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Impact of Environmental Conditions and Management on Soil Arthropod Communities in Vineyard Ecosystems

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Abstract: The importance of soil biodiversity and soil-based ecosystem services in the context of viticulture has recently been emphasized. Over 85% of soil fauna species richness is represented by edaphic arthropod communities. Edaphic arthropod responses to soil characteristics and management practices can be considered as good bioindicators of soil quality. Here, 168 soil samples that were collected from 2014 to 2019 in several vineyards of different Italian wine-growing areas were analyzed to explore how arthropod communities respond to several factors that are characteristic of vineyard ecosystems. The analysis of the combined effects of the primary abiotic variables (the chemical and physical characteristics of soil) and management practices (organic vs. conventional, soil inter-row management) on soil biological quality (assessed by QBS-ar index) identified soil temperature and soil texture as the abiotic factors exerting the most significant effect on the QBS-ar values. Organic vineyards exhibited higher QBS-ar values compared to those of conventionally managed vineyards, and subsoiling negatively influenced the soil biological quality.

Keywords: soil biological quality; vineyard; organic management; soil temperature; soil texture; subsoiling

1. Introduction

Soil biota is the primary actor in soil ecological processes and plays a pivotal role in the provisioning of soil-based ecosystem services [1,2]. Soil contains a vastly diverse range of organisms, which include microorganisms, small and large invertebrates, and small mammals [3]; however, over 85% of the species richness of the soil fauna is represented by edaphic arthropods [4]. Therefore, arthropod community diversity can be considered as a good bioindicator of soil quality [5,6]. Numerous studies have investigated the relationships among arthropod diversity and abundance and environmental factors (e.g., soil abiotic variables and meteorological factors) and agronomic practices (e.g., canopy and soil management) [7–16].

The importance assigned to soil arthropods requires the identification of ready-to-use tools for assessing arthropod biodiversity [17]. The QBS-ar index is an acronym of soil biological quality-arthropods (in Italian "Qualità Biologica del Suolo") and is one of the most frequently applied indexes for the evaluation of edaphic arthropod communities in the agricultural sector. This index was proposed by Parisi [18], and its application proved to be useful in discriminating different disturbance levels related to different land use [19,20] or management systems [21,22]. QBS-ar applications are quite easy, as high taxonomic skills are not required. This index focuses on the identification of biological forms that are based on specific functional traits (e.g., pigmentation level, body dimensions) that are linked to different adaptation levels to the soil environment. The index is based on the principle that the greater the sensitivity of a soil arthropod taxon to variability and perturbation of soil conditions, the greater the importance of that taxon as an indicator of soil biological quality.

The QBS-ar has already been applied in research examining forests [23,24] and several agricultural agroecosystems [10,25–27]. Current research shows a growing interest in investigating soil biological quality in vineyards.

The wine-growing sector represents one important agricultural compartment, and it covers approximately 7.3 million hectares worldwide, with approximately 3.3 million located in Europe [28]. Sustainability within the wine-growing sector is becoming a major issue. In particular, available knowledge demonstrates that chemical and physical characteristics, soil environmental conditions, and management affect soil vineyard biodiversity; the relationship between vineyard management and soil arthropods represents a key element in promoting the transition to an ecologically and economically sustainable viticulture [29]. Ghiglieno et al. [30] explored the effect of abiotic variables, such as meteorological conditions and the chemical–physical composition of vineyard soils on the QBS-ar index. Regarding vineyard management, some effects of different inter-row management techniques on edaphic arthropod communities have been previously characterized [31–35], while differences in soil biological quality between conventionally and organically managed vineyards remain largely unexplored [30,34,36]. Therefore, the current understanding of how arthropod communities respond to the complexity of interaction factors characterizing vineyard ecosystems is still far from being complete.

