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Below-ground biodiversity in agricultural systems: The role of crop-specific management in shaping soil arthropod communities

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ABSTRACT

Soil arthropod communities play a crucial role in ecosystem functioning, yet their response to agricultural land use and management practices remains poorly understood. This study aims to assess (i) soil biological quality, (ii) arthropod biodiversity, and (iii) community structure across different agricultural systems, evaluating the effects of soil management strategies (organic, integrated, conservative). A total of 414 sampling areas were investigated (during spring and, where the same crop was maintained, autumn, in the years 2019 and 2022) across arable land, vineyards, orchards, and grasslands, with soil properties characterization (texture, humidity, bulk density) and soil arthropods extracted and identified to the order or class level. The QBS-ar and QBS-c indices, Shannon diversity (H'), and Pielou's Evenness (J) were used to evaluate soil biological quality and community structure. Results indicate that agricultural management significantly influences soil biological quality and arthropod abundance. Organic management improved biodiversity and QBS-ar in alfalfa and cereals but not in leguminous crops. Vineyards exhibited higher arthropod densities than arable land, where soil biological quality was most impacted. Seasonal variation influenced community structure, but not diversity indices. Specific arthropod taxa correlated with distinct land uses, with Pseudoscorpionidae, Isopoda, and Protura associated with vineyards, while Myriapoda, Diplura, and Hymenoptera thrived in organically managed alfalfa. These findings highlight the role of agricultural management in shaping soil arthropod communities and emphasize the need for crop-specific management approaches to enhance soil biodiversity and ecosystem services.

1. Introduction

Approximately 23 % of all known organisms inhabit the soil, with arthropods constituting 85 % of these taxa, thus making them a principal component of soil biota (Decaëns et al., 2006; Elmquist et al., 2023). Soil arthropods play a vital role in maintaining soil health and supporting ecosystem processes within agroecosystems, contributing to enhanced plant productivity through litter decomposition, nutrient cycling, and the regulation of pests and pathogens (Culliney, 2013; Neher and Barbercheck, 2019). Furthermore, they serve as valuable indicators of soil quality. Among soil arthropods, edaphic mesofauna i.e. organisms ranging from 0.1 to 2 mm in size, show highly diverse feeding habits, ranging from detritivores to predators and inhabit the litter and upper soil layers (Heydari et al., 2020). The abundance and diversity of soil arthropods provide essential insights into the biological responses of soil to environmental changes, given their high sensitivity to land management practices and the positive correlation of specific taxa with soil health (Pankhurst et al., 1995; Parisi et al., 2005; Schuster et al., 2019). Within this group, certain taxa, such as Acari and Collembola, are commonly employed to monitor soil variation and quality, however, the use of many other groups belonging to edaphic mesofauna remains limited (Menta and Remelli, 2020). Over the last two decades, mesofauna have gained increasing relevance in environmental monitoring programs and in the assessment of soil quality across forested, urban, and agricultural landscapes (Arboláez et al., 2023). These organisms (largely composed of microarthropods) play essential ecological roles, and their growing use in biological soil quality assessments, even when identified at a coarse taxonomic resolution, stems from their high sensitivity to environmental disturbances (Rüdisser et al., 2015), their functional relevance to key soil processes (Culman et al., 2010), and the cost-effectiveness of their analysis compared to more expensive microbial techniques such as DNA/RNA sequencing or phospholipid fatty acid

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profiling.

Soil quality indicators can be developed based on the ecological traits of soil fauna (Morante-Filho et al., 2016). The interactions between soil invertebrates and their ecological niches reflect specific environmental conditions due to their sedentary life habits and the distinct community compositions observed across various habitats and locations (Elie et al., 2018; Feng et al., 2019; Madzaric et al., 2018; Menta et al., 2019). Consequently, scientists have sought to evaluate soil conditions and quality using bioindicator-based methods to monitor processes such as land degradation, recovery, and the impacts of management practices on ecosystems (de Lima et al., 2017; Pelosi and Römbke, 2018). Some methods rely on associations within soil microarthropod communities, while others focus on the ecomorphological traits of the soil fauna community, which are closely related to soil quality, such as the QBS-ar index or QBS-c (Soil Biological Quality based on Collembola) (Menta and Remelli, 2020; Parisi and Menta, 2008; Yin and Koide, 2019).

Understanding soil microarthropod communities is essential for developing effective management strategies for both wild and cultivated ecosystems. The activity and diversity of soil organisms are shaped by a hierarchy of abiotic and biotic factors. Key abiotic factors include climate (temperature and moisture), soil texture and structure, salinity, and pH (van der Putten et al., 2010). In cultivated ecosystems, agricultural practices play a major role in influencing both biotic and abiotic soil characteristics, thereby altering microarthropod communities and ultimately affecting soil productivity (Tsiafouli et al., 2015). These changes are primarily driven by landscape homogenization—resulting in the loss of semi-natural habitats—the toxicity of pesticides, and the mechanization of agricultural practices (Aksoy et al., 2017). Collectively, these factors reduce the diversity and abundance of the plant species on which arthropods depend Blaise et al., 2022). Currently, there is no universally applicable formula for measuring soil health and quality (Bastida et al., 2008), nor does an entirely effective soil bioindicators toolbox exists (Havlicek, 2012). Furthermore, the unique characteristics of each land use complicate the generalization of information obtained from soil microarthropods; conditions considered optimal in arable land may not apply to vineyards or grasslands. Additionally, a paucity of literature exists comparing different agricultural land uses in terms of soil community assemblage and, even if some attempts have been made to identify bioindicators (Menta et al., 2017). Research conducted report sometimes contrasting findings regarding soil quality, particularly in terms of soil microarthropod communities. On one hand, studies have reported QBS-ar values ranging from 137 to 230 in vineyards, which suggests that vineyard soils may exhibit higher quality compared to arable soils (e.g., (Rüdisser et al., 2015). This assessment indicates that vineyards may support a more favourable environment for certain soil microarthropods, which can contribute to soil health and ecosystem functioning. Conversely, a comprehensive study in France, which analysed over 750 samples from various land-use conditions—including forests, grasslands, arable lands, vineyards, urban vegetable gardens, and urban soils—concluded that vineyard soils were the most negatively impacted by human activities (Joimel et al., 2017). Despite higher total microarthropod densities observed in vineyards compared to other agroecosystems, these soils demonstrated significantly lower Collembola species richness and evenness, as well as the lowest Collembola ecomorphological index, accompanied by the highest Acari/Collembola ratio (Joimel et al., 2017). These findings highlight a dichotomy in the perceived quality of vineyard soils: while certain indicators suggest a potential for higher quality, other measures reveal significant disturbance levels and reduced diversity. This contrast highlights the complexity of evaluating soil health and emphasizes the need to use multiple, complementary metrics to fully capture the ecological dynamics of vineyard ecosystems.

