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Differences in Soil Mite Community Structure under Sichuan Pepper Planting Model in the Rocky Desertification Control Area of Huajiang Gorge

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Abstract: To understand soil mite community structure and ecological environment under Sichuan pepper cultivation in rocky desertification areas, and to explore the intrinsic mechanisms of soil mites as indicators in the control of rocky desertification. The present study selected the Huajiang Rocky Desertification Comprehensive Control Areas as the research site, with Sichuan pepper fields representing ecological restoration and corn fields representing traditional farming practices. A total of 120 samples were collected from the study areas in July 2024.The results of the study indicated that a total of 4,824 soil mites were captured, classified into three order,69 families, and 120 genera. Of these, 3,538 mites were identified in Sichuan pepper habitats, classified into three order, 66 families, and 118 genera. In the context of Sichuan pepper habitats, there was a notable increase in the number of families, genera, and individual densities of soil mites when compare to those found in corn habitats. Furthermore, the diversity and evenness indices of mites exhibited higher values in Sichuan pepper habitats compared to traditional corn habitats. In terms of similarity indices, the mites in the two habitats exhibited moderate dissimilarity. With regard to similarly indices, the mites in the two habitats exhibited moderate dissimilarity. The findings suggest that the soil mite community structure in Sichuan pepper habitats has undergone changes, resulting in enhanced suitability for soil mite habitation. The rocky desertification area under Sichuan pepper cultivation is in an initial restoration phase, exhibiting signs of relatively improved ecological conditions. However, this study only conducted a differential analysis of the soil mite community structure under Sichuan pepper and corn habitats. Further research is required to ascertain whether changes in the soil mite community structure under these two habitats are correlated with environmental factors.

1. Introduction

Rocky desertification is defined as an environmental issue caused by the destruction of surface vegetation due to human activities, natural environmental factors, or a combination of both. This results in soil erosion, fertility loss, and land degradation[1-2]. Rocky desertification is a widespread phenomenon, particularly in karst regions. Karst regions are characterized by a vulnerable ecological environment, characterized by low vegetation coverage and a thin soil horizon, which constitutes a natural binary structure of water and soil separation. As a result, these areas are predominantly economically underdeveloped. The unsustainable practices of deforestation and land cultivation by the local population for survival have led to the severe degradation of vegetation, making natural restoration a challenging prospect. This has ultimately given rise to extensive areas of rocky desertification, which has exerted a profound impact on the regional economic development and has notable repercussions on human subsistence and socioeconomic advancement[3][4][5].The environmental and ecological problems of karst areas are highly typical and representative, both nationally and globally.

The Huajiang Canyon region serves as a prime example of a karst lithoid desertification area. The ecological environment within this zone is characterised by its exceptional vulnerability, which is attributable to the influence of its intrinsic arid and hot climatic conditions. Consequently, the agricultural crops and vegetation in this area are subject to certain constraints, resulting in a relatively monotonous biodiversity composition. Consequently, the local population traditionally relied on drought-resistant and easy-to-grow corn as their primary food crop and economic source[6]. Nevertheless, corn, being a prevalent crop, possesses a low market value. The prolonged cultivation of corn further depletes soil fertility and reduces yields, thereby rendering it challenging to sustain local livelihoods[7-8].This resulted in additional land being reclaimed for corn cultivation, thus creating a vicious cycle whereby "the poorer, the more land is exploited; the more land is exploited, the poorer". In comparison with vegetation, corn exhibits weaker water and soil conservation capabilities, which ultimately serves to exacerbate severe rocky desertification in the region. In order to halt the progression of desertification and address local ecological issues, the government, in collaboration with experts in the field, implemented a series of control measures. Given the area's unique environmental and economic conditions, experts recommended the implementation of soil-conserving vegetation, such as Sichuan pepper and honeysuckle, which would be economically valuable. Nevertheless, the crop that has been cultivated for an extended period is Sichuan pepper, which possesses drought resistance and strong capabilities for water and soil conservation. In comparison with the initial management strategies for rocky desertification, the current approach to governance places greater emphasis on the interconnections within the ecological spheres, including the animal sphere[9][10][11].

Soil mites are small arthropods with diverse morphologies, habits, and habitats, widely distributed across a variety of soil environments [12].These organisms are of pivotal significance to the functioning of the subterranean ecosystem. They play pivotal roles in the formation and development of soil, as well as in the decomposition of organic matter and the cycling of nutrients. Furthermore, they contribute to material cycling and the flow of energy within the underground ecosystem[13-14]. Soil mites are capable of providing a preliminary indication of changes in the soil environment[15].

Rocky desertification control in this area has traditionally focused on surface vegetation restoration, with considerations limited to the physical and chemical properties of vegetation and water-soil systems. Research on underground ecosystems has been insufficient, with few studies on subterranean organisms such as soil mites. This neglects the role of underground ecosystems and the indicative functions of soil mites in environmental changes. There is a lack of integrated studies linking rocky desertification, vegetation, and soil mites in the area.

Therefore, this study selected the Huajiang Gorge rocky desertification control demonstration area as the research site, with Sichuan pepper, a representative local economic crop, as the research object. The aim was to reveal changes in soil mite community structure under the Sichuan pepper planting model and to identify indicator mite species associated with this planting model. The present study seeks to optimise restoration models and provide theoretical support for local rocky desertification management, ecological improvement, and biodiversity conservation by integrating the indicative roles of soil mites into efforts to control rocky desertification.

