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Development of an integrated indicator for assessing management impacts on soil quality: A case study in organic viticulture

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ABSTRACT

Given that soil is an invaluable resource for viticulture, it is important to maintain its properties in order to keep it healthy and optimize ecosystem processes underpinning productivity. Although measuring sustainability poses challenges, it remains crucial for developing specific management strategies designed for a given geographic area. This study introduces the Management Impact on Soil Quality (MISQ), an integrated indicator designed to assess how common management practices influence the attributes of soil health in organic vineyards. The MISQ evaluates five key management components: soil disturbance, regeneration of soil organic matter, terrestrial ecotoxicity impact of copper, efficiency of nutrient (NPK) use, and biodiversity. This indicator was applied using data collected from an organically-managed vineyard in Franciacorta, a grape-producing area in Northern Italy over the years 2014, 2015, 2019 and 2021. The results indicate how enhanced soil function depends on increased supply of organic matter and diversified cover cropping with legumes, thereby improving soil biodiversity. However, managing potential nutrient surplus and recognizing the risks associated with tillage for row spacing management are also crucial factors. These results provide viticulturists with a valuable tool for assessing the effects of agronomic techniques on soil quality, thereby facilitating sustainable management practices. This study highlights the need to preserve the soil multifunctionality, which is critical for nutrient cycling, soil structural stability and biological population control. The straightforward approach of the MISQ makes it suitable for use in different environments, thereby promoting effective management strategies that mitigate a negative impact on soil functionality.

1. Introduction

Soil security is a fundamental concept that ensures the long-term availability and functionality of soils to support human and environmental needs. It encompasses not only soil health but also factors such as governance, economics, and sustainable management to maintain soil resources for future generations (McBratney et al., 2014). As a key component of soil security, soil health considers soil as a living ecosystem, emphasizing its biological activity, resilience, and capacity for self-regeneration and adaptation to changing conditions (Lal, 2016; Weil and Brady, 2017). Healthy soils support biodiversity, sustain plant and microbial life, resist degradation, and maintain their functions over time (Lehmann et al., 2020). Preserving soil health is essential for agricultural productivity, carbon sequestration, and climate resilience, making it a cornerstone for achieving the Sustainable Development Goals (Hou et al., 2020). However, soil degradation caused by intensive agriculture, deforestation, and climate change threatens both soil health and overall soil security by reducing fertility, increasing erosion, and depleting organic matter. Addressing these challenges requires sustainable land management strategies that restore and protect soil functions. In this context, soil quality plays a crucial role by providing the measurable foundation upon which soil health is built. While soil health focuses on biological and ecological dynamics, soil quality reflects the soil's capacity to perform essential functions such as nutrient cycling,

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water retention, and pollutant filtration. Assessing soil quality involves integrating physical, chemical, and biological properties to evaluate the soil's ability to support ecosystem functions and agricultural sustainability (Karlen et al., 2001; Seifu and Elias, 2018; Sepehya et al., 2024). Recognized as a key indicator of sustainable management, soil quality directly influences biological productivity, environmental quality, and ecosystem health (Herrick, 2000). Growing awareness of soil security has led to the introduction of new policies aimed at its protection. In particular, the European Union has developed regulatory frameworks, such as the European Soil Monitoring Law, to ensure sustainable management and promote the restoration of degraded soils (Kotschik et al., 2024). Assessing soil quality comprehensively and accurately is often complex and costly, as it requires integrating multiple multifunctional requirements and considering the impacts related to its use. Consequently, adopting an approach based on cross-functional indicators, which can simultaneously account for multiple soil functions, enables more efficient and sustainable assessment (Bone et al., 2010). Various approaches have been proposed for developing indicators to assess soil quality in agricultural contexts, including indices derived from the averaging of specific soil properties (Luo et al., 2017), composite indices based on expert scoring (Drobnik et al., 2018), and the use of Principal Component Analysis (PCA) to identify the principal components that explain most of the variability as synthetic indicators of soil quality (Bedolla-Rivera et al., 2020; Chandran et al., 2023; Sofi et al., 2016).

