	1.01±0.00	0.92±0.05	0.93±0.01	0.00
Clay	0.12	1.09±0.06	1.00±0.00	0.99±0.00	0.99±0.01	1.04±0.02	1.04±0.01	0.87±0.02	0.92±0.01	0.00
Silt	1.17	2.01±0.11	1.00±0.00	0.98±0.01	0.97±0.02	1.03±0.05	1.07±0.05	0.85±0.09	0.91±0.05	4.50
BD	0.03	1.06±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.97±0.05	0.94±0.01	3.00
Macro	0.01	1.07±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.01±0.02	1.01±0.00	0.99±0.06	0.93±0.00	0.00
Micro	0.02	1.05±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.97±0.05	0.94±0.01	3.00
TP	0.04	1.06±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.01	1.01±0.00	0.95±0.05	0.94±0.01	5.00
OC	0.13	1.01±0.05	1.00±0.00	0.99±0.00	0.90±0.00	1.10±0.02	1.04±0.00	0.88±0.09	0.92±0.01	-3.66

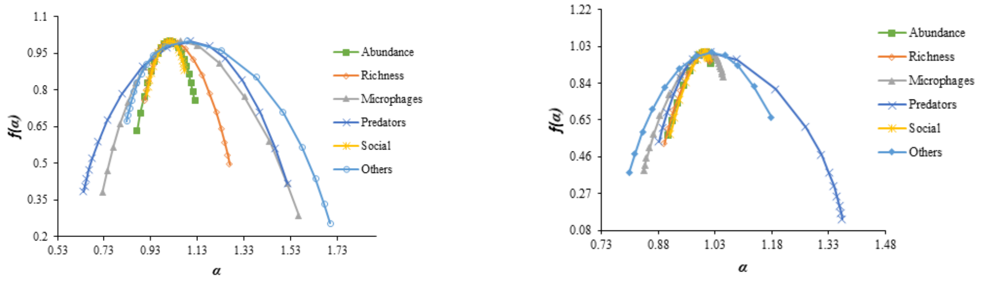
pH	0.06	1.06±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.01	1.01±0.00	0.93±0.06	0.94±0.01	7.00
P	0.17	1.09±0.04	1.00±0.00	0.99±0.00	0.92±0.00	1.08±0.08	1.03±0.00	0.93±0.03	0.93±0.01	-3.00
K	0.03	1.06±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.01	1.01±0.00	0.97±0.05	0.94±0.01	3.00
Ca	0.14	1.08±0.05	1.00±0.00	0.99±0.00	0.99±0.00	1.11±0.03	1.04±0.00	0.87±0.04	0.91±0.01	-3.42
Mg	0.07	1.01±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.02±0.03	1.02±0.00	0.90±0.00	0.94±0.01	0.00
SB	0.03	1.07±0.01	1.00±0.00	0.99±0.00	0.93±0.00	1.03±0.06	1.02±0.00	0.95±0.04	0.93±0.01	-8.00
CEC	0.01	1.08±0.02	1.00±0.00	0.99±0.00	0.93±0.00	1.06±0.02	1.02±0.00	0.91±0.01	0.93±0.01	-3.75
0.15-0.3 m										
Sand	0.08	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.03±0.08	0.93±0.08	0.90±0.05	2.33
Clay	0.14	1.03±0.02	1.00±0.00	0.99±0.01	0.97±0.03	1.00±0.03	1.05±0.35	0.89±0.12	0.84±0.03	2.20
Silt	0.19	1.07±0.05	1.00±0.00	0.98±0.04	0.96±0.07	1.01±0.08	1.10±0.09	0.88±0.15	0.83±0.04	1.44
BD	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.01±0.01	0.93±0.19	0.91±0.05	7.00
Macro	0.08	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.03±0.08	0.93±0.18	0.90±0.05	2.33
Micro	0.08	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.03±0.08	0.93±0.18	0.90±0.05	2.33
TP	0.08	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.03±0.08	0.93±0.18	0.90±0.04	2.33
OC	0.40	1.25±0.08	1.00±0.00	0.97±0.00	0.95±0.01	1.02±0.01	1.35±0.03	0.84±0.02	0.81±0.01	0.54
pH	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.01±0.02	0.94±0.09	0.91±0.06	6.00
P	0.07	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.02±0.05	0.93±0.08	0.90±0.05	3.50
K	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.01±0.02	0.93±0.09	0.91±0.06	7.00
Ca	1.56	2.46±0.35	1.00±0.00	0.97±0.00	0.97±0.03	1.05±0.06	1.05±0.06	0.90±0.07	0.87±0.03	0.00
Mg	0.07	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.02±0.05	0.93±0.08	0.91±0.05	3.50
SB	0.06	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.01±0.03	0.94±0.09	0.91±0.05	6.00
CEC	0.09	1.01±0.01	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.03±0.08	0.92±0.08	0.89±0.05	2.66
Typical Cerrado - T2										
0-0.05 m										
Sand	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.00	1.00±0.00	1.09±0.02	0.91±0.05	0.94±0.01	1.00
Clay	0.13	1.06±0.00	1.00±0.00	0.99±0.00	0.99±0.01	1.00±0.00	1.14±0.07	0.89±0.04	0.92±0.05	0.78
Silt	1.18	2.07±0.15	1.00±0.00	0.97±0.00	0.94±0.03	1.04±0.05	1.04±0.05	0.84±0.03	0.89±0.01	0.00
BD	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.01±0.03	0.91±0.05	0.94±0.01	9.00
Macro	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.00±0.02	0.91±0.05	0.93±0.01	0.00
Micro	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.08±0.02	0.91±0.05	0.94±0.01	1.12
TP	0.06	1.00±0.00	1.00±0.00	0.99±0.01	0.94±0.01	1.00±0.00	1.08±0.02	0.91±0.05	0.94±0.01	1.12
OC	0.60	1.47±0.04	1.00±0.00	0.97±0.00	0.90±0.05	1.03±0.06	1.41±0.05	0.82±0.03	0.86±0.01	0.55
pH	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.00±0.00	1.09±0.01	0.91±0.05	0.94±0.01	1.00
P	0.15	1.06±0.00	1.00±0.00	0.99±0.00	0.99±0.02	1.00±0.02	1.13±0.03	0.87±0.04	0.91±0.01	1.00
K	0.25	1.10±0.01	1.00±0.00	0.98±0.01	0.95±0.01	1.01±0.02	1.19±0.00	0.82±0.04	0.86±0.01	1.05
Ca	1.21	2.08±0.19	1.00±0.00	0.96±0.00	0.98±0.06	1.05±0.06	1.02±0.06	0.81±0.03	0.86±0.01	-8.00
Mg	0.13	1.04±0.00	1.00±0.00	0.99±0.00	0.99±0.02	1.00±0.02	1.00±0.04	0.85±0.03	0.90±0.01	0.00
SB	0.17	1.07±0.01	1.00±0.00	0.98±0.02	0.95±0.02	1.01±0.02	1.16±0.09	0.85±0.03	0.90±0.09	1.06
CEC	0.15	1.05±0.09	1.00±0.00	0.98±0.00	0.97±0.02	1.00±0.02	1.08±0.02	0.84±0.03	0.89±0.09	2.00
0.05-0.15 m										
Sand	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.00	1.01±0.00	1.00±0.01	0.92±0.05	0.94±0.01	-9.00
Clay	0.22	1.14±0.07	1.00±0.00	0.98±0.01	0.90±0.00	1.11±0.03	1.20±0.03	0.88±0.05	0.91±0.01	2.55
Silt	0.23	1.09±0.03	1.00±0.00	0.97±0.04	0.98±0.09	1.08±0.08	1.13±0.04	0.81±0.05	0.88±0.02	5.40
BD	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.01±0.00	1.08±0.01	0.91±0.05	0.94±0.01	1.42
Macro	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.01±0.00	1.00±0.01	0.92±0.05	0.94±0.01	-9.00