Beyond the impacts of agricultural land use, broader concerns regarding the sustainability, environmental impacts, and health effects of intensive farming have led to an increased demand for the development of less impacting management systems such as integrated, conservative, or organic farming. Integrated farming aims to minimize the use of pesticides and fertilizers through improved targeting and cultural control of weeds, pests, and diseases (Mäder et al., 2002). Conservation practices which include minimal soil disturbance, permanent soil cover, and diversified crop rotation—alongside organic agriculture, which prohibits chemical inputs, are alternative management strategies aimed at reducing environmental impacts. These approaches theoretically enhance biodiversity and ecological functioning, thereby improving ecosystem services delivery (Boeraeve et al., 2022). Most studies have compared these alternative systems with conventional farming practices, demonstrating that organic agriculture positively influences flora and fauna at both individual plot and farm levels (Hole et al., 2005; Mäder et al., 2002). The most pronounced effects of organic practices are typically observed in annual arable crops, followed by special crops such as viticulture and fruit production, while the weakest effects are noted in grasslands (Pfiffner and Stöckli, 2023). Research by Menta et al. (2020) indicates that conservation systems and broader reductions in anthropogenic practices provide improved conditions for soil fauna. Another research by Carpio et al. (2019) highlighted that soil cover crops significantly enhance arthropod diversity in intensive agroecosystems. However, there is a scarcity of studies directly comparing these alternative sustainable management practices with one another (Castaldi et al., 2024). In vineyards, a multi-indicator approach has shown that organic management is generally more beneficial for most environmental aspects of agroecosystems compared to integrated management, without negatively impacting grape yield. When evaluating sustainability across organic, integrated, and conventional farming systems, organic practices outperform both integrated and conventional methods in terms of nitrogen losses, pesticide risk, herbaceous plant biodiversity, and other environmental indicators. Notably, the authors highlight that the environmental impacts related to pesticide use and nitrogen indicators in this study were found to be similar for integrated and conventional farming practices. In this context it is also important to highlight that multi-taxa approach in vineyards has proved to be a profitable way to predict the impact of land management (Maienza et al., 2023).

The European Commission recognizes integrated crop management as particularly important for balancing modern farming practices with the need to achieve positive environmental outcomes (Schaetzl, 1986). Even though soil arthropods are significant components of soil biodiversity and play essential roles in regulating processes within the soil ecosystem, the assessment of cropping system diversification aimed at enhancing soil health in agricultural contexts rarely encompass soil arthropod biodiversity and community structure. Consequently, soil arthropods are often overlooked in management decision-making processes.

When examining the influence of soil characteristics on soil microarthropod communities, variations across different types of agricultural land use are expected; however, the nature and specificity of these differences have yet to be fully understood. When considering the general composition and structure of soil arthropod communities within a given agricultural land use, it becomes crucial to assess how soil management practices alter these communities. The question arises as to the degree to which specific soil management strategies impact these communities in the context of varied cropping systems.

In response to these issues, the present study aims to characterize (i) soil biological quality, (ii) microarthropod biodiversity, and (iii) community structure across different agricultural land-use systems, and to evaluate the influence of soil management practices on soil mesofauna. This investigation seeks to clarify the extent to which observed differences are driven by inherent features of land use and crop-specific practices, versus those resulting from the applied soil management techniques. Ultimately, this study aims to provide valuable insights into the role of arthropods as indicators and agents of sustainable soil management.

2. Materials and methods

2.1. Study area

The sites were chosen according to the following criteria:

- accession of farms to Measures M10 (integrated pest management) and M11 (organic farming) of the 2014–2020 RDP;
- representativeness of the main agricultural soils of the plain and hills in Emilia-Romagna Region;
- representativeness of the main land uses such as orchards and vineyards, arable crops, grassland and permanent meadows in Emilia-Romagna Region.

On the basis of these principles, 49 sites where identified (30 in the plain and 19 in the hills) (Fig. 1a-b).

The soils of the monitoring sites fall into the soil functional groups (SFG) most widespread in the region (Table 1).

Soil samples were collected across various agricultural management systems (conservative, organic, and integrated) and land uses (arable land, permanent meadows, orchard, and vineyard) to evaluate the effects of agricultural practices on soil health.

Samples were collected during spring and, where the same crop was maintained, autumn, in the years 2019 and 2022. A total of 414 sampling points were initially collected. Of these, 393 were included in the analyses (Table S1), as some belonged to crops with too few replicates to allow for meaningful comparisons. For arable land, both organic and conservative management were considered, and specific crop types were distinguished: Alfalfa, Annual grassland (under conservative management), Cereals, Corn (under organic management), Leguminous crops. The broader category of legumes includes a wide variety of species with differing ecological roles, growth habits, and nutrient requirements. Analysing them as a single group may obscure important differences. Alfalfa (*Medicago sativa*) is managed as a forage crop with mowing cycles and rotational grazing, requiring different machinery and techniques. Moreover, it has distinct growth patterns (perennial), nitrogen fixation capabilities, root structure, and forage quality compared to other leguminous plants like field chickpeas, peas, or soybeans; for all these reasons it was considered separately from the other leguminous. Orchards were all under integrated management, while for vineyards both integrated and organic management were considered. Thus, for grasslands, orchards, and vineyards, sampling was stratified by agricultural management, season, and year; and for arable land also by crop type. In orchards and vineyards, sampling was conducted only in the inter-row areas and not beneath the tree canopy, as in many vineyards and peach orchards the soil under the canopy had been ploughed and was therefore altered compared to the inter-row, which was vegetated and thus more representative of the soil community in those study areas.

Table 1
Soil functional groups in the 49 monitoring sites.

SFG	General Texture	USDA textural classes	Drainage	N. sites
A	Fine	silty clay, clay	good, moderate, poor	11
B	Moderately fine	silty clay loam, clay loam where clay content> 35 %	good, moderate, poor	5
C	Medium-fine	silty clay loam, clay loam, sandy clay loam where clay content< 35 %	good, moderate, poor	14
D	Medium	silt loam, silt	good, moderate, poor	10
E	Moderately Coarse	sandy loam, loam	good, moderate	9

2.2. Soil physico-chemical analysis

Within each monitoring site, three sampling areas were identified, corresponding to three cells of a regular grid with a 20-meter spacing (Fig. 2).