This study aimed to explore the combined effects of the primary abiotic variables (soil chemical and physical characteristics) and management practices (organic vs. conventional, soil inter-row management) on the soil arthropod community (QBS-ar index). The analysis is based on data collected from several field studies conducted from 2014 to 2019 in different Italian viticultural areas. The knowledge acquired from the multifactorial analysis of the responses of edaphic fauna to several abiotic variables and agronomic practices is crucial for the definition of sustainable soil management practices and, thus, for a sustainable wine-growing system.

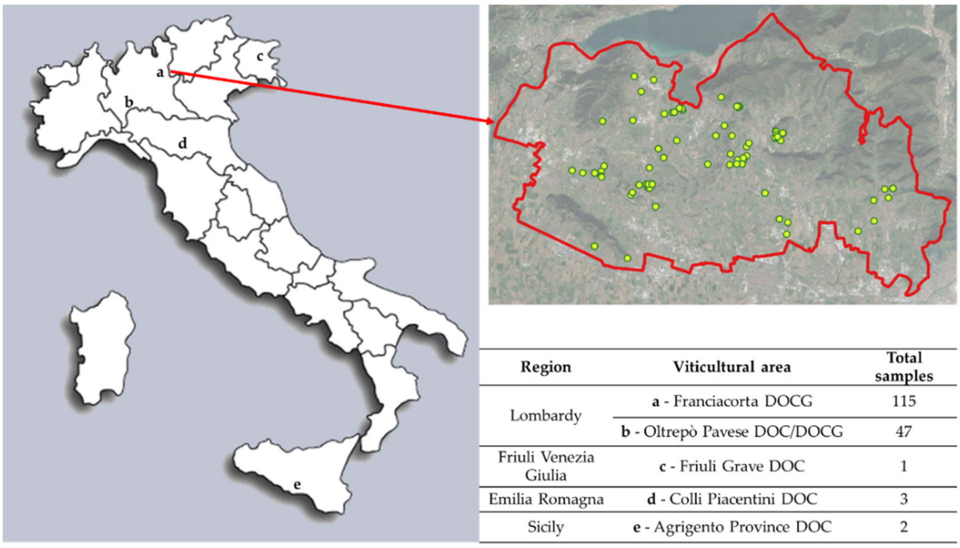
2. Materials and Methods

2.1. Study Sites Description

A total of 168 soil samples were collected from 2014 to 2019 in five different Italian wine-growing regions. Figure 1 presents the locations of the wine-growing areas and the number of samples collected in each area. Over 65% of the investigated vineyards were located in the Franciacorta DOCG area. Approximately 48% of samples were collected during spring, while 52% were collected during autumn.

2.2. Abiotic Variables

Soil environmental variables. Soil moisture and soil temperature data were gathered from the fifth generation of European ReAnalysis (hereinafter, ERA5-land) hourly database. The ERA5-land provides globally complete and consistent datasets at a high spatial ($0.1^\circ \times 0.1^\circ$) and temporal (hourly) resolution [37] that are computed at different depth levels for soil-related variables. We extracted the data for the first two soil layers (average depths of 3.5 and 17.5 cm) and interpolated them linearly to obtain hourly soil moisture (M) and hourly soil temperature (T) data at a soil depth of 15 cm. Bilinear interpolation using climate data operator (CDO) commands [38] was performed.



Region	Viticultural area	Total samples
Lombardy	**a** - Franciacorta DOCG	115
	b - Oltrepò Pavese DOC/DOCG	47
Friuli Venezia Giulia	**c** - Friuli Grave DOC	1
Emilia Romagna	**d** - Colli Piacentini DOC	3
Sicily	**e** - Agrigento Province DOC	2

Figure 1. Location of the five wine-growing areas included in the study (**left**). In the highlighted area of Franciacorta DOCG (**right**), the sampled vineyards are indicated by yellow dots.

