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Phytoseiidae mite (Parasitiformes: Phytoseiidae) assemblages from different Cerrado vegetation types

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Original research

ABSTRACT

Phytoseiidae are predatory mites with some species widely used in biological control programs. Currently, 2,985 species have been described, among them, 260 species have already been recorded in Brazil. Several species of phytoseiid mites that inhabiting native vegetation remnants in Brazil have the potential to act as predators of crop pests contributing to natural biological control. Here, we accessed the diversity of phytoseiid mites on plants in three Cerrado vegetation formations. Twenty-one natural vegetation remnants distributed in the grassland, forest and savannah vegetation formations in the municipalities at Barro Alto and Niquelândia, Goiás State, Brazil, were sampled. All sampled remnants were close to areas exploited for nickel mining. Species richness of mites was estimated by first-order Jackknife method in order to compare phytoseiid mite communities in vegetation formations. The similarity in communities among different vegetation formations was evaluated using non-metric multidimensional scaling (NMDS) and ANOSIM. A total of 279 phytoseiid mites distributed in 19 species and 11 genera were sampled. The richness of mite species estimated for the grassland formation was lower than the one of the forest and savannah remnants. However, the composition of the phytoseiid species did not vary among vegetation formations. The most abundant phytoseiid species sampled were *Euseius sibelius* (De Leon) (67 specimens), *Euseius citrifolius* Denmark and Muma (47) and *Transeius bellottii* (Moraes and Mesa) (29). The present work demonstrated that remnants of natural vegetation of the Cerrado can serve as important reservoirs for the conservation of Phytoseiidae biodiversity, even under the impacts caused by nickel mining activities, and potentially provide ecosystem services for sustainable agricultural yields.

Keywords Acari; Brazilian Savannah; ecosystem services; Mesostigmata; native vegetation; predators

Introduction

The Brazilian Cerrado represents the second largest biome in Latin America, encompassing an approximate area of 2 million of km² (Ribeiro and Walter 2008). Due to its considerable species richness and notable levels of endemism, the Cerrado biome is recognized as one of the world's

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biodiversity hotspots (Myers *et al.* 2000; Myers 2003; Brooks *et al.* 2006; Loyola *et al.* 2009; Sano *et al.* 2019). Cerrado is characterized by diverse mosaic of vegetation types, including savannas, grasslands, and forests, which harbour a rich array of flora and fauna (Mendonça *et al.* 1998). Beyond its biodiversity significance, the Cerrado provides crucial ecosystem services to society, including agricultural benefits such as crop pollination and natural biological control (Teixeira *et al.* 2017).

Phytoseiid mites (Parasitiformes: Mesostigmata: Phytoseiidae) are predatory commonly used as biological control agents targeting phytophagous mites, whiteflies, and thrips (McMurtry and Croft 1997; McMurtry *et al.* 2013, 2015). These mites show distinct feeding behaviour (McMurtry *et al.* 2013), while the majority is generalist targeting a wide range of pest species, which contributes to their utility in pest management strategies. Furthermore, these mites inhabit a variety of habitats, including agricultural fields, orchards, and natural vegetation (McMurtry *et al.* 2013, 2015). Up to now 2,985 phytoseiid species have been taxonomically described, with 260 of these species recorded within Brazil (Demite *et al.* 2025; Lofego *et al.* 2024). Despite the vast extent and complexity of the Cerrado biome, numerous mite species inventories have been conducted on the fauna of this important family of predatory mites, but most of them have been conducted on vegetation remnants close to agriculture, with little attention to species occurrence according to Cerrado vegetation formations (Lofego *et al.* 2004; Demite *et al.* 2009, 2016, 2017, 2021; Rezende and Lofego 2011; Rezende *et al.* 2014; Abreu *et al.* 2017; De Araújo and Daud 2017; Teixeira *et al.* 2017; Conceição *et al.* 2021; Duarte *et al.* 2021; Moraes *et al.* 2022).

At the same time as agricultural intensification occurred, there is an increase in nickel exploration at the Cerrado biome of Goiás State (Neri *et al.* 2011). In regions designated for mineral exploration, the land has become degraded and generally loses its structure and function (Primack and Massardo 2001). However, despite the intense impact generated by nickel mining activities, a high diversity of predatory mites is expected to occur in the remaining vegetation. The remnants of Cerrado vegetation can serve as important indicators of ecosystem sustainability by harbouring mite species that contribute to ecological balance and enhance ecosystem resilience (Medeiros 2019; Abreu *et al.* 2017; Teixeira *et al.* 2017).

To enhance our knowledge of phytoseiid diversity within the native vegetation of the Cerrado, this study investigated the phytoseiid mite assemblages in three Cerrado vegetation formations adjacent to nickel mining areas. Additionally, we assess potential disparities in species richness and composition among these formations to pinpoint which habitats harbour the highest diversity of Phytoseiidae, thereby offering ecosystem services. In addition, we analysed the relationship between the estimated richness of Phytoseiidae and the distance from natural vegetation remnants to mining sites, aiming to assess the possible effect of this activity on the community structure of Phytoseiidae mites. We expect to find greater diversity of mites in environments with greater heterogeneity and structural complexity, since they present greater availability of ecological niches and resources, allowing to support greater abundance and diversity of fauna (Schuelze and Mooney 1997; Altieri 2002). Moreover, we expect to find higher estimated richness of Phytoseiidae in the most distant natural vegetation remnants from nickel mining sites, as these natural areas are less affected by mining activities.

