Predicting the Evolution of Epigeic Arthropods in a Vineyard Landscape Using Machine Learning

Vladimír LANGRAF[1]*   Mariana ELIAŠOVÁ[2]   Kornélia PETROVIČOVÁ[3]

[1]Department of Zoology and Anthropology, Constantine the Philosopher University in Nitra, SLOVAKIA

[2]Administration of Protected Landscape Area Ponitrie, SLOVAKIA

[3]Faculty of Agrobiology and Food Resources, Slovak University of Agriculture in Nitra, SLOVAKIA

e-mails: [1]langrafvladimir@gmail.com, [2]mariana.eliasova@sopsr.sk, [3]kornelia.petrovicova@gmail.com

ORCID IDs: [1]0000-0002-3839-3036, [2]0009-0007-1159-8748, [3]0000-0002-1581-2517

*Corresponding author

ABSTRACT

The agricultural landscape, which includes viticulture and grape growing, significantly affects the spatial distribution and the development of biodiversity in the landscape. Therefore, in our study, we focused on the development of epigeic arthropods under the conditions of the vineyard landscape. We conducted the research over the three years 2021-2023 in 8 study areas representing 4 types of vineyard landscape use (Intensive vineyard, semiintensive vineyard, abandoned vineyard, meadow (original vineyard)). We collected epigeic arthropods using the pitfall traps method at monthly intervals. During the research, we recorded 56,403 individuals belonging to 22 taxa, eudominant representation was confirmed in the taxa Hymenoptera (40.59%), Coleoptera (18.67%), and Araneida (11.65%). Statistical analysis confirmed the highest number of species and individuals in the intensive vineyard and meadow (original vineyard). Using machine learning, we confirmed the same evolution of epigeic arthropods over time for all types of vineyard land use except semiintensive vineyard. We also predicted an increase in epigeic arthropods for the month of July 2025 for all types of land use. The results of our research provide new information on the development of epigeic arthropods in vineyard ecosystems, which is important for the maintenance of sustainable agriculture that supports the preservation of biodiversity.

Keywords: Epigeic groups, spatial dispersion, vineyards, management, Central Europe.

INTRODUCTION

One of the most important commercial fruit crops worldwide is Vitis vinifera Linné 1753, which is grown for the wine industry and table purposes. Due to climate change, vineyards are increasingly expanding into areas where the vines were not previously grown. From a global perspective, they are a major sector of Mediterranean ecosystems (Hannah et al., 2013). The global goal is to ensure sustainable human well-being without significant negative impacts on biodiversity. Agriculture, which includes viticulture, plays an important role in food production. The expansion of agricultural land, associated with the planting of monocultures and the use of agrochemicals, has the greatest negative impact on global biodiversity (Hunter, Smith, Schipanski, Atwood, & Mortensen, 2017; Zabel, Delzeit, Schneider, Seppelt, Mauser, & Václavík, 2019; Muñoz-Sáez, 2024). By 2050, it will be necessary to increase food production by 70%, since the global population is estimated to increase to 9.8 billion people, leading to the development of innovative and sustainable agriculture (Santillán, Iglesias, La Jeunesse, Garrote, & Sotes, 2019).

