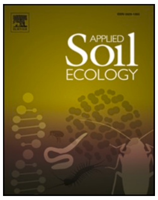
Applied Soil Ecology 214 (2025) 106358

Contents lists available at ScienceDirect

Applied Soil Ecology

journal homepage: www.elsevier.com/locate/apsoil



Biodiversity of oribatid mites as a tool to monitor soil health in the agroecological transition: Digging deeper into French Mediterranean vineyards☆

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ARTICLE INFO

Keywords:
Soil mesofauna
Viticulture
Inter-row vegetation
Sustainable agriculture
Bioindicators

ABSTRACT

Oribatid mites play a vital ecological role in soil ecosystems by driving key processes like decomposition and nutrient cycling. Their abundance and sensitivity to environmental changes make them valuable bioindicators of soil health. This study evaluates varying agricultural management practices through shifts in oribatid mite communities, using them as a tool to monitor the progress of the agroecological transition in Mediterranean vineyards. In autumn 2023, soil samples were collected from 30 plots consisting of conventional and organic vineyards with varying inter-row vegetation cover management intensities, as well as natural garrigue vegetation used as a reference. A total of 7574 oribatid mites were extracted using a modified Berlese-Tullgren funnel. We analyzed the effect of vineyard management practices on oribatid mite abundance, family richness, and diversity using generalized linear models. Natural systems exhibited significantly higher abundance, richness, and diversity compared to vineyard soils. Among vineyards, those with permanent vegetation cover had mite communities more similar to natural systems ($p = 0.212$), while temporarily covered and bare soil showed reduced richness ($p < 0.001$ for both) and abundance ($p < 0.001$ for both). No strong differences in oribatid mite abundance and richness were observed between conventional and organic vineyards ($p = 0.341$ and 0.053, respectively), although organic plots showed higher diversity ($p = 0.0205$). Indicator analysis revealed several oribatid mite families strongly associated with natural habitats and vineyards with permanent vegetation cover. These findings suggest that agroecological practices might create more suitable conditions for oribatid mites in vineyards, helping to maintain communities similar to those found in natural habitats.

1. Introduction

Vineyards are a key agroecosystem in Europe, especially in Mediterranean climate areas, due to their significant socio-economic and cultural value. In 2023, France led global wine production (20 % of the total) and ranked second in vineyard area, covering about 792,000 ha (OIV, 2024). Occitanie, characterized by a Mediterranean climate, is the largest wine-producing region in the country, spanning 259,000 ha (34 % of the nation's vineyards), with Aude and Hérault alone accounting for more than half of that total (DRAAF Occitanie, 2024). Vineyard practices significantly affect soil health and biodiversity (Giffard et al., 2022; Winkler et al., 2017). Among them, pesticide applications are particularly high in vineyards, with a Treatment Frequency Index (TFI) of 12.4 (Agreste, 2023)—an indicator quantifying the frequency of pesticide

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☆ This article is part of a Special issue entitled: 'Soil Biodiversity in Europe' published in Applied Soil Ecology.

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https://doi.org/10.1016/j.apsoil.2025.106358
Received 29 March 2025; Received in revised form 21 June 2025; Accepted 30 July 2025

treatments. Moreover, intensive tillage for weed control induces erosion, reduce organic matter, and disrupt soil biodiversity (Linares et al., 2014; Patterson et al., 2019). Such negative impacts clearly highlight the urgent need for a shift toward more sustainable agricultural practices, as emphasized by the Kunming-Montreal Global biodiversity framework and reported by the European Environment Agency (Convention on Biological Diversity, 2022; EEA, 2024). One such approach is agroecological practices, that aim to minimize environmental impact while strengthening the resilience and functionality of farming systems (Altieri et al., 2005; Duru et al., 2015; Magdoff, 2007). This approach is grounded in the integration of ecosystem services, for maintaining the ecological balance of agroecosystems (Comerford et al., 2013).

Soils constitute the habitat of about 60 % of the world's life Anthony et al., 2023), support complex food webs (Buchkowski et al., 2023), including in agroecosystems (Buchkowski and Lindo, 2021; Magdoff, 2007). This soil biodiversity play a crucial role in agrosystem function and services, which are essential for agricultural sustainability (Barrios, 2007). Mites (Arachnida, Acari)—reported to be the most abundant soil-dwelling microarthropods (Groot et al., 2016; Gulvik, 2007)—represent a significant and functionally important part of the soil mesofauna. Among these, oribatid mites (Acariformes, Sarcoptiformes, Oribatida), with 11,500 described species included in 172 families, represent one of the most abundant groups in the uppermost soil horizons, with densities reaching up to several hundred thousand individuals per square meter in natural areas (Behan-Pelletier and Lindo, 2023; Subías, 2022). They are a key component of ecosystems, particularly in organic matter decomposition, nutrient cycling, and soil formation (Barreto and Lindo, 2018; Hubert et al., 2000). By fragmenting organic matter through feeding (Seastedt, 1984), oribatid mites facilitate microbial activity. Their role in breaking down organic material and producing fecal pellets enhances surface area for decomposition significantly influencing soil structure (Behan-Pelletier, 1999). Despite being traditionally considered mycophagous, oribatid mites feed on a wide range of materials throughout their active life stages. Their diet includes living and dead plant matter, fungi, moss, lichens, decaying flesh, and some species also prey on nematodes (Schneider et al., 2004). As a result, they function as primary consumers (i.e., secondary decomposers) within the fungal channel of the soil food web (Buchkowski and Lindo, 2021), but can also influence the bacterial channel by feeding on bacteriophagous nematodes (Heidemann et al., 2014; Heidemann et al., 2011). Due to their feeding behavior, some species may contribute to pest and disease control and therefore be important in agriculture. For instance, the grapevine root pathogenic fungus *Rhizoctonia solani* J.G.Kühn, which can be regulated by *Scheloribates azumaensis* Enami, Nakamura & Katsumata, 1996 (Enami and Nakamura, 1996).

Oribatid mites as well as other soil microarthropods are significantly affected by agroecosystem management (Giffard et al., 2022). Variations in soil management such as tillage, fertilization, and pesticide application could influence these microarthropods, through two main mechanisms. First, by shaping litter traits and then influencing the litter decomposition process by modifyng the quality and availability of plant litter (Nascimento et al., 2019). Second, by altering the soil's physical and chemical properties (Costantini et al., 2015), directly influencing the microhabitats and living conditions of oribatid mites (Coletta et al., 2025). Understanding how oribatid mite communities respond to management practices is crucial for establishing the relationship between their community structure and ecological functions. This integrated knowledge is useful for guiding agroecological transitions and promoting sustainable agroecosystem management (Behan-Pelletier, 1999; Gulvik, 2007; Lebrun, 1995).

Oribatid mites, in particular, have a great ecological indicator value of soil health, reflecting how agricultural systems influence soil biological functioning (Ashwood et al., 2022; Austruy et al., 2022; Behan-Pelletier, 1999; Lehmitz et al., 2020; Pravia et al., this issue). Their effectiveness as bioindicators is supported by several key characteristics including that they exhibit high diversity and abundance, and are present in soils year-round (Lebrun, 1995; Norton and Behan-Pelletier, 2009). They also fulfill varied trophic roles, with most species possessing low fecundity and long lifespans, making them particularly susceptible to environmental disturbances (Lebrun, 1995; Norton and Behan-Pelletier, 2009).

Despite the recognized importance of oribatid mites for agroecosystem functioning, comprehensive data on the oribatid mite communities in Europe remain scarce. To the best of our knowledge, this is the first study on oribatid mites diversity in French vineyards. Although some studies on microarthropods have been indeed conducted, oribatid mites have not been identified in detail (e.g., Costantini et al., 2018; Costantini et al., 2015; Joimel et al., 2017; Ostandie et al., 2021; Peverieri et al., 2009). A larger number of studies have been conducted in Italian vineyards (Bordoni et al., 2019; Costantini et al., 2018; Favretto et al., 1992; Nannelli and Simoni, 2002; Simoni et al., 2018) but rarely with high taxonomic resolution. Furthermore few other studies on other European vineyards were conducted at family (Fiera et al., 2020) or species levels (Nannelli and Simoni, 2002; Seniczak et al., 2018).