Based on M and T, we computed a set of soil environmental indicators. The average of the daily minimum, mean, and maximum soil temperature (T_min, T_med, and T_max, respectively) and the average soil moisture (M_med) were calculated for two time intervals that were included during the 7-day period prior to the sampling date (referred to as short-term period: indicator prefix 'short_') and the 30-day period prior to the sampling date (referred as medium-term period: indicator prefix 'medium_'). Moreover, cumulative degree day (DD) indicators were calculated during the medium-term period based on the following thermal thresholds: $T \geq 30$ °C (DD_hot), $T \leq 10$ °C (DD_cold); 18 °C $\leq T <$ 30 °C (DD_warm), 10 °C $\leq T <$ 20 °C (TL), and $T \geq 20$ °C (TH). Furthermore, we included within the analysis the indicators associated with soil moisture, as suggested by Ghiglieno et al. [39] for our assessment during the medium-term period:

$$\mathrm{MD} = \frac{1}{24}\sum|\mathrm{M_i} - 0.35|, 0 \leq \mathrm{M} \leq 0.35 \tag{1}$$

$$\mathrm{MH} = \frac{1}{24}\sum(\mathrm{M_i} - 0.35),\ \mathrm{M} > 0.35 \tag{2}$$

MD is the sum of the daily absolute deviations of soil moisture from the threshold value, when M is lower than 0.35. MH is the cumulative daily soil moisture that exceeds 0.35.

Chemical and physical characterization of soils. Soil samples were collected at a depth of approximately 0–20 cm; leaf litter layer was excluded. All samples were mixed homogeneously, air-dried, and passed through a 2 mm sieve for chemical analysis. Soil chemistry was characterized according to the Italian regulation (DM 13 September 1999), including soil texture (sand, silt, clay g/kg of soils), pH, organic matter content (expressed in g kg^{-1} of soil) (SOM), available P expressed as P_2O_5 (mg kg^{-1} of soil), available K expressed as K_2O (mg kg^{-1} of soil), and available Mg expressed as MgO (mg kg^{-1} of soil). These variables were categorized according to the following criteria: soil texture [40] (p. 125), pH [41] (p. 66), organic matter content [42] (p. 31), available P [43] (p. 4), available K (previously converted from K to K_2O, conversion factor 1.2046) [42] (p. 45), and available Mg (converted from Mg to MgO, conversion factor 1.6579) [42] (p. 45).

2.3. Vineyard Age and Management Variables

Vineyard age. Vineyard age was categorized into four classes based on the number of years that the vines had been planted at the time of sampling, and these categories included vineyards up to 3 years old, vineyards of at least 4 and at most 10 years old, vineyards of at least 11 and at most 20 years old, and vineyards older than 20 years.

Vineyard management. Vineyard management was categorized into two main groups that included conventionally managed vineyards (hereinafter 'conventional') and organic managed vineyards in compliance with the European Regulation on organic farming (regulation (EC) no. 2018/848 and subsequent amendments and additions) (hereinafter 'organic'). Organic vineyards were further subdivided in three groups according to the time elapsed at the time of sampling since the start of the conversion period. The sub-groups included 'organic $\leq$ 3' vineyards that were within the 3-year conversion period provided by European regulations on organic farming, and '3 < organic $\leq$ 9' and 'organic > 9' groups that included certified organic vineyards for which between 4 and 9 years or greater than 9 years (respectively) have elapsed, including conversion period.

Soil management. Three aspects of soil management were considered, including tillage (subsoiling), fertilization, and grass cover. Subsoiling referred to the presence or absence of deep tillage (approximately 30 cm) in the autumn preceding sampling. Fertilization indicated whether fertilization had been performed in the autumn prior to sampling. Grass cover was classified into six classes of the prevailing plant species that were identified in the vineyard grass community during the year of sampling: seeded mixture prevailing legumes (SML), seeded mixture prevailing species other than legumes and graminaceous (SMO), spontaneous grass cover prevailing legumes (SpL), spontaneous grass cover prevailing graminaceous (SpG), spontaneous grass cover prevailing species other than legumes and graminaceous (SpO), and grass cover absence, where continuous tillage was performed with the aim of eliminating spontaneous grass cover (Tillage).