Given the growing interest in sustainable agricultural practices, soil quality assessment is particularly relevant in viticulture, where soil conditions directly influence both environmental sustainability and crop productivity (Baiano, 2021; García-Navarro et al., 2023). Vineyard management can lead to high rates of soil loss, influenced by factors such as topography, soil properties, and precipitation. In particular, vineyards, especially those without inter-row vegetation cover, are among the most erosion-prone crops due to management practices and soil characteristics (Prosdocimi et al., 2016; Raclot et al., 2009). In viticulture, as in other perennial crops, mechanization poses a high risk of soil degradation, particularly due to compaction. This process can be influenced by both the soil's intrinsic vulnerability and the agricultural practices adopted. Factors such as high traffic intensity, the use of high-pressure tires, and the absence of cover crops, which reduce soil bearing capacity, can exacerbate the problem in vineyards (Polge de Combret - Champart et al., 2013). Additionally, tillage can contribute to the depletion of organic matter and impact long-term soil fertility (Chopin et al., 2008). Improper use of pesticides can lead to groundwater contamination (Zambito Marsala et al., 2020), while intensive use of fungicides in vineyards may cause soil contamination, affecting biodiversity and altering soil ecosystems (Komárek et al., 2010).

In response to these environmental concerns, organic viticulture has gained popularity as a valuable solution for advancing sustainable agriculture (Ostandie et al., 2021). However, despite its benefits, organic viticulture also faces challenges related to soil quality. Among the pesticides authorized in organic viticulture, copper is the primary fungicide to combat downy mildew, but its progressive accumulation in soils poses a threat to soil fertility (Cesco et al., 2021). Copper accumulation in organic vineyards is often excessive (Jez et al., 2023), and some European vineyards have already exceeded the ecotoxicological threshold (Imfeld et al., 2021). Copper is highly toxic to soil ecosystems, with significant environmental impacts. Its ecotoxicity varies spatially, with higher toxicity observed in acidic and sandy non-calcareous soils due to lower buffering capacity, and in low-alkalinity waters where copper remains more bioavailable (Peña et al., 2018; Viveros Santos et al., 2018).

Viticultural practices, if not done properly, can also result in water deficiency and nutrient loss, low nitrogen availability, low organic matter content, and poor drainage capacity, making it difficult to restore soil fertility (Costantini, 2018). An excess of some nutrients, particularly N and P, poses a threat to the environment and potentially to our health.

Strategies for sustainable vineyard management should also prioritize enhancing soil biodiversity. For example, cover cropping with different species and combinations can impact plant nutrient and water uptake, soil health and grape quality (Lazcano et al., 2020). However, assessing how vineyard management has an impact on soil quality becomes a challenge when considering the multidimensional heterogeneity of these impacts.

In this context, indicators serve as a fundamental tool, as they are variables based on qualitative or quantitative data - observed, measured or calculated from other data - that provide information on more complex or less accessible variables (Latruffe et al., 2016).

The choice of how to aggregate and weigh indicators depends on their degree of compensability and the purpose. Equal weighting is a pragmatic solution in the absence of a clear consensus on their relative importance, while more advanced methods can offer greater accuracy, albeit with potential limitations related to subjectivity and data sensitivity. Aggregation is also crucial: a linear method allows full compensability between indicators, potentially masking critical issues, whereas a geometric aggregation reduces compensability, giving more weight to weaker indicators and promoting targeted interventions (Nardo et al., 2008).