For each monitoring site, 3 soil samples (replicates) were collected. The following set of physico-chemical parameters was determined according to the official Italian methods (Giunta, 2009): texture (sieve method for sand and pipette method for silt and clay), bulk density (coring method), moisture (thermo-gravimetric method). The texture analysis is derived from a composite sample obtained by mixing all samples from the three replicates. Each replicate corresponded to a composite sample with a thickness of 0–30 cm (from 9 sampling points arranged in a cross pattern, then mixed). Bulk density and moisture were measured from a single sample (core) taken from each replicate at 10–20 cm depth.

2.3. Sampling, extraction and characterization of soil arthropods

For microarthropods sampling, 3 soil cores (replicates, see Fig. 2) of 10x10x10cm were collected in each monitoring site. Soil arthropods extraction was conducted using Berlese-Tüllgren extractors for 10 days. The extracted specimens were collected and preserved in a mixture of preservative liquid (typically a 2:1 ratio of ethyl alcohol and glycerine). The extracted arthropod samples were analysed under a stereomicroscope. The microarthropods were identified to the order level for Chelicerata, Hexapoda, and Insecta, and to the class level for Myriapoda. Edaphic microarthropods exhibit morphological traits indicative of adaptation to soil environments. Therefore, within each higher taxonomic group, the QBS method requires identifying the biological form (morphotype) that shows the highest degree of adaptation to the

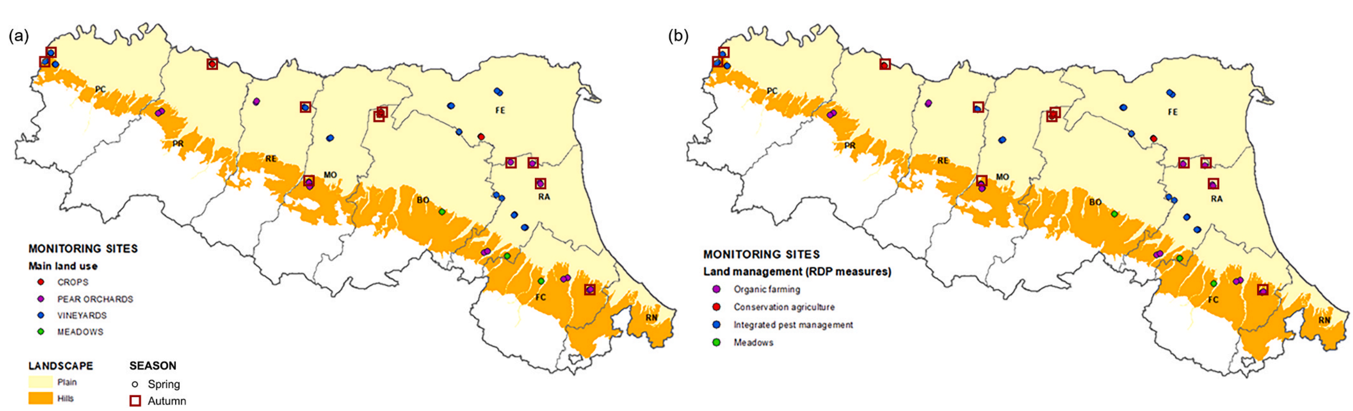

Fig. 1. Distribution of the 49 monitoring sites according to (a) main land use and (b) management (RDP measures).

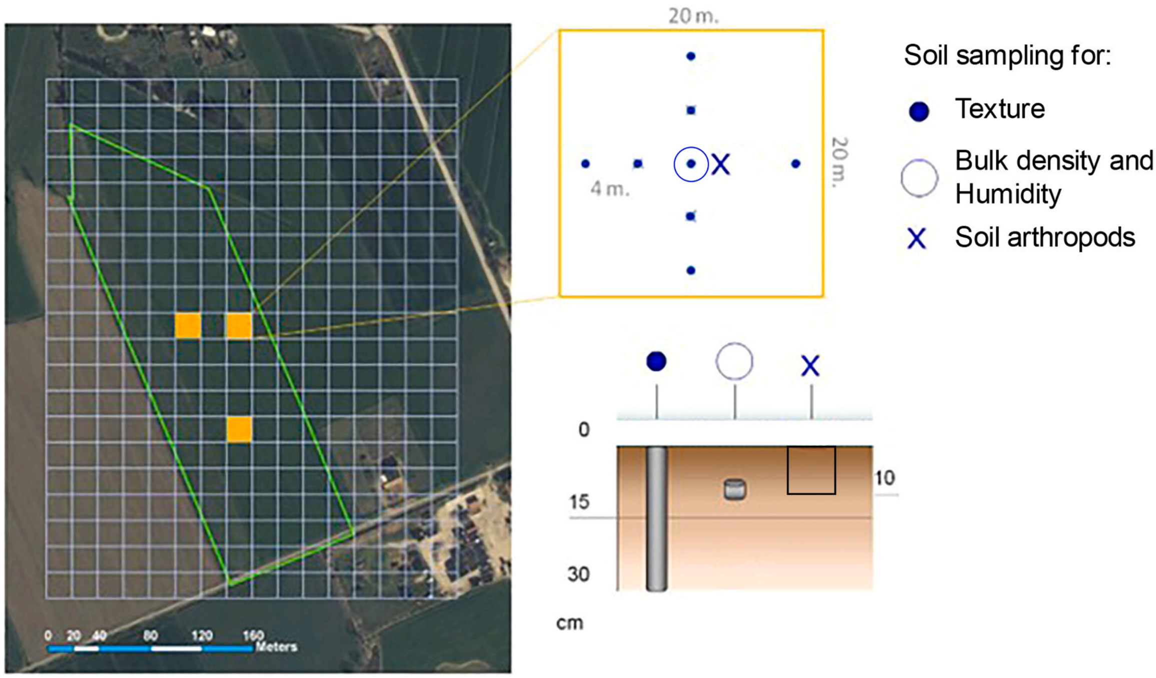

Fig. 2. Sampling scheme. Green box: monitoring site, orange boxes: replicates, blue-filled dots: soil subsamples for texture analysis, blue circle: soil core for bulk density and humidity, blue cross: soil core for arthropods extraction.

edaphic habitat. This morphotype is then assigned an eco-morphological index (EMI) score, proportional to its level of adaptation. The corresponding EMI value for each higher taxon is used in the calculation of Soil Biological Quality indices based on arthropods and Collembola (QBS-ar and QBS-c, respectively; Parisi, 2001; Parisi and Menta, 2008). In addition, a count was made of the number of ecomorphological groups, of the total abundance and of the individuals belonging to each group, and the Shannon biodiversity (H') index. H′ reflects the diversity of groups, and was calculated as follows:

$$H' = - \sum_{i=1}^{S} p_i \ln(p_i)$$

Where:

- S is the total number of groups.
- p_i is the proportion of individuals belonging to the i-th group, calculated as

$$p_i = n_i \quad / \quad N$$

where n_i is the number of individuals of the i-th group, and N is the total number of individuals in the community.

