Sustainable management of vineyard soils: an experimental approach to investigate the responses of the edaphic arthropod community

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Abstract

This research aims to investigate the response of the edaphic arthropod community (assessed with the QBS-ar index) to vineyard soil management, through a field experiment conducted in the context of the F.A.Re.Su.Bio Project (European Agricultural Fund for Rural Development - Lombardy Region). Nineteen vineyards located in two Italian wine-growing regions, Franciacorta DOCG and Oltrepò Pavese DOC/DOCG, were monitored over a period of 3 years (2019-2021), in order to investigate the combined effects of primary abiotic variables characterising the soil environment, such as the chemical and physical composition of soil, and soil management practices including organic fertilisation, organic fertiliser incorporation, tillage and the use of different artificial cover crop on the QBS-ar index. The results obtained from the study showed that a moderate disturbance of the soil could lead to positive effects on QBS-ar, as well as sowing practice. Of the chemical and physical characteristics of soil, texture proved to be the variable most influencing variation in QBS-ar; other influencing variables included chemical components of soil such as initial (2019) QBS-ar, total Cu, pH, CEC, and exchangeable phosphorous content. This study provided an indication of how the combined effects of soil management influence soil biological quality, and how to improve soil biodiversity.

Keywords: soil biological quality, artificial sowing, cover crop, organic fertilisation, soil tillage

INTRODUCTION

Among soil components, soil fauna is one of the most significant in determining soil quality in agroecosystems (Teixeira et al., 2021). The edaphic arthropod community represents over 85% of the species richness of soil fauna (Bagyaraj et al., 2016) and plays a pivotal role in the provisioning of soil-based ecosystem services (Bünemann et al., 2018). Soil arthropods are considered good bioindicators to changes in environmental conditions (Juan-Ovejero et al., 2019), soil properties (Ruf et al., 2003), and soil management practices (Marasas et al., 2001). Several studies of agroecosystems have focused on soil arthropod community as soil quality bioindicators highlighting the influence of soil chemical and physical characteristics such as soil texture (van Capelle et al., 2012), SOM content (Potapov et al., 2017), pH (Santorufo et al., 2012) and heavy metal concentration (Bengtsson et al., 1983) on soil biota. Numerous studies have also investigated the relationships between arthropod diversity and abundance, and agronomic practices such tillage (Ghiglieno et al., 2021) and cover crop management (Warren Raffa et al., 2021). Specifically, some authors have explored the effect of soil management and the abiotic variables of agricultural soil on the QBS-ar Index (Ghiglieno et al., 2019). This 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 arthropods in agroecosystems. This index was proposed by Parisi (2001) and focuses on the identification of biological forms based on specific functional traits (e.g., pigmentation level and body size) 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.

This research aims to investigate the response of the soil arthropod community, measured using the QBS-ar Index to different vineyard soil management practices, adopting multifactorial analysis. This approach makes it possible to evaluate the combined effects of primary abiotic variables (soil environmental conditions, soil chemical and physical characteristics) and management practices (organic fertilisation, organic fertiliser incorporation, tillage and use of different artificial cover crops) on QBS-ar. The results obtained from this study lead to an increase in knowledge regarding the responses of edaphic fauna to several abiotic variables and agronomic practices.

MATERIALS AND METHODS

Study sites description

This research was developed in the context of the F.A.Re.Su.Bio Project (European Agricultural Fund for Rural Development - Lombardy Region). A total of 19 vineyards located in two Italian wine-growing regions, Franciacorta DOCG and Oltrepò Pavese DOC/DOCG, were involved in experimental activities. Figure 1 presents the locations of experimental vineyards: 10 vineyards were located in the Franciacorta DOCG area, while 9 were located in the Oltrepò Pavese DOC/DOCG area.