Epigeic arthropods play an important role in maintaining a healthy ecosystem in vineyards, contributing to the maintenance of soil microbial activity and soil health (Kremen & Miles, 2012). These groups include diverse organisms such as isopods, diplopods, coleoptera, hymenoptera, spiders, and others that live on the soil surface. They participate in the decomposition of organic material, thus facilitating the cycling of nutrients essential for vine growth. They improve soil structure by aerating the soil and promoting water retention, which is vital for the maintenance of vines, especially in dry periods. They contribute to increasing soil biodiversity, natural pollination, pest control, and improving soil quality through processes such as organic matter decomposition and aeration (Tschumi, Ekroos, Hjort, Smith, & Birkhofer, 2018; Litavský, Majzlan, Stašiov, Svitok, & Fodor, 2021; Pazourková et al., 2021; Porhajášová & Babošová, 2022; Putchkov & Brygadyrenko, 2022; Langraf & Petrovičová, 2024). Their presence supports biodiversity and the overall resistance of vineyards to diseases and stressful environments, thus also increasing the quality of grapes. Importantly, healthy communities of epigeic arthropods can contribute to the natural regulation of pests and diseases, reducing the need for chemical pesticides and supporting organic farming (Addison, Baauw & Groenewald, 2013; Vuillot, Coron, Calatayud, Sirami, Mathevet, & Gibon, 2016). Therefore, maintaining biodiversity in vineyards is crucial not only for environmental protection, but also for the long-term sustainability of wine production. Their presence can also improve soil quality and support the growth and development of vine plants. Therefore, it is important to promote soil biodiversity and protect epigeic arthropods in viticulture. As vineyards increasingly adopt sustainable practices, understanding and supporting these ecological groups of insects can lead to improved grape quality and yield, ultimately benefiting both producers and consumers in the wine industry (Adhikari, Adhikari, Weaver, Bekkerman, & Menalled, 2019; Paiola, Assandri, Brambilla, Zottini, Pedrini, & Nascimbene, 2020; Willmer, 2022).

AI-based ecological modelling focuses on addressing key challenges in contemporary ecology, such as simulating species distributions, predicting abundance and responses to climate change, and quantifying the spatial variability of biodiversity.

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Chang (2023) demonstrated that machine learning and deep learning methods can effectively predict biodiversity based on environmental drivers, with deep neural networks significantly outperforming traditional models in the accuracy of biodiversity estimation across broad environmental scales. Jemeljanova, Kmoch, & Uuemaa (2024) extended this perspective by adapting machine learning approaches for spatial environmental data, emphasizing the importance of accounting for spatial auto correlation in the development of robust ecological models. Lhoumeau, Pinelo, & Borges (2025) highlight the growing importance of AI in assessing biodiversity dynamics and supporting conservation measures, where advanced models have shown improvements in the exploration of ecological scenarios.

For sustainable viticulture, its yields and the protection of biodiversity, scientific evidence is needed to help in decision-making and guide producers and companies in the wine industry. Therefore, in our research we focused on the spatial dispersion of epigeic arthropods in vineyards. Our study is among the first pilot studies that link Machine Learning methods (K-means clustering) with trends in the abundance of epigeic arthropods in different forms of vineyard use in an agricultural landscape.

MATERIALS AND METHODS

We conducted epigeic arthropod research during the years 2021 - 2023 in 8 study areas. The studied area was located in the geomorphological region of the Danube Uplands. The study area falls under a warm and moderately humid climate with mild winters. The location data for the study areas are in Table 1.

Table 1. The location data for the study areas 1-8.

Study area	Habitat	m.a.s.l.	Geographic coordinates
S1	abandoned vineyard	282	48°25'11"N 18°26'37"E
S2	meadow	282	48°25'15.832"N 18°26'27.555"E
S3	meadow	284	48°25'16.908"N 18°26'29.525"E
S4	abandoned vineyard	281	48°25'17.768"N 18°26'32.383"E
S5	Intensive vineyard	262	48°25'31.646"N 18°26'46.027"E
S6	Semi-intensive vineyard	280	48°25'35.204"N 18°26'48.818"E
S7	Semi-intensive vineyard	278	48°25'36.049"N 18°26'49.687"E
S8	Intensive vineyard	274	48°25'41.464"N 18°26'54.235"E

The characteristics of the individual study areas are as follows:

S1 and S2— Overgrown, abandoned vineyard, where the vines are overgrown with *Prunus spinosa* and *Rosa rubiginosa* species.

S3 and S4—Meadow, which was originally a vineyard 50 years ago and is mowed twice a year.

S5 and S6—Intensive vineyard, which, once a year, the grass is mowed, the old vines are removed,and a new one is planted.