2.4. Statistical analysis

To robustly address the complex structure of our data, we implemented a multifaceted statistical framework combining both univariate and multivariate approaches.

The Factorial Analysis of Mixed Data (FAMD) was performed to explore the relationship between soil characteristics, sampling period and arthropod parameters. The analysis was conducted on the following variables: (i) soil characteristics: Texture (sand and clay), Humidity, Bulk density, Agricultural management per crop, (ii) sampling period: Season, Year, (iii) arthropod parameters: Shannon index, QBS-ar, QBS-c, and the Acarina/Collembola ratio. The dataset included both quantitative (e.g., sand, clay, Humidity, Bulk density, Shannon index, QBS-ar, QBS-c, Acarina/Collembola) and categorical variables (e.g., agricultural management, Season, Year). The mixed nature of the data, with continuous and categorical variables, required the use of FAMD (package: *FactoMineR*), which handles both types of variables simultaneously. The visualization of the FAMD results was performed using the *factoextra* package, to help to interpret the contribution of each variable to the principal components and identify patterns within the data. This method reduces the dimensionality of the dataset and allows the identification of underlying patterns, which is essential for understanding how soil characteristics and arthropod parameters interact within the context of agricultural management. Once the parameters contributing the most to the data variability were identified using FAMD, the assumptions for ANOVA were tested for the arthropod parameters. Since the assumptions for normality and homogeneity of variances were not met, non-parametric tests were applied for further analysis. To address potential nested effects (e.g., repeated sampling within sites across years and seasons), we initially attempted mixed-effect models (e.g., GLMMs). However, these models suffered from overfitting due to data structure and imbalance (unequal sampling across seasons and years). Given these limitations, we proceeded with non-parametric tests (Kruskal-Wallis and Mann-Whitney) for univariate comparisons of arthropod parameters among crops and management types, which are robust to non-normality and heteroscedasticity. To test for differences in arthropod parameters between crops, and within them, between management types, the Kruskal-Wallis test was used. When significant differences were found, Mann-Whitney pairwise comparisons (package: *dplyr*) were performed to identify specific group differences. In the case of arable land, the same non-parametric tests were applied, focusing on differences in arthropod parameters between crops within this specific land type. To evaluate the effects of soil characteristics and land management on soil arthropod communities, a PERMANOVA test (package: *vegan*) was conducted, based on Bray-Curtis dissimilarity matrices. A square root transformation of the data was applied before calculating dissimilarities to reduce the influence of highly abundant taxa, preventing domination by taxa with very high abundances. Following the PERMANOVA analysis, Non-Metric Multidimensional Scaling (NMDS) was applied to visualize (package: *ggplot2*) the relationships between soil arthropod communities and the sampling period, management and crop type factors. The *pairwise.adonis* function (package: *pairwiseAdonis*) was then used to conduct pairwise comparisons to understand how management and crop type affect soil arthropod assemblages. Where significant differences were found between management types within crops, a SIMPER analysis (package: *labdsv*) was applied to identify the most influential taxa driving these differences. The SIMPER analysis was used to determine which taxa contributed most to the observed management differences, with a focus on those taxa accounting for a cumulative contribution of approximately 75 % of the differences. For the taxa contributing to the cumulative difference (~75 %), Kruskal-Wallis tests followed by Mann-Whitney pairwise comparisons were applied to assess differences in their abundance between crops with the same management type and within crops between different managements.

All statistical analyses were performed using R v4.4.0 (R Core Team, 2024). A significance level of $p \leq 0.05$ was considered for all tests.

3. Results

3.1. Effects of soil characteristics and land management on soil arthropods parameters

The Factorial Analysis of Mixed Data (FAMD) conducted on soil characteristics and arthropod parameters revealed that soil texture, agricultural management per crop, and arthropod parameters significantly contribute to the overall variability of the dataset (Fig. S1). In contrast, the contributions of Year, Season, Bulk Density, and Humidity were found to be negligible.

A negative correlation was observed between clay and sand proportions. Higher clay content was predominantly associated with arable land—mainly under conservation management—and grasslands, whereas higher sand content was characteristic of orchards and organically managed vineyards (Table 2).

The FAMD results indicated that most arthropod parameters showed an increasing trend in vineyards than in arable land. This finding was corroborated by pairwise comparisons, which revealed a significant positive effect of vineyards compared to arable land on the following metrics: abundance, the number of ecomorphological groups, QBS-ar, and the Shannon Index (Fig. 3).

When comparing different management practices within the same crop type, organic management in both arable land and vineyards resulted in lower microarthropod abundances compared to conservation and integrated management. Moreover, in vineyards, organic management was associated with lower QBS-c values, whereas in arable land it yielded higher Shannon diversity index values relative to conservation management. Focusing specifically on arable land, differences in management practices were evident in the number of ecomorphological groups, QBS-ar values, and Shannon diversity index among those crops for which data were available under both management regimes (alfalfa, cereals, and legumes). (Fig. 4). Specifically, all three metrics exhibited higher values under organic management compared to conservative management for both alfalfa and cereals. However, for legumes, the QBS-ar values were higher under conservative management than under organic management.

Within the same management practices, crops showed greater dissimilarity under organic management than under conservative management. Under conservative management, only the abundance and Shannon index varied significantly. Annual grasslands exhibited the highest abundance, thereby increasing the mean abundance observed in conservation-managed arable land, while leguminous crops showed the highest biodiversity. In contrast, under organic management, all arthropod metrics—including abundance, diversity, and ecomorphological richness—were higher in alfalfa and cereal crops compared to maize and leguminous crops. Alfalfa demonstrated the highest values for abundance, number of EMI groups, and QBS-ar.

3.2. Effects of soil characteristics and land management on soil arthropods communities

Considering all the above soil characteristics and sampling periods, the composition of soil arthropod communities was affected by soil management, crop type, sampling period (year and season), and clay content ($p < 0.001$ for all), but not by sand content.