Building on this knowledge, by including a large number of vineyards managed under different systems, our study evaluates how vineyard management influences oribatid mite diversity, abundance, and community structure, while assessing their potential as bioindicators of soil health. Specifically, this study addresses two main research questions: (i) How do different vineyard management practices affect the biodiversity and community composition of oribatid mites? (ii) Can oribatid mite communities serve as reliable bioindicators of soil health in Mediterranean vineyards? In this context, the present study aims to characterise oribatid mites communities in French Mediterranean vineyards to provide technical scientific evidences to support the agroecological transition. The present study also includes a large number of vineyards, with different management practices, allowing to assess the impact of such systems on oribatid mite diversity and community assemblage; evaluating their potential as bioindicators of soil health. We hypothesize that agroecological practices —particularly organic management and permanent inter-row vegetation— increase the abundance and diversity of oribatid mites compared to conventional systems. Furthermore, we expect that taxa serve as indicators of soil quality along a gradient of agroecological practices, as supported by the ideas in Wezel et al. (2014). By analyzing how vineyard management shapes oribatid mite communities and correlating these patterns with soil physicochemical and microbiological properties, we aim to uncover meaningful indicators of ecosystem functioning that can inform sustainable viticulture.

2. Material and methods

2.1. Study sites

This study was conducted in the French wine-growing regions of Aude and Hérault (Occitanie), accross different municipalities (La Caunette, Laure-Minervois, Assas, Cournonterral, Vic-la-Gardiole and Pic-Saint-Loup) located between 43°50′ N and 43°17′ N, and between 3°54′ E and 2°29′ E. The region has a Mediterranean climate (Csa), with an average annual temperature of 15.5 °C and annual rainfall of 570 mm (Conseil Departemental de l'Herault, 2024). Soil texture of the vine plots considered range from loam, clay loam and sandy clay loam (Natural Resources Conservation Service, 2025). The supplementary information Table S1 provides details on the location and soil texture of the sampled plots.

Given the inherent spatial heterogeneity of vineyard soils—driven by variations in soil structure, microclimate, and management practices—reliable bioindication requires a carefully designed sampling strategy capable of capturing this variability. This principle is well established in environmental monitoring, as highlighted by Koley (2021), who demonstrated that spatial variability and geogenic factors can significantly influence environmental assessments, particularly in contaminated ecosystems. In our study, sampling across vineyards with differing management regimes was carried out to ensure that patterns in oribatid mite communities could be attributed to management practices and environmental gradients.

The study includes a natural system (fragments of garrigue vegetation), serving as a reference to minimal human intervention area, and vineyard systems under different agricultural management practices (detailed in Table S1). We examined two types of management separately: (i) pest management strategy (conventional and organic) and (ii) inter-row vegetation cover management. In total, we sampled 30 plots: 24 from vineyards (10 conventional vineyards and 14 organic vineyards), and six from adjacent garrigue vegetation (natural system). The vegetation cover management in the inter-row of vines was classified into: permanent cover (no weed management for at least two years prior to sampling) in one conventional and four organic vineyards, temporary cover (weed managed conducted one to two years prior to sampling) in two conventional and seven organic vineyards, and bare soil (annual weed management) in seven conventional and three organic vineyards. A detailed visual representation of the distribution of sampling sites across the different vineyard management categories and natural system is included in Fig. S1.

2.2. *Soil sampling*

In each of the 30 plots, nine samples of the topsoil layer (0–5 cm) were collected for arthropod extraction at 15-m intervals. Soil samples were randomly taken between vine rows using aluminum cylinders (9 cm diameter × 5 cm high). The collected samples were then placed in individual PVC tubes with a mesh-covered base (2 mm square openings), lined with gauze layers to prevent soil loss. Each sample was labeled, sealed in plastic bags, and immediately stored in coolers with ice packs. Samples were transported to the laboratory at the Centre de Biologie pour la Gestion des Populations, Montferrier-sur-Lez for microarthropods extraction on the same day of sampling. All samples were collected within four days (October 23rd to 26th, 2023).

Soil samples for physicochemical and microbiological analyses were collected on November 28th and 30th, 2023. For each plot, one composite sample was created from ten soil subsamples collected from the 0–20 cm depth layer using a cylindrical soil corer (5 cm diameter × 20 cm high). These samples were sent to the laboratory within two days after their collection. One-quarter of these composite samples was sieved through a 4 mm mesh, freeze-dried and stored at −40 °C in the soil conservatory of the INRAE GenoSol platform (Dijon, France) for DNA sequencing. The other ¾ of the sample were air-dried and stored at room temperature for subsequent physicochemical analysis. Lastly, for soil aggregate stability analysis, five samples of aggregates were collected from the 5–20 cm depth layer in each plot using a spade.

2.3. *Oribatid mite extraction and identification*

We used modified Berlese-Tullgren funnels to extract the microarthropods from soil. The method employs a heat source (LightHouse ECOHEAT®, 80 W) positioned above the soil sample to create a temperature gradient, which in turn establishes a hygrometry gradient that progressively reduces moisture. This process induces the microarthopods to move downward into vials containing 70 % ethanol for preservation. The samples remained in the extractor for 10 days and the temperature increased gradually by 5 °C a day, starting at 20 °C, and reaching a maximum of 50 °C.

Soil microarthropods were sorted under a Leica stereomicroscope (Leica M165C), and oribatid mite specimens (larvae to adult) were counted and identified into morphospecies based on their external morphological characteristics (Behan-Pelletier and Lindo, 2023). Five representative individuals from each morphospecies were then selected for further identification. For this, specimens were put in 50 % lactic acid for 48 h and then, mounted using Hoyer's medium and dried in an incubator (Memmert) at 45 °C for 10 days. Observations were conducted using phase-contrast microscope (Leica DMLB, 10–100 magnification) and digital microscope (Keyence VHX-500 model with VHZ 100 UR lens, 100–1000 magnification).

For final identification at the family level, an identification key was used as the primary reference (Behan-Pelletier and Lindo, 2023). See Table S5 for details on the morphospecies of each family. The choice of family-level identification follows a taxonomic sufficiency approach, supported by evidence that this resolution captures the majority of the ecological signal relevant for bioindication. Specifically, Meehan et al. (2019) demonstrated that for oribatid mites, community metrics such as richness, diversity, and composition are highly correlated between species- and family-level data.

2.4. *Soil parameters*

To evaluate the influence of soil properties on oribatid mite communities, a comprehensive characterization of the vineyard soils was conducted. The methodology for soil analysis is provided in the supplementary information, along with the results of microbiological and physicochemical analyses presented in Tables S2-S4.

Soil physicochemical parameters were assessed at the INRAE Soil Analysis Laboratory (LAS) following standardized protocols (NF ISO 11465, NF X 31–107, NF ISO 10693, NF X 31–106, ISO 13878, NF ISO 10694, NF ISO 11263, NF X 31–147, NF ISO 10694, NF ISO 10390, NF X31–515 and NF ISO 22036). The soil parameters analyzed at LAS (with abbreviations used in the analysis) were: clay (Clay), silt (Silt), sand (Sand), soil moisture (Humidity), pH (pH), calcium carbonate ($CaCO_3$), organic carbon (Corg), total carbon (Ct), total nitrogen (Nt), organic matter (OM), carbon-to-nitrogen ratio (CN), available phosphorus (Pav), aluminum (Al), calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), and total phosphorus (P). Mean weight diameter of aggregates (MWD) was assessed at the facilities of Institut Agro Montpellier, based on the Le Bissonnais (1996) method.

Microbial parameters were assessed based on DNA extraction and quantification using the standardized protocol of the INRAE GenoSol platform (Terrat et al., 2015). Microbial biomass (BMM) was quantified as the total amount of extracted DNA. Bacterial and fungal diversity were characterized by high-throughput sequencing of the 16S rRNA (for prokaryotes) and 18S rRNA (for fungi) genes. The number of bacterial (OTUbac) and fungal (OTUfun) operational taxonomic units was obtained after sequence processing with the BIOCOM-PIPE pipeline (Djemiel et al., 2020).