S7 and S8—Semi-intensive vineyard, which, once a year, the grass is cut and the vines are pruned.The old vines are removed, and no new ones are planted.

The epigeic arthropod material was collected during the years 2021 - 2023 from April to October at regular monthly intervals. Five fall traps were placed in a line in each study area, i.e. a total of 40 fall traps during all 3 years of collection. The distance between each pitfall trap is 10 m. Formalin (4%) was used as a preservative. Epigeic arthropods were determined according to Schierwater & DeSalle (2021).

Statistical Analysis

The spatial structure of taxa under different land use conditions (Intensive vineyard, semi-intensive vineyard, abandoned vineyard, meadow) was analysed by principal component analysis (PCA) in the Canoco5 programme (Ter Braak & Šmilauer, 2012).

In the Python 3.12 program (2023), we performed the normality of the data distribution (Shapiro-Wilk test) which was violated and based on this we used non-parametric Kruskal-Wallis test, with which we tested the differences in the number of individuals between land uses using. Subsequently, we used a post hoc test (Tukey's HSD test) to examine pairwise differences among all land-use types (intensive vineyard, semi-intensive vineyard, abandoned vineyard, and meadow).

Using machine learning, we determined the number of clusters using the elbow method, based on which we subsequently predicted the development number of individuals in time series using the K-means method. Before applying the K-means algorithm, the variables (number of individuals, time series) were standardized using Z-score normalization. The K-means algorithm is based on Euclidean distance, which is sensitive to the scale of variables. Without normalization, the variable number of individuals would dominate over the time index. Using the elbow method, we determined the number of clusters to be 3 for all land-use types (intensive vineyard, semi-intensive vineyard, abandoned vineyard, and meadow). The silhouette scores for clustering were: Intensive vineyard = 0.7, meadow = 0.73, semi-intensive vineyard = 0.76, and abandoned vineyard = 0.8.

We predicted the abundance for the year 2025 using multivariate linear regression. The dependent variable being predicted is the number of individuals (Os Y). The independent variables used for the prediction are time series, separately for each type of vineyard land use.

RESULTS

During the entire research period from 2021 to 2023, we recorded 56,403 individuals belonging to 22 taxa. Eudominant representation was confirmed in the taxa Hymenoptera (40.59%), Coleoptera (18.67%), Araneida (11.65%). The dominant representation was confirmed in the taxa Glomerida (6.24%), Isopoda (5.55%). The remaining taxa had a subdominant representation of the subrecedent (Table 2.).

We tested the association of epigeic arthropods with land use (intensive vineyard, semi-intensive vineyard, abandoned vineyard, meadow) using principal component analysis (PCA. SD = 0.6 on the first ordinate axis). The variability of taxa on the first ordinate axis is 50.12% and on the second cumulative axis it is 86.38%.

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Table 2. Overview of taxa collected in the study areas.

Taxon	Intensive vineyard	Meadow	Semi-intensive vineyard	Abandoned vineyard	Σ	%
Acarina	4	8	0	1	13	0,02%
Araneida	1716	1645	1387	1825	6573	11,65%
Auchenorrhyncha	1	2	13	0	16	0,03%
Blattodea	0	4	0	2	6	0,01%
Coleoptera	2365	3880	2348	1939	10532	18,67%
Collembola	115	666	109	381	1271	2,25%
Dermaptera	135	92	194	75	496	0,88%
Ensifera	0	0	0	3	3	0,01%
Geophilomorpha	20	2	27	3	52	0,09%
Glomerida	705	1308	578	930	3521	6,24%
Hemiptera	385	479	401	355	1620	2,87%
Hymenoptera	7278	5840	5062	4716	22896	40,59%
Chordeumatida	1	0	0	1	2	0,00%
Isopoda	713	989	667	764	3133	5,55%
Julida	727	1000	460	517	2704	4,79%
Lithobiomorpha	40	131	85	76	332	0,59%
Mantodea	0	1	0	0	1	0,00%
Opilionida	319	284	177	241	1021	1,81%
Orthoptera	344	1093	574	180	2191	3,88%
Polydesmida	0	2	7	0	9	0,02%
Scorpionida	0	2	1	0	3	0,01%
Zygentoma	3	3	1	1	8	0,01%
Σ individuals	14871	17431	12091	12010	56403	100,00%