Soil arthropod community assemblages differed significantly across most pairwise comparisons of crop types ($p < 0.01$ for Cereals vs. Vineyard; $p < 0.05$ for other comparisons), except between Vineyards and Permanent Meadows (Fig. 5).

Additionally, several taxa displayed significant indicator values: (i) Pseudoscorpionidae ($p < 0.01$) in Orchards and Vineyards, (ii) Diplopoda ($p < 0.001$) in Meadows and Vineyards, and (iii) Hemiptera ($p < 0.001$), Isopoda ($p < 0.05$), and Protura ($p < 0.01$) in Orchards, Permanent Meadows, and Vineyards.

Management practices also influenced arthropod community differences in all comparisons ($p < 0.01$), except when grassland was compared with organic or integrated management (Fig. 6).

Considering the differences between managements within a same crop, significant differences in arthropod community assemblages were observed between conservative and organic management in arable land ($p < 0.01$), but no differences were detected within vineyard cultivation.

In arable land, significant differences between organic and conservative management were detected across all three crops considered—Alfalfa, Cereals, and Leguminous ($p \leq 0.01$).

Even if with different cumulative contributions (Table S2), the most influential taxa in driving management differences within arable land crops were: Acarina (Fig. S2), Chilopoda, Diplopoda, Pauropoda, Symphyla (Fig. S3), Collembola, Diplura (Fig. S4), Coleoptera adults, Coleoptera larvae, Diptera larvae, Hymenoptera (Fig. S5).

For these taxa, significant differences - when observed - consistently indicated higher abundances under organic management. Furthermore, the majority of differences among crops under the same management regime were observed within organic systems, with alfalfa generally exhibiting the highest abundances.

4. Discussion

In arable land, arthropods are influenced by various management practices, including tillage, fertilizer application, agrochemical use, and harvesting. Although these practices have been documented to influence the abundance and diversity of specific arthropod groups (Gagic et al., 2017; Holzschuh et al., 2009), the relative strength of these effects and their variability among arthropod groups remain poorly understood.

Table 2

Mean ± standard error of the physico-chemical parameters (humidity, bulk density, clay and sand content) obtained across different land uses under varying agricultural management practices.

	Arable land		Vine		Orchard	Permanent Meadow
	Conservative	Organic	Integrated	Organic	Integrated	Grasslands
Humidity (%)	18.2 ± 4.1	18.5 ± 3.1	19.4 ± 5.5	16.9 ± 3.0	16.8 ± 3.2	22.0 ± 4.7
Bulk density (g/cm^3)	1.6 ± 0.3	1.6 ± 0.3	1.6 ± 0.2	1.6 ± 0.2	1.7 ± 0.2	1.7 ± 0.2
Clay (%)	39.3 ± 3.9	32.7 ± 5.6	34.4 ± 12.7	21.6 ± 8.9	22.7 ± 4.6	42.0 ± 9.5
Sand (%)	4.8 ± 2.1	9.6 ± 6.4	12.4 ± 8.4	40.4 ± 11.4	20.3 ± 11.5	9.0 ± 6.6