2. Survey of the Study Region and Research Methodology

2.1 Overview of the Study Region

The Huajiang Comprehensive Control Research Area is located at 105°63′37″E–105°69′07″E and 25°67′02″N–25°68′76″N, within the Huajiang Grand Canyon. It lies along the banks of the Beipan River, at the border of Zhenfeng County and Guanling County in Guizhou Province.The topographical features of the region are typified by a subtropical karst plateau canyon, with an altitude range of 530 metres at the lowest point to 1,200 metres at the highest, resulting in a relative elevation difference of approximately 700 metres.The region is characterized by steep mountains and deep valleys, with significant river incision and erosion. These geomorphological features create a foehn effect, leading to a hot and dry river valley climate.The annual temperature of this region is higher than that of subtropical monsoon regions at the same latitude, with prolonged periods of high temperatures in summer. The dry-hot river valley climate also results in relatively warm winters.The mean annual temperature is 18.4 ℃, with an accumulated temperature above 10 ℃ of 6,540 ℃. The frost-free period exceeds 300 days, and the annual precipitation is 1,100 mm.The Huajiang Gorge features two vertical natural zones, with an altitude of approximately 850 m as the dividing line. Above 850 m is the humid to semi-humid evergreen and deciduous broad-leaved forest zone, while below 850 m lies the semi-arid to semi-humid deciduous and evergreen broad-leaved forest zone.The vegetation is predominantly drought-tolerant, exhibiting lithophilic, drought-resistant, and calciphilic characteristics typical of limestone plant communities.The soil composition primarily consists of yellow soil and limestone soil, exhibiting a diminutive soil profile with a general depth range of 5 to 20 centimeters.

2.2 Plot Setup and Sample Collection

The Huajiang Rocky Desertification Comprehensive Control Area was selected as the study area, with Sichuan pepper fields and corn fields chosen as the research plots.Within the designated area, five Sichuan pepper fields and five cornfields were established as parallel plots to replace the quadrats.In each parallel plot, six distinct sampling points were selected. A cylindrical stainless-steel soil corer (10 cm × 6.4 cm) was utilised to collect one soil sample from the upper layer (0–5 cm) and another from the lower layer (5–10 cm).A total of 120 samples were collected for the purposes of the study.The samples were meticulously packaged in individual cotton bags, accompanied by precise labelling, and subsequently transported to the designated laboratory for the extraction of soil animals.

2.3 Collection and Identification of Mite Specimens

Collection of Mite Specimens: The soil samples intended for the test were subjected to the Tullgren method for separating soil animals. During this process, the temperature was maintained below 35°C, and the samples were continuously baked for 48 hours. Following the processing of soil samples using the Tullgren funnel to extract soil animals, the subsequent step involves the placement of Petri dishes containing the extracted soil animals under a microscope. The soil mites are then meticulously separated from the rest of the soil animal community using a fine brush and soft forceps. This process necessitates precision and attention to detail to ensure that the mites are handled gently to avoid damage and to maintain their integrity for further study or identification. The separated specimens are then subjected to fixation and cleansing with 70% ethanol. Subsequent to this process, the mite specimens are preserved in small plastic tubes containing a lactophenol solution for the purpose of clearing. This renders the specimens transparent, thus facilitating examination and study under the microscope. Identification of Mite Specimens: The identification of clarified mite specimens was conducted through microscopic observation of mounted samples. This process was primarily informed by the following reference materials: A Manual of Acarology (Third Edition)[12], Acarology[17], Illustrated Key to Soil Animals of China[18], Soil Oribatid Mites of Northeast China[19], and An Overview of Chinese Acaridae[31].With the exception of those representing nymphal stages and incomplete specimens due to their truncated morphological characteristics, all specimens were identified to the genus level.The classification system employed in this text is chiefly aligned with the system delineated in "A Manual of Acarology" (Third Edition)[16].

2.4 Data Processing and Analysis

2.4.1 Classification of Community Dominance

The classification of genus dominance was conducted across four levels, with the calculation of these levels based on two percentages: the proportion of individuals of each genus within its respective habitat, and the proportion of individuals across all habitats.Specifically, genera with >10% were classified as dominant (++++), 1%–10% as common (+++), 0.5%–1% as rare (++), and <0.5% as extremely rare (+)[20].

2.4.2 Community Diversity

The diversity of the community was analysed using the Shannon-Weiner diversity index (H'), Margalef richness index (SR), Pielou evenness index (J), and Simpson dominance index (C) as metrics [21].

The formulas are as follows:

Shannon-Weiner Diversity Index:

$$H' = -\sum_{i=1}^{S} P_i \ln P_i$$

Pielou Evenness Index:

$$J = H/\ln S$$

Margalef Richness Index:

$$SR = (S-1)/\ln N$$

Simpson Dominance Index:

$$C = 1 - \sum_{i=1}^{S} {P_i}^2$$

In the above formulas, P_i represents the proportion of the *i* genus or species in the total abundance, *N* is the total abundance of all mite groups, and *S* is the number of groups (genera or species).

2.4.3 Community Similarity

The analysis of community similarity was conducted employing the Jacard similarity index (q) and the Morisita-Horn similarity index (CMH).[22] The two indices differ in that q is qualitative, focusing on differences in species composition and using genus counts to analyze similarity whereas

CMH is quantitative, considering the abundance of each species and using genus counts along with individual numbers [23].

The formulas are as follows:

Jacard Similarity Index: $q = c/(a + b - c)$

Here, a and b represent the number of genera in communities A and B, respectively, and c is the number of shared genera between the two communities.

Morisita-Horn Similarity Index:

$$C_{MH} = 2(N_a)(N_b)\sum_{i=1}^{s}(a_i b_i) \Big/ \left\{(N_b)^2\sum_{i=1}^{s}(N_a)^2 + (N_a)^2\sum_{i=1}^{2}(N_b)^2\right\}$$

Here, S is the total number of genera, a_i and b_i are the individual counts of the i genus in communities A and B, respectively, and N_a and N_b are the total individual counts of all genera in communities A and B.

The thresholds for determining similarity are as follows: 0.75–1.0 indicates extremely similar, 0.5–0.74 indicates moderately similar, 0.25–0.49 indicates moderately dissimilar, and 0–0.24 indicates extremely dissimilar [15].

2.5 Data Organization and Calculation

Initial organisation and calculation of the data was conducted using Excel 2019. Subsequent analysis involved one-way analysis of variance (ANOVA) on the soil mite community diversity across different habitats, with utilisation of SPSS 25.0 and Origin 2024 software.For data that did not meet normal distribution or homogeneity of variance, Kruskal-Wallis variance analysis, a non-parametric test, was applied.Finally, the graphs were created using Origin.