On the ordination plot we see that the taxa Ensifera, Hmynoptera, and Chordeumatida preferred conditions in abandoned vineyard and semi-intensive vineyard. Taxa Polydesmida, Auchenorrhyncha, Dermaptera, and Geophilomorpha correlated with Intensive vineyard. The taxa Acarina, Blattodea, Glomerida, Collembola, and Mantodea preferred meadow conditions. The remaining taxa preferred meadow habitat and intensive vineyard, where most taxa were confirmed (Fig. 1).
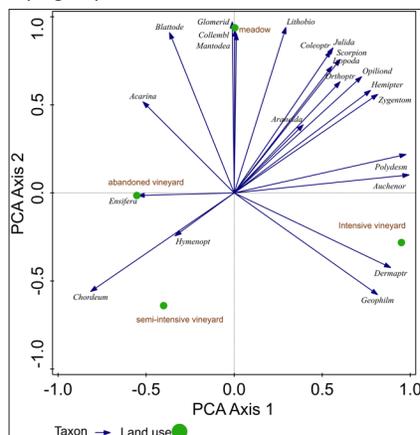

Figure 1. PCA analyses of taxa linkage to land use.

Using the Shapiro-Wilk test, we confirmed the broken normality of the distribution of the number of individuals (p=0.0001), based on which we used the nonparametric Kruskal-Wallis test. With this test, we analysed the difference in the number of individuals between land uses (intensive vineyard, semi-intensive vineyard, and abandoned vineyard, meadow). The result was the confirmation of a statistically significant difference in the number of individuals between land uses (p=0.0412). We confirm the highest number of individuals in the meadow and intensive vineyard, the lowest in the semi-intensive vineyard and abandoned vineyard (Fig. 2). Subsequently, using Tukey's HSD test, we confirmed a significant difference in the number of individuals between the meadow and the semi-intensive vineyard (p = 0.0206, effect sizes = 0.87), as well as between the meadow and the abandoned vineyard (p = 0.01647, effect sizes = 0.9). No significant difference was found between the intensive vineyard and the meadow (p = 0.8778, effect size = 0.17), the intensive vineyard and the semi-intensive vineyard (p = 0.1845, effect size = 0.62), the intensive vineyard and the abandoned vineyard (p = 0.1541, effect size = 0.65), and the semi-intensive vineyard and the abandoned vineyard (p = 0.9147, effect size = 0.07).
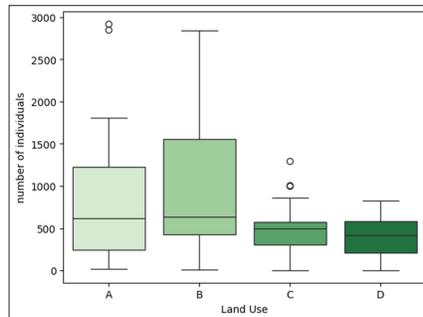

Figure 2. Difference in number of individuals between land uses. Explanations: A = intensive vineyard, B = meadow, C = semi-intensive vineyard, D = abandoned vineyard.

Using the K-means algorithm, which is part of machine learning, we predicted the number of clusters in the time series, according to which we can assess the development of the number of epigeic arthropods in different land use conditions. First, we determined the number of clusters suitable for the analysis of our data using the elbow method. From the results, we see that the number of suitable clusters is 3 for all land use types (Fig. 3).