Material and methods

Sampling areas

A total of 81 plots were established for analysis at 21 sampling sites within the natural vegetation remnants of the Cerrado. These sampling sites were situated in the municipalities of Niquelândia and Barro Alto, Goiás State, Brazil (Figure 1 and Table 1). Most of the sampling sites (13) were located within or immediately adjacent to the mining area at distances of less than 600 meters. Five sampling sites were located within a range of 1 to 5 km from the mining area, while three were located between 10 and 30 km away.

The natural vegetation remnants sampled were categorized into three primary plant formations based on the classification by Ribeiro and Walter (2008): forest (F), savannah (S), and grassland (G). According to Ribeiro and Walter (2008), forest formations represent regions primarily covered by trees, capable of creating either a continuous or fragmented canopy. The savannah formation denotes a landscape where trees and shrubs are spaced apart and spread across a ground mostly covered by grasses (Coutinho 2006; Ribeiro and Walter 2008; Batalha 2011). In contrast, grassland formations encompass areas where grasses dominate alongside sparse shrubs, without a significant presence of trees (Ribeiro and Walter 2008). In this way, 11 natural vegetation remnants sampled were identified as belonging to the savannah type, while eight of these remnants were classified as forest and two as grassland.

Sampling and identification

At each of the 21 sampling sites, we conducted two sampling lines, spaced 150 meters apart. For each sampling line, we established two 5 x 5 m quadrat samples (sampling plots): one located 10 meters from the edge of the vegetation remnant and the other 50 meters from the edge. This approach resulted in four sample plots per sampling site, for a total of 84 sample plots. Due to inaccessibility, three samples could not be collected, resulting in a final total of 81 sample plots available for mite collection. Two surveys were conducted, one in March 2015 and one in January 2016, both during the rainy season. In each survey, 20 leaves were collected from around the mid-canopy of all trees present in each sample plot, regardless of the surrounding vegetation type. Although some plots were located in areas classified as grassland, a vegetation formation within the Cerrado domain, this vegetation type is characterized by scattered and widely spaced trees. The focus of our sampling was solely on the trees. The 20 sampled leaves were placed in individually labelled paper bags, with one bag for each plant specimen. The bags were then stored in refrigerated Styrofoam boxes. It was not possible to identify the species of all plants sampled in the sampling plots because the field collection team did not have a botanist available to assist with this task. The lack of specialized botanical expertise during sampling limited the taxonomic resolution of the collected specimens, which affected the completeness of the floristic inventory.

The extraction of mites was conducted by washing the sampled leaves with 30% alcohol, following the protocol of Araújo *et al.* (2022). The samples were examined under a stereomicroscope and all mites found were mounted on slides with Hoyer's medium (Moraes and Flechtmann 2008). Specimen identification and counting were performed under a phase-contrast optical microscope using specialized dichotomous keys for genera and subgenera (Chant and McMurtry 2007) and works on descriptions, redescriptions, and revisions of Phytoseiidae to identify taxa at the species level (e.g., Denmark 1966; Demite *et al.* 2016, 2021; Barbosa and Demite 2023; Silva *et al.* 2024; Lofego *et al.* 2024; Ferragut and Navia 2024). The identified specimens were deposited in the Acari Collection at the Universidade Estadual Paulista (UNESP), São José do Rio Preto, São Paulo, Brazil.

Data analysis

Sampling effort varied between vegetation types due to differences in the number of trees in each sampling plot, which could bias direct species richness comparisons. Therefore, we used the first-order Jackknife method (Jackknife 1) to mitigate this effect and obtain a more reliable estimate of expected richness. This method minimizes the effects of differences in sampling effort and provides a more accurate approximation of true species richness in each plot. Since our primary focus is on species composition rather than abundance, Jackknife 1 is the most appropriate choice, as it corrects for the underestimation of richness due to insufficient sampling (Heltshe and Forrester 1983). The species richness of Phytoseiidae was estimated for each Cerrado vegetation type using the first-order Jackknife method (Jackknife 1) (Heltshe and Forrester 1983), performing 999 permutations with the "*vegan*" package (Oksanen *et al.* 2013) in RStudio 4.3.1 (R Core Team 2025). The estimated richness for each vegetal type (forest, grassland or savannah) was represented in a graph built with "*ggplot*" package (Wickham 2006) in RStudio 4.3.1 (R Core Team 2025). The comparison of estimated mite richness among Cerrado formations was calculated using cumulative Jackknife values and was subsequently visually assessed by checking the overlap of error bars (confidence intervals) with the mean, as proposed by Cumming *et al.* (2007). This approach allows us to compare Jackknife values while accounting for the progressive variability of Jackknife 1 values across samples, providing a more accurate understanding of how estimated species richness values vary among vegetation types. To complement this approach, we performed a Kruskal-Wallis statistical test using the cumulative Jackknife 1 richness to assess significant differences in estimated species richness values among vegetation types, as the assumptions of normality in the data distribution and homogeneity of variances were not met. Subsequently, if the Kruskal-Wallis test shows a statistically significant difference in the estimated predatory mite richness among the three vegetation types, we use Dunn's test post-hoc to determine which vegetation types are significantly different. We used the "*stats*" package in Rstudio for the Kruskal-Wallis and Dunn analyses (R Core Team 2025). Additionally, we used the estimated richness (Jackknife 1) separately for each sample plot to determine possible differences among the sampling plots located at the edge (10 m) and interior (50 m) in the natural vegetation remnants. Since the assumptions of normal data distribution and homogeneity of variances were not satisfactorily met, we opted for the non-parametric statistical Mann-Whitney U test to assess differences in estimated richness between the sampling plots established at the edge and interior in the natural vegetation remnants. We also verified the effect of distance of each sample plot from the nickel mining areas by Spearman correlation using Jackknife 1 estimated richness values for each sample plot as response variable. Additionally, we generated a graph illustrating the relationship between distance to mining sites and estimated richness (Jackknife 1) of predatory mites. For these analyses, we used the "*stats*" package to perform the Mann-Whitney U test and Spearman correlation, and the "*ggplot2*" package for data visualization and graphical representation (Wickham 2016; R Core Team 2025). All statistical analyses were conducted in Rstudio (R Core Team 2025). For all statistical analyses, we considered $\alpha = 0.05$ as the significance level.