Micro	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.01±0.00	1.00±0.01	0.92±0.05	0.94±0.01	-9.00
PT	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.01±0.00	1.00±0.01	0.92±0.01	0.94±0.01	-9.00
OC	0.08	1.02±0.04	1.00±0.00	0.99±0.00	0.92±0.01	1.03±0.00	1.09±0.05	0.90±0.04	0.93±0.01	2.16
pH	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.01±0.00	1.09±0.02	0.91±0.69	0.94±0.01	1.25
P	0.10	1.01±0.02	1.00±0.00	0.99±0.00	0.91±0.00	1.03±0.00	1.01±0.09	0.90±0.04	0.91±0.01	-6.5
K	0.08	1.01±0.00	1.00±0.00	0.99±0.00	0.92±0.00	1.02±0.00	1.04±0.03	0.89±0.05	0.92±0.01	6.5
Ca	0.29	1.20±0.03	1.00±0.00	0.98±0.01	0.90±0.03	1.03±0.03	1.22±0.02	0.88±0.05	0.91±0.02	0.78
Mg	0.18	1.10±0.08	1.00±0.00	0.99±0.00	0.94±0.01	1.08±0.05	1.18±0.01	0.89±0.04	0.91±0.03	1.90
SB	0.09	1.01±0.02	1.00±0.00	0.99±0.00	0.91±0.00	1.03±0.00	1.01±0.09	0.89±0.04	0.92±0.01	-7.00
CEC	0.18	1.09±0.09	1.00±0.00	0.98±0.01	0.99±0.02	1.00±0.03	1.18±0.04	0.87±0.04	0.91±0.01	0.722
0.15-0.3 m										
Sand	0.07	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.00	1.00±0.00	1.01±0.00	0.91±0.05	0.93±0.01	9.00
Clay	0.26	1.07±0.01	1.00±0.00	0.98±0.00	0.97±0.00	1.01±0.00	1.18±0.04	0.83±0.03	0.84±0.01	1.05
Silt	0.58	1.48±0.04	1.00±0.00	0.97±0.00	0.96±0.01	1.03±0.01	1.43±0.10	0.87±0.05	0.91±0.02	0.40
BD	0.06	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.00	1.00±0.00	1.09±0.00	0.91±0.05	0.94±0.01	1.00
Macro	0.01	1.00±0.00	1.00±0.00	0.99±0.00	0.99±0.00	1.00±0.00	1.05±0.00	0.91±0.05	0.93±0.01	1.80
Micro	0.01	1.00±0.00	1.00±0.00	0.97±0.00	0.94±0.00	1.00±0.00	1.05±0.00	0.91±0.05	0.93±0.01	1.80
TP	0.01	1.09±0.00	1.00±0.00	0.99±0.00	0.94±0.01	1.02±0.00	1.01±0.00	0.91±0.05	0.93±0.01	-11.00
OC	0.70	1.09±0.01	1.00±0.00	0.99±0.00	0.95±0.02	1.07±0.02	1.16±0.04	0.89±0.05	0.92±0.01	2.00
pH	0.60	1.00±0.00	1.00±0.00	0.99±0.00	0.95±0.01	1.00±0.00	1.00±0.00	0.91±0.05	0.94±0.01	0.00
P	0.15	1.03±0.00	1.00±0.00	0.93±0.00	0.95±0.01	1.00±0.00	1.06±0.00	0.84±0.03	0.87±0.01	2.66
K	0.06	1.00±0.00	1.00±0.00	0.97±0.00	0.94±0.01	1.00±0.00	1.01±0.00	0.91±0.05	0.94±0.01	9.00
Ca	0.11	1.04±0.00	1.00±0.00	0.94±0.00	0.98±0.01	1.00±0.00	1.08±0.03	0.88±0.04	0.92±0.01	1.50
Mg	0.28	1.15±0.01	1.00±0.00	0.96±0.01	0.94±0.03	1.01±0.00	1.24±0.04	0.84±0.03	0.87±0.01	0.73
SB	0.10	1.02±0.00	1.00±0.00	0.96±0.00	0.92±0.00	1.00±0.00	1.05±0.00	0.89±0.05	0.92±0.01	2.20
CEC	0.09	1.02±0.00	1.00±0.00	0.96±0.00	0.91±0.00	1.00±0.00	1.03±0.01	0.89±0.05	0.92±0.01	3.66

BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; OC: organic carbon; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; SB: sum bases; CEC: cationic exchange capacity; D_0: Capacity dimension; D_1: Entropy dimension; D_2: Correlation dimension; Δ: Multifractality; A: asymmetric.

Os espectros de singularidade [$f(\alpha)$ versus α] para as variáveis biológicas (Figura 2) demonstraram comportamento multifractal, havendo assimetria para os ramos do espectro (esquerdo e direito) para as diferentes variáveis em T1 e T2 (Figura 2a e 2b).

Os espectros de singularidade [$f(\alpha)$ versus α] para os atributos físicos e químicos do solo (Figura 3) são assimétricos e apresentaram diferentes graus de multifractalidade (Figura 3). Em T1 e T2, os atributos físicos de maneira geral, possuem ramos assimétricos para a esquerda, demonstrando que existem valores de medidas elevados distribuídos nas escalas, sendo que o silte apresenta as maiores diferenças na multifractalidade (Figura 3b, 3e e 3f) nas camadas e entre parcelas (T1 e T2).



a) Soil biological indicators in T1

b) Soil biological indicators in T2

Figura 2. Espectro de singularidade para os indicadores biológicos do solo em T1 (Cerrado Ralo) e T2 (Cerrado Típico) no Parque Estadual do Mirador, Maranhão (Brasil)

O espectro de singularidade [*f(α)* versus *α*] para os atributos químicos apresentam diferentes graus de multifractalidade em profundidade e entre parcelas, porém, de maneira geral os dados possuem assimetria dos ramos para a esquerda indicando que há valores de medidas elevados nas escalas das variáveis (Figura 3). O conteúdo de CO apresentou variação nas escalas de variabilidade para todas as camadas e nas parcelas (T1 e T2). O Ca (Figura 3m) e Mg (Figura 3l e 3m) apresentaram diferenças na assimetria dos ramos em T2 nas camadas de 0.05-0.15 m e 0.15-0.30 m, com assimetria dos ramos para a direita, indicando que nas escalas ocorrem valores de medidas baixos.