Using the K-means algorithm, which is an unsupervised clustering method used to identify patterns and structures in data sets, we performed a time series analysis for all land use categories - intensive vineyard, semi-intensive vineyard, abandoned vineyard and meadow. The aim of applying this method was to identify natural groups (clusters) with similar dynamics of development over time and thus gain an overview of changes in the number of individuals in individual categories. Based on the clustering results, it was possible to identify three dominant clusters that represent different development trends during the monitored period. The analysis showed that during all monitored years, there were significant changes in the number of individuals in the categories of intensive vineyard, meadow and abandoned vineyard. In terms of time, a significant decrease was recorded

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in 2022 compared to 2021, followed by a subsequent increase in 2023, which points to the instability and dynamics of changes in these habitat types. In the case of semi-intensive vineyards, the K-means method revealed a significant increase in 2023 compared to 2021 and 2022, during which the number of individuals remained at a relatively constant level. These results suggest that semi-intensive vineyards may have been affected by improved environmental conditions or a change in management methods in the last observation period, which was reflected in increased abundance of individuals (Fig. 4).
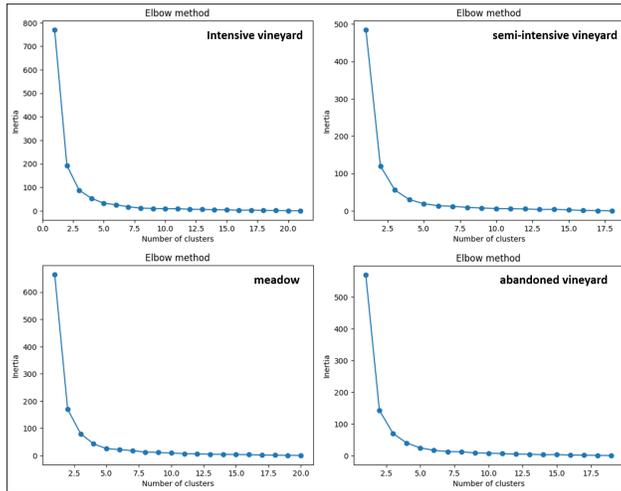

Figure 3. Elbow Method for determining the number of clusters for K-means of individual land uses.
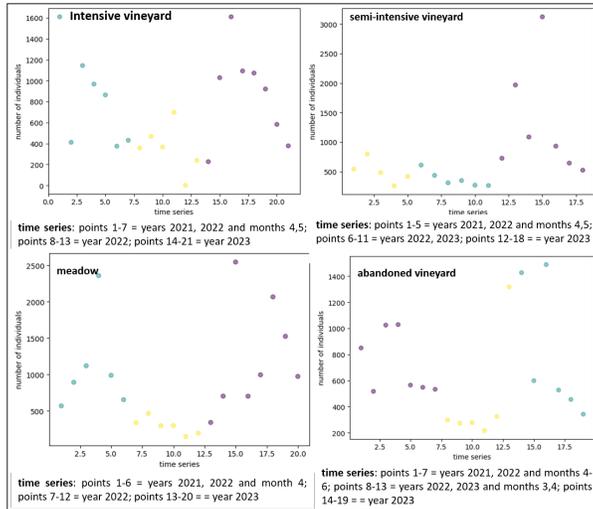

Figure 4. Predicting clusters using the K-means algorithm based on land use.

Based on multivariate linear regression, we analyzed the number of individuals in the time series and their prediction in 2025 in the 7th month for each use of vineyards