Moreover, we applied a non-metric multidimensional scaling (NMDS) test using a Jaccard matrix to evaluate the similarity of mite communities among the three different vegetation formations. The statistical significance of the groups generated by NMDS was evaluated through Analysis of Similarity (ANOSIM) (Bootstrap = 9,999 permutations; Clarke 1993). The ANOSIM and NMDS tests were performed using the Past 3.23 software (Hammer *et al.* 2001).

Results

A total of 279 Phytoseiidae mites, distributed in 19 species, were collected across all the samples carried out (Table 2). Of these, 130 mites of 15 species were collected in 40 forest plots, 137 mites of 15 species in 38 savannah plots, and only 12 mites of four species in three grassland plots. The most abundant species in all samples were *Euseius sibelius* (De Leon), *E. citrifolius* Denmark and Muma, and *Transeius bellottii* (Moraes and Mesa), with these three species dominating sampling sites 17 (Forest), 5 (Savannah), and 5 (Savannah), respectively (Table 3). The species with the lowest recorded frequency were *Arrenoseius lofegoi* Barbosa and Demite, *Galendromimus* (*G.*) *kynolithus* Silva, Gondim Jr. and Demite, *Neoseiulus goiano* Demite, Cavalcante and Lofego, *Proprioseiopsis dominigos* (El-Banhawy), and *Typhlodromus* (*Anthoseius*) *transvaalensis* (Nesbitt), with only one individual collected for each (Table 2).

Amblydromalus insolitus Nuvoloni and Lofego, *Galendromus* (*G.*) *annectens* (De Leon), *Phytoseius intermedius* Evans and MacFarlane, and *P. dominigos* were only recorded in the municipality of Niquelândia. In contrast, the species *Amblyseius compositus* Denmark and Muma, *A. lofegoi*, *G.* (*G.*) *kynolithus*, *Neoseiulus californicus* (McGregor), *N. goiano*, *N. tunus*, and *T.* (*A*) *transvaalensis* were only sampled in remnants within the municipality of Barro Alto (Table 3).