3. Results and Analysis

3.1 Composition of Soil Mite Communities

A total of 4,822 soil mites were captured in this study, belonging to 3 orders, 69 families, and 120 genera (Table 1).In terms of taxonomic composition, the order Mesostigmata included 14 families, 28 genera, and 814 individuals; the order Prostigmata included 2 families, 2 genera, and 17 individuals; and the order Oribatida included 55 families, 92 genera, and 3,991 individuals.The ratios of families, genera, and individual numbers accounting for the total families, total genera, and total individual numbers in the orders Mesostigmata, Trombidiformes, and Sarcoptiformes are 20.29%, 21.85%, 16.87%, 2.9%, 1.68%, 0.35%, 79.71%, 78.15% and 82.77%, respectively.A total of 3,906 individuals of Oribatida were identified, belonging to 87 families and 53 genera. The Oribatida family accounted for 75.81% of the total families, 71.19% of the total genera, and 81.2% of the total individuals in the sampling area, while the Mesostigmata family accounted for 14.28%, 18.03%, and 16.52%, respectively.These results indicate differences in species abundance across taxa. The number of families, genera, and individuals follows the trend: Oribatida > Mesostigmata > Prostigmata. The families, genera, and individuals within Oribatida dominate the study area, making it the primary focus of this research.

In the study area, 3,538 soil mites were identified in Sichuan pepper habitats, belonging to 3 orders, 62 families, and 118 genera (Figure 1).In Sichuan pepper habitats, Mesostigmata, Prostigmata, and Oribatida comprised 14, 1, and 49 families; 26, 1, and 91 genera; and 578, 8, and 2,953 individuals, respectively (Table 1).These families, genera, and individuals accounted for 21.21%, 1.52%, and 75.76% of the total families, genera, and individuals; 22.03%, 0.85%, and 77.12%; and 16.34%, 0.2%, and 83.47%, respectively.A total of 422 predatory Mesostigmata were identified, belonging to 9 families and 21 genera. Oribatida consisted of 2,873 individuals, belonging to 47 families and 84 genera.The two aforementioned groups accounted for 14.52%, 17.8%, and 11.9% of the total families, genera, and individuals of all mites in Sichuan pepper habitats, and 75.81%, 71.19%, and 81.2%, respectively.

Within the confines of corn habitats, a total of 1,286 soil mites were identified, categorised into three orders, 34 families, and 55 genera (Figure 1).The soil mites found in this habitat were identified as belonging to the Mesostigmata, Prostigmata, and Oribatida, with the former comprising 7 families, the latter comprising 1 and 41 genera, and the latter comprising 236, 10, and 1,040 individuals, respectively (Table 1).The families of Mesostigmata, Prostigmata, and Oribatida accounted for 20.59%, 2.94%, and 76.47% of the total families, respectively. The genera accounted for 23 .64%, 1.82%, and 74.55%, respectively. The individuals accounted for 18.35%, 0.78%, and 80.87% of the total individuals, respectively.In the corn habitat, 220 predatory Mesostigmata and 1,035 Oribatida individuals were identified, belonging to 6 families and 11 genera, and 25 families and 39 genera, respectively. The former accounted for 17.65%, 20%, and 17.11% of the total families, genera, and individuals of all mites in the corn habitat, while the latter accounted for 73.53%, 70.91%, and 80.48%, respectively.

A total of 51 genera were shared among all the mite taxa found in Sichuan pepper fields (SPF) and corn fields (CF). The Sichuan pepper habitat exhibited 67 unique genera, whereas the corn habitat contained only 4 unique genera. The trend in terms of abundance (families, genera, and individuals) was that SPF was greater than CF, with the magnitude of change being greatest for individuals, followed by genera, and then families (Figure 1).

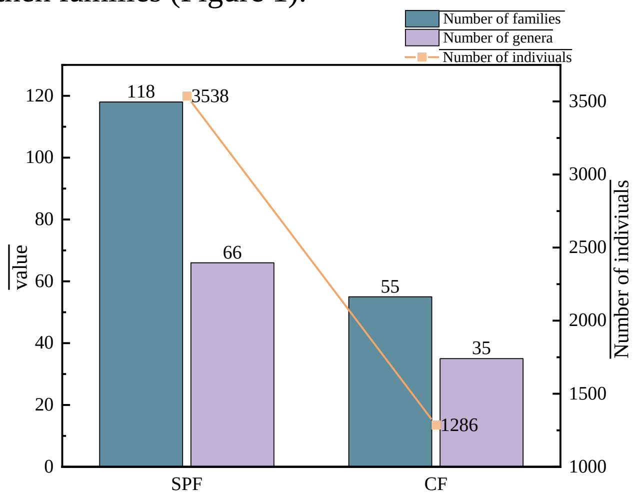


Figure 1 Total population composition of mites in different habitats in the study area

Notes: SPF represents Sichuan pepper field, CF represents Cornfield.

3.2 Dominance Composition and Differences of Soil Mite Communities in Two Habitats

The analysis of soil mite families collected from the study area (see Table 1) revealed that the family Oppiidae (Oribatida) was the most prevalent in terms of genus richness. This dominance was determined by calculating the ratio of the number of genera within the family to the total number of genera. The family Oppiidae comprised 16 genera, accounting for 13.11% of the total genera.The family Epilohmanniidae was identified as the dominant family, comprising 488 individuals, which represented 10.12% of the total individuals. Notably, Epilohmanniidae was solely represented by the genus Epilohmannia.Concurrently, the genus Epilohmannia was the most prevalent in terms of individual abundance among soil mites.

Within the Sichuan pepper plantation habitat, the Oppiidae family was found to be the most prevalent, comprising 15 genera and accounting for 12.71% of the total families observed.From the standpoint of individual abundance in families, the Epilohmanniidae, Tectocepheidae, and Protoribatidae are the dominant families, with numbers of 354, 359, and 354 individuals, respectively. Their proportions in the total number of families are 10.01%, 10.15%, and 10.01%, respectively. Consequently, the genera Epilohmannia (Epilohmanniidae), Tectocepheus (Tectocepheidae), and Protoribates (Protoribatidae) were the dominant genera in this habitat, with individual counts of 354, 359, and 354, respectively, totalling 1,067 individuals.The three genera accounted for 10.01%, 10.15%, and 10.01% of the total individual abundance, respectively.Fifteen genera, including Nenteria (Nenteriidae), Rhodacarus (Rhodacaridae), Sphaerochthonius (Sphaerochthoniidae), and Papillacarus (Papillacaridae), were identified as common genera in this habitat, collectively accounting for 31.63% of the total individuals.Furthermore, 26 genera, including Ramusella (Oppiidae) and Berlesezetes (Oribatellidae), were categorised as rare genera.The remaining 65 genera, including Gemmazetes (Gymnodamaeidae) and Pedrocortesella (Corticoribatidae), were considered to be extremely rare (Table 1).