separately. The overall model explained a medium proportion of the variability in the number of individuals (R^2 = 0.6096), with the effect of time being statistically significant (p = 0.016; 95% CI = ⟨179; 1250⟩). Individual vineyard categories were also statistically significant: Intensive vineyard (p = 0.0088; 95% CI = ⟨210; 1250⟩), Semi-intensive vineyard (p = 0.0188; 95% CI = ⟨200; 1200⟩), Abandoned vineyard (p = 0.0097; 95% CI = ⟨218; 1050⟩), and Meadow (p = 0.0338; 95% CI = ⟨180; 1130⟩). Separate regression models for individual land-use categories were also significant: Intensive vineyard (R^2 = 0.61), Semi-intensive vineyard (R^2 = 0.64), Abandoned vineyard (R^2 = 0.17), and Meadow (R^2 = 0.62). We used the model to predict the values of individuals before 2025 in the month of July, where we will see that there will be a gradual increase in all types of land use (Fig. 5).
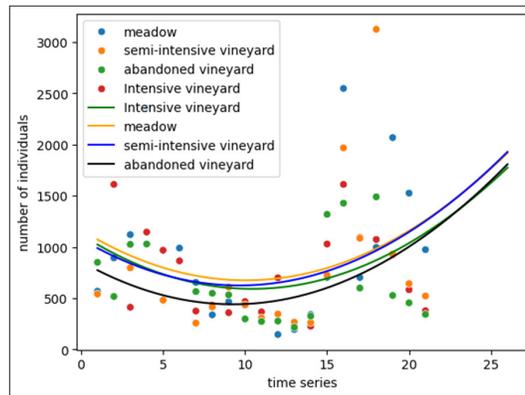

Figure 5. Multivariate linear regression of the occurrence of individuals in time series for land use. Time series: points 1-6 = year 2021, points 7-13 = year 2022, points 14-21 = year 2023, points 22-29 = year 2024, points 30-34 = year 2025.

DISCUSSION

Our results show that land use significantly influences the composition and abundance of epigeic arthropods. In total, we recorded 56,403 individuals belonging to 22 taxa, with the most significant representation being Hymenoptera (40.59%), beetles (18.67%), and spiders (11.65%). These results are consistent with studies that Hymenoptera and beetles are among the dominant taxa in agroecosystems (Smith, Brown & Lee, 2019; Johnson & White, 2020; Brown & Johnson, 2021).

The diversity was highest in meadow areas and intensive vineyards, probably due to higher food availability and microhabitat variability (Jones & Wilson, 2017; White & Green, 2020). Similar results have been reported in other studies, highlighting that traditional vineyards and extensively used meadows provide better conditions for a wide range of invertebrates (Robinson & Thompson, 2020; Green & Silva, 2021). On the contrary, abandoned vineyards and semi-intensive vineyards showed lower abundance and diversity, which may be related to transient ecosystem changes (García & Nelson, 2016; Silva & Palmer, 2019).

Using principal component analysis (PCA), we confirmed that the variability of species composition is significantly influenced by land use type. The results showed that

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Ensifera, Hymenoptera, and Chordeumatida preferred abandoned and semiintensive vineyards, while Polydesmida, Auchenorrhyncha, Dermaptera, Geophilomorpha, Acarina, Blattodea, Glomerida, Collembola, Mantodea, Lithobiomorpha, Julida, Coleoptera, Scorpionida, Isopoda, Orthoptera, Opilionida, Hemiptera, Zygentoma and Araneida were more common in intensive vineyards and meadow habitats. The association of intensively managed vineyards with Auchenorrhyncha and Dermaptera can be interpreted as a consequence of periodic disturbance of inter-row spaces, which creates short-term pulses of low vegetation and ruderal herbs. These pulses provide temporary resources for herbivorous taxa while simultaneously increasing the mobility of omnivores and predators. The presence of Geophilomorpha and Polydesmida under this type of land use indicates that mechanical soil interventions do not necessarily lead to a decline in all soil predators and detritivores, but may temporarily increase the availability of microhabitats and prey in the surface soil horizons. Such a mechanism is consistent with findings that intensive management can increase the activity-density of epigeic organisms without a corresponding increase in their actual population density (Pfingstmann, Paredes, Buchholz, Querner, & Bauer, 2019; Becker & Wang, 2022).

The meadow was characterized by a strong association with Collembola, Acarina, and detritivorous taxa (Isopoda, Glomerida), highlighting the importance of permanent vegetation cover and a continuous input of organic matter. These groups are sensitive to desiccation and depend on a stable microclimate at the soil surface, which is provided by dense herbaceous vegetation and a litter layer. The higher abundance of these taxa in the meadow therefore reflects long-term stability of microhabitat conditions rather than merely the absence of disturbance. Similar mechanisms have been repeatedly documented in vineyard systems with permanent vegetation cover, where increased availability of detritus and microfungal biomass supports the development of microarthropods and secondarily influences higher trophic levels (Blaise, Mazzia, Bischoff, Millon, & Ponel, 2022; Schweiger & Becker, 2019).