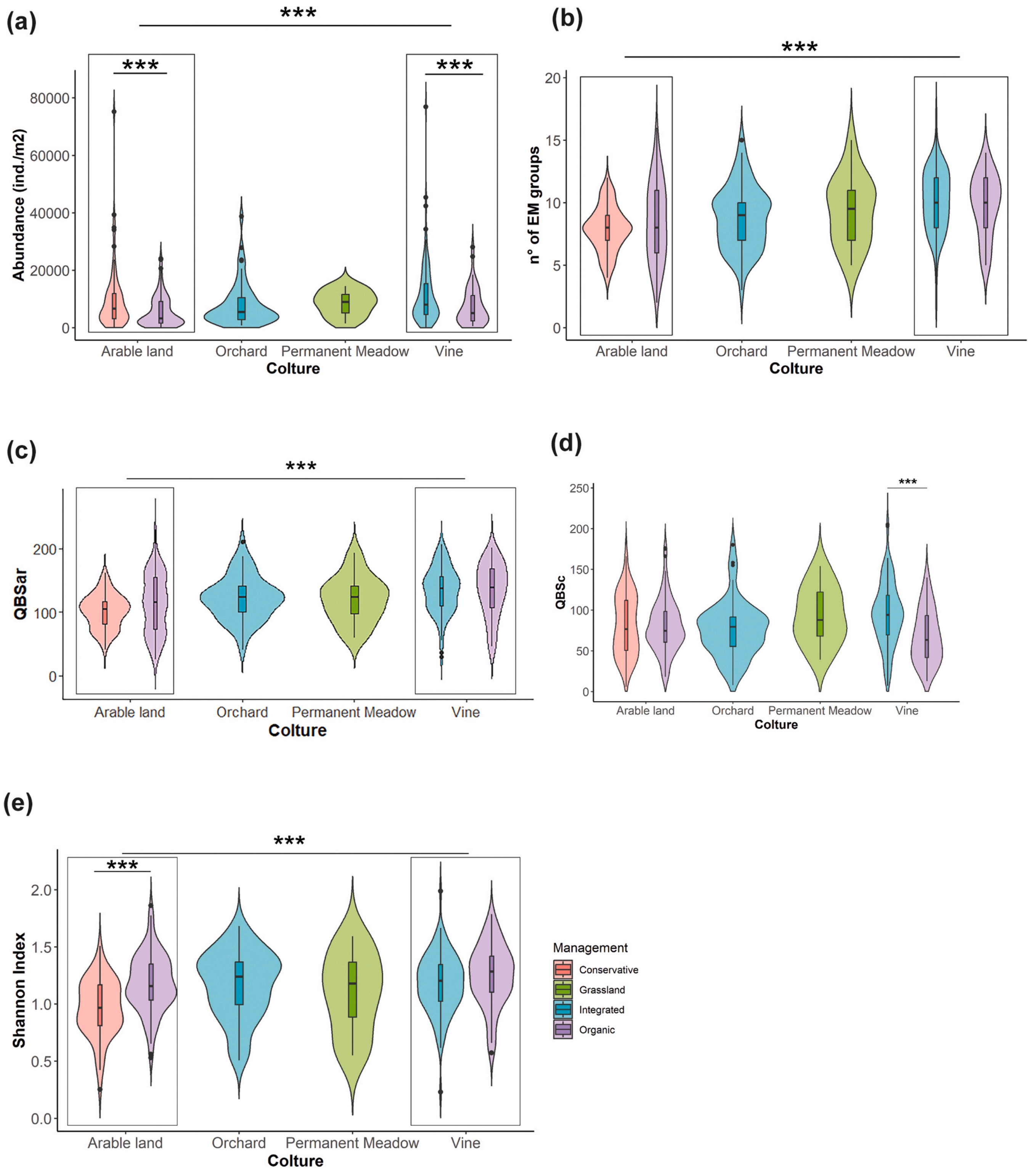

Fig. 3. The violin plots represent: (a) arthropods total abundance (ind/m^2), (b) n° of ecomorphological groups, (c) QBS-ar, (d) QBS-c, and (e) Shannon Index distributions across different land uses and agricultural management practices. The black boxplots within the violins display the median and interquartile range. Asterisks indicate significant differences between land use types or management practices: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Although most arthropods in this study were identified only to the order or class level, this taxonomic resolution is consistent with the requirements of the QBS-ar and QBS-c indices, which rely on morphological traits related to soil adaptation rather than species identity. While this approach may limit detailed ecological or functional interpretations, it provides robust indications of the overall response of soil fauna to environmental conditions. Indeed, aggregating species-level responses into higher taxonomic groups allows the detection of broader ecological patterns and reflects the magnitude of disturbance beyond species-specific variability.

Moreover, this level of taxonomic resolution has important practical advantages. It enables the application of soil biological quality

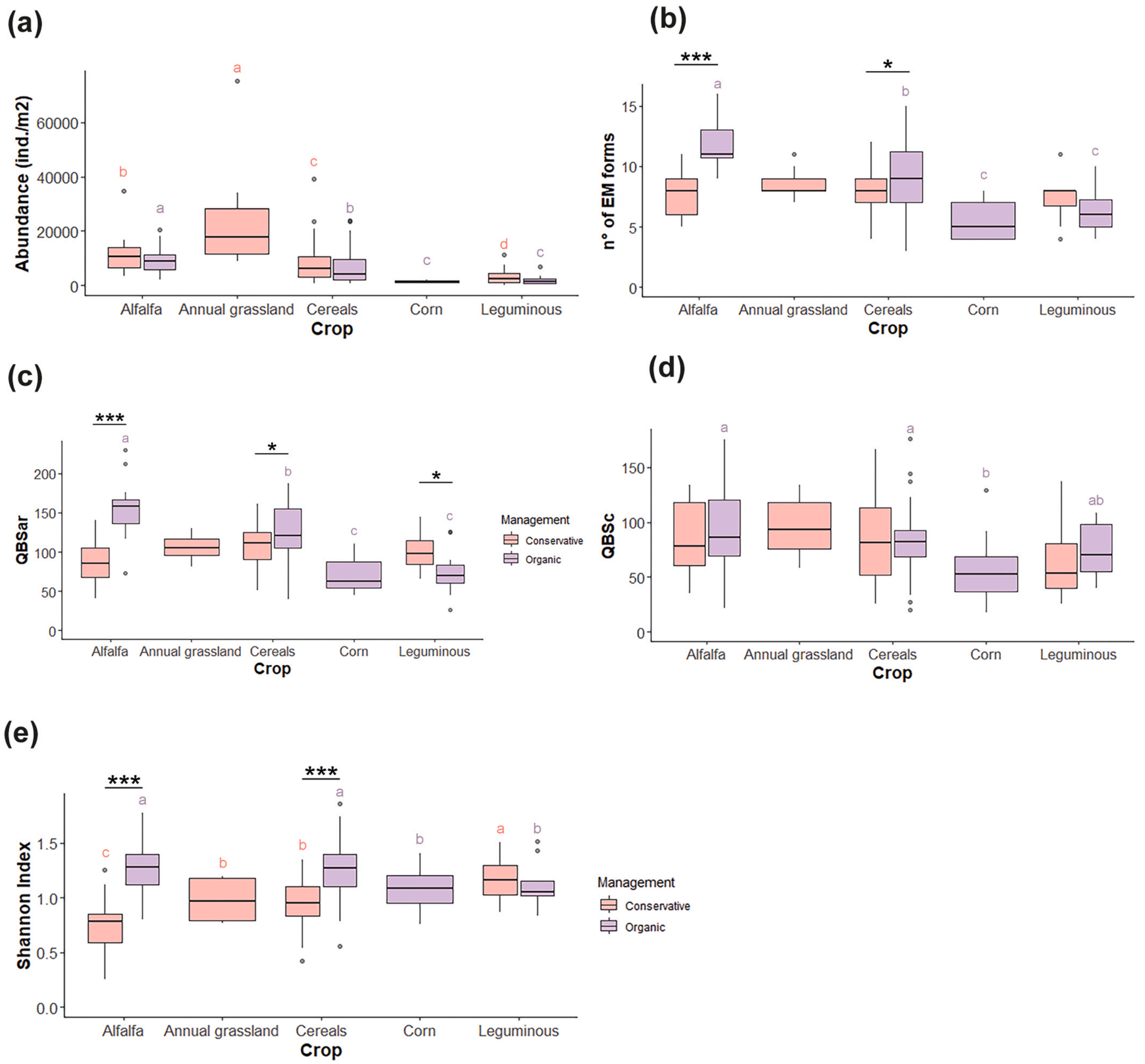

Fig. 4. The boxplots display the median and interquartile range of: (a) arthropods total abundance (ind/m^2), (b) n° of ecomorphological groups, (c) QBS-ar, (d) QBS-c, and (e) Shannon Index distributions across different arable land crops and agricultural management practices. Asterisks indicate significant differences between management practices: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, while different letters indicate significant differences between crops within the same management.

assessments by a broader range of users, including non-specialists, thus supporting large-scale and long-term monitoring initiatives (Gkisakis et al., 2016). As such, it enhances the scalability and accessibility of biodiversity assessments in agroecosystems. This approach has been recognized as particularly valuable for rapid biodiversity surveys (Cotes et al., 2010), especially in the early phases of investigation where comparisons across land uses or management regimes are needed, and where financial or taxonomic resources may be limited (Biaggini et al., 2007). Our findings underscore the role of agricultural management as a key driver of soil biological quality and overall arthropod abundance. Consistent with Joimel et al. (2017), who compared ecosystems such as forests, grasslands, arable lands, vineyards, urban vegetable gardens, and urban soils, microarthropod densities were reported to be higher in vineyards than in other agroecosystems. Moreover, contrary to findings like Coletta et al. (2024), our study revealed that arable land, rather than vineyards, was the most negatively impacted, particularly in terms of soil biological quality (QBS-ar) and biodiversity; consistently with the few studies conducted in vineyards finding QBS-ar values ranging from 137 to 230, indicating potential higher quality than in arable soils (e.g., (Rüdisser et al., 2015)). In Lombardy vineyards, Ghiglieno et al. (2020) observed that organic management, even after a short adoption period (three years post-conversion), enhanced microarthropod diversity. In contrast, our results showed that this positive effect of organic practices was observed only in arable land when compared to conservative practices. No statistically significant differences were detected between vineyards managed under organic and integrated practices. Moreover, organic practices seemed to have a negative impact on arthropod abundance in both arable land and vineyards when compared to conservative and integrated practices, respectively. In vineyards, organic management seemed to negatively affect also the collembolan community showed by the QBS-c index. Some factors, such as vegetation cover, soil characteristics, compaction levels, and organic matter content,