2.5. *Data analyses*

We conducted all statistical analyses using R software (R Core Team, 2024). The abundance of all life stages (larvae to adults) of oribatid mites at each sampling site was analyzed using generalized linear models (GLMs). To account for overdispersion in the count data—likely due to the gregarious behavior of mites (i.e., some samples containing significantly more individuals than average)—a negative binomial distribution was applied. Family richness and the Shannon-Wiener Diversity Index were calculated for adult mites only. GLMs with a Poisson distribution were used to analyze family richness at each sampling site, while GLMs with a Gaussian distribution were applied to analyze the Shannon-Wiener Diversity Index, following validation of normality and homoscedasticity assumptions. Abundance, family richness, and diversity were analyzed as functions of pest management strategy and inter-row vegetation cover, using separate models for each explanatory variable. All models were validated using the *DHARMa* package (Hartig and Lohse, 2022) to assess residual diagnostics and ensure model assumptions were met. Pairwise comparisons among model categories were conducted using estimated marginal means (EMMs) with the *emmeans* package (Lenth, 2023).

The oribatid mite assemblage matrix—consisting of adult identified to the family level and unidentified immatures—for each sampling site was analyzed using Permutational Multivariate Analysis of Variance (PERMANOVA) with 999 permutations, based on Bray-Curtis dissimilarity. The analysis was performed with the *adonis2* function in the *vegan* package (Oksanen et al., 2001) to determine whether assemblage composition differed across pest management strategies and inter-row vegetation cover. Furthermore, we performed a distance-based redundancy analysis (db-RDA) using Bray-Curtis dissimilarity with the capscale function from the *vegan* package to visually assess the oribatid mite assemblage structure for the vineyard categories. Pest management strategy and inter-row vegetation cover were added (one at a time) as the constraining variables for the db-RDA.

We performed indicator analysis on the mites family dataset using the *multipatt* function from the *indicspecies* package (De Cáceres and Legendre, 2009). This method identifies families that are significant indicators of specific categories by combining two factors: specificity (the proportion of a family's occurrences in a particular group relative to all groups, indicating how strongly the family is associated with that group) and fidelity (the proportion of plots within the group where the family is present, indicating how frequently the familyoccurs within that group). The analysis was used to determine whether certain taxa were positive indicators of different pest management strategies, inter-row vegetation cover, or natural systems.

To visualize the relationship between each oribatid mite family across the different categories of pest management strategy and inter-row vegetation cover management, we created a heatmap based on point biserial coefficients. These coefficients were calculated using the *multipatt* function, with the exclusion of families that occurred exclusively in a single sampling site (out of the 30 sites) to prevent sampling site effects from influencing the results. A key advantage of point biserial coefficients is their ability to take negative values, which indicates that taxa may tend to “avoid” certain environmental conditions. In contrast, positive values suggest a preference for those conditions. Hierarchical clustering with Euclidean distance and complete linkage was applied to both species and the environmental categories, allowing for the identification of patterns of similarity within the data. This clustering visually highlights groups of families and environmental conditions (pest management strategy and inter-row vegetation cover) that are more closely associated.

Lastly, to evaluate the influence of soil physico-chemical and microbiological properties of the vineyards, Mantel tests were performed to assess the relationships between variations in oribatid mite community composition (Bray-Curtis distance) and environmental variables (Euclidean distance), identifying the main factors shaping mite community structure. Soil variable correlations were assessed using Pearson's method. The results were visualized with the *linKET* package. (Huang, 2021). To examine the relationship between soil fungal and bacterial communities (at the phylum level) and oribatid mite assemblages, we conducted a Mantel test using the vegan package with Bray-Curtis dissimilarity matrices. Given the non-normal distribution of the data, we applied Spearman's correlation method and performed 999 permutations to evaluate statistical significance.

3. Results

3.1. *Influence of agricultural management practices on oribatid mite total abundance, family richness and diversity*

Among soil extracted microarthropods, mites were the dominant group, accounting for 79 % of the total abundance. Oribatid mites were the most abundant mite group, representing 49 % of all mites retrieved. A total of 7574 oribatid mites were collected across all sampling sites, including both adults (5916 individuals identified to the family level) and immature individuals. Across the 30 plots, we identified 56 morphospecies, belonging to 21 superfamilies, and 37 families (Table 1).

Table 1
Abundance, relative abundance (%) and total number of occuring sites (N) of oribatid mite families.

Family	Abundance	Relative Abundance	N
Aphelacaridae Grandjean	27	0.46	4
Astegistidae Balogh	278	4.70	11
Ceratozetidae Jacot	33	0.56	10
Cosmochthoniidae Grandjean	39	0.66	9
Cymbaeremaeidae Sellnick	83	1.40	5
Damaeidae Berlese	10	0.17	4
Damaeolidae Grandjean	70	1.18	8
Eniochthoniidae Grandjean	42	0.71	4
Epilohmannidae Berlese	61	1.03	14
Eremaeidae Oudemans	4	0.07	1
Euphthiracaridae Jacot	70	1.18	14
Euzetidae Grandjean	64	1.08	10
Galumnidae Jacot	423	7.15	23
Gustaviidae Oudemans	12	0.20	5
Gymnodamaeidae Grandjean	292	4.94	19
Haplochthoniidae Hammen	42	0.71	2
Haplozetidae Grandjean	587	9.92	5
Hypochthoniidae Berlese	9	0.15	3
Liacaridae Sellnick	5	0.08	2
Licneremaeidae Grandjean	24	0.41	6
Lohmannidae Berlese	7	0.12	2
Neoliodidae Sellnick	58	0.98	5
Nothridae Berlese	108	1.83	14
Oppiidae Sellnick	787	13.30	26
Oribatulidae Thor	95	1.61	11
Oripodidae Jacot	4	0.07	1
Parakalummidae Grandjean	11	0.19	6
Passalozetidae Grandjean	20	0.34	2
Pheroliodidae Paschoal	228	3.85	3
Phthiracaridae Perty	7	0.12	3
Plateremaeidae Perty	74	1.25	8
Punctoribatidae Thor	88	1.49	14
Scheloribatidae Grandjean	753	12.73	27
Sphaerochthoniidae Grandjean	29	0.49	4
Tectocepheidae Grandjean	1441	24.36	29
Trhypochthoniidae Willmann	21	0.35	4
Oribatida sp.	10	0.17	1
Immatures	1658	–	27
TOTAL	**5916**	**100**	**30**

Adult oribatid mite densities ranged from 4944 to 12,229 individuals/ m^2 in natural systems, and from 472 to 16,440 individuals/m^2 in vineyard systems.

A significant effect of pest management strategy (Fig. 1A) was detected on mean abundance ($\chi2(2,27) = 14.749$, $p < 0.001$, $\eta2 = 0.312$), family richness ($\chi2(2, 27) = 36.172$, $p = 1.398e{-}8$, $\eta^2 = 0.613$) and Shannon-Wiener index ($F(2, 27) = 10.261$, $p < 0.001$, $\eta^2 = 0.432$). The natural systems exhibited the highest mean abundance (538.33 ± 82.72), family richness (17.67 ± 1.17), and Shannon-Wiener index (2.02 ± 0.1) (Fig. 1). No significant difference in abundance and richness was observed between organic (211.29 ± 62.83 and 10.07 ± 0.82, respectively) and conventional (137.4 ± 27.08 and 7.2 ± 0.83, respectively) vineyards ($p = 0.341$ and 0.053, respectively), although both vineyard types were significantly different from natural systems ($p = 0.0261$ and $p = 0.001$, respectively). However, organic vineyards showed significantly higher values of diversity (1.66 ± 0.06, $p = 0.0205$), comparable to those of natural system.