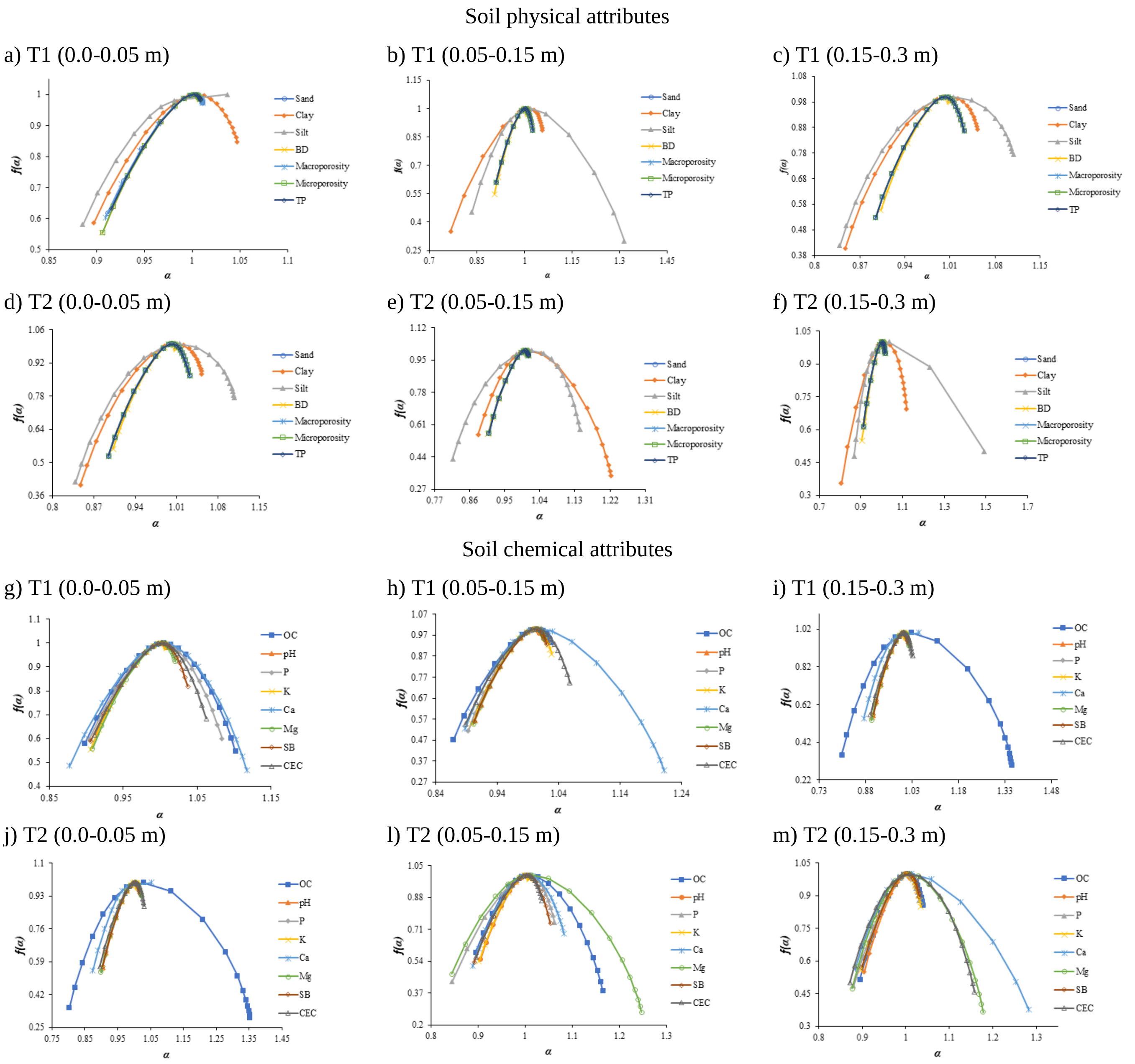


Figura 3. Espectro de singularidade para atributos físicos e químicos do solo em T1 e T2 no Parque Estadual do Mirador, Maranhão. Atributos físicos em T1: a) 0.0-0.05 m; b) 0.05-0.15 m; c) 0.15-0.3 m; atributos físicos em T2: d) 0-0.05 m; e) 0.05-0.15 m; f) 0.15-0.3 m; atributos químicos em T1: g) 0.0-0.05 m; h) 0.05-0.15 m; i) 0.15-0.3 m; atributos químicos em T2: j) 0.0-0.05 m; l) 0.05-0.15 m; m) 0.15-0.3 m.