2.4. Soil Biological Quality Evaluation (QBS-ar)

A cubic sample of soil (with a dimension of 10 × 10 × 10 cm) was collected in each vineyard at the same depth as that described for chemical and physical soil analysis. Arthropods were extracted by placing the soil sample in a Berlese–Tüllgren funnel under a 60 W incandescent bulb, and this caused soil arthropods to migrate toward the damp portion of the soil sample (away from the light) and to fall through the funnel cavity into a preserving solution (2/3 alcohol and 1/3 glycerol). The biological forms, taxonomic entities, and biological stages were determined according to the QBS-ar method [44].

2.5. Data Analysis

A multiple linear regression (MLR) model was applied with the aim of analyzing the linear relationships among the response variable (QBS-ar) and the explanatory variables; these variables include factors related to soil environmental indicators (see Table 1), soil chemical and physical categorical variables, and management variables (see Table 2). Considering the large set of potential predictors, a bidirectional stepwise selection [45] was applied to select the best subset of explanatory variables that could explain the variance of the response variable based on the minimization of the Akaike information criterion [46]. Statistical analysis was performed using R software (version 4.0.4), MASS package.

Table 1. Descriptive statistics for continuous factors related to vineyard age, soil chemical characteristics, soil environmental indicators, and QBS-ar in 168 soil samples collected from five different Italian wine-growing regions from 2014 to 2019.

Factors	Units	Mean ± SD *	Range (Minimum, Maximum)
Vineyard age	years	13.3 ± 6.7	1.0–41.0
MH	Pure number	0.55 ± 0.47	0.00–2.34
MD	Pure number	1.50 ± 1.32	0.02–4.80
TL	°C	111 ± 40	53–184
TH	°C	38.8 ± 31.5	0.5–99.8
medium_T_min	°C	17.4 ± 3.6	10.5–24.1
medium_T_max	°C	22.1 ± 3.8	14.1–29.2
medium_T_med	°C	19.3 ± 3.5	12.9–26.5
medium_M_med	m^3 m^{-3}	0.31 ± 0.06	0.19–0.42
DD_hot	°DD	0.29 ± 0.95	0.00–6.23
DD_cold	°DD	0.09 ± 0.36	0.00–3.31
DD_warm	°DD	79.4 ± 64.8	0.0–219.9
short_T_min	°C	16.9 ± 3.1	10.6–23.8
short_T_max	°C	21.7 ± 3.4	16.3–30.8
short_T_med	°C	19.3 ± 3.0	13.7–27.1
short_M_med	m^3 m^{-3}	0.32 ± 0.05	0.16–0.41
QBS-ar		113 ± 46	11–226

[*] SD: standard deviation.

Table 2. Frequency distribution of categorical factors related to vineyard age, soil chemical and physical variables, vineyard management, and soil management in 168 soil samples collected from five different Italian wine-growing regions from 2014 to 2019.

Factors	Categories	Freq. Dist.	Factors.	Categories	Freq. Distr.
Vineyard age	0 < vineyard age ≤ 3 4 ≤ vineyard age < 10 11 ≤ vineyard age ≤ 20 vineyard age > 20	3.6% 28.6% 56.0% 11.9%	Vineyard management	conventional organic ≤ 3 3 < organic ≤ 9 organic < 9	19.6% 33.3% 28.6% 18.5%
Soil texture	clay/clay loam/silty clay silty clay loam loam silt loam sandy loam	10.1% 20.8% 28.0% 16.1% 25.0%	P	very low < 14 * low 14 ÷ 28 * medium 28 ÷ 45 * high 45 ÷ 70 * very high > 70 *	13.7% 29.8% 16.7% 24.4% 15.5%
SOM	low 8 ÷ 12 ** medium 12 ÷ 20 ** good 20 ÷ 40 **	16.7% 23.2% 60.1%	pH	acid 5.5 ÷ 6.0 sub-acid 6.1 ÷ 6.7 sub-alkaline 7.3 ÷ 7.9 alkaline 8.0 ÷ 8.6	13.7% 20.8% 25.6% 39.9%
Mg	very Low < 83 *** low 83 ÷ 166 *** medium 167 ÷ 249 *** good 250 ÷ 332 *** rich 333 ÷ 414 *** very rich > 414 ***	4.8% 32.7% 22.6% 10.7% 6.0% 23.8%	K	low 48 ÷ 96 **** medium 97 ÷ 145 **** good 146 ÷ 217 **** rich 218 ÷ 289 **** very rich > 289 ****	22.6% 23.2% 32.8% 15.5% 6.0%
Subsoiling	yes no	38.7% 61.3%	Grass cover	SML SMO/SpL SpG SpO Tillage	17.3% 5.4% 46.4% 17.0% 1.8%
Fertilization	yes no	36.3% 63.7%			