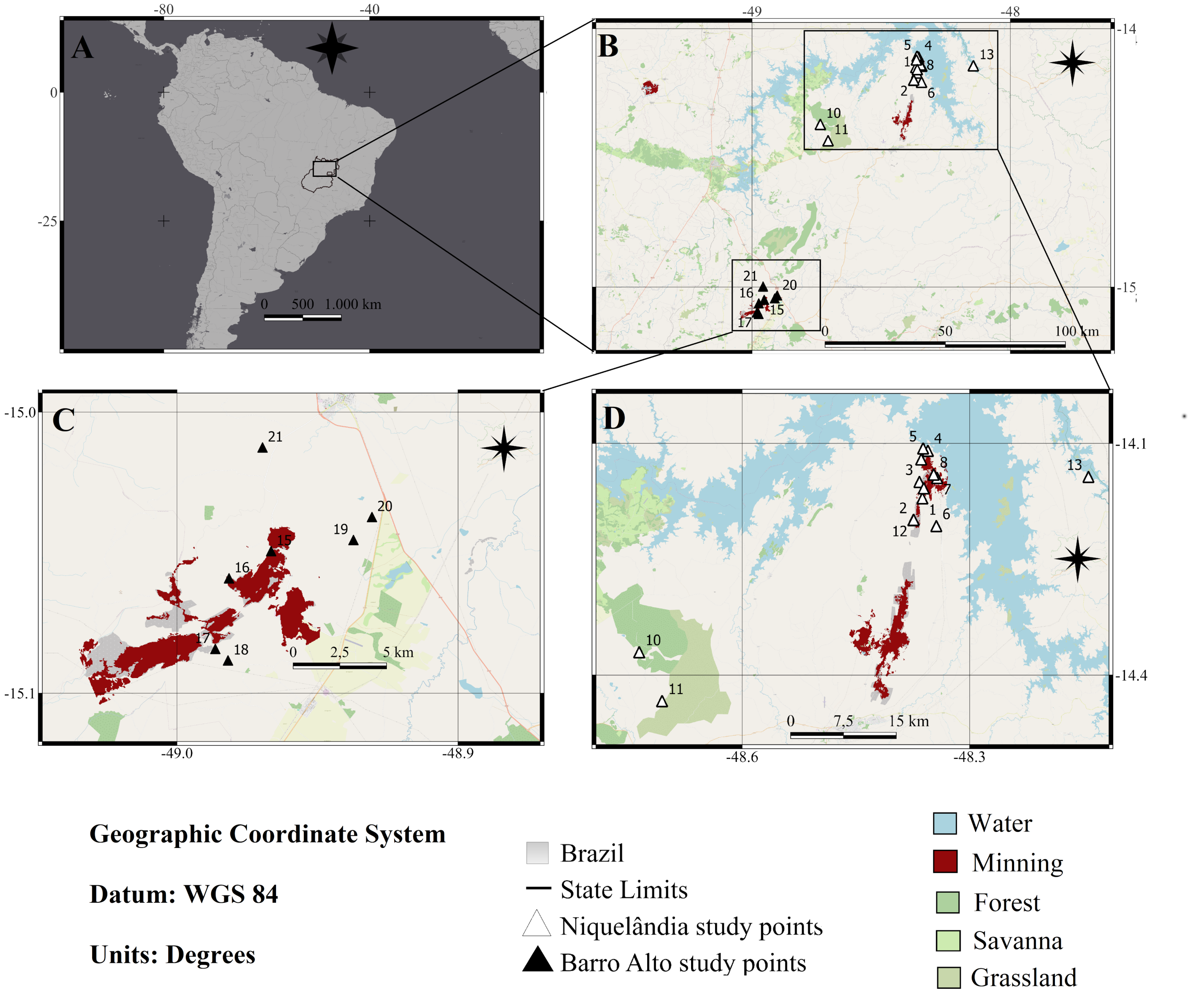

Figure 1 Location of the 21 sampling sites in the Cerrado at the municipalities of Barro Alto and Niquelândia, Goiás, Brazil. (Legend: A = South America; B = Goiás State; C = Barro Alto sampling sites; D = Niquelândia sampling sites).

Regarding the vegetation formations, *P. nahuatlensis* De Leon and *E. citrifolius* were the most abundant species in the grassland formations, while *E. sibelius*, *E. citrifolius*, and *T. bellottii* were the most abundant in the forest and savanna vegetations (Table 2). *Euseius citrifolius*, *E. sibelius*, *P. nahuatlensis*, and *T. bellottii* were recorded in all sampled vegetation types (Table 2). In contrast, *Amblyseius chiapensis* De Leon, *A. compositus*, *N. californicus*, and *N. goiano* were found only in forest formations, while *A. lofegoi*, *G.* (*G.*) *kynolithus*, *P. dominigos*, and *T.* (*A.*) *transvaalensis* were exclusive to savannah. Eleven species were common to both forest and savannah formations. Grasslands did not show any exclusive species, indicating that the species in this vegetation formation represent a subset of the Phytoseiidae assemblages from forest and savannah formations (Table 2).

The estimated species richness of Phytoseiidae was higher in savannah and forest formations compared to grassland formations (Kruskal-Wallis test, $\chi^2 = 13.13$, $df = 2$, $P = 0.001$) when analysed using the cumulative approach of estimated richness (Figure 2). The results of Dunn's test confirm the pattern observed in Figure 2, indicating that grassland had a significantly lower estimated richness compared to forest (Dunn's test, $Z = 3.57$, $P = 0.003$) and savannah (Dunn's test, $Z = -3.56$, $P = 0.0003$). However, the estimated richness (Jackknife 1) of Phytoseiidae mites did not differ between forest and savannah (Dunn's test, $Z = 0.61$, $P = 0.56$).

Table 1 Geographic coordinates of the 21 sampling sites for Phytoseiidae mites established in the different Cerrado vegetation type in the municipalities of Barro Alto and Niquelândia, Goiás State, Brazil.

Remnants	Municipality	Formation	Latitude(S)	Longitude(W)
1	Niquelândia	Savannah	14º10′15.8″	48º21′44.5″
2	Niquelândia	Grassland	14º11′57.5″	48º22′27.7″
3	Niquelândia	Savannah	14º08′59.5″	48º21′58.7″
4	Niquelândia	Forest	14º06′34.4″	48º21′18.4″
5	Niquelândia	Savannah	14º06′23.3″	48º21′41.1″
6	Niquelândia	Forest	14º11′85.3″	48º20′38.4″
7	Niquelândia	Forest	14º08′40.7″	48º20′34.6″
8	Niquelândia	Savannah	14º08′25.1″	48º20′51.1″
9	Niquelândia	Savannah	14º07′14.4″	48º21′50.1″
10	Niquelândia	Forest	14º22′13.2″	48º44′09.1″
11	Niquelândia	Grassland	14º26′01.0″	48º42′20.6″
12	Niquelândia	Savannah	14°11′56″	48°22′26″
13	Niquelândia	Forest	14°08′36″	48°08′36″
14	Niquelândia	Savannah	14°09′29″	48°21′38″
15	BarroAlto	Savannah	15º02′57.1″	48º57′11.2″
16	BarroAlto	Savannah	15º03′45.9″	48º58′26.7″
17	BarroAlto	Forest	15º05′52.5″	48º58′51.3″
18	BarroAlto	Forest	15º06′13.1″	48º58′28.5″
19	BarroAlto	Forest	15º02′37.2″	48º54′43.6″
20	BarroAlto	Savannah	15º01′56.0″	48º54′10.4″
21	BarroAlto	Savannah	14º59′51.3″	48º57′26.6″