Within the environment of the cornfield, the family Oppiidae emerged as the predominant family in terms of genus composition, encompassing seven genera and accounting for 12.73% of the total families of soil mites within this habitat. Regarding individual abundance at the family level, Epilohmanniidae, Rhodacaridae, and Lohmanniidae were dominant, with individual counts of 134, 179, and 185, accounting for 10.42%, 13.92%, and 14.39% of the total individuals in the cornfield habitat, respectively. In terms of genus-level individual abundance, the genera Rhodacarus (Rhodacaridae), Papillacarus (Papillacaridae), and Epilohmannia (Epilohmanniidae) were dominant in this site, with individual counts of 158, 163, and 134, representing 12.29%, 12.68%, and 10.42% of the total individuals, respectively.

A total of fourteen genera, including Haplochthonius (Haplochthoniidae), Eremulus (Eremulidae), Protoribates (Protoribatidae), Zygoribatula (Oribatulidae), and Scheloribates (Scheloribatidae), were identified as common genera. Conversely, eight genera, such as Cryptoppia (Oppiidae) and Lanceoppia (Oppiidae), were classified as rare genera. Twenty-nine genera, including Gsamasiphis (Gamasiphidae) and Blattisocius (Blattisociidae), were considered to be extremely rare (Table 1).

The family Oppiidae was prevalent in both the Sichuan pepper plantation and the cornfield habitats, constituting a significant proportion of the genus composition. Similarly, Epilohmanniidae exhibited a high degree of abundance in both habitats, with Epilohmannia being the dominant genus shared by both.This finding suggests that Oppiidae exhibited a high occurrence frequency in the study area and demonstrated a high genus-level species richness, while Epilohmanniidae and Epilohmannia exhibited high individual abundance.Subsequent studies may observe environmental changes by monitoring the variations in these highly abundant mite species.In the Sichuan pepper plantation, the dominant families and genera exhibited consistent individual abundance percentages and counts. This finding indicates that species richness among dominant families is predominantly reflected in individual abundance rather than genus count, and that individual distribution is relatively concentrated.In contrast, the cornfield habitat demonstrated discrepancies. Among the predominant families in terms of individual abundance, Rhodacaridae and Lohmanniidae comprised 3 and 4 genera, respectively, suggesting a more equitable distribution of individual abundance within the dominant families in the cornfield habitat.

Table 1 Soil mite community composition and population distribution

Family	Genus	Number of individuals (dominance) SPF	CF	TOTAL
Mesotigmata: Uropodina(infraorder)				
Oplitidae	*Oplitis*	5(+)		5(+)
Trematuridae	*Nenteria*	138(+++)	13(++)	151(+++)
	Trichouropoda	8(+)	3(+)	11(+)
Dinychidae	*Dinychus*	1(+)		1(+)
	Uroobovella	4(+)		4(+)
Parasitidae	*Parasitus*	12(+)		12(+)
	Neogamasus	12(+)		12(+)
	Vulgarogamasus	14(+)		14(+)
Mesotigmata: Gamasina(infraorder)				
Rhodacaridea	*Rhodacarus*	126(+++)	158(++++)	284(+++)
	Rhodaacarellus	7(+)	5(+)	12(+)
	Dendrolaelaps	22(++)	16(+++)	38(++)
Ascidae	*Arctoseius*	5(+)	2(+)	7(+)
Ologamasidae	*Gsamasiphis*	17(+)	3(+)	20(+)
Macrochelidae	*Macrocheles*	21(++)		21(+)
Blattisociidae	*Lasioseius*	7(+)		7(+)
	Blattisocius	4(+)	6(+)	10(+)
	Cheiroseius	22(++)	1(+)	23(+)
Parholaspididae	*Parholaspius*	52(+++)	7(++)	59(++)
Pachylaelapidae	*Pachyseius*	9(+)		9(+)
	Pachylaelaps	26(++)	9(++)	35(++)
Laelapidae	*Pneumolaelaps*	12(+)	12(++)	24(++)
	Gymnnolaelaps	11(+)		11(+)
	Geolaelaps	13(+)	1(+)	14(+)
	Cosmolaelaps	8(+)		8(+)
Melicharidae	*Proctolaelaps*	7(+)		7(+)
Zerconidae	*Parazercon*	15(+)		15(+)
Trombidiformes(order):Prostigmata (suborder)				
Microtrombidiidae	*Microtrombidium*	7(+)		7(+)
Stigmaeidae	*Stigmaeus*		10(++)	10(+)
Sarcoptiformes(order):Oribatida (suborder)Macropylina group				
Archeonothridae	*Zachvatkinella*	18(++)		18(+)
Hypochthoniidae	*Malacoangelia*	7(+)	1(+)	8(+)
	Eohypochtonius	6(+)		6(+)
Trichthoniidae	*Trichthonius*	7(+)		7(+)
Cosmochthonoidae	*Cosmochthonius*	21(++)		21(+)
	Phyllozetes 属	70(+++)	41(+++)	111(+++)
Haplochtoniidae	*Haplochtonius*	51(+++)	103(+++)	154(+++)
Brachychthoniidae	*Eobrachychthonius*	11(+)		11(+)
	brachychthonius	9(+)		9(+)
Sphaerochthoniidea	*Sphaerochthonius*	123(+++)	42(+++)	165(+++)
Phthiracaridae	*Steganacarus*	14(+)	17(+++)	31(++)
	Hoplophthiracarus	10(+)		10(+)
	Hoplophorella	8(+)		8(+)
Euphthiracaridae	*Rhysotritia*		9	9(+)
Lohmannidae	*Papillacarus*	115(+++)	163(++++)	278(+++)