"*" P_2O_5 mg kg^{-1}; "**" g kg^{-1}; "***" MgO mg kg^{-1}; "****" K_2O mg kg^{-1}.

3. Results

3.1. Descriptive Analysis

Descriptive statistics and frequency distributions. The descriptive statistics for the continuous factors related to vineyard age, soil environmental indicators, and QBS-ar included in the multiple linear regression model are reported in Table 1, and the frequency distributions of categorical factors are reported in Table 2. The QBS-ar index exhibits great variability and ranges from 11 to 226.

Taxa identification and EMI attribution. Table 3 shows taxa identified in the analyzed samples. A total of 25 taxa were identified from the QBS-ar method application. The range of EMI scores associated to each taxon is also reported.

Table 3. Taxa identified in the analyzed samples and the associated range of EMI scores.

Taxa	Number of Samples Where Taxon Was Identified	Range of EMI Scores	Taxa	Number of Samples Where Taxon Was Identified	Range of EMI Scores
Mites	157	20	Isopoda	34	10
Other holometabolous insects	23	1	Lepidoptera (larvae)	7	10
Chilopoda	78	10–20	Pauropoda	105	20
Coleoptera	90	1–20	Symphyla	125	10
Coleoptera (larvae)	85	10	Opiliones	2	10
Collembola	160	1–20	Protura	91	20
Diplopoda	52	10–20	Pseudoscorpiones	49	20
Diplura	91	20	Psocoptera	20	1
Diptera	32	1	Thysanoptera	23	1
Diptera (larvae)	70	10	Araneae	14	1–5
Hemiptera	105	1–10	Palpigradi	2	20
Hymenoptera	147	1–5	Microcoryphia	2	10
Hymenoptera (larvae)	26	10			

3.2. Linear Regression Analysis

The stepwise multiple linear regression model exhibits a good fit to the data, where it explains half of the variability of the QBS-ar values (adjusted R-squared value = 0.477). The explanatory variables that were statistically significant were vineyard management, subsoiling, soil texture, TL, TH, Short_T_med, and DD_warm (Table 4), while TL (cumulative daily soil temperature degrees exceeding 10 °C, when T was between 10 °C and 20 °C) possessed a *p*-value that was slightly higher than 0.05. The effects of each factor should be interpreted based on the consideration that all the other variables are equal. The results are presented in the following sections.

Table 4. Table presenting factors that significantly influenced QBS-ar.

Factors	Coefficient Estimates	Std. Error	*p*-Value
Management: organic ≤ 3	28.793	11.136	0.011 *
Management: $3 <$ organic ≤ 9	23.060	9.361	0.015 *
Management: organic > 9	8.250	11.717	0.001 **
Subsoiling	−13.482	6.446	0.038 *
Soil texture: Loam	17.374	6.744	0.011 *
Soil texture: Clay Loam	41.305	9.836	<0.001 ***
Soil texture: Silty clay loam	45.873	8.145	<0.001 ***
TL	0.273	0.142	0.057 ·
TH	0.992	0.231	<0.001 ***
short_T_med	−9.470	1.659	<0.001 ***
medium_DD_warm	0.352	0.084	<0.001 ***

"***" $p < 0.001$; "**" $p < 0.01$; "*" $p < 0.05$; "." $p < 0.1$.