Table 2 Number of individuals of Phytoseiidae species found in the three Cerrado vegetation types of the municipalities of Barro Alto and Niquelândia, GO, Brazil, during 2015 and 2016. Vegetation types: (G) Grassland, (F) Forest, and (S) Savannah.

Species	**Vegetation type**			**Total**
	G	F	S	
Amblydromalus insolitus Nuvoloni and Lofego	0	1	1	2
Amblyseius chiapensis De Leon	0	2	0	2
Amblyseius compositus Denmark and Muma	0	2	0	2
Arrenoseius lofegoi Barbosa and Demite	0	0	1	1
Euseius citrifolius Denmark and Muma	2	24	21	47
Euseius sibelius (De Leon)	1	37	29	67
Euseius uai Demite and Lofego	0	2	3	5
Galendromimus (*G.*) *kynolithus* Silva, Gondim Jr. and Demite	0	0	1	1
Galendromus (*G.*) *annectens* (De Leon)	0	1	1	2
Neoseiulus californicus (McGregor)	0	4	0	4
Neoseiulus goiano Demite, Cavalcante and Lofego	0	1	0	1
Neoseiulus tunus (De Leon)	0	8	5	13
Phytoseius guianensis De Leon	0	1	1	2
Phytoseius intermedius Evans and MacFarlane	0	1	1	2
Phytoseius kaapre Demite, Lofego and Feres	0	3	1	4
Phytoseius nahuatlensis De Leon	3	2	8	13
Proprioseiopsis dominigos (El-Banhawy)	0	0	1	1
Transeius bellottii (Moraes and Mesa)	1	12	16	29
Typhlodromus (*Anthoseius*) *transvaalensis* (Nesbitt)	0	0	1	1
Unidentified immatures	5	29	46	80
Richness	4	15	15	19
Abundance	12	130	137	279

On the other hand, no differences were found between the plots established in the edge (10 m) and interior (50 m) of natural vegetation remnants (Mann-Whitney U test, $W = 593.50$, $P = 0.99$) (Figure 3). Furthermore, the distance to the nickel mining sites did not affect the estimated richness of Phytoseiidae mites in Cerrado vegetation remnants (Spearman's correlation, $\rho = -0.008$, n = 81, $P = 0.59$) (Figure 4).

The NMDS analysis revealed overlap in mite species composition among the three vegetation formations, indicating a high level of similarity in Phytoseiidae species composition across the three Cerrado vegetation types (Figure 5). This result is consistent with the ANOSIM test, which also showed no significant differences in Phytoseiidae species composition among the three Cerrado vegetation formations (ANOSIM, r = 0.007, $P = 0.65$).

Discussion

Despite the proximity to nickel mining sites, the Cerrado remnants evaluated in this study supported a considerable diversity of Phytoseiidae mite species, including those with potential agricultural importance, such as *E. sibelius*, *E. citrifolius*, *N. tunus*, and *T. bellottii* (McMurtry *et al.* 2015). Our results were comparable to the findings of Demite *et al.* (2021), who reported 21 Phytoseiidae species in remnants of natural vegetation and cultivated forests. These results suggest that the diversity of Phytoseiidae mites in mining affected areas or adjacent regions is similar to that observed in native vegetation remnants and cultivated forests, highlighting the resilience of these predatory mite species under different environmental conditions.

Although several scientific studies have investigated the diversity of Phytoseiidae mites in the natural vegetation of the Cerrado biome (Lofego *et al.* 2009; Rezende and Lofego 2011; Rezende *et al.* 2014; Abreu *et al.* 2017; Demite *et al.* 2017; Teixeira *et al.* 2017; Silva

Table 3 Number of specimens of phytoseiid species reported by sampling site in the municipalities of Niquelândia and Barro Alto, Goiás State, Brazi*.