4. DISCUSSÃO

Os resultados demonstraram que a estrutura vegetacional influenciou a abundância de organismos em T1 e T2 (Tabela 1), porém, T2 apresentou maior riqueza de grupos taxonômicos, reflexo do maior estrato arbóreo neste ambiente (Ribeiro e Walter, 2008; IBGE, 2012). Gholami et al. (2017) estudando as relações espaciais da fauna edáfica e paisagem, relataram que a composição da vegetação influencia a abundância e a riqueza de organismos. Por outra parte, Wagg et al. (2014) descrevem que a fauna do solo é influenciada pelo microclima, disponibilidade de recursos alimentares e conteúdo de material orgânico. Desta maneira, as diferenças estatísticas entre os atributos biológicos nas parcelas T1 e T2 (Tabela 1) são resultado das características ambientais de cada uma das formações de Cerrado em estudo.

A categorização da fauna do solo considerando a sua funcionalidade (Tabela 1), permitiu descrever que na paisagem as diferenças estatísticas para os grupos funcionais já eram esperadas, uma vez que, os ambientes possuem particularidades, demonstrando que há equilíbrio ecológico entre os grupos funcionais em T1 e T2, uma vez que apenas os Predadores não apresentaram diferenças nas médias, e ocupam o topo da cadeia trófica. De acordo com Correia e Oliveira (2002) e Rafael et al. (2012) ambientes perturbados apresentam desequilíbrio na cadeia trófica, sendo que os predadores são os mais influenciados pelo aumento ou diminuição de organismos em níveis tróficos inferiores. O grupo Social foi o mais abundante em ambas as áreas, representados principalmente pela família Formicidae (Tabela 1), que são organismos generalistas, com elevada capacidade de dispersão (Prado et al., 2019), e ocupando diferentes nichos ecológicos (Silva et al., 2017).

Se verifica que há diferenças estatísticas para as médias dos atributos texturais (argila e silte), conteúdo de CO, macronutrientes (Ca e Mg) e capacidade de troca catiônica (CTC - Tabela 2). T1 foi alocado em área com predomínio de Latossolo Amarelo Distrófico, e T2 alocado em área com Neossolo Litólico Distrófico, desta maneira, as diferenças estatísticas ocorrem em função da classe de solo. De acordo com Bandeira et al. (2013) os solos do Cerrado maranhense possuem baixa fertilidade natural, e são desenvolvidos na sua maioria a partir de sedimentos, justificando assim as diferenças para os atributos físicos e químicos do solo. O conteúdo de CO refletiu a formação vegetal presente nas parcelas experimentais, sendo que em T2 a camada de 0.0-0.05 m apresentou o maior valor de CO (15.60 g dm^{-3}), demonstrando a elevada capacidade de aporte de resíduos vegetais pelo Cerrado Típico em relação ao Cerrado Ralo. Por outra parte, destacamos que o Cerrado Típico está alocado em Neossolo Litólico Distrófico, justificando assim as diferenças estatísticas para os valores do conteúdo de argila e silte nas parcelas, relacionado ao grau de intemperismo do solo (Santos et al., 2018).

Os valores de CV (%) classificados de acordo com Warrick e Nielsen (1980) foram considerados elevados (> 60%) para as variáveis biológicas, demonstrando elevada variação da fauna do solo em T1 e T2. Para os atributos físicos e químicos do solo, os valores demonstraram maior variação em T2, descrevendo heterogeneidade para silte, CO, Ca, P, K, Mg e CTC (Tabela 2), comportamento já esperado devido a menor dinâmica com ambiente conforme relatado por (Aquino et al., 2015).

Os dados em estudo apresentaram diferentes graus de multifractalidade (Δ), evidenciados pela diferença entre os valores de D_q (Tabela 3 e 4). Em T1 e T2, o grupo Predadores descreveu a maior multifractalidade [$\Delta = 0.64$ (T1) e $\Delta = 0.33$ (T2)], refletindo um sistema mais heterogêneo, enquanto, os organismos Social apresentaram menor multifractalidade [$\Delta = 0.09$ (T1) e $\Delta = 0.06$ (T2)].