3.3. *Effect of Abiotic Variables*

Environmental soil indicators. All environmental indicators that significantly influenced QBS-ar were related to soil temperature (Table 3). QBS-ar values were positively influenced by TH ($p < 0.001$), medium_DD_warm ($p < 0.001$), and TL ($p = 0.057$), and they were negatively affected by short_T_med ($p < 0.001$).

Chemical and physical soil variables. The linear regression model identified a significant relationship between soil texture and QBS-ar. In particular, the QBS-ar on average is higher in soils possessing loam, clay loam, and silty clay loam textures than in soils exhibiting the other texture categories (clay, silty clay, silt loam, sandy loam), and these data are described in Figure 2.

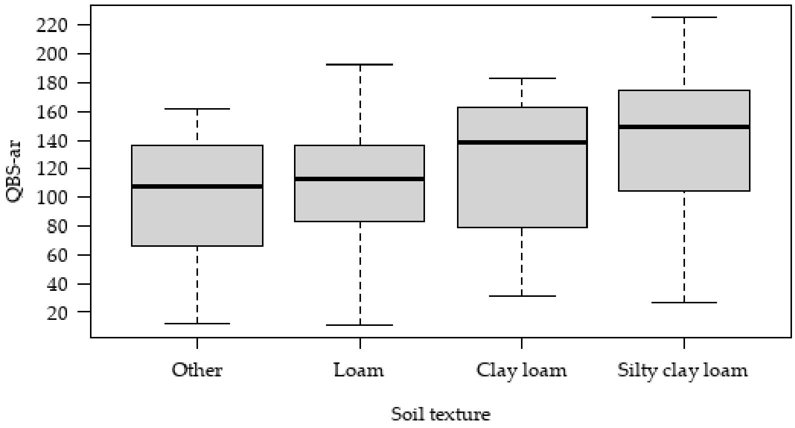


Figure 2. The boxplots provide the frequency distributions of QBS-ar values in the 168 soil samples divided according to soil texture categories. The category "Other" includes clay, silty clay, silt loam, and sandy loam soils.

3.4. *Effect of Management Variables*

Vineyard management. The model results revealed that the expected value of QBS-ar in soils sampled from organic-managed vineyards was higher than was that in soils sampled from conventionally managed vineyards. This positive effect is already statistically significant in the first 3 years of adoption of the organic management protocol ($p = 0.011$), that corresponds to the period of conversion from conventional to organic management. The positive influence of organic management was maintained during the periods encompassing 3–9 years after adoption ($p = 0.015$) and beyond 9 years from adoption ($p = 0.001$).

Soil management. Subsoiling was the only soil management practice that significantly influenced QBS-ar ($p = 0.038$). Subsoiling reduced the value of QBS-ar with respect to soils where subsoiling has not been applied (Figure 3).

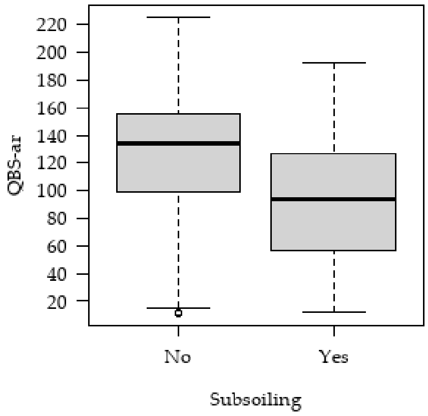


Figure 3. The boxplots provide the frequency distributions of QBS-ar values in the 65 soil samples where subsoiling was performed during autumn prior to sampling (**right**) and in the 103 soil samples where subsoiling was not performed (**left**).