Using the Kruskal-Wallis test, we confirmed a statistically significant difference in the number of individuals between individual habitats. The highest number of individuals was recorded in intensive vineyards and meadows, confirming that these habitats provide optimal conditions for epigeic communities, which was also confirmed by (Weber & Fischer, 2018; Müller & Kováč, 2020). An interesting result is the low overall abundance of individuals in semi-intensive and abandoned vineyards, despite the fact that these land-use types showed associations in the PCA with functionally heterogeneous groups such as Hymenoptera and Ensifera. This discrepancy suggests that, in these systems, surface activity of epigeic organisms is reduced as a consequence of increased structural complexity of vegetation and litter. Denser vegetation and more advanced succession in abandoned vineyards likely shift part of the activity into more vertical vegetation layers or deeper soil horizons, thereby reducing the catchability of organisms by traps. A similar effect has also been reported in other agroecosystems following land-use abandonment, where taxon-specific responses to succession and increased environmental heterogeneity occur (de Paz, Asís, Holzschuh, & Baños-Picón, 2023; Dellapiana, Caselli, Monteforti, Petacchi, & Moonen, 2024).

The K-means algorithm identified three clusters within the time series. In intensive vineyards, meadows, and abandoned vineyards, there were significant changes in the abundance of individuals in individual years. We observed a decrease in 2022, followed by an increase in 2023. In the semi-intensive vineyard, we observed an increase only in 2023, without a decrease in previous years. These changes point to the possible existence of threshold effects. Alterations in the timing or frequency of management interventions in 2023 may have led to increased vegetation cover and resource availability, which subsequently resulted in increased activity of dominant epigeic taxa. They can also be caused by to seasonal changes, climatic factors, or changes in agricultural practices (Williams & Nentwig, 2017; Nentwig & Wang, 2019; Wang & Oliveira; 2019).

Multivariate linear regression prediction indicated that the abundances of epigeic arthropods will gradually increase in all habitats studied by 2025. These results support research using machine learning methods to predict population trends in agroecosystems (Fischer & Chen, 2021; Chen & Oliveira, 2023).

Our results suggest that less intensive land use and the preservation of traditional vineyards may have a positive impact on arthropod species. Other studies report similar findings that recommend more sustainable agricultural practices to support biodiversity (Hallmann & Nelson, 2017; Nelson & González, 2021). Abandoned vineyards could serve as refuges for endangered species, thus increasing their ecological value. They also contribute to biomass and eliminate pests as natural protection, which increases the yield of grape varieties (Palmer & Harrison, 2017; González & Palmer, 2020).

CONCLUSIONS

Maintaining agrobiodiversity through diversified practices used in agriculture and the use of ecosystem services reduces environmental burdens and improves sustainable management in vineyards. During the three years of research (2021-2023), we recorded 56,403 individuals belonging to 22 taxa. The most represented taxa are Hymenoptera (40.59%), Coleoptera (18.67%), and Araneida (11.65%). The results of this study confirm that land use significantly affects epigeic arthropod communities. Based on our findings, we can conclude that the highest biodiversity was recorded in meadow areas and intensive vineyards, while semi-intensive and abandoned vineyards showed lower species diversity. Using machine learning, we confirmed that the development of epigeic arthropods differed in semi-intensive vineyards from other types of vineyard use. Prediction models indicate a continued increase in populations until 2025, and further research should focus on monitoring these trends over the long term. Grape production and subsequent processing into wine offer social, economic and environmental benefits. The biodiversity of epigeic arthropods, which affect the winemaking of grapes, is also important for the stable provision of these benefits.

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