Species	Sampling sites																					
	Niquelândia														Barro Alto							Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Amblydromalus insolitus Nuvoloni and Lofego										1				1								**2**
Amblyseius chiapensis De Leon**				1													1					**2**
Amblyseius compositus Denmark and Muma**																	2					**2**
Arrenoseius lofegoi Barbosa and Demite																1						**1**
Euseius citrifolius Denmark and Muma**	3			1	8		3	1		1	2		3	1	1	5	5	6	5		2	**47**
Euseius sibelius (De Leon)**	3	1		6	2		9	1	1	2			2		4	8	11	7		1	9	**67**
Euseius uai Demite and Lofego**						1									1		1			2		**5**
Galendromimus (*G.*) *kynolithus* Silva, Gondim Jr. and Demite																1						**1**
Galendromus (*G.*) *annectens* (De Leon)**			1				1															**2**
Neoseiulus californicus (McGregor)																	2	1	1			**4**
Neoseiulus goiano Demite, Cavalcante and Lofego**																		1				**1**
Neoseiulus tunus (De Leon)**															3		3	5			2	**13**
Phytoseius guianensis De Leon**													1		1							**2**
Phytoseius intermedius Evans and MacFarlane**	1			1																		**2**
Phytoseius kaapre Demite, Lofego and Feres					1					2									1			**4**
Phytoseius nahuatlensis De Leon**				1						1	3			1		1				4	2	**13**
Proprioseiopsis dominigos (El- Banhawy)**			1																			**1**
Transeius bellottii (Moraes and Mesa)**	2	1	5	1	6	1	4		1	2			1		1	1	2	1				**29**
Typhlodromus (Anthoseius) transvaalensis (Nesbitt)															1							**1**
Unidentified immatures	4	2	2	4	6		6		1	1	3	3	1	2	8	6	12	3	2	3	11	**80**
Richness	**4**	**2**	**3**	**6**	**4**	**2**	**4**	**2**	**2**	**6**	**2**		**4**	**3**	**7**	**6**	**8**	**6**	**3**	**3**	**4**	**19**
Abundance	**13**	**4**	**9**	**15**	**23**	**2**	**23**	**2**	**3**	**10**	**8**	**3**	**8**	**5**	**20**	**23**	**39**	**24**	**9**	**10**	**26**	**279**

*****Coordinates of the sample points in Table I.

****** Previously reported for the Cerrado in the Goiás State, Brazil (Rezende and Lofego 2011; Rezende *et al*. 2012; Demite *et al.* 2017; Teixeira *et al.* 2017; Barroso *et al.* 2019; Duarte *et al*. 2021; Moraes et al. 2022; Demite *et al.* 2025).

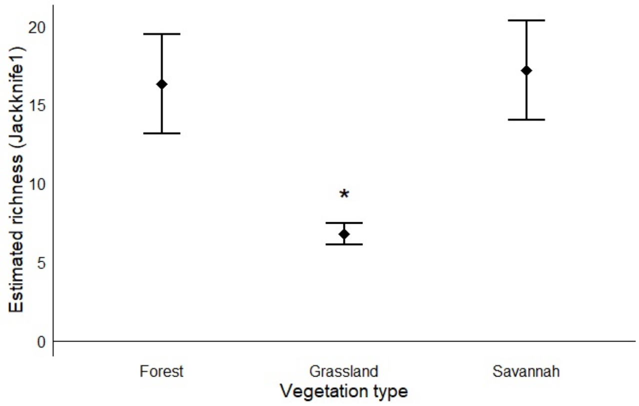

Figure 2 Mean species richness estimated by the Jackknife 1 method for Phytoseiidae fauna in the three Cerrado vegetation formations in the municipalities of Niquelândia and Barro Alto, Goiás, Brazil. Error bars indicate the 95% confidence intervals ($\alpha = 0.05$). * Indicates statistically significant differences.

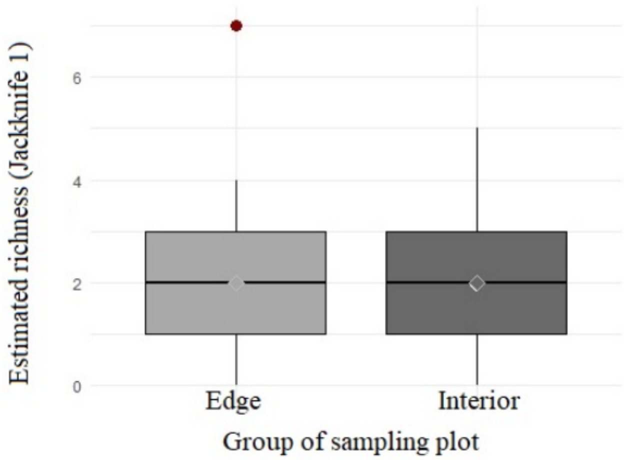

Figure 3 Estimated species richness (Jackknife 1) between sampling plots established in the edge (10 m) and interior (50 m) of natural vegetation remnants.

et al. 2020; Duarte *et al.* 2021; Moraes *et al.* 2022), our study provides a comprehensive assessment of Phytoseiidae diversity, identifying all taxa to the species level. Furthermore, this study introduces a novel ecological analysis by examining how proximity to mining areas may influence the diversity and composition of Phytoseiidae mite communities, considering the Cerrado vegetation formations in which the sampling sites are located.

Amblydromalus insolitus, *A. lofegoi*, *G.* (*G.*) *kynolithus*, *P. kaapre*, *T.* (*A.*) *transvaalensis* and *N. californicus* are reported here for the first time in the state of Goiás. Moreover, *A. lofegoi* and *G.* (*G.*) *kynolithus* were described from individuals sampled in Mata Atlântica (Barbosa and Demite 2023) and Caatinga (Silva *et al.* 2024) biomes, in Bahia and Pernambuco states, respectively. Here we reported *A. lofegoi* and *G.* (*G.*) *kynolithus* for the first time for Cerrado remnants from Goiás State.