	Cryptacarus	42(+++)	15(+++)	57(+++)
	Lohmannia	29(++)	6(+)	35(++)
	Vepracarus	21(++)	1(+)	22(+)
	Mixacarus	16(+)		16(+)
	meristacarus	4(+)		4(+)
Epilohmanniidae	*Epilohmannia*	354(++++)	134(++++)	488(++)
Nothridae	*Nothrus*	93(+++)	54(+++)	147(+++)
Camisiidae	*Camisia*	13(+)		13(+)
	Platynothrus	1(+)		1(+)
Trhypochthoniidae	*Trhypochtoniellus*	12(+)	2(+)	14(+)
	Trhypochthonius	59(+++)	4(+)	63(+++)
	Allonothrus	77(+++)	6(+)	83(+++)
Malaconothridae	*Malaconothrus*	22(++)	3(+)	25(++)
Gymnona group				
Nanhermannlidae	*Nanhermannia*	10(+)		10(+)
	Masthermannia	7(+)		7(+)
Hermanniellidae	*Hermannobates*	14(+)	2(+)	16(+)
Damaeidae	*Damaeus*	9(+)		9(+)
	Epidamaeus	10(+)		10(+)
Cepheoidae	*Cepheus*	9(+)		9(+)
Lichodamaeidae	*Lichodamaeus*	19(++)		19(+)
Eremulidae	*Eremulus*	36(+++)	98(+++)	134(+++)
Damaeolidae	*Fosseremus*	32(++)	7(++)	39(++)
Ctenobelbidae	*Ctenobelba*	13(++)		13(+)
Liacaridae	*Liacarus*	5(+)		5(+)
Carabodidae	*Carabodes*	5(+)		5(+)
Autognetidae	*Autogneta*	20(++)		20(+)
Oppiidea	*Oppia*	2(+)	7(+)	9(+)
	Ramusella	34(++)	19(+++)	53(+++)
	Multioppia	40(+++)		40(++)
	Microppia	22(++)	4(+)	26(++)
	Discoppia	10(+)		10(+)
	Striatoppia	14(+)		14(+)
	Oppiella	9(+)		9(+)
	Acroppia	4(+)	4(+)	8(+)
	Sphagnoppia	21(++)		21(+)
	Lauroppia	17(+)		17(+)
	Cryptoppia	10(+)	9(++)	19(+)
	Lanceoppia	10(+)	7(++)	17(+)
	Condyloppia	5(+)	2(+)	7(+)
	Lasiobelba	8(+)		8(+)
Quadroppiidae	*Quadroppia*	5(+)		5(+)
Otocepheidae	*Otocepheus*	7(+)		7(+)
Astegistidae	*Cultroribula*	18(++)	4(+)	22(+)
Tectocepheidae	*Tectocepheus*	359(++++)	47(+++)	406(+++)
Suctobelbidae	*Suctobelba*	18(++)	1(+)	19(+)
	Suctobelbella	28(++)	1(+)	29(++)
	AlloSuctobelba	14(+)	1(+)	15(+)
Eremaeidae	*Eueremaeus*	17(+)		17(+)
Belbodamaeidae	*Belbodamaeus*	10(+)		10(+)
Thyrisomidae	*Gemmazete*	10(+)		10(+)
Pedrocortesellidae	*Pedrocortesella*	16(+)		16(+)
Poronta group				
Scutoverticidae	*Suctovertex*	27(++)		27(++)
Oribatula	*Zygoribatula*	19(++)	75(+++)	94(+++)
	Oribatula	8(+)		8(+)
Microzetidae	*Berlesezetes*	31(++)		31(++)

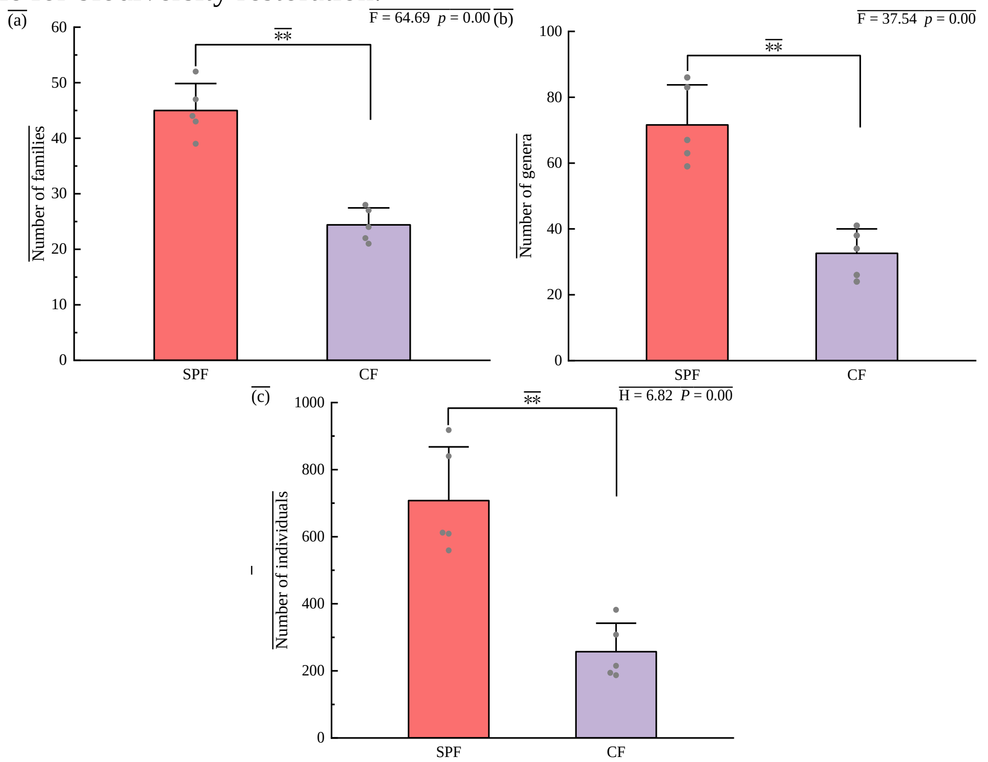
Mochlozetidae	*Mochlozetes*	16(+)	6(+)	22(+)
Scheloribatidae	*Scheloribates*	49(+++)	63(+++)	112(+++)
Parakalummidae	*Parakalummus*	4(+)		4(+)
	Neoribates	11(+)		11(+)
Galumnidae	*Trichogalumna*	14(+)		14(+)
	Pergalumna	15(+)		15(+)
	Galumna	23(+)	5(+)	28(++)
	Lepiogalumna		1(+)	1(+)
Haplozetidae	*Peloribates*	22(++)		22(+)
	Haplozete	354(+++)	3(+)	357(+++)
	Rostrozetes	10(+)		10(+)
	perxylobates	24(++)		24(++)
	Vilhenabates	27(++)		27(++)
Xylobatidae	*Xylobates*	28(++)	3(+)	31(++)
protoribatidae	*protoribates*	42(+++)	72(+++)	114(+++)
Achipteridae	*Achipteria*	18(++)		18(+)
Ceratozetidae	*Melanozetes*	18(++)		18(+)
Zetomotrichidae	*Ghilarovus*	4(+)	2(+)	6(+)
Sarcoptiformes(order):Astigmata(suborder)				
Acaridae	*Acarus*	20(++)		20(+)
	Rhizoglyphus	16(+)	4(+)	20(+)
	Tyrophagus	19(++)	1(+)	20(+)
Histiostomidae	*Histiostoma*	15(+)		15(+)
Number of individuals		3538	1286	4824
Total number of genera		118	55	120
Total number of family		66	35	69