A significant effect of inter-row vegetation cover management (Fig. 1B) was also observed when analyzing mean abundance ($\chi2(3, 26) = 26.207$, $p < 0.001$, $\eta^2 = 0.451$), family richness ($\chi2(3, 26) = 38.317$, $p < 0.001$, $\eta^2 = 0.566$) and Shannon-Wiener index ($F(3, 26) = 4.037$, $p = 0.017$, $\eta^2 = 0.318$). Vineyards with permanent cover displayed abundance, richness, and diversity similar to natural systems ($p = 0.745$, $p = 0.097$, and $p = 0.457$, respectively). In contrast, both temporary cover and bare soil had significantly lower values for abundance ($p < 0.001$ for both) and richness ($p < 0.001$ for both) compared to natural systems, though no significant differences were found between the two cover

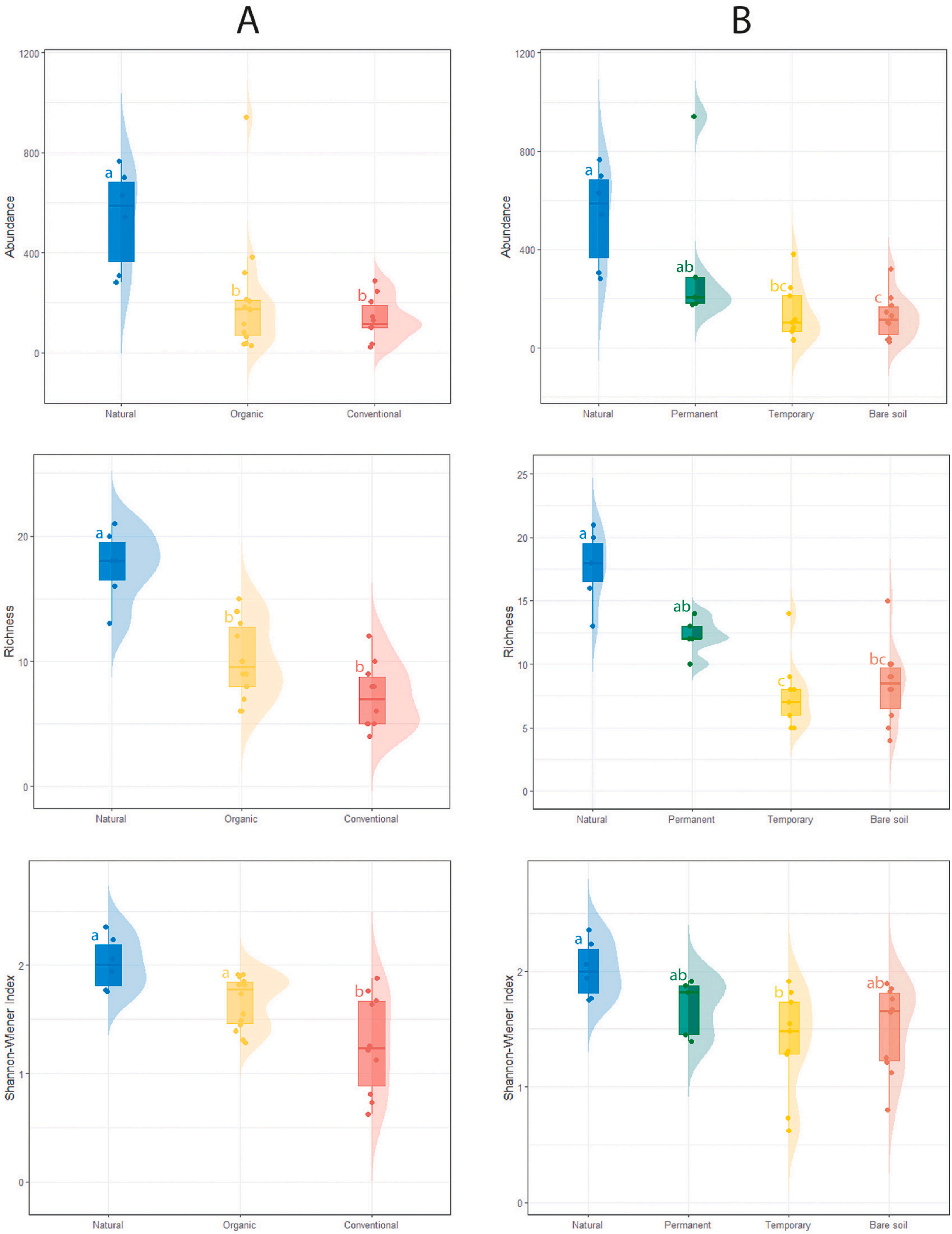

Fig. 1. Total abundance (nymphs to adults), family richness (adults) and Shannon-Wiener Diversity index (adults) of oribatid mites across sampling sites, grouped by pest management strategy and inter-row vegetation cover management. Different letters indicate significantly different groups according to the estimated marginal means of the GLM ($p < 0.05$).

types ($p = 0.986$ and $p = 0.916$). Temporary cover was the only treatment that showed significantly lower diversity compared to the natural system ($p = 0.014$), although no differences in diversity were observed between vineyards, regardless of the vegetation cover management of the inter-rows.

3.2. *Influence of agricultural management practices on oribatid mite community assemblage*

The oribatid mite community assemblage of natural systems differed from that of vineyards when analyzing both pest management strategy and inter-row vegetation cover (Fig. 2). No significant differences were observed among vineyards with different pest management strategies or different inter-row vegetation cover management. However, vineyards with permanent vegetation cover had community composition similar to natural systems ($p = 0.212$), which was not observed in vineyards with temporary cover or bare soil ($p = 0.003$ for both).

3.3. *Indicator family and clusters analysis*

Eight families were found to be strong indicators of the natural systems ($p < 0.01$ and IdVal >0.6): Gymnodamaeidae, Cymbaeremaeidae, Cosmochthoniidae, Ceratozetidae, Sphaerochthoniidae, Neoliodidae, Pheroliodidae, and Gustaviidae (Table 2). Among them, the families Ceratozetidae and Gymnodamaeidae also showed to be bioindicator of vineyards with permanent cover. However, no specific family indicator was identified for vineyard systems (organic or conventional, nor for vineyards with temporary cover or bare soil) at that same significance threshold.

Table 2
Indicator analysis results, for each group of vineyards + natural systems, presenting specificity (A), fidelity (B), indicator value (IndVal) and significance (p) of the oribatid mite families.

Site grouping	Families	A	B	IndVal	p
Pest Management Strategy					
Natural	Gymnodamaeidae	8.436	1.000	0.918	0.0002 ***
	Cymbaeremaeidae	1.000	8.333	0.913	0.0002 ***
	Cosmochthoniidae	9.143	8.333	0.873	0.0004 ***
	Ceratozetidae	8.183	8.333	0.826	0.003 **
	Sphaerochthoniidae	1.200	6.667	0.816	0.0003 ***
	Neoliodidae	9.772	6.667	0.807	0.0004 ***
	Pheroliodidae	1.000	5.000	0.707	0.0037 **
	Gustaviidae	9.211	5.000	0.679	0.0048 **
	Trhypochthoniidae	6.897	5.000	0.587	0.0244 *
	Liacaridae	1.000	3.333	0.577	0.0347 *
Inter-row Vegetation Cover Management					
Natural	Cymbaeremaeidae	1.0000	0.8333	0.913	0.0003 ***
	Cosmochthoniidae	0.8496	0.8333	0.841	0.0009 ***
	Sphaerochthoniidae	1.0000	0.6667	0.816	0.0012 **
	Neoliodidae	0.9386	0.6667	0.791	0.0016 **
	Pheroliodidae	1.0000	0.5000	0.707	0.0075 **
	Gustaviidae	0.8475	0.5000	0.651	0.0258 *
Natural + Permanent	Ceratozetidae	0.9808	0.8182	0.896	0.0006 ***
	Gymnodamaeidae	0.8544	0.9091	0.881	0.0072 **
	Oribatulidae	0.8964	0.6364	0.755	0.0286 *
	Trhypochthoniidae	1.0000	0.3636	0.603	0.0432 *
Natural + Permanent + Bare soil	Oppiidae	0.9174	0.9524	0.935	0.0365 *

The clustering of point-biserial coefficients for families revealed that natural systems were the most distinct from vineyards despite management practices (Fig. 3), exhibiting a higher prevalence of taxa. The dendrogram for vineyard pest management strategies and inter-row vegetation showed a very high cophenetic correlation coefficient ($r = 0.9872$ and 0.9859 respectively), indicating an excellent fit between the dendrogram structure and the original association distances. Certain families were uniquely abundant in natural systems, further separating them into distinct clusters. Organic and conventional vineyards (Fig. 3A) had lower prevalence for certain families. Similarly, two clusters of vineyards were identified for vegetation cover (Fig. 3B). Vineyards with permanent cover were the most distinct, with most taxa exhibiting intermediate prevalence levels, while vineyards with temporary cover and bare soil are grouped within the same cluster level, where most families showed lower abundance. Among all clusters, bare soil was the most distant from the natural system.