Although various indicators have been proposed for assessing soil quality in viticulture, no specific tools have been developed to comprehensively analyze the integrated effects of viticultural practices on soil quality. In this study, an integrated indicator is proposed to measure the impact of management on soil quality in organic vineyards, with the aim of providing a comprehensive assessment and supporting viticulturists in adopting sustainable practices. Specifically, the Management Impact on Soil Quality (MISQ) indicator is introduced as a tool to comprehensively evaluate the effects of management practices on soil quality. Unlike existing indices, the MISQ considers a broad range of soil functions, including nutrient cycling, biodiversity, and resilience to degradation. Designed for operational use in vineyard management, it provides viticulturists with an effective tool to monitor and improve sustainability. This approach ensures a more comprehensive and reliable evaluation of the impact of viticultural practices on soil functionality and, consequently, soil quality. The aim is to offer a thorough assessment of soil quality and support viticulturists in achieving sustainable vineyard management. After identifying and normalizing the evaluation indicators, a case study is presented in an organically managed vineyard located in the Franciacorta grapevine-producing-growing area over a four-year assessment period.

2. Material and methods

2.1. Conceptual model of the management soil indicator

In order to evaluate the impact of management practices on soil quality, we developed the Management Impact on Soil Quality (MISQ) integrated indicator, based on an integrated assessment of five main management components: soil disturbance, regeneration of soil organic matter, terrestrial eco-toxicity impact of copper, efficiency of nutrient (NPK) use, and biodiversity (Fig. 1), as indicated by the equation below:

$$\mathrm{MISQ} = \sqrt[5]{S_{dis} \cdot R_{som} \cdot C_{tox} \cdot N_{eff} \cdot P_{bio}} \tag{1}$$

where $S_{dis}, R_{som}, C_{tox}, N_{eff},$ and P_{bio} are the indicators related to the five components of MISQ (Table 1). Details on these indicators are presented in the following section. In this study, the assessment components refer to an organic viticulture scenario; therefore, the selected indicators are based on practices and products permitted under the EU organic production regulation (EP, EC, 2018) .

The MISQ is based on a geometric mean that reflects the specific nature of each indicator. This method is particularly useful when positive indicators are expressed in ratio scales as it involves partial compensability, which means that poor performance in some indicators can be offset by sufficiently high values in other indicators. Moreover,