A maior heterogeneidade ou multifractalidade para Predadores em T1 e T2 (Tabela 3), reflete a ecologia desta categoria funcional (Roy et al., 2018), uma vez que, os resultados descrevem que ao longo do transecto a distribuição não é homogênea. Por outra parte, o grupo

Social apresentou menor grau de multifractalidade entre as variáveis biológicas, sendo também explicado pela sua ecologia, uma vez que estes organismos possuem elevada capacidade de exploração ambiental (Prado et al., 2019), descrevendo que no transecto as escalas são uniformemente preenchidas. Silva e Siqueira (2020) descreveram que Formicidae é o grupo mais ocorrente em amostragem de fauna edáfica, principalmente em sistemas florestais, preenchendo assim, os segmentos ao longo do transecto.

O grau de multifractalidade (Δ) para os atributos físicos e químicos do solo foi variável entre tratamentos e profundidades estudadas (Tabela 4). O silte apresentou a maior multifractalidade entre os atributos físicos para as duas parcelas experimentais e profundidades, porém, em T1 o grau de multifractalidade (Δ) do conteúdo de Silte é maior que em T2, devido ao intemperismo. Corroborando com Vidal Vázquez et al. (2013) e Siqueira et al. (2018) que descrevem que a multifractalidade de variáveis do solo é resultante dos fatores de intemperismo.

Para os atributos químicos nas parcelas o conteúdo de Ca e CO foram os mais heterogêneos, em termos de multifractalidade (Δ - Tabela 4). A multifractalidade para o Ca em T1 e T2 foi influenciada pelo grau de intemperismo dos solos das parcelas, uma vez que, em T1 a multifractalidade do Ca aumenta em profundidade, enquanto, em T2 a multifractalidade diminuiu com a profundidade. De acordo com Raij et al. (2001) o Ca tem sua solubilidade aumentada com a diminuição do pH, corroborando com os resultados da análise química (Tabela 2), uma vez que, o pH na camada de 0.15-0.3 m têm o seu grau de multifractalidade aumentado em T1, em relação as demais camadas. O CO tem a sua multifractalidade (Δ) aumentada em profundidade para o Latossolo Amarelo Distrófico (T1) e para Neossolo Litólico Distrófico (T2), indicando que em profundidade as medidas são mais heterogêneas nas escalas. De acordo com Marinho et al. (2017) o aumento da heterogeneidade do CO em profundidade descreve a importância para o conhecimento do estoque de carbono em profundidade.

D_0 fornece uma informação global ou média do sistema, associando para cada segmento a presença ou ausência de valores na amostragem, dessa maneira, quando os valores D_0 são iguais ou próximos a 1, a variável estudada possui valor numérico em todos os pontos amostrais (Posadas et al., 2009; Banerjee et al., 2011). D_1 quantifica o grau de desordem de sistema, sendo os valores compreendidos entre $0 < D_1 < 1$, conforme Posadas et al. (2009) e Vidal Vázquez et al. (2013), desta maneira, as variáveis em estudo evidenciaram uniformidade de distribuição de valores nos segmentos. Os valores de D_2 indicam como as escalas são correlacionadas ao longo do transecto (Wilson et al., 2015), assim, se verifica que, em T1 os organismos Predadores apresentaram a menor correlação entre as escalas, resultando em maior assimetria (AI = -2.12 - Tabela 3). Assim, as variáveis biológicas, físicas e químicas do solo descrevem sistemas multifractais para as escalas avaliadas, seguindo a tendência de $D_0 > D_1 > D_2$ (Banerjee et al., 2011; Vidal Vazquéz et al., 2013; Dafonte Dafonte et al., 2015; Siqueira et al., 2018).

Os espectros de singularidade para os atributos biológicos, físicos e químicos do solo apresentaram curvas em formato de parábola (Figuras 2 e 3), havendo diferenciação na assimetria dos ramos para a direita ou esquerda (Figuras 2 e 3 e Tabelas 3 e 4). Com relação a fauna do solo, os espectros de singularidade descrevem que os dados em T2 possuem maior assimetria, do que em T1. A maior assimetria em T2, descreve que apesar da maior homogeneidade do estrato vegetal nesta formação, os organismos da fauna possuem maior complexidade ecológica. Nunes et al. (2019) estudando a fauna do solo sob diferentes gradientes de vegetação, descrevem que formações vegetais mais complexas possuem maior diversidade de invertebrados, corroborando com a maior riqueza de organismos descritas para T2 (25 grupos) em relação a T1 (19 grupos - Tabela 1). Em T1, os dados de fauna edáfica apresentaram valores de assimetria negativos (AI - Tabela 3), enquanto, T2 apresentou assimetria positiva. Valores de assimetria positiva indicam domínio de valores de medidas baixos ao longo do transecto, enquanto, assimetria negativa indica domínio de valores elevados de medidas (Banerjee et al., 2011; Vidal Vázquez et al., 2013; Dafonte Dafonte et al., 2015; Bertol et al., 2017; Siqueira et al., 2018).