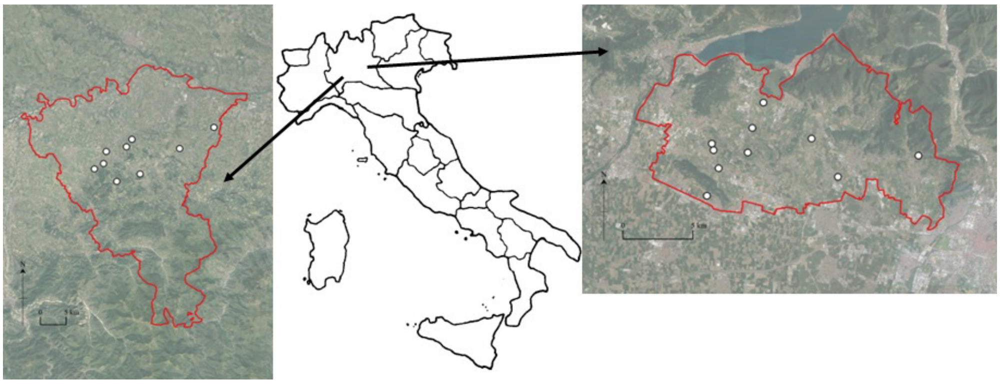

Figure 1. Location of the 2 wine-growing areas included in the study: Franciacorta DOCG (top right) and Oltrepò Pavese DOC/DOCG (bottom right). The 19 vineyards included in the study are shown with white dots.

Experimental design

Two experiments were carried out. The first (SOIL MANAGEMENT) was aimed at exploring the effect of spontaneous cover crop (UNT) compared to the effect of sown cover crop (SOWN) and organic fertilisation (ORG). This experiment involved 9 vineyards (7 located in Franciacorta DOCG and 2 in Oltrepò Pavese DOC/DOCG). With the SOWN treatment, 40 kg ha^{-1} of a mixture of buckwheat, Alexandrine clover, Persian clover, phacelia, horseradish (Miscela Sovescio Nove - Arcoiris) were distributed. With the ORG treatment, fertiliser input was applied, considering a standardised content of total organic carbon (TOC) of 1 t ha^{1}. Organic fertiliser was immediately incorporated into the soil at a depth of 15 cm. During the season, the spontaneous cover crop in UNT and ORG was periodically mowed, while with the SOWN treatment the cover crop was rolled in spring, mowed in summer and incorporated into the soil in autumn, after sowing the following year. The second experiment (SOIL ORG FERTILISATION) was carried out in the remaining 10 vineyards (3 located in Franciacorta DOCG and 7 in Oltrepò Pavese DOC/DOCG) with the aim of comparing the effects of different organic fertiliser incorporation. A standard input of organic fertiliser was established as 1 t ha^{-1} of total organic carbon (TOC). Incorporation was carried out at three levels: i) surface distribution of organic fertiliser without incorporation (ORG); ii) surface distribution of organic fertiliser followed by immediate incorporation by raking up to a depth of 20 cm (ORG-INC1); iii) surface distribution of organic fertiliser followed by immediate incorporation to a depth of 20 cm and periodic raking to a depth of 20 cm (ORG-INC2). The treatments were organised into three blocks, each consisting of inter-row sections of 15 m. The treatments were repeated in autumn 2019 and autumn 2020 in the same blocks over the whole trial period.

Soil environmental variables and indicators

Volumetric soil water (SW) and soil temperature (ST) data were selected from fifth generation European ReAnalysis (hereafter ERA5-land) hourly database. ERA5-land provides globally complete and consistent data sets with a high spatial resolution (0.1°×0.1°, about 8-11 km in Lombardy) and temporal resolution (hourly) (Muñoz-Sabater et al., 2021) in NetCDF format computed at different depth levels (named "layers") for soil-related variables. We extracted the data for the first two soil layers (average depth of 3.5 and 17.5 cm) and interpolated them linearly to obtain hourly soil moisture and hourly soil temperature data at a soil depth of 15 cm. All the previous processing was conducted in R (R Core Team, 2021), NetCDF data extraction required the "ncdf4" package (Pierce, 2021). Based on SW and ST, we calculated a set of indicators for each time interval (7 and 30 days) prior to the sampling date, according to Liu et al. (2017). The selected indicators can estimate thermal stress (ind1), the degree of thermal suitability (ind2) and water stress (drought and moisture, ind3).