The basic information of SPF,CF sample plots is shown in Table 1. + + + + denotes dominant taxa; + + + denotes common taxa; + + denotes rare taxa; + denotes very rare taxa.

3.3 Distribution structure of soil mite communities at the habitat level in different habitats

In the Huajiang rocky desertification control area, the cultivation of corn has been a long-standing agricultural practice, in stark contrast to the more recent introduction of Sichuan pepper plantations, which occurred within the past two decades. The soil ecosystems in these two habitats differ, and the structural characteristics of the soil mite communities inhabiting them also vary.The distribution of soil mite communities in terms of family count, genus count, and individual abundance in these two habitats is shown in Figure 2.A statistically significant discrepancy was observed in the number of families observed between the Sichuan pepper ecosystem (SPE) and the cornfield (CF) ($F = 64.69$, $p < 0.01$). Specifically, the average number of mite families was found to be considerably higher in SPE (45 ± 2.18 families) in comparison to CF (24.4 ± 1.36 families) (Figure 2a).In relation to the number of genera, SPE and CF exhibited a highly significant difference ($F = 37.54$, $p < 0.01$). The mean number of mite genera was higher in SPE (71.6 ± 5.44 genera) than in CF (32.6 ± 3.31 genera) (Figure 2b).In terms of individual abundance, SPE and CF again exhibited a highly significant difference ($H = 6.82$, $p < 0.01$). The average number of individuals was significantly higher in SPE (707.6 ± 71.67 individuals) than in CF (257.2 ± 37.99 individuals) (Figure 2c).

The findings suggest that the average number of families, genera, and individuals of soil mites in the Huajiang rocky desertification control area exhibited a consistent trend, aligning with the observations presented in Section 2.2. Specifically, the values were observed to be consistently higher in the SPE than in the CF.A statistical analysis was conducted on the family, genus, and individual counts of mites in the two habitats, revealing significant differences between SPE and CF, particularly in terms of individual abundance.In general, the population density of mites in SPE was found to be greater than that in CF, with a higher abundance of families, genera, and individuals of mites observed in SPE.It can be hypothesised that the diversity of mite communities in SPE and CF also reflects this pattern of difference.It is hypothesised that these variations are attributable to disparities in vegetation types between SPE and CF, which consequently engender divergent soil ecosystem characteristics. This finding indicates that, in comparison with corn cultivation, the planting of Sichuan pepper is more conducive to increasing the number of soil mite families, genera, and individuals, rendering it more suitable for biodiversity restoration.



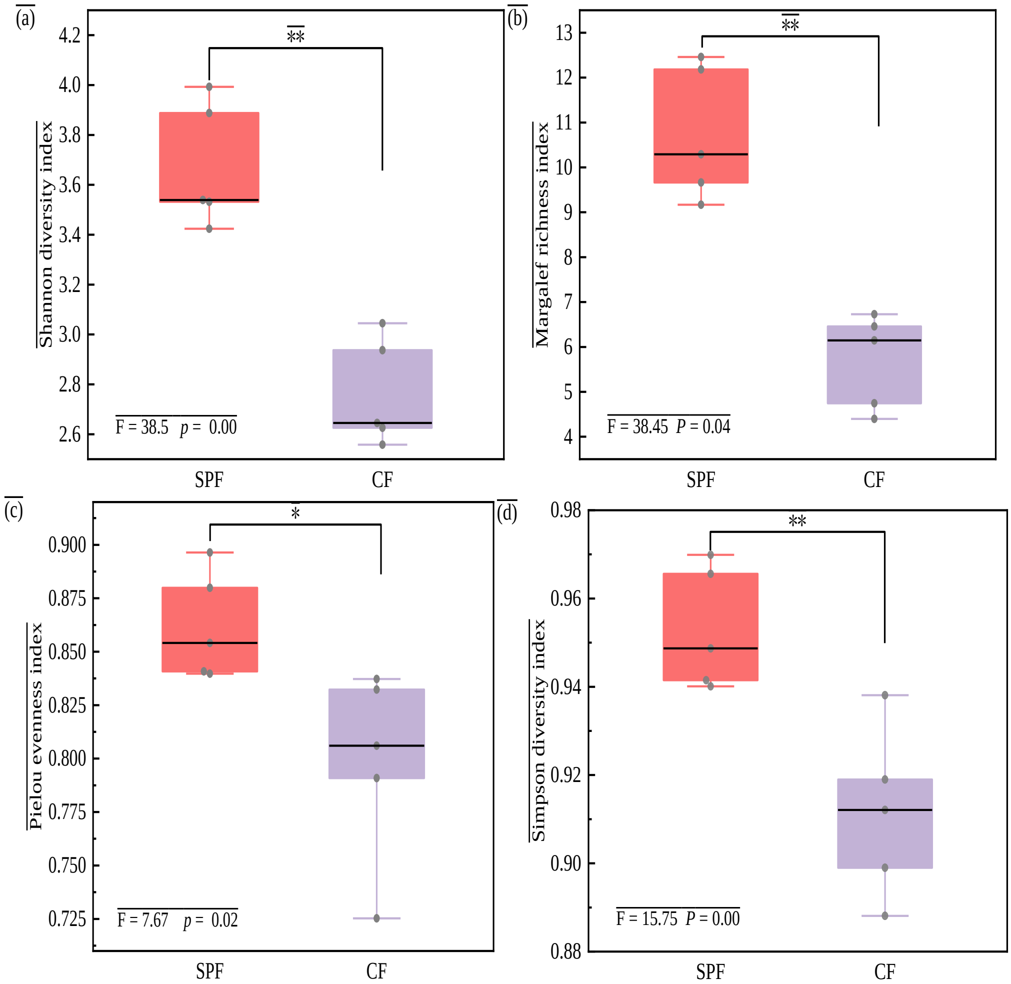
Notes: SPF represents Sichuan pepper field, CF represents Cornfield. F is a one-way ANOVA statistic between different habitats types; '*' represents a significant difference between the two habitats types at p=0.05 level, while '* *' represents a significant difference between the two habitats types at p=0.01 level; The bar chart with standard error bars shows the distribution of sample data, with an average ± standard error (n=2).