Os espectros de singularidade para os atributos físicos do solo (Figuras 3a, 3b, 3c, 3d, 3e e 3f) de maneira geral, possuem assimetria positiva, indicando domínio de valores de medidas baixos no transecto (Dafonte Dafonte et al., 2015; Marinho et al., 2017). O conteúdo de silte em T1 na camada de 0.05-0.15 m e em T2 na camada de 0.15-0.3 m, descreveu que para a região de singularidade mínima (ramo direito), ocorrem valores baixos de medidas, porém, nem todas as escalas estão preenchidas, confirmando a heterogeneidade da variável (Tabela 4 e Figura 3b e 3f). Os demais atributos físicos (areia, argila, densidade absoluta, macroporosidade e microporosidade) possuem gráficos do espectro de singularidade com comportamento similar nas escalas com assimetria dos ramos para a esquerda, indicando domínio de valores de medidas elevados (Vidal Vázquez et al., 2013).

O espectro de singularidade (Figuras 3g, 3h, 3i, 3j, 3l e 3m) para os atributos químicos apresentaram gráficos com diferentes graus de multifractalidade (Tabela 4) e assimetria (Tabela 4 Figura 3), sendo maiores diferenças descritas para a camada superficial (0.0-0.05 m) em T1 e T2. Em T1 o espectro de singularidade para as variáveis químicas na camada de 0.0-0.05 m (Figura 3g) possui maior amplitude e assimetria, enquanto, para T2 (Figura 3j) possui menor amplitude e menor assimetria dos ramos (Tabela 4), com exceção do CO que apresenta espectros com maior amplitude. De acordo com Vidal Vázquez et al. (2013) as propriedades de dimensionamento para o OC, estão associados ao material de origem e feições do terreno, corroborando com os nossos resultados, uma vez que, os solos do PEM são desenvolvidos a partir de arenitos (Bandeira, 2013), porém, as parcelas estão alocadas em diferentes feições da paisagem, influenciando a multifractalidade do CO (Δ = 0.12 em T1 e Δ = 0.60 em T2) nesta camada (0.0-0.05 m - Tabela 4).

Para T2 nas camadas de 0.05-0.15 m e 0.15-0.3 m o conteúdo de Ca (Figura 3m) e Mg (Figura 3l e 3m) apresentaram ramos com maior amplitude, quando comprados aos demais elementos nestas camadas, porém com valores de assimetria positivos (Tabela 4), indicando que existe domínio de valores de medidas baixos associados a esta maior multifractalidade. É importante destacar que, a diferenciação relacionada a T2 pode estar associada ao grau de intemperismo do solo nesta parcela, quando comparado a T1, conforme relatado por Raij et al. (2011) e Santos et al. (2018).

5. CONCLUSÃO

Os atributos biológicos, físicos e químicos apresentaram diferentes graus de multifractalidade, sendo que a multifractalidade da fauna do solo foi influenciada pelo gradiente de vegetação, e a multifractalidade dos atributos físicos e químicos está relacionada ao material de origem, tipo de solo e formas do relevo.

A análise multifractal permitiu o entendimento da dinâmica das relações ecológicas para os organismos da fauna do solo, refletindo as estruturas de cadeia trópica.

O conteúdo de silte, CO, Ca e Mg apresentaram elevada heterogeneidade de escalas entre tratamentos e nas profundidades avaliadas, associada ao material de origem e posição na paisagem.

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CONSIDERAÇÕES FINAIS

As informações contidas no presente trabalho representam contribuições para o conhecimento da diversidade e riqueza da fauna edáfica, atributos físicos e químicos do solo em formações de Cerrado (Savana) e sistemas de usos e manejos do solo no estado do Maranhão. As ferramentas matemáticas utilizadas no presente estudo evidenciaram a dinâmica e a complexidade dos atributos edáficos nas diferentes paisagens estudadas.