$$\text{ind1} = \sum_{1}^{h\in\{168,720\}} \begin{cases} 0.01416667 & ST < 0 \mid ST \geq 40 \\ 4{,}722 * 10^{-5} * ST^2 - 1{,}889 * 10^{-3} * ST + 1{,}417 * 10^{-2} & 0 \leq ST < 10 \mid 30 \leq ST < 40 \\ 0 & 10 \leq ST < 30 \end{cases}$$

$$\text{ind2} = \sum_{1}^{h\in\{168,720\}} \begin{cases} 0 & ST < 10 \mid ST \geq 30 \\ -7{,}813 * 10^{-4} + 7{,}813 * 10^{-5} * ST & 10 \leq ST < 26 \\ 9{,}375 * 10^{-3} - 3{,}125 * 10^{-4} * ST & 26 \leq ST < 30 \end{cases}$$

$$\text{ind3} = \sum_{1}^{h\in\{168,720\}} \begin{cases} 3{,}788 * 10^{-5} * SW^2 - 7{,}954 * 10^{-4} * SW + 4{,}167 * 10^{-3} & SW \leq 10 \\ 0 & 10 \leq SW < 45 \\ 6{,}313 * 10^{-8} * SW^2 - 1{,}578 * 10^{-6} * SW - 5{,}682 * 10^{-5} & SW \geq 45 \end{cases}$$

where h represents the hours prior to the sampling day (included), assuming 168 (7 days, prefix "short_") or 720 (30 days, prefix "medium_"). Inverse distance weighting (IDW) interpolation (power value = 2) was performed to estimate sampling point indicator values with the four nearest points of the ERA5-land grid. All previous processing was conducted in R (R Core Team, 2021). These indicators based on knowledge of the niche space aim to describe stress and suitable conditions. The SW thresholds of xeric stress were established according to Choi et al. (2002, 2006). The optimal SW range was assumed to be between 10 and 45%, according to Wiwatwitaya and Takeda (2005), Heiniger et al. (2015), O'Lear and Blair (1999), Xu et al. (2012); water stress was assumed to be effective over 45%. Biotic responses to ST were assessed by taking into account the lower development threshold of springtails and mites (Ermilov and Łochyńska, 2008; Uvarov, 2003), which was taken as the threshold for thermal stress (below 10°C). Non-limiting ST conditions were evaluated between 10 and 30°C, with an optimum at 26°C (Choi et al., 2002).

Chemical and physical characterisation of soils

Soil samples were collected in autumn 2019 (before treatment application) at a depth of approximately 0-20 cm, excluding the leaf litter layer. All samples were mixed homogeneously, air-dried, and passed through a 2-mm sieve for chemical analysis. Soil chemistry was characterised according to Italian regulations (D.M. 13/09/1999). Complete soil characterisation of each experimental vineyard was performed, including soil texture, pH, cation exchange capacity (CEC – meq 100 g^{-1}), total copper (mg Cu kg^{-1}), active limestones (g $CaCO_3$ kg^{-1}), available phosphorus (mg P_2O_5 kg^{-1} of soil), exchangeable potassium (mg K_2O kg^{-1} of soil), and exchangeable magnesium (mg MgO kg^{-1} of soil). Soil texture was categorised according to texture triangle classes (Soil Science Division Staff, 2017).

Soil biological quality evaluation (QBS-ar)

In 2019 and 2021 a cubic sample of soil (with a dimension of 10×10×10 cm) was collected in each block 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. A 60-W incandescent bulb placed above the sample caused soil arthropod migration towards the damp portion of the soil sample (away from the light), eventually falling out of the soil into a preserving solution (2/3 alcohol and 1/3 glycerol). The biological forms, taxonomic entities, and ecomorphological indexes were determined according to the QBS-ar method (Menta et al., 2018).

Data analysis

A multiple linear regression (MLR) model was applied with the aim of analysing linear relationships between the response variable (QBS-ar variation 2019-2021) and the explanatory variables; these variables include variables related to soil environment indicators, soil chemical and physical categorical variables, and management variables. Considering the large set of potential predictors, bidirectional stepwise selection (Venables and Ripley, 2002) was applied to select the best subset of explanatory variables that could explain the variance of the response variable, based on minimisation of the Akaike Information Criterion (AIC) (Yamashita et al., 2007). Statistical analysis was performed using R software (version 4.0.4), MASS package.

RESULTS AND DISCUSSION

Table 1 shows the descriptive statistics for the continuous variables included in the multiple linear regression model, respectively for the SOIL MANAGEMENT and SOIL ORG FERTILISATION experiment. Continuous variables are represented by soil chemical characteristics, soil environment indicators and initial (2019) QBS-ar. The decision to include initial QBS-ar was inspired by other studies that emphasised the different reaction of different soil conditions to soil management (Thiele-Bruhn et al., 2012), in terms of soil biological quality and fertility.