In this study, *E. sibelius*, *E. citrifolius*, *P. nahuatlensis* and *T. bellottii* were identified in the three vegetation types (grassland, forest and savannah). These species were also most abundant in forest and savannah formations, suggesting remarkable resilience in their ability to persist in different vegetation formations within the same biome, including grasslands, a more

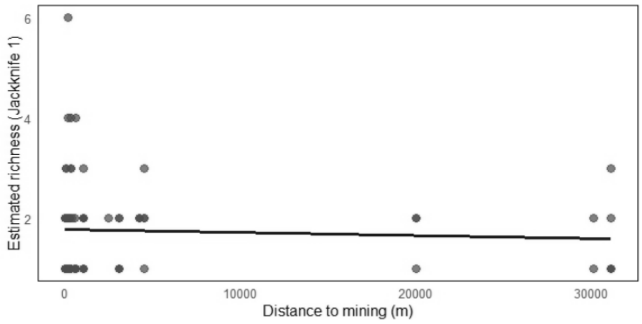

Figure 4 Spearman correlation between distance (meters) to the mining areas and estimated species richness (Jackknife 1) of Phytoseiidae mites in natural vegetation remnants in the municipalities of Barro Alto and Niquelândia, Goiás State, Brazil.

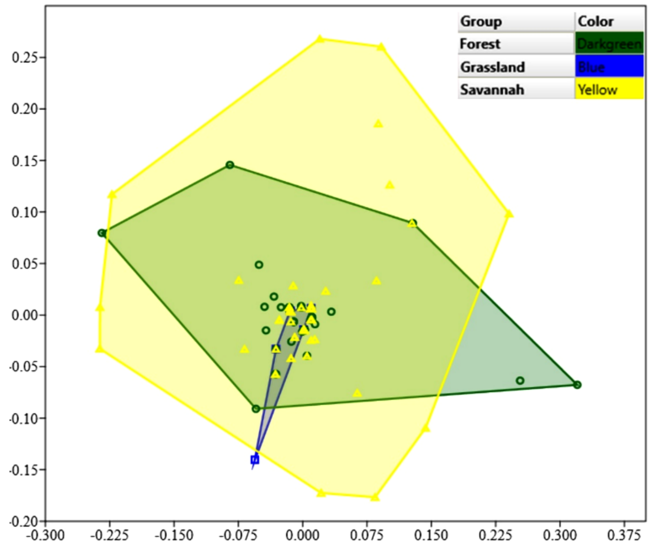

Figure 5 Jaccard similarity demonstrated by non-metric multidimensional scaling (NMDS) analysis, used to compare Phytoseiidae species composition among the three Cerrado vegetation formations in the municipalities of Niquelândia and Barro Alto, GO. Legend: Forest = Dark Green circles; Grassland = Blue squares; Savannah = Yellow triangles.

homogeneous environment composed of grasses with more widely spaced trees. This finding is particularly relevant given that the Cerrado biome is experiencing a trend toward the reduction of natural vegetation fragments (Primack and Massardo 2001; Neri *et al.* 2011), which may provide further insight into which Phytoseiidae mite species are more resilient to declines in abundance even under the effects of habitat loss.

On the other hand, *A. chiapensis*, *A. compositus*, *N. californicus*, and *N. goiano* were found exclusively in sampling plots within forest formations; *A. chiapensis* and *A. compositus* were recorded in two different sampling plots, with one individual per sample, while *N. californicus* was found in three different samples, totalising four individuals, and a single individual of *N. goiano* was recorded in one sampling plot. *Arrenoseius lofegoi*, *G.* (*G.*) *kynolithus*, *P. domingos* and *T.* (*A.*) *transvaalensis* were found exclusively in the savannah formation, with a single individual sampled for each species in different sampling plots. The low abundance and limited occurrence of these species raises uncertainties as to whether factors such as vegetation formation type, proximity to mining areas, or the location of sampling plots within the natural vegetation remnant play a determining role in the occurrence of these Phytoseiidae species. In addition, other factors that may operate at different levels or smaller scales, such as intrinsic characteristics of host plants, may also influence community abundance and species composition.

There remains a knowledge gap regarding recently described Phytoseiidae species, such as *A. lofegoi* and *G.* (*G.*) *kynolithus*, mainly due to the limited time available to conduct studies that could elucidate their feeding preferences and potential as natural enemies of agricultural pests. Among other Phytoseiidae species, *N. californicus* is widely recognized as an effective natural enemy of several pests, especially tetranychid mites such as *Tetranychus urticae* Koch, *Panonychus ulmi* (Koch), and *Panonychus citri* (McGregor) (Monteiro 2002). *Amblyseius chiapensis* has been proposed as a potential natural enemy of *T. urticae* (Amaral *et al.* 2020), and information on its oviposition rate is available in Amaral *et al.* (2018). *Amblyseius compositus* has been studied and confirmed as a potential predator of *Brevipalpus* species (Reis *et al.* 2007). In addition, *Amblyseius* species have been classified as subtype III-b of predatory mites, which includes generalist predators with a preference for plants with glabrous leaves (McMurtry *et al.* 2013).