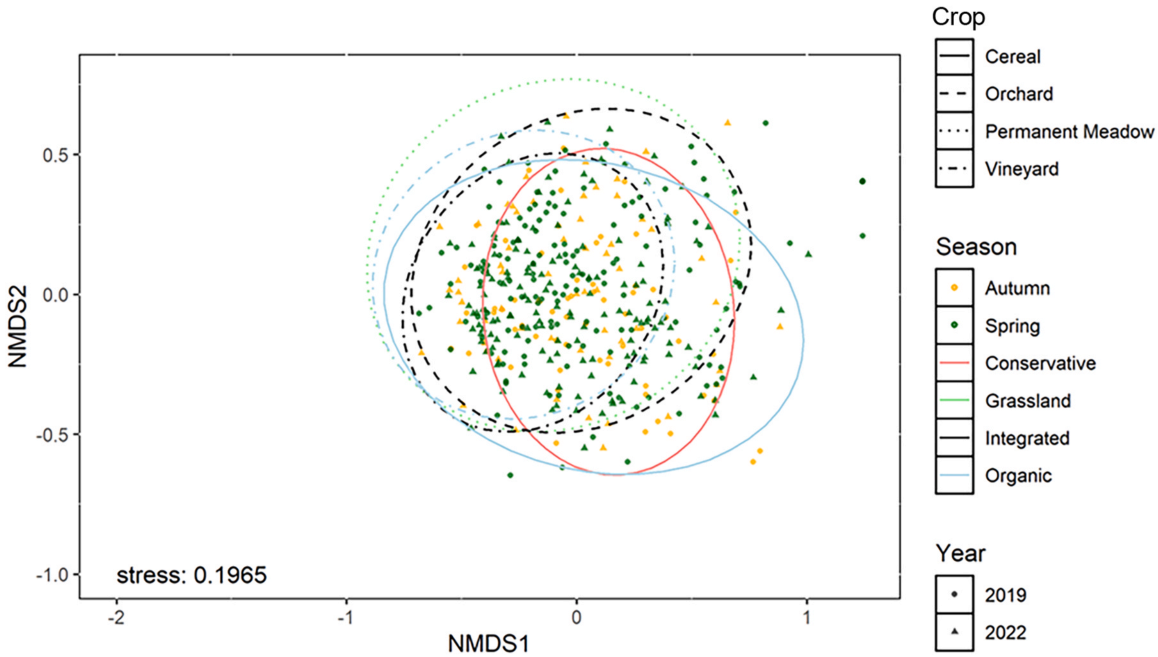

Fig. 5. Bray-Curtis-based NMDS plot of the arthropod community composition. Points represent samples, with color and shape indicating the Season and Year, respectively. Ellipses represent the crop and agricultural management to which the sample belongs, with shape and colour corresponding to these factors, respectively.

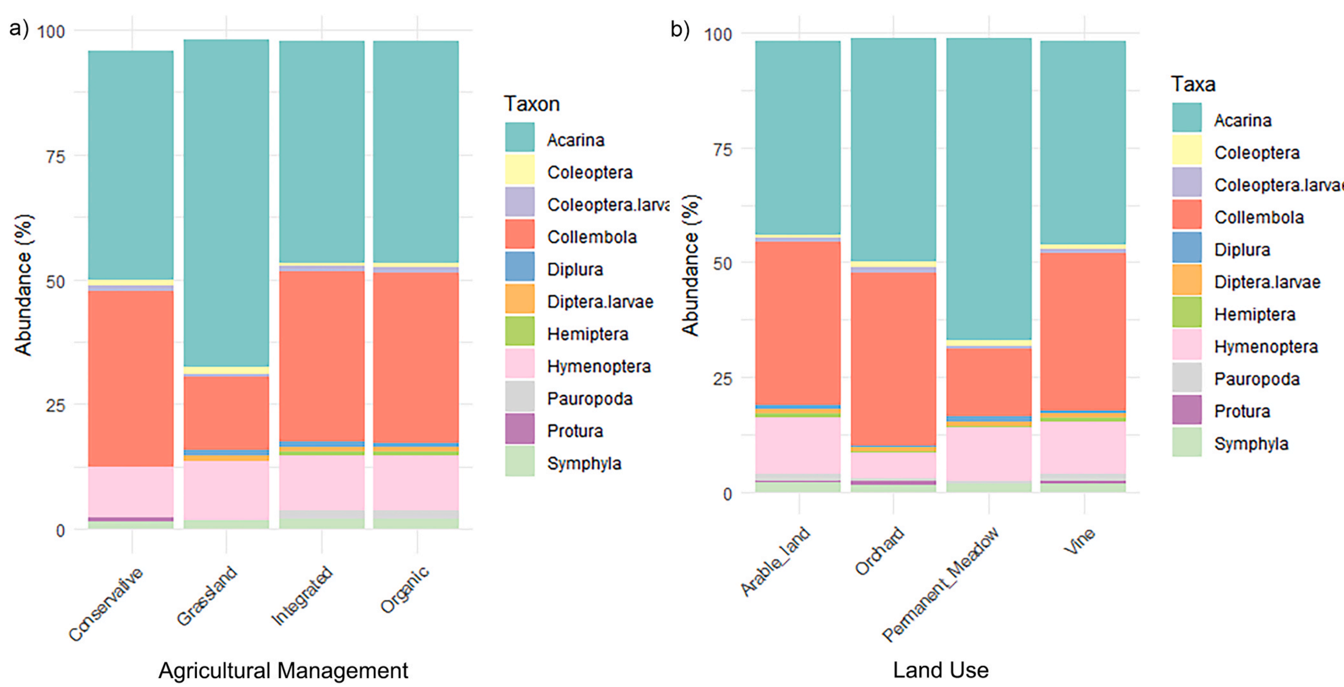

Fig. 6. Taxa bar plot representing the most representative orders composing (a) the agricultural management types, and (b) the different land uses. The cumulative relative abundance of specific orders (accounting for at least the 0.7 % of the total arthropods abundance) is shown: each bar represents a different agricultural management type or land use and each coloured box an order.

which are influenced by weed and soil management, also play a role in shaping microarthropod communities (Gardi et al., 2008; Giffard et al., 2022; Visioli et al., 2013). In our study, distinct crop types within arable land significantly affected soil arthropod communities, with the impacts of management varying across crops. For example, while organic management generally had a detrimental effect in arable land, it positively influenced biodiversity and QBS-ar in alfalfa and cereal crops but seemed to have a negative impact in leguminous crops.