At the second level of clustering (x-axis), the dendrogram for oribatid mite families showed a moderate cophenetic correlation for both variables ($r = 0.657$ and 0.6076), suggesting that the family clustering only partially reflects the underlying distance structure, likely due to a more continuous distribution of association strengths across families. For pest management strategy (Fig. 3A), one cluster includes families with low prevalence across all systems. Another includes those abundant in natural systems, further divided into families that are more associated in organic vineyards and those consistently low in both organic and conventional vineyards. In terms of inter-row vegetation cover (Fig. 3B), families form two main clusters. One includes those mostly associated to natural systems. The other cluster includes families generally avoidant across all systems, or moderately associated in natural systems and permanent cover vineyards.

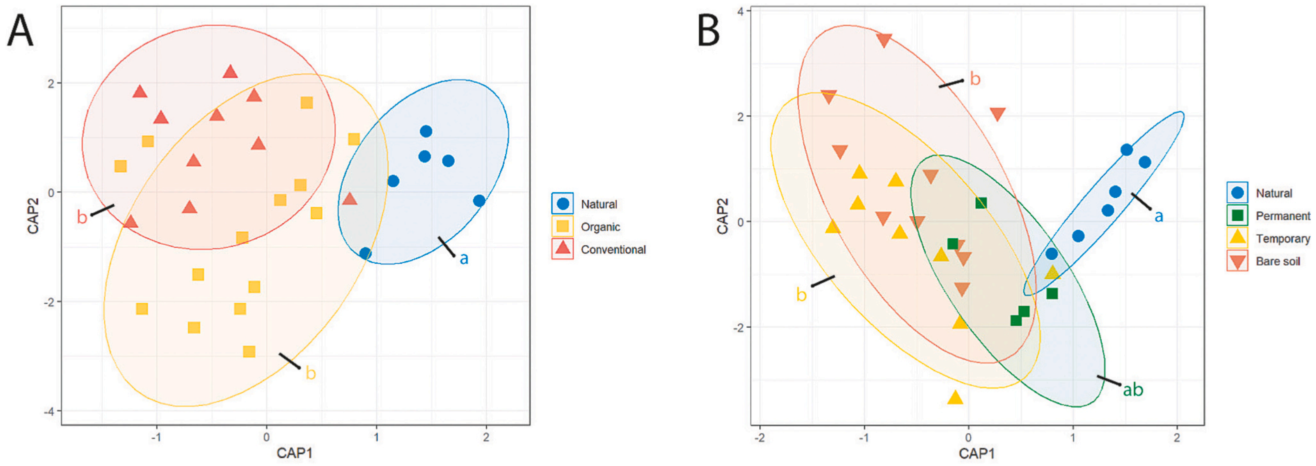

Fig. 2. db-RDA based on Bray-Curtis distance of oribatid mite community composition at the family level, constrained by pest management strategy (A) and inter-row vegetation cover management (B). The points represent the sampling sites. Points that are closer to each other indicate greater similarity. Different letters next to the ellipses denote significantly distinct groups based on the partitioning of sums of squares from the distance matrix in the PERMANOVA ($p < 0.05$).

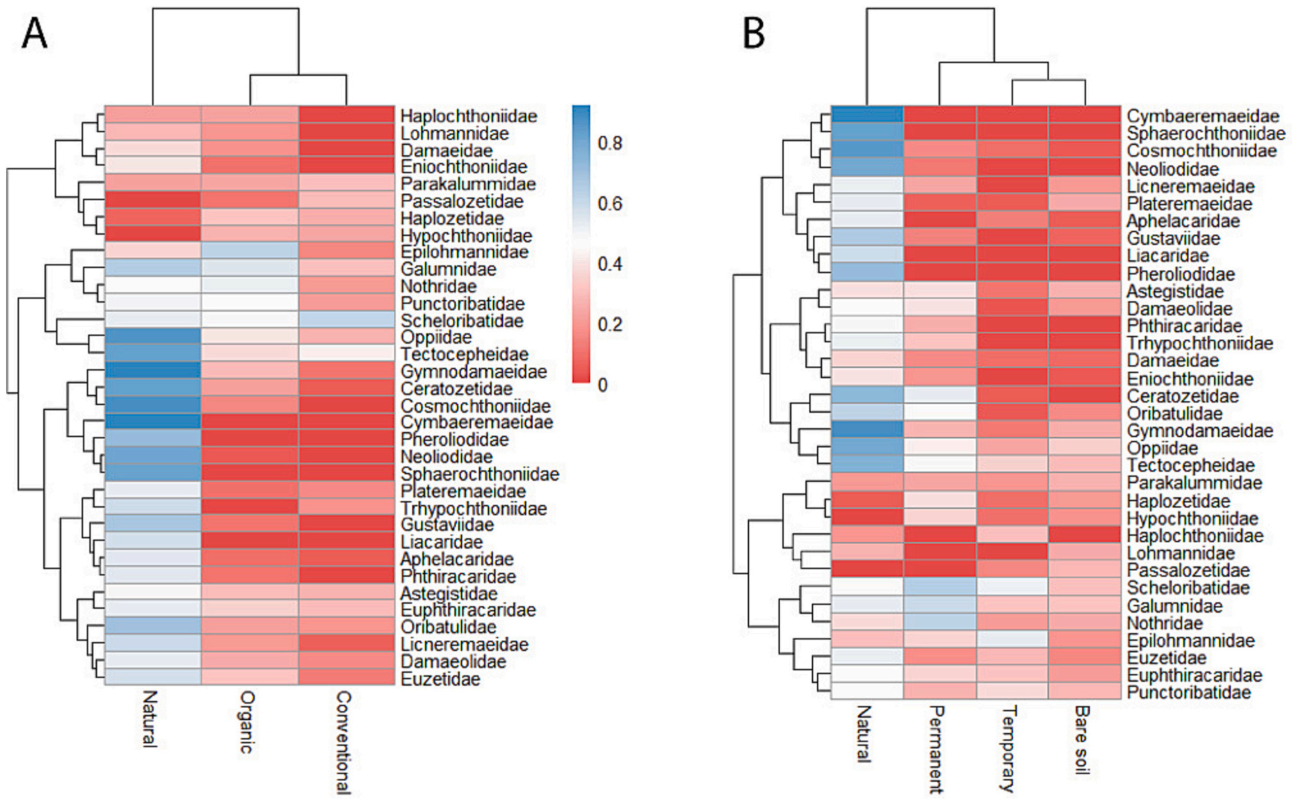

Fig. 3. Heatmap of point biserial coefficients for oribatid mite families across pest management strategies (A) and inter-row vegetation cover management (B), with hierarchical clustering.

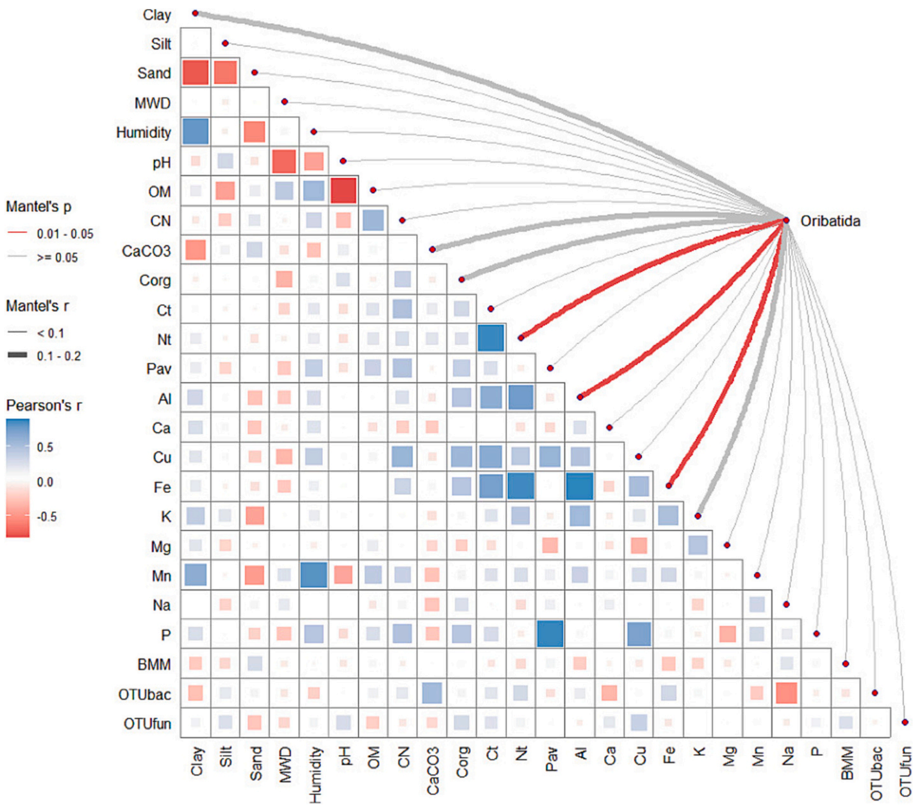

Fig. 4. Mantel's tests between environmental variables and the communities of the oribatid mites. The heatmap displays the pairwise correlations between environmental variables. The lines indicate the results of the Mantel tests, with the line width representing Mantel's r statistic and the color reflecting Pearson's correlation coefficient. Abbreviations for the environmental variables are provided in the in material and methods section.