4. Discussion and Conclusions

The QBS-ar index has been described by many authors as a useful indicator for discriminating among different soil disturbance levels and soil biological quality [19,22,44,47,48]. QBS-ar has been used in both semi-natural habitats and agroecosystems [10,21,23–27]. Previous studies performed in low disturbed environments, such as grasslands and woodlands, exhibited average QBS-ar values ranging between 140 and 173 [21]. Experiments examining vineyards revealed high variability among QBS-ar values that ranged from 98 to 203 depending on the farming systems [34]. In our study, the average value for the QBS-ar index is equal to 113.5 (±46.1), with a minimum value of 11 and maximum value of 226. These results are in agreement with those of Menta et al. [22] and suggest that vineyard ecosystems can potentially reach QBS-ar values similar to or even higher than environments with lower disturbance levels.

Results obtained from our analysis revealed that the effects of environmental soil indicators on QBS-ar were predominantly associated with soil temperature. This is fully in agreement with scientific evidence emphasizing the important effects of soil temperature on edaphic arthropod survival, development, and reproduction [49,50]. In particular, soil temperature in the range of 10 °C–20 °C, as evaluated in the medium-term period, has a positive effect on QBS-ar. This positive effect is of greater intensity if the soil temperature ranges from 18 °C to 30 °C. These findings are in agreement with those of previous studies that identified that the optimal temperature range for development and growth was between 20 °C and 30 °C [51,52]. Analysis of the effect of soil environmental conditions in the short-term period (7 days before sampling) revealed a negative relationship between average temperature (short_T_med) and QBS-ar. This result may be related to the ability of soil organisms during the short-term period to mitigate the effect of high temperature by migrating to deeper soil layers, where they are then not identified in the analyzed soil sample [53–55].

In our study, soil moisture that was assessed both in the medium and short periods did not exhibit a significant relationship with QBS-ar. The average values for soil moisture in our samples are 0.31 and 0.32 $m^3\ m^{-3}$ in the short-term and medium-term periods, respectively. These values are very close to the threshold of 0.35 $m^3\ m^{-3}$, which is considered as the optimal value for survival and reproduction for some edaphic species [56,57]. Therefore, in the sampling conditions of our study, soil moisture stress conditions that may have influenced QBS-ar likely did not occur.

Soil texture was the only physical soil parameter that affected QBS-ar, where it caused an increase in this index in soils with loamy soil texture or with loam in association with fine soil fractions (clay loam and silty clay loam). The influence of soil texture on some specific taxa of soil arthropods has been demonstrated by other authors [58,59], although arthropod responses to soil texture variations are not unique. For example, Van Capelle et al. [60]

observed that all Collembola life-forms (both atmobionts and euedaphic) were equally promoted in finer texture conditions and that loamy texture reduced the presence of these taxa.

Results of experiments investigating the role of management in influencing edaphic arthropod community responses have been of particular importance for the definition of sustainable agronomic practices to preserve and/or increase soil biological quality. Arthropod communities are positively influenced by organic management with respect to conventional management. This is in agreement with previous studies performed in a vineyard environment [30,34,39]. Regarding the timing of the adoption of organic management, QBS-ar value is significantly improved during the first 3 years of adoption according to other experiences carried out in vineyard ecosystems [39].

Results obtained from soil management variable analysis highlighted the negative effect of subsoiling on the QBS-ar index. This soil management practice led to a decrease in QBS-ar values, thus supporting the scientific evidence that emphasizes the sensitivity of edaphic arthropods to soil tillage in the short term [21,32]. However, a more detailed investigation of the role of tillage requires consideration in regard to the long-term effects of agronomic practices on soil arthropod responses, as suggested previously [61,62].

This study, in relation to the large number of observations considered and the variability of the geographical context observed, provides relevant knowledge regarding the effects of soil abiotic conditions and management practices in the vineyard ecosystem on edaphic arthropods. The opportunity to consider different variables related to different dimensions, such as environmental and management, represents an element of innovation that supports the comprehension of how arthropod communities respond to the complexity of interaction factors characterizing vineyards.

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Conflicts of Interest: The authors declare no conflict of interest.

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