Table 1. Descriptive statistics for continuous variables for SOIL MANAGEMENT and SOIL ORG FERTILISATION experiments.

Continuous variables	Units	SOIL MANAGEMENT		SOIL ORG FERTILISATION	
		Mean ± SD[a]	Range (minimum, maximum)	Mean ± SD[a]	Range (minimum, maximum)
Total Cu	mg kg^{-1}	92.20±36.42	51.80-144.00	55.08±20.13	29.70-98.10
pH		7.51±0.59	6.50-8.20	7.59±0.97	5.7-8.4
CEC	meq 100 g^{-1}	20.09±6.74	9.90-29.40	21.13±5.53	11.60-31.20
Active limestone	g $CaCO_3$ kg^{-1}	8.89±19.47	0.00-61.00	42.80±46.03	0.00-114.00
Available phosphorus	mg P_2O_5 kg^{-1}	49.78±33.59	16.00-136.00	34.70±31.48	7.00-121.00
Exchangeable potassium	mg K_2O kg^{-1}	147.20±40.66	98.00-218.00	202.10±92.99	73.00-355.00
Exchangeable magnesium	mg MgO kg^{-1}	262.60±123.11	117.00-544.00	810.00±817.84	116.00-2852.00
QBS-ar 2019	Pure number	139.90±30.48	67.00-190.00	143.80±38.67	55.00-248.00
ind1_short		0.03±0.08	0.00-0.26	0.19±0.20	0.00-0.50
ind2_short		0.10±0.03	0.01-0.13	0.06±0.06	0.00-0.14
ind3_short		0.00±0.00	0.00-0.00	0.00±0.00	0.00-0.00
ind1_medium		0.12±0.32	0.00-1.03	0.69±0.69	0.00-1.57
ind2_ medium		0.53±0.18	0.03-0.61	0.30±0.27	0.02-0.62
ind3_ medium		0.00±0.00	0.00-0.00	0.00±0.00	0.00-0.00

[a]SD: standard deviation.

Texture was considered as a categorical factor with a frequency of distribution represented as follows: i) for SOIL MANAGEMENT, clay 22.2%, clay loam 11.1%, sandy loam 33.4%, silty loam 22.2%, silty clay loam 11.1%; ii) for SOIL ORG FERTILISATION, clay 11.1%, clay loam 11.1%, sandy loam 22.2%, silty loam 22.2%, silty clay loam 33.4%.

The variation in QBS-ar from 2019 and 2021, ranges between -105.00 and +99.00 (average value of +7.50±43.06) and between -101.00 and +146.00 (average value of -14.98±49.44), respectively, for SOIL MANAGEMENT and SOIL ORG FERTILISATION experiment.

Multiple linear regression analysis

The stepwise multiple linear regression model was applied separately for each of the two experiments (SOIL MANAGEMENT and SOIL ORG FERTILISATION).

Table 2 shows the variables selected as explanatory by the model referred to both experiments (SOIL MANAGEMENT and SOIL ORG FERTILISATION), and their statistical significance in influencing the variation of QBS-ar index (from 2019 to 2021). The effect of each variable is based on the consideration that all other significant variables are equal, and, in case of categorical variable, it should be interpreted considering the respective reference category.

Table 2. Table presenting the variables selected as explanatory by the models applied to the SOIL MANAGEMENT experiment to evaluate SOM and QBS-ar variation (2019-2021).