3.4. Influence of soil physico-chemical and microbiological parameters on oribatid mite communities

Across all soil variables, three of them presented a significant correlation with the oribatid mite community composition: total nitrogen (Nt), aluminum content (Al) and iron content (Fe). Despite being significant (p between 0.01 and 0.05), those correlation are weak, presenting low Mantel's r (0.1 to 0.2) (Fig. 4).

No correlation was observed between the fungal and oribatid mite communities ($p = 0.206$) (Fig. 5). However, a weak but significant correlation ($p = 0.04$; Mantel's $r = 0.19$) was observed between oribatid mite and bacterial communities in soil.

4. Discussion

4.1. Influence of agroecological management practices on oribatid mite abundance, richness and diversity

The densities of oribatid mite observed in this study are comparable to those reported in other studies conducted in Mediterranean climates, particularly in calcareous soils with clay loam texture (Costantini et al., 2015; Gagnarli et al., 2015). In Italian vineyards, mite densities ranging from 9262 to 48,419 individuals/m^2, with an average of 21,524 individuals/m^2, have been reported by Gagnarli et al. (2015). Coletta et al. (2025), also in Italian vineyards, recorded mean densities of 28,280 mites/m^2, with 8662 oribatid mites/m^2. Mazzoncini et al. (2010) recorded densities of 10,334 and 16,659 mites/m^2 in the organic and conventional systems in Mediterranean stockless arable land of Italy, of which approximately 7700 and 9900 individuals/m^2 were oribatid mites, respectively. According to Austruy et al. (2022) in agricultural soils of southwestern France (Midi-Pyrénées), regardless of the soil's physico-chemical characteristics and the type of crops, oribatid mites are one of the most abundant microarthropods.

Abundance, richness, and diversity of oribatid mites were here found to be significantly greater in natural systems compared to vineyards—a pattern already observed globally (Austruy et al., 2022; Behan-Pelletier, 1999; Gergócs and Hufnagel, 2009; Seniczak et al., 2018). The natural system, characterized by continuous vegetation cover, availability of organic litter and less anthropic perturbations, might provide the most favorable environment for oribatid mites, creating varied ecological niches and supporting thus more species (Austruy et al., 2022; Seniczak et al., 2018; Simoni et al., 2018; Todria et al., 2021), which is supported by our study.

Although no significant differences were found in oribatid mite abundance and richness between organic and conventional vineyards, organic vineyards exhibited greater diversity. However, this result could be influenced by the fact that most organic vineyards had vegetation-covered inter-rows, while the majority of conventional vineyards had bare soil. This suggests a gradient of agroecological management practices that may be more favorable to soil oribatid biodiversity.

Significant differences in oribatid mite abundance were observed based on inter-row vegetation cover. In vineyards, preserving cover vegetation between rows promotes high density of adult oribatid mites (Giffard et al., 2022). The present results also show that inter-row with permanent cover support higher oribatid mite abundance than more intensively managed vineyards with temporary cover or bare soil. Permanent cover helps protect the soil from erosion (Pedroza-Parga et al., 2022), regulates soil temperature (Duveiller et al., 2018; Song et al., 2018) and moisture, and creates a favorable microclimate for oribatid mite proliferation (Procházka and Brom, 2011; Traff et al., 2013). This reinforces the idea that maintaining permanent vegetation cover not only stabilizes microclimatic conditions (e.g., moisture, temperature) but also increases the input of organic matter, including root exudates and litter. Such inputs likely sustain oribatid mite populations directly by providing energy-rich substrates, or indirectly through the stimulation of fungal biomass, which serves as a primary food source for many oribatid species. This trophic linkage between vegetation structure, fungal diversity, and oribatid communities, although not statistically evidenced in our analysis of soil paramenters, is well-supported functionally in the literature (Lindo and Visser, 2003, 2004).

These patterns align with broader research on soil fauna responses to land use and management. For instance, Birkhofer et al. (2012) demonstrated that soil fauna, including mites, respond significantly to both land-use type and abiotic soil properties. In particular, their finding that mite abundance was negatively correlated with nitrate concentrations is highly relevant to our results. In our study, vineyards with bare or temporary vegetation cover—typically associated with lower organic matter and potentially higher mineral nitrogen availability—exhibited reduced oribatid mite abundance and richness. While we did not directly measure soil nitrate concentrations, previous studies have shown that permanent vegetation cover plays a crucial role in reducing soil nitrate levels by taking up mineral nitrogen and storing it in plant biomass (Dabney et al., 2001; Tonitto et al., 2006; Burger et al., 2017). In contrast, bare soils lack this biological nitrogen sink, which can lead to nitrate accumulation (Sainju et al., 2002), and negatively affect soil mite populations. These findings highlight how both biotic (vegetation cover)

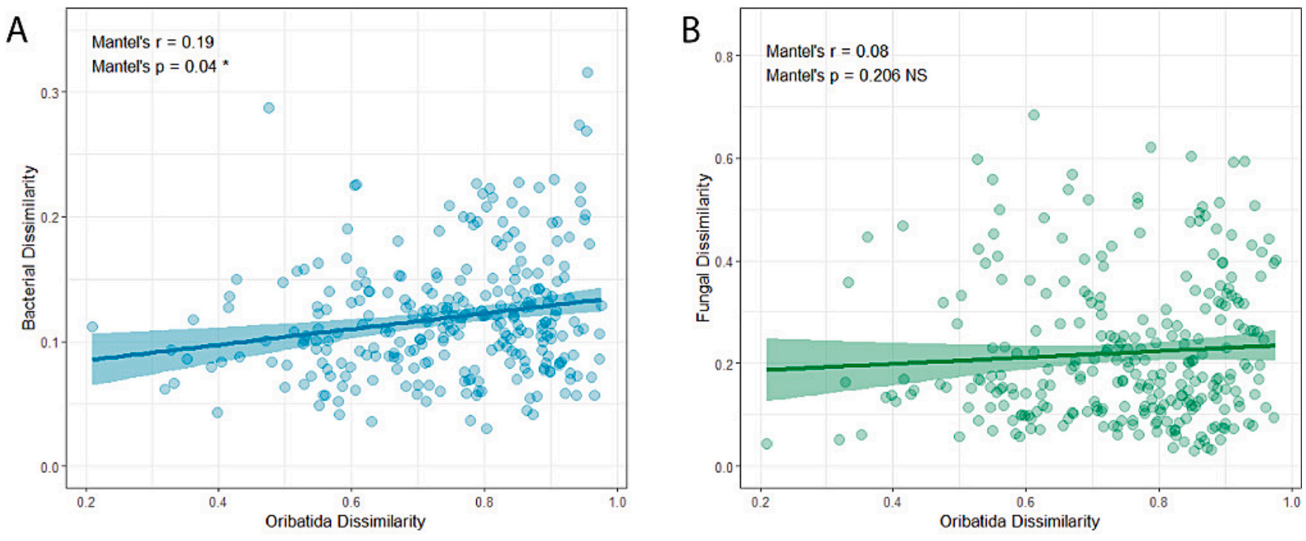

Fig. 5. Mantel's tests between bacterial (A) and fungal (B) communities and oribatid mite communities.

and abiotic (soil nutrient dynamics) factors interact to shape soil microarthropod communities in vineyard ecosystems.

Although certain management practices are often considered ecological, they do not always benefit oribatid communities. In a French vineyard study lasting three years, the application of composted manure, incorporation of green manure, sowing, and dry mulching significantly reduced the mean abundance of oribatid mites and other microarthropods (collembolans and gamasids)(Simoni et al., 2018). However, our results align with general trends observed across vineyard ecosystems, where vegetation management intensity plays a pivotal role in shaping soil biodiversity and ecosystem services. A comprehensive meta-analysis by Winter et al. (2018) demonstrated that reducing vegetation management intensity—particularly through permanent cover vegetation—significantly enhances both biodiversity and key soil-related ecosystem services without compromising crop yield under most conditions. Therefore, promoting permanent vegetation cover stands as a key practical recommendation for vineyard managers and policy makers aiming to sustain soil biodiversity and improve agroecosystem functioning.