Figure 2 Number of mite families (a), genera (b), and individual numbers (c) in different habitats

3.4 Community diversity of soil mites in different habitats

In the two habitats of the study area, the Shannon diversity index (H), Margalef richness index (SR), Pielou evenness index (J), and Simpson diversity index were utilised as indicators to represent the diversity of soil mite communities. The variations of these indices in the Sichuan pepper ecosystem (SPF) and the cornfield (CF) are demonstrated in Figure 3.Overall, there were significant differences in various indices between SPF and CF habitats, and the specific analysis is as follows.With regard to the mean Shannon diversity index, SPF (3.68 ±0.11) was higher than CF (2.76 ± 0.1), with a highly significant difference between the two habitats ($p < 0.01$) (Figure 3a).For the Margalef richness index, the trend was similarly SPF (0.95 ± 0.01) > CF (0.91 ± 0.01), and a significant difference was found between the two habitats ($p < 0.01$) (Figure 3b).In terms of the average Pielou evenness index, SPF (10.752 ± 0.67) was greater than CF (5.69 ± 0.47). The significance level between the two habitats was consistent with that of the richness index, showing a significant difference ($p < 0.05$) (Figure 3c).The Simpson diversity index revealed an average value of SPF (0.86 ±0.01) > CF (0.8 ±0.02), indicating a predominance of SPF over CF. This finding aligns with the Shannon diversity index, suggesting a highly significant correlation ($p < 0.01$) (Figure 3d).

In summary, the average trends of the diversity indices for soil mite communities in SPF and CF were generally consistent. These trends were consistent with the variations in genus and individual distribution patterns between the two habitats described in section 2.2.However, a divergence in the alterations of the diversity index averages between the two habitats was observed. Specifically, the average changes in the Shannon diversity index (H) and the Simpson diversity index were consistent, showing a highly significant correlation. The mean changes in the richness index and the evenness index were consistent, both showing significant differences. It is hypothesised that, in comparison with corn cultivation, the planting of Sichuan pepper is more conducive to increases in mite diversity, evenness, and richness, particularly in promoting the restoration of mite diversity. This may be because Sichuan pepper cultivation more effectively improves the soil ecological environment, leading to differences between SPF and CF.



Notes: SPF represents Sichuan pepper field, CF represents Cornfield. F is a one-way ANOVA statistic between different habitats types; '*' represents a significant difference between the two habitats types at p=0.05 level, while '* *' represents a significant difference between the two habitats types at p=0.01 level; The bar chart with standard error bars shows the distribution of sample data, with an average ± standard error (n=2).

Figure 3 Shannon diversity index (a), richness index (b), evenness index (c), and Simpson diversity index (d) of soil mites in different habitats

3.5 Similarity of Soil Mite Communities in Different Habitats

We used the Morisita-Horn similarity index and the Jaccard similarity index to compare the similarity between the two habitats. The similarity calculations for soil mites in the SPF and CF habitats are shown in Table 2.Overall, the soil mites in the two habitats show dissimilarity in both indices. The specific results are as follows: From the Morisita-Horn similarity index comparison, the similarity index between SPF and CF is 0.407, which is between the threshold of 0.25 and 0.49, indicating a moderate dissimilarity. From the perspective of the Jaccard similarity index, the similarity index for soil mites in SPF and CF habitats is 0.454, also falling between the threshold values of 0.25 and 0.49, indicating moderate dissimilarity. In conclusion, soil mites in the SPF and CF habitats exhibit moderate dissimilarity, both in terms of species composition and abundance. We speculate that this may be due to the different vegetation planted in the two areas, which has led to changes in soil properties and, consequently, differences in the underground ecosystems. Thus, we hypothesize that the soil ecosystem changes brought about by planting Sichuan pepper differ significantly from those caused by planting corn. Sichuan pepper has a more pronounced effect on the restoration of rocky desertification compared to corn. This likely explains why the different vegetation planted in the two areas leads to changes in soil properties and the underground ecosystems, which in turn results in changes in the soil mite communities.

Table 2 Similarity index of soil mite communities among different habitats

Habitat	SPF	CF
SPF	*	0.407
CF	0.454	*

Note: Morisita-Horn similarity index on the diagonal and Jacard similarity index below the diagonal; * indicates a similarity level of 1