Experiment	Explanatory variable	Coefficient estimates	Std. error	p-value
SOIL MANAGEMENT	Reference: Treatment - UNT			
	Treatment - ORG-INC	0.671	6.855	0.922 n.s.
	Treatment - SOWN	12.648	6.874	0.070 .
	Reference: soil texture - loam			
	Soil texture - clay loam	-36.043	20.447	0.082 .
	Soil texture - silty loam	18.509	16.489	0.265 n.s.
	Soil texture - silty clay loam	-13.001	17.264	0.454 n.s.
	Soil texture - sandy loam	-33.506	11.037	0.003 **
	Total Cu	0.678	0.134	<0.001 ***
	pH	30.269	15.470	0.054 .
	QBS-ar 2019	-1.052	0.118	<0.001 ***
SOIL ORG FERTILISATION	Reference: treatment - ORG			
	Treatment - ORG-INC1	19.294	8.430	0.025 *
	Treatment - ORG-INC2	7.411	8.447	0.383
	Reference: soil texture - loam			
	Soil texture - clay loam	93.428	43.721	0.036 *
	Soil texture - silty loam	31.436	37.966	0.410
	Soil texture - silty clay loam	115.581	43.920	0.010 *
	Soil texture - sandy loam	-11.850	34.802	0.734
	CEC	0.650	1.425	<0.001 ***
	QBS-ar 2019	-1.009	0.112	<0.001 ***
	Available phosphorus	0.650	0.380	0.091 .

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

The model applied to SOIL MANAGEMENT experiment shows a good fit for the data, with an adjusted R-squared value of 0.658. Treatment was selected by the model as an explanatory variable revealing the positive effect of the SOWN treatment on QBS-ar variation in comparison to UNT (p-value<0.1). This response suggests that sown cover crop acts a positive role on soil biological quality providing different positive ecosystem services even though other researchers (Warren Raffa et al., 2021) associated this beneficial effect to spontaneous vegetation and not to artificial cover crop. The effect of texture is evident in influencing QBS-ar variation with a positive effect was associated with a sandy loam texture (p-value<0.01), in agreement with van Capelle et al. (2012). Other chemical characteristics of soils selected by the model as explanatory variables and significantly influencing the QBS-ar value, with a p-value of <0.001, were the initial value of QBS-ar (2019), and surprisingly total Cu content. As regards the former, the lower the initial QBS-ar (2019) value, the more positive the QBS-ar change at the end of the research period (2021). The positive effect of Cu content on QBS-ar variation contrasts with some evidence reported in the literature, which associates a heavy metal increase in the soil with a reduction in soil biological quality. However, some authors have already reported a positive effect of low Cu concentrations on some taxa of edaphic arthropods (Bengtsson et al., 1983). It must also be considered that, as shown in Table 1, the level of total Cu ranged between a minimum of 51.8 mg kg^{-1} and a maximum of 144.0 mg kg^{-1} with an average value of 92.2 mg kg^{-1}, which is considered below the threshold considered to be relevant by the reference legislation (Legislative Decree 152/06, Annex 5, Part IV, Table 1).

The model applied to SOIL ORG FERTILISATION showed a good fit for the data, with an adjusted R-squared value of 0.564. Treatments significantly influenced the variation in QBS-ar recording a positive effect of the organic matter incorporation (ORG-INC1) (p value<0.05) in comparison with surface distribution (ORG); as highlighted by other authors (Conti, 2015) a moderate soil disturbance could, in fact, be effective in enhancing soil biological quality by contrasting soil compaction which can occur in no tilled management. Furthermore, incorporation took place almost a year before the sampling of QBS-ar, giving the soil fauna the opportunity to recover after mechanical intervention (Gagnarli et al., 2021). Texture was selected as an explanatory variable by the model applied. Specifically, clay fraction (clay loam and silty clay loam textures) led to a positive effect on QBS-ar variation compared to loam texture (p value<0.5). As reported in model referring to SOIL MANAGEMENT, initial QBS value (2019) is negatively related to QBS-ar variation. Other soil chemical components showed a significant influence QBS-ar variation and specifically, CEC and available phosphorus which are positively related to QBS-ar variation. Probably due to a similar sampling period and the proximity of the sampled regions, environmental indicators (ind1, ind2 and ind3) were not selected as explanatory variables in any of the models applied.

CONCLUSIONS

This paper provides indications of how the combined effects of soil abiotic variables and soil management influence soil biological quality. The main results can be summarised as follows:

- a moderate soil disturbance can lead to positive effects on QBS-ar as well as artificial cover crop sowing practice;
- of the chemical and physical characteristics of soil, texture was shown to be the variable most influencing variation in QBS-ar;
- soils with poorer initial QBS-ar conditions react more quickly and positively to soil management;
- environmental indicators were not selected as explanatory variables in any of the models applied, while other chemical components of soil, such as total Cu, pH, CEC, and exchangeable phosphorus had an influence QBS-ar variation.

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