This study underscores the importance of not only land use and soil management practices but also the sampling period in shaping arthropod community structure. This is consistent with findings from previous studies that have reported seasonal variations in arthropod community structure, driven by climatic conditions and resource availability (Frampton et al., 2000; Santorufo et al., 2014). Furthermore, this study confirms that while the sampling period does not significantly affect arthropod indices, it influences community structure. Seasonal variations in abundance and activity, which are directly associated with periodic changes in weather, have been demonstrated in various arthropod groups (Shakir and Ahmed, 2014), including Collembola (Gbarakoro, Umoren, 2016), Coleoptera (Anlaş et al., 2021; Ernst and Buddle, 2013), Formicidae (Pérez-Bote and Romero, 2012), Acari (Kaczmarek and Marquardt, 2010), millipedes (Ramanathan and Alagesan, 2011), Araneae (Mukhtar, 2012), and Orthoptera (García-Robledo et al., 2010).

Land use and management also significantly affected arthropod community structure in this study by shaping habitat features. Habitat type encompasses a combination of characteristics, including abiotic factors, vegetation structure, management practices, and anthropogenic pressures (Lazzerini et al., 2007). Numerous studies have demonstrated that habitat structure and complexity can profoundly influence diversity and composition of fauna in terrestrial systems (Hanski and Singer, 2001; Perner and Malt, 2003). Certain studies have observed that arthropods may exhibit strong associations with specific plant species, reaching their highest diversity in species-rich and structurally complex environments (Di Giulio et al., 2001).

In line with the expectations in the present study, Collembola and Acari were the most frequently identified taxa, confirming their status as the most dominant arthropod groups in soil ecosystems (Ghiglieno et al., 2020). Taxa correlating with specific land uses generally belonged to well adapted ecomorphological forms, none of which showing significant correlation with arable land. For instance, some biological forms indicative of undisturbed soil conditions, such as Pseudoscorpionidae, Isopoda, and Protura, were frequently observed in vineyards. This finding aligns with previous research highlighting the association of these taxa with undisturbed soil conditions in vineyards (Giffard et al., 2022).

Below-ground arthropod communities are shaped by crop type, suggesting that planting specific crops can promote soil arthropods and their associated ecosystem services (Elmquist et al., 2023). As highlighted in other studies (González del Portillo et al., 2022), the biodiversity benefits of alfalfa cultivation may vary among taxa. For example, in this study, Myriapoda, Hymenoptera, and Diplura appeared to benefit particularly from alfalfa, especially under organic management. Similar to other legumes, alfalfa's green parts are rich in proteins, and its capacity to fix atmospheric nitrogen makes it a valuable crop from both production and conservation perspectives (Murphy-Bokern et al., 2017). Furthermore, as a semi-perennial crop, alfalfa is associated with lower soil disturbance compared to annual crops, enabling many arthropods to complete their life cycles, particularly stages that occur in the soil (Soroka and Otani, 2011). To enhance biodiversity in alfalfa cultivation, management practices should aim to reduce agrochemical inputs (e.g., pesticides and fertilizers) and adjust cutting frequency to align with biodiversity conservation goals (González del Portillo et al., 2022). In this study, organic management of alfalfa supported greater arthropod abundance—notably Myriapoda, Diplura, and Hymenoptera—compared to conservative practices. Conversely, adult Coleoptera benefited more from the presence of other leguminous crops, particularly when organically managed. This finding aligns with (Lemic et al., 2021), who reported that Coleoptera in soybean crops belong to the eudominant fauna category.

Several taxa in this study responded similarly to alfalfa and wheat, with wheat generally supporting slightly higher population densities. Myriapoda, in particular, were more abundant in leguminous crops under conservation management, suggesting that reduced disturbance and specific crop characteristics may favor their presence. Conversely, organic management appeared to promote higher densities in alfalfa and wheat, potentially due to increased plant diversity, organic matter input, or the absence of synthetic inputs. In cereal crops, differences between management systems were less pronounced overall; however, the higher abundance of taxa such as Pauropoda, Diplura, and Hymenoptera under organic management indicates a potential sensitivity of these groups to soil disturbance or chemical inputs, highlighting their utility as indicators of management intensity. Chabert and Sarthou (2020) observed that conservation agriculture provides higher soil structural stability compared to organic systems but slightly reduced water infiltration. This suggests that many soil arthropods may be more sensitive to humidity or chemical soil properties rather than soil structure.

5. Conclusion

In conclusion, this study highlights the complex interactions between agricultural management practices, crop types, and seasonal variations in shaping soil arthropod communities and their associated ecosystem services. While organic management generally promotes soil biodiversity in certain crops such as alfalfa and cereals, it can have detrimental effects on arthropod abundance and diversity in other contexts, such as vineyards and leguminous crops. These findings underscore the importance of tailoring management practices to specific crops and ecosystems to maximize biodiversity and ecosystem services. Furthermore, the study confirms the significant influence of seasonal variations and habitat complexity on soil arthropod community structure, emphasizing the need for integrative approaches that consider temporal and spatial factors in agricultural landscapes. The adoption of practices that meet the ecological requirements of major soil arthropod groups can support the development of sustainable agricultural systems that promote both soil health and biodiversity. Due to the crop-specific variability in the responses of soil arthropod communities, it is essential to identify management strategies tailored to individual cropping systems in order to mitigate negative impacts. Future research should continue to investigate the interplay between soil biological quality, crop-specific management, and the long-term effects of different agricultural practices on below-ground biodiversity.

CRediT authorship contribution statement

Cristina Menta: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Carla Scotti:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Data curation. **Paola Tarocco:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Fabio Gatti:** Writing – review & editing, Investigation, Data curation. **Sara Remelli:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cristina Menta reports financial support was provided by Emilia-Romagna Region. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109850.

Data availability

Data will be made available on request.

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