4.2. Influence of agricultural management practices on oribatid mite community assemblage, indicator family and clusters analysis

The oribatid mite assemblages in the garrigue differed considerably from those found in vineyards. Agroecosystems, such as vineyards, are typically subject to frequent disturbances, which often result in simplified ecological conditions (Behan-Pelletier, 1999). As a result, we assumed that oribatid mite communities in vineyards would resemble those found in early successional habitats. In contrast, organic and conventional vineyards showed higher similarity to each other, suggesting that organic practices alone were not sufficient to cause significant changes in the oribatid mite community. This may be partly explained by the heterogeneity of soil management practices in organic systems (e.g., intensive tillage or mechanical weeding as an alternative to herbicides (Mazzoncini et al., 2010)) as well as by the possibility that organic and conventional pesticides do not exert substantially different selection pressures to oribatids on soil.

Although organic vineyards reduce chemical inputs (Merot et al., 2020), they often rely on mechanical tillage for weed control, which can introduce significant physical disturbance to soil habitats. Such disturbance could potentially counterbalance some of the expected biodiversity gains associated with the absence of synthetic pesticides. These findings are corroborated by a previous study conducted on abandoned arable land in Patardzeuli village, Eastern Georgia, where pesticide application did not significantly affect the oribatid mite communities, whereas ploughing negatively impacted them (Murvanidze et al., 2019). Similarly, on fields cultivated with winter wheat on France, Cortet et al. (2002) reported that pesticide effects were minor compared to those of tillage practices. While our study was not designed to disentangle the specific effects of tillage versus pesticide application, this hypothesis may partly explain the relatively similar oribatid mite abundances observed between the two management systems.

Regarding inter-row vegetation cover management, we expected that vineyards with permanent cover, would exhibit a higher level of ecological succession than bare soil. The similarity between the natural system and permanently covered inter-rows suggests that these managed systems can provide comparable ecological conditions, supporting this similarity. Agricultural practices that leave the soil exposed can therefore have severe negative impacts on soil biodiversity, reducing the ecosystem's ability to sustain diverse microarthropod communities, as demonstrated by a recent study in Mediterranean Italy on arable lands, olive groves, and vineyards (Coletta et al., 2025). In contrast, vegetation cover promotes the formation of diverse ecological niches, providing shelter and food for oribatid mites (Lindo and Visser, 2004; Nascimento et al., 2019). Bare soil is often associated with higher erosion, temperature and moisture fluctuations, and reduced organic matter, all of which limit habitat availability for oribatids (Behan-Pelletier, 1999).

This pattern is consistent with findings from the Countryside Survey in Great Britain, which reported that oribatid mite species richness and community composition varied significantly across broad habitat types (Pravia et al. this issue). In that study, wooded habitats and areas with higher organic matter content, such as moorlands and bogs, supported greater species richness, whereas intensively managed agricultural lands had significantly lower richness. Additionally, oribatid mite richness was found to increase with soil carbon content and decrease with increasing soil pH, reinforcing the sensitivity of these communities to habitat quality and soil properties. These insights support the idea that both vegetation structure and soil characteristics are key drivers shaping oribatid assemblages in terrestrial ecosystems.

Several studies highlight the importance of oribatid mites as bioindicators of soil quality, as they are sensitive to factors such as agricultural management, the presence of contaminants, and the availability of organic matter (Austruy et al., 2022; Giffard et al., 2022; Simoni et al., 2018; Zhang et al., 2023). Nevertheless, such studies rarely explore indicator values beyond the family level. In contrast, Meehan et al. (2019) demonstrated that oribatid mites can effectively indicate soil disturbance even when identified at coarser taxonomic ranks. In our study, most identifications were conducted at the family level, which has been recognized as sufficient for detecting patterns related to disturbance (Meehan et al., 2019). This supports a more practical and time-efficient approach to bioindication, without compromising ecological relevance.

In this study, and elsewhere (Barreto et al., 2021), *Tectocepheus velatus* (Michael, 1880) was the most abundant species and the sole representative of the Tectocepheidae family. This species is widely recognized as one of the most frequent and common oribatid mites, often found in intensively used habitats. It is a pioneer species in both natural and anthropogenic environments, serving as a bioindicator of disturbed soils (Skubała and Gulvik, 2005). However, despite their abundance, the Tectocepheidae family was not a reliable indicator of specific agricultural systems or management practices, as it was found across all sites.

When analyzing pest management, we did not identify indicators of vineyards (conventional/organic), while eight families were considered indicators of natural systems. This suggests that oribatid mite communities in vineyards are not highly distinct at the family level. A similar trend was observed in Spanish vineyards, where oribatid mite communities showed comparable composition in organic and conventional systems, likely due to their tolerance to herbicides used in conventional vineyards and sensitivity to the more intensive mechanical soil cultivation practiced in organic ones (Seniczak et al., 2018). However, while the principle of taxonomic sufficiency demonstrated by Meehan et al. (2019) indicates that family-level data capture the majority of ecological patterns in oribatid communities, it does not entirely rule out the possibility that some species-level indicators may be omitted due to the coarser taxonomic resolution. Species-level identification might therefore reveal more subtle community differences or specialized responses to vineyard management practices that are not detectable at the family level.

As for inter-row vegetation, the families Ceratozetidae and Gymnodamaeidae were presently identified as bioindicators of more ecological practices associated with low levels of disturbance, such as the garrigue ecosystem and vineyards with permanent cover. It is possible that the role of these two families as indicators of natural systems and vineyards with permanent cover contributes to the closer similarity between the two communities observed in the community composition analyses and clusters analysis. Manu et al. (2019) revealed that the occurrence of some Oribatida species was strongly correlated with vegetation coverage, which is also supported by our findings. These two families have been previously reported in Spanish vineyards under both conventional and organic management (Seniczak et al., 2018).

It is difficult to compare the presence of these families with other study sites, as, after a disturbance occurs, colonization by pioneer species and succession processes depend on the region and microhabitats (Skubała and Gulvik, 2005). For example, species of Gymnodamaeidae have been associated with medium levels of pollution (Manu et al., 2019), while species of Ceratozetidae were reported as pioneer species in post-industrial dumps, but not in glacier forelands (Skubała and Gulvik, 2005). Also Ceratozetidae were bioindicators of boreal forest sites disturbed by harvest and linear features like roads (Meehan et al., 2019).

Clustering analyses reveal a clear disparity in the prevalance of oribatid mite families between natural systems and vineyards. Differences in family composition and clustering patterns may be related to the trophic roles of oribatid mites and the availability of specific resources in each habitat, as this group displays a remarkable diversity of functional guilds—including phytophagous species, lichen-feeders, primary and secondary decomposers, predators, and scavengers (Magilton et al., 2019). Previous studies indicate that resource competition and trophic structure jointly regulate the assembly of oribatid mite communities (Magilton et al., 2019). In this context, species can either cooccur, leading to aggregation within microhabitats, or avoid each other, resulting in spatial segregation. This resource-based mechanism of community structuring may help explain the similarity observed between mite communities in vineyards with permanent cover and those in natural systems, as well as between vineyards with temporary cover and bare soil, where resource availability and trophic structures are likely more similar. Zhang et al. (2023) reported a positive correlation between predator and prey diversity, further supporting the importance of resource-driven dynamics in shaping these communities.

Nonetheless, it is important to note that the indicative value of these families likely reflects the specific combination of habitats studied, and some of these taxa may be broadly present in other types of natural or semi-natural habitats beyond this Mediterranean context. More detailed taxonomic identification and further studies on trophic interactions are essential to improve our understanding of how agricultural management practices influence oribatid mite communities by unraveling hidden patterns of niche differentiation and functional roles within their assemblages (eg. species within the same genus—previously sharing similar niches—may have undergone niche differentiation to reduce competition) (Magilton et al., 2019).