There is insufficient information on *N. goiano* and *P. dominigos* to determine their life history parameters or to assess their potential as natural enemies of agricultural pests. However, *Neoseiulus* species are classified as type II, referring to selective predators of tetranychid mites while *Proprioseiopsis* exhibit vertical movement among their plant hosts and are classified as subtype III-e, generalist predators in leaf litter and debris environments (McMurtry *et al.* 2013). In addition, *T.* (*A.*) *transvaalensis* has been studied as a potential biological control agent for pests affecting physic nut (*Jatropha curcas* L.), showing high potential as a generalist predator in the regulation of *Polyphagotarsonemus latus* (Smiley) populations (Cañarte *et al.* 2017).

The estimated species richness for the Cerrado remnants indicated that savannah areas hosted a comparable mite species richness to forest formations, demonstrating that different Cerrado vegetation types exhibit considerable mite diversity. Moraes *et al.* (2022) also found greater plant mite species richness in savannah than grassland in the Parque Nacional das Emas, an important Cerrado conservation unit in Brazil. Therefore, these areas should be considered in public policies for biodiversity conservation (Demite *et al.* 2017). The diversity of mite fauna in Cerrado formations may be related to environmental heterogeneity. Cerrado biome is characterized by a mosaic of different types of environments, ranging from grasslands to forests (Ribeiro and Walter 2008), represented by its distinct vegetation formations (e.g., forest, rocky fields, savannah, riparian forests), creating a heterogeneous gradient within a given area (Silva *et al.* 2002). Greater environmental heterogeneity promotes a high functional diversity of species, as it increases the likelihood of the ecosystem supporting more species that can respond favourably to various environmental disturbances due to the abundance of resources and diverse environmental conditions provided by a more complex ecosystem (e.g., food, refuge, mating sites) (Schuelze and Mooney 1997; Levin 1999; McCann 2000; Montoya *et al.* 2001; Altieri 2002). Phytoseiidae mites are often found on the undersides of leaves where they can avoid excessive exposure to desiccation or predators while benefiting from a stable microenvironment. In addition, they can adapt to environmental fluctuations by using plant structures (e.g., domatia) as refugia that provide shelter from extreme weather conditions or disturbances. Consequently, the presence of these favourable conditions directly influences their reproductive success and overall population dynamics (McMurtry *et al.* 2013). Both forest and savannah are more structurally and functionally complex habitats than grassland (Ribeiro and Walter 2008).

Each vegetation formation is shaped by a particular climatic regime, which influences the presence of plant species with specialized structures adapted to that regime, such as spines, domatia, pubescent or glabrous leaves (Ribeiro and Walter 2008). These structures, in turn, may influence the composition of Phytoseiidae mites, as certain species prefer to inhabit plants that provide such characteristics (McMurtry *et al.* 2013). However, as shown by the NMDS and ANOSIM analyses, the vegetation types of the Cerrado harbour a similar species composition of the Phytoseiidae fauna, suggesting that factors operating at smaller scales may play a critical role in structuring these communities. For example, some Phytoseiidae species (Type III species according to McMurtry *et al.* 2013) exhibit preferences for certain characteristics of their host plants that facilitate the development and reproduction of these mite species (McMurtry *et al.* 2013). Therefore, further studies are needed to elucidate the effect of possible influences of plant traits from different vegetation types on mite fauna composition.

Apart from the similarity in the species composition among vegetation types, the estimated richness of Phytoseiidae did not differ between the sampling plots located in the interior (50 m) and those at the edge of the natural vegetation remnant (10 m). Moreover, the distance from mining sites did not affect the estimated richness of mites. Mining activities result in loss of native vegetation, habitat fragmentation, and soil contamination (Neri *et al.* 2011). All the vegetation remnants studied are highly fragmented and probably they suffer the same effects of mining activities, which can promote homogenization in the Phytoseiidae fauna on plants from these vegetation remnants. This means that fewer species are exclusive to a particular vegetation type, and a greater number of mite species are shared among vegetation types. These findings raise new questions about how Phytoseiidae mite communities respond to habitat fragmentation and loss in threatened natural vegetation remnants. In order to achieve a comprehensive understanding of the impact of human activity on mite structure assemblages, it is imperative to conduct comparative studies between preserved and highly fragmented vegetation remnants.

Conclusion

This study reported some mites previously found in the Cerrado vegetation and noted new occurrences of phytoseiid mites in the bioma and Goiás, Brazil. This is the second study to compare mite assemblages among different vegetation formations within the Cerrado biome (Moraes *et al.* 2022). In this study, we also explore how environmental impact factors, such as mining activities, can modify the composition of Phytoseiidae mite communities in the Cerrado. We also aim to conduct an exploratory ecological analysis to ascertain how the distance of natural vegetation remnants from mining areas affects these arthropods. Cerrado vegetation remnants with greater structural complexity can support a higher species richness of Phytoseiidae compared to more homogeneous vegetation formations, such as grassland formations. Additionally, Cerrado remnants harboured potential species for biocontrol programs, such as *E. citrifolius*, *E. sibelius*, *N. californicus*, *N. tunus,* and *T. bellottii*, even in close proximity to nickel mining areas. This highlights the importance of conserving the biome, as these natural areas can serve as crucial reservoirs of Phytoseiidae biodiversity with potential for natural pest regulation in agriculture.

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