No primeiro capítulo foi evidenciado a importância da comunidade de Coleoptera para a manutenção do equilíbrio ecológico do solo em diferentes sistemas de usos e manejos, sendo a abundância e riqueza maior para os sistemas naturais e agroflorestais (cerrado preservado, cerrado antropizado e eucalipto), quando comparado a sistemas manejos (soja e milho). A composição de besouros foi associada as propriedades físicas do solo, como densidade absoluta, argila, macroporosidade e silte, constituindo um importante indicador de qualidade do solo.

A fauna invertebrada estudada no Parque Estadual do Mirador (PEM) em formações de Cerrado Ralo e Cerrado Típico, apresentada no Capítulo II, evidenciou a importância da composição vegetal para a presença de organismos edáficos, uma vez que a maior diversidade, riqueza e equitabilidade são encontradas na formação com Cerrado Típico (parcela com maior densidade de indivíduos arbóreos). As associações entre os grupos Solifugae, Araneae e Diptera (organismos que são reguladores de cadeia trófica) foram evidenciadas no Cerrado Típico, refletindo a dinâmica desse ambiente. Organismos como Formicidae, Coleoptera e Collembola foram associados a qualidade química do solo em ambas as fisionomias, portanto, são importantes para a incorporação de nutrientes no solo.

A variabilidade espacial do componente arbóreo em formações de cerrado (Cerrado Denso, Cerrado Típico e Cerrado Ralo – Capítulo III) no Parque Estadual do Mirador, avaliada por meio de ferramentas de geoestatística, indicou homogeneidade para o Cerrado Típico, enquanto, as demais formações apresentaram-se mais heterogêneas. O padrão vegetal evidenciou comportamento autorregenerativo do estrato arbóreo em todas as formações estudadas, indicando que na comunidade ocorre o recrutamento de indivíduos, e, portanto, encontra-se em equilíbrio. A variabilidade espacial da vegetação ao longo do PEM apresenta diferentes valores de continuidade espacial, reflexo do padrão vegetal de cada formação de Cerrado.

As relações de escalas da comunidade de artrópodes do solo (Capítulo IV) estudadas no município de Chapadinha (por meio de ferramentas de geoestatística e multifractais) evidenciaram que os organismos do solo são influenciados pela composição vegetal de cada parcela, sendo a abundância e a riqueza dos artrópodes do solo associadas a fisionomias com maior quantidade de indivíduos arbóreos (Cerrado Típico e Cerrado Denso). As ferramentas multifractais (análise multifractal e joint multifractal) foram eficientes para detectar a variabilidade de escalas da fauna do solo, assim como, para refletir a concentração de valores ao longo do suporte geométrico.

No capítulo V, a fauna do solo no Cerrado Ralo constitui um sistema com maior heterogeneidade de escalas no suporte geométrico, e consequentemente, representa o sistema com maior assimetria no espectro de singularidade. A abundância de indivíduos por armadilha dia (Ind. arm^{-1}. dia^{-1}) foi a variável preditora que melhor descreveu as associações de escalas entre as diferentes categorias funcionais (polinizadores, predadores e social), uma vez que melhor descreve a heterogeneidade da fauna edáfica.

Os atributos biológicos, físicos e químicos o solo evidenciaram diferentes graus de multifractalidade no PEM (Capítulo VI), influenciados pelas características intrínsecas de cada parcela experimental. A fauna foi influenciada pelo gradiente de vegetação, enquanto, os atributos físicos e químicos do solo foram influenciados pelo material de origem, assim como pelo tipo de solo. A caracterização dos atributos edáficos por meio da análise multifractal, possibilitou a compreensão da dinâmica das relações entre os invertebrados do solo e dos atributos físicos e químicos do solo, refletindo assim, as relações de cadeia trófica, bem como, a importância dos organismos edáficos para a qualidade desses atributos.

Nossos resultados indicam que a fauna edáfica representa importante elemento na caracterização do Cerrado, seja como componente dinâmico, ou como indicador de qualidade do solo, prestando relevantes serviços ecossistêmicos, além de ser parte ativa e sensível dos ecossistemas. Assim, vale destacar que o componente arbóreo nas paisagens de Cerrado, constitui importante fator para a ocorrência dos artrópodes do solo, condicionando os padrões de riqueza e abundância, e influenciando também na variabilidade espacial de escalas da fauna do solo. O uso de ferramentas geoestatística, multifractais e joint multifractais na caracterização dos atributos edáficos mostrou-se eficientes, descrevendo as escalas de variabilidade e permitindo a compreensão da dinâmica das propriedades edáficas ao longo das fisionomias de Cerrado.

De maneira geral, nosso trabalho fornece dados sobre a estrutura da comunidade vegetal, fauna edáfica, atributos físicos e químicos no bioma Cerrado, que subsidiarão futuros estudos no estado do Maranhão.