4.3. Influence of soil physico-chemical and microbiological parameters on oribatid mite communities

Aluminum (Al), iron (Fe), and total nitrogen (Nt) were the only soil variables correlated with differences in oribatid mite communities in the vineyards. However, no clear evidence suggests how the aluminum content could be linked to the oribatid mite community composition, although we hypothesize that, similarly to iron content, it could be linked to a pollution gradient and the oribatid mite's sensitivity to the accumulation of this metal. Elevated iron concentrations in soil are often linked to pollution and this metal can accumulate in microarthropods, including oribatid mites (van Straalen et al., 2001). A previous study showed that different oribatid mite species vary in their ability to accumulate iron, with some families being more sensitive to metal contamination than others (Zaitsev and van Straalen, 2001). These authors found this sensitivity to contribute to shifts in community composition along a gradient of polluted soils. Since vineyards, especially those near large urban areas, are prone to some degree of soil pollution, we hypothesize that iron contamination may explain the observed correlation between metal concentration and differences in oribatid mite communities. However, as our study was not specifically designed to assess pollution effects, it remains unclear whether this pattern is driven by environmental contamination, natural soil geochemistry, or other unmeasured factors affecting oribatid assemblages.

A previous study on cropping systems in southern France also found a significant positive correlation between soil total nitrogen content and the abundance of microarthropods, including oribatid mites (Austruy et al., 2022). The presence of soil fauna, dominated by mites, increase the mobility and availability of inorganic nitrogen (Gergócs et al., 2022). In a microcosme experiment, the presence of *Scheloribates moestus* Banks (Scheloribatidae) led to a significant increase in available nitrate, ammonium and both dissolved organic C and N (Wickings and Grandy, 2011). Also, soil-dwelling microarthropods can significantly affect nitrogen metabolism of soil bacteria and fungi (Gergócs et al., 2022; Osler and Sommerkorn, 2007). The variability of oribatid mite communities in the vineyards soil could thus be linked to the microbial communities, which can also affect soil nitrogen flux. While numerous studies highlight pH as a key factor influencing soil microarthropods, including oribatid mites (Guo and Siepel, 2020; Kim and Jung, 2008; Manu et al., 2019), its lack of impact in this study may be due to the narrow pH range of the sampled sites (8.20–8.55). Moreover organic matter and water content are commonly associated with variations in soil microarthropod communities (Caruso et al., 2019; Jakšová et al., 2020). Among these communities, oribatid mites, as mostly detritivores, contribute to the decomposition of organic matter, thereby influencing nitrogen mineralization and the cycling of other essential soil nutrients (Wickings and Grandy, 2011). However no significant correlation was found between organic matter or water content and oribatid mites in this study, possibly due to species-specific responses. Different species within the same genus or family can display distinct preferences on soil properties (Feketeová et al., 2021; Guo and Siepel, 2020; Ľuptáčik et al., 2012).

Oribatid mites are often considered generalist fungivores, but the literature suggests that their relationship with fungi may be more complex. While our study found no direct influence of fungal communities on oribatid mites in vineyards, Koukol et al. (2009) and Schneider and Maraun (2005) highlight that oribatid dietary preferences are not uniform. Rather than a gradual preference for fungi, oribatid mites might form a heterogeneous mosaic, with different species favoring different fungal taxa, as suggested by the authors. Indeed, this variability may explain the lack of a clear effect of fungal communities on oribatid mites in vineyards, as species-specific interactions between mites and fungi could be highly diverse, with some studies suggesting that oribatid mites show only minor differences in their preference for fungi (Maraun et al., 1998; Schneider and Maraun, 2005). Furthermore, the immense diversity of soil fungi may obscure subtle patterns of trophic specialization, especially since our study examined relationships at family taxonomic levels rather than species-specific interactions.

Finally, bacterial communities had a more significantly effect on oribatid mites. One possible explanation for this result might be the indirect relationship between bacteria, nematodes, and oribatid mites through trophic interactions within the soil food web. Soil-dwelling nematodes may represent a dietary resource for oribatid mites (Epsky et al., 1988; Heidemann et al., 2014; Heidemann et al., 2011). Most of nematodes on soil are bacterial-feeding (van den Hoogen et al., 2019) and can influence the composition and diversity of bacterial communities in the soil, as demonstrated by several studies (Blanc et al., 2006; Jiang et al., 2017; Xiao et al., 2014). Based on this, we suggest that the predation of bacterial-feeding nematodes by oribatid mites might explain the correlation between oribatid and bacterial communities.

5. Conclusion

Our study highlights the significant impact of agroecological management practices on oribatid mite communities. Overall, these practices foster more favorable conditions for oribatid mites, preserving communities that are more similar to those found in natural systems. Moreover, this sensitivity highlights their important role as bioindicators of soil health and ecosystem disturbance. Natural ecosystems provide the most favorable conditions for oribatid mites, supporting higher abundance, richness, and diversity. In contrast, vineyard systems, particularly those under conventional pest management practices and bare inter-rows with frequent disturbances, display lower abundance, richness, and diversity. Among the management practices studied, inter-row vegetation cover is a key factor, influencing oribatid communities, with permantly covered vineyards providing a more favorable environment for oribatid diversity and abundance.

Furthermore, our study identified key oribatid mite families as strong indicators of systems such as the garrigue vegetation and vineyards with permanent inter-row vegetation cover, reinforcing the role of oribatid mites as bioindicators of soil health and that sustainable management practices can help maintain soil biodiversity. These findings underscore the importance of adopting agroecological management practices to sustain soil biodiversity and ecosystem functionality. By reducing synthetic inputs, maintaining permanent ground cover, and enhancing habitats, it is possible to create a more resilient and ecologically balanced agricultural system.

Despite variations in sample size across vineyard categories—driven by the challenge of finding homogeneous conditions— this study underscores the real-world complexity of agricultural systems and the diversity of viticultural practices. By addressing these limitations through more comprehensive approaches—pest management strategy and inter-row vegetation cover management —, we can refine our understanding of vineyard ecosystems and ultimately support more sustainable agricultural management practices.

By integrating oribatid mite bioindicators into soil health assessment frameworks, we can further refine sustainable management strategies that promote biodiversity conservation. This way, agriculture and ecosystem health should be harmonized (Smith et al., 2024), supporting a successful agroecological transition that ultimately ensures the long-term resilience and sustainability of viticultural landscapes. Our findings reinforce the idea that maintaining permanent inter-row vegetation and adopting herbicide-free management are key recommendations for vineyard practitioners and policymakers aiming to preserve soil biodiversity and enhance ecosystem functioning. To build on these findings, future research should focus on long-term monitoring of oribatid mite populations to assess seasonal and interannual variations in response to agricultural management. Studies with identification at the species level are needed to decipher specific ecological interactions that are often impossible to assess—or masked—when analyses are limited to the family level. Additionally, expanding the study to other agroecosystems and incorporating functional trait analyses and trophic interactions will provide deeper insights into the ecological roles of different oribatid mite taxa.

CRediT authorship contribution statement

Thais Juliane do Prado: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lucas L. Godoy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Carlos Barreto:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Halima Rajoul:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Marie-Stéphane Tixier:** Writing – review & editing, Visualization, Validation, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Anne Merot:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Denise Navia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition.

Funding

Project MonSoil ‘Exploring the potential of soil mites for monitoring and promoting the agroecological transition- a case study in viticulture’, convention No. 2204–031, was funded through Labex AGRO 2011-LABX-002 ANR-10-LABX-0001-01 integrated to the programme I-site de l'Université de Montpellier coordinated by Agropolis Foundation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Dr. **Leo Garcia,** Dr. **Elena Kazakou** and Dr. **Adrien Rusch**: for assisting funding acquisition and valuable technical scientific suggestions. Dr. **Brice Giffard**: for assisting in the construction of the extractor and valuable technical scientific suggestions. Dr. **Eric Frago**: for sampling methodology suggestions. **Ávyla R. A. Barros** and Dr. **Philippe Auger**: for assisting in the construction of the extractor and in soil sampling. **Jean-Marc Thuillier** and **Vincent Danneville**: for assisting in the building of the extractor. **Noémi Séon**: for assisting in soil sampling and soil aggregate analysis. **Lucas Ducros**: for assisting in the mite slide-mouting. Dr. **Eduardo Shimbori**: for the morphospecies photos on the Keyence microscope. Dr. **Alice Charalabidis**: for assisting in soil sampling and statistical analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2025.106358.

Data availability

Data will be made available on request.

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