4. Discussion

4.1 Differences in Soil Mite Composition and Dominant Genera

In this study area, a total of 4,824 soil mites were collected, belonging to 3 orders, 69 families, and 120 genera. A total of 3,538 mites were recorded in the SPF habitat, belonging to 3 orders, 66 families, and 118 genera, while 1,286 mites were recorded in the CF habitat, belonging to 3 orders, 35 families, and 55 genera. With regard to family, genus, and individual abundance, SPF was found to be greater than CF. This rocky desertification area is in the early stage of restoration, which is in accordance with the findings of numerous scholars that family, genus, and individual numbers increase during the rocky desertification recovery process. This finding is consistent with the observations of the scholar Chen Hu, who conducted a study on the alterations in soil mite community structure during the initial phase of moderate rocky desertification recovery in the Chaoying watershed of Bijie. However, it should be noted that there is a slight discrepancy between the conclusions of the present study and those of Chen Hu's study on soil mites in the Huajiang Dingtan area of severe rocky desertification control. His study indicated that soil in habitats with longer recovery periods, such as Sichuan pepper forests and Sichuan pepper combined with honeysuckle forests, had rich family and genus diversity of mites. In contrast, soil in habitats with shorter recovery periods, such as honeysuckle forests, exhibited higher individual abundance and density. This study aligns with Chen Hu's findings in terms of family and genus composition but shows slight differences in individual abundance. The conclusions of this study on the changes in soil mite communities in rocky desertification control areas demonstrate both similarities and differences with other scholars' findings. Specifically, as follows: Specifically, the number of mite genera, individual abundance, and individual density in the Rosa roxburghii land increased more significantly than in the corn land, indicating differences in the composition and structure of the soil mite communities (Rosa roxburghii (shi li) land vs. corn land). In comparison to corn land, the grass restoration environment exhibited a substantial increase in the number of families, genera, and individual mites, suggesting that the grass restoration model fosters a more diverse composition of soil mite communities.In summary, two main reasons can be deduced. Firstly, differences in vegetation type and the duration of vegetation planting can lead to changes in the soil ecological environment, and accordingly, the structure of the soil mite community will also change. Secondly, human disturbance has reduced the density and diversity of the soil mite community to a certain extent. The CF employs traditional agricultural practices, which frequently entail ongoing field management operations such as sowing, plowing, fertilising, and weeding during the cultivation process[24][25][26], particularly leading to a reduction or even disappearance of the density of rare groups[27][28][29].

With regard to the prevalence of dominant genera, this study identified substantial disparities in the predominant soil mite genera between the CF habitat, which represents conventional farming, and the SPF habitat, which represents rocky desertification restoration. Research on soil mites under different types of rocky desertification revealed that the genus Tectocepheus, identified as a dominant genus, is mainly distributed in environments with severe rocky desertification. As demonstrated in the studies conducted by Chen Hu and others [15][17].Tectocepheus has been observed to typically inhabit environments that are either disturbed or in the early stages of successional development. This finding suggests that, although the soil environment in SPF habitats has undergone initial recovery, the restoration process remains relatively slow. In this study, the dominant genera in SPF restored habitats were Epilohmannia, Tectocepheus, and Scheloribates. In maize fields, the dominant genera were Rhodacarus, Papillacarus, and Epilohmannia. The SPF habitat exhibited a higher abundance of soil mites of rare taxa compared to the CF habitat, indicating that the ecological conditions in SPF are in a preliminary stage of recovery, with the ecosystem gradually improving. This renders SPF a more suitable habitat for soil mites, whereas traditional agricultural activities have, to some extent, exacerbated the expansion of rocky desertification.

4.2 Differences in Soil Mite Community Diversity and Similarity across Habitats

Diversity indices are of paramount importance when evaluating the composition of soil mite communities. They effectively reflect changes within the community environment and represent its complexity and stability through a series of numerical metrics. It has been demonstrated by preceding studies that habitat quality is positively correlated with various mite diversity indices. That is to say, superior habitat conditions result in increased individual counts and greater species richness of mites. Consequently, elevated evenness and diversity indices of mites are imperative for ecological restoration and enhancing environmental conditions, rendering them significant for studies on ecological recovery [23][26][30].The present study found that the diversity and evenness indices of mites in the Sichuan pepper field (SPF) habitat were higher than those in the cornfield (CF) habitat. This finding is consistent with the results of previous research. This indicates that the SPF habitat is more conducive to the increase in mite abundance and diversity, supporting mite recovery. The observed changes in the soil mite community structure indicate that the soil ecosystem is still in the early stages of recovery, with the restoration of soil conditions progressing at a gradual pace. This finding is consistent with the results of Chen Hu's study on soil mites under different vegetation restoration models in areas of severe rocky desertification. This finding serves to reinforce the notion that the planting of Sichuan pepper can serve as an effective indicator of ecological restoration, as it is more conducive to the improvement of ecological conditions.

The mite community similarity index is a quantitative measure of the degree of similarity in community composition, reflecting successional changes and interrelationships to a certain extent [23].In this study, the calculated Morisita-Horn similarity index and Jacard similarity index both indicated low similarity between the SPF and CF habitats, categorized as moderately dissimilar. This finding is consistent with the results obtained by Wei Qiang in his research on soil mites in different grass-growing models in areas of rocky desertification [23].The results of the calculation demonstrated a minor discrepancy between the Morisita-Horn similarity index and the Jacard similarity index, thereby indicating that Sichuan pepper planting exhibits distinct characteristics compared to maize planting with regard to both individual counts and species composition. This finding indicates that the soil mite community structures in these two habitats exhibit relatively stable differences, with the Sichuan pepper field being closer to natural succession.

5. Conclusion

The Huajiang Rocky Desertification Comprehensive Control Area is a typical karst plateau region characterized by sparse vegetation and a fragile ecosystem. Soil mite community structures are influenced by different vegetation types. In this study, a total of 4,824 soil mites were captured, belonging to 3 orders, 63 families, and 122 genera. Of these, 3,538 mites were found in Sichuan pepper habitats, belonging to three orders, 62 families, and 118 genera. In the context of Sichuan pepper habitats, a marked increase in the number of families, genera, and individual densities of soil mites was observed when compared to maize habitats. The diversity and evenness indices for mites exhibited higher values in Sichuan pepper habitats than in traditionally cultivated maize habitats. Specifically, the Shannon and Simpson diversity indices demonstrated highly significant disparities between the two habitats ($P > 0.01$).Simpson evenness and Margalef richness indices showed significant differences ($P > 0.05$).With regard to similarity indices, mites in the two habitats exhibited moderate dissimilarity. The findings suggest that the soil mite community structure in Sichuan pepper habitats has undergone changes, rendering them more conducive to mite habitation. The area of rocky desertification under Sichuan pepper cultivation is currently in an initial restoration phase, with relatively improved ecological conditions. However, the present study exclusively analysed the disparities in soil mite structures between Sichuan pepper and maize habitats. Further research is required to ascertain whether changes in soil mite structures are associated with environmental factors.

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