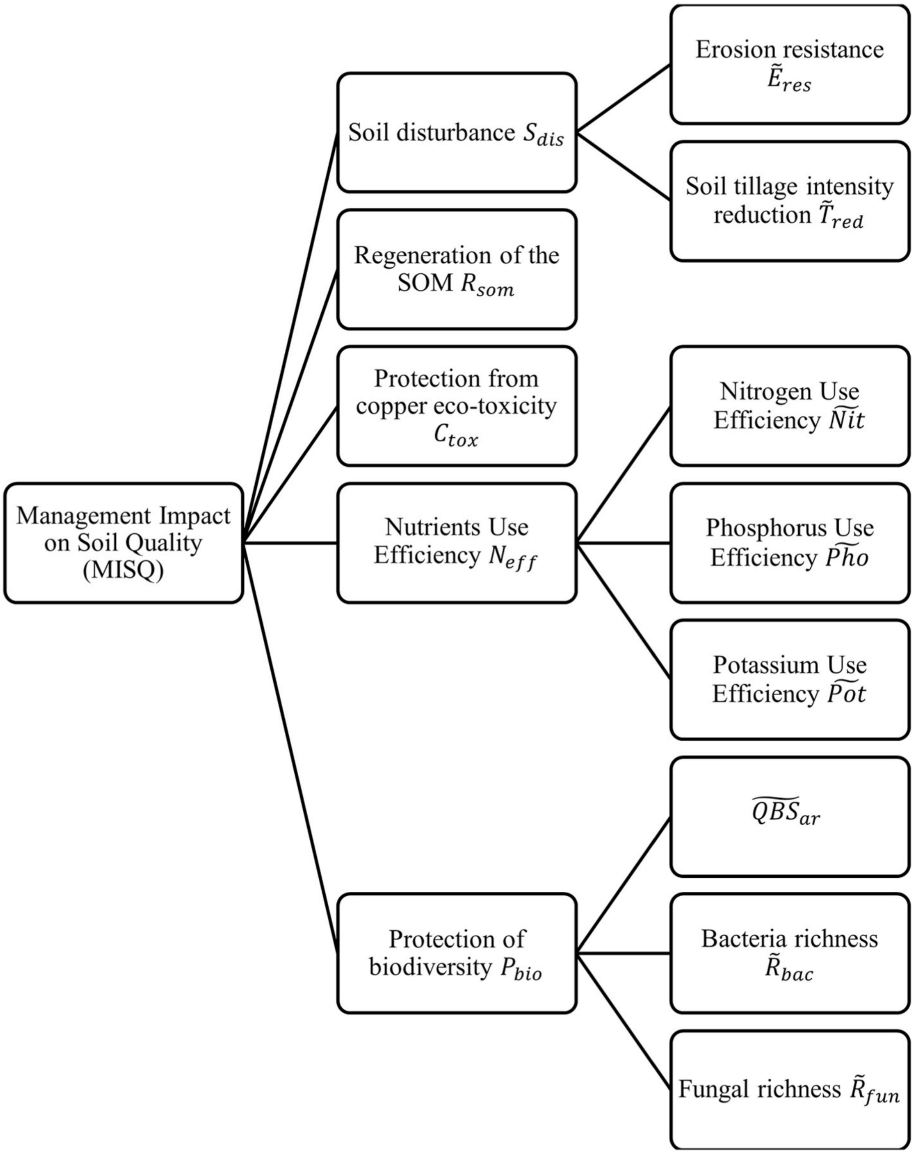

Fig. 1. Conceptual model of the Management Impact on Soil Quality (MISQ) indicator.

partial compensability is lower when using the geometric mean method compared to linear aggregation, especially with indicators presenting low values (Nardo et al., 2008). Both the arithmetic and geometric mean are stable when the positive and negative trends and their magnitude are balanced (van Strien et al., 2012). However, when just one indicator reaches zero, the geometric mean, and hence the integrated indicator, goes to 0. This characteristic is significant when a score of 0 for one of the elements making up the indicator becomes a crucial factor, thereby nullifying the assessment of the entire phenomenon represented by the integrated indicator. For these reasons, the geometric mean has been widely used as an aggregation method (Bacchini et al., 2020), particularly in the case of biodiversity indicators (Korner-Nievergelt et al., 2022).

The proposed integrated indicator aims to assess the effects of agricultural practices on soil quality. Since soil quality is also strongly influenced by site-specific soil properties (Sepehya et al., 2024), analyzing its changes over time requires an assessment that considers a temporal horizon, starting from a reference baseline. In this context, the MISQ proves particularly suitable for intra-site and interannual evaluations, allowing for an accurate analysis of the effects of viticultural management practices on soil quality.

2.2. Quantification of individual components of the MISQ integrated indicator

Each component is characterized by an indicator, which considers two or more aspects relating to a specific theme. When performing an integrated analysis, the variables representing aspects under examination, which may be expressed in different units, must be converted into a common unit of measurement. The normalization step is essential when preparing data to be included into an aggregated score (Pollesch and Dale, 2016), which in this case is the MISQ. In defining the normalization threshold, we used two different approaches, depending on the nature of each variable: one based on the maximum or minimum values of the variable and the other on the optimal value relating to the MISQ (Castoldi and Bechini (2010). The proposed indicators have been adapted to the larger-the-better normalization scheme developed by Krajnc and Glavič (2005), where, in a range of 0–1, values closer to 1 are considered optimal. Details of normalizations are given in Table 2.

Soil disturbance indicator. The indicator of Soil disturbance (S_{dis}) considers the erosion resistance ($\widetilde{E}_{res}$) and soil tillage intensity reduction ($\widetilde{T}_{red}$) as sub-indicators:

Table 1
Potential negative and positive impacts assessed by each of the five MISQ indicators for each management component.

Management components	Potential impact		Indicator
	Negative	Positive	
Soil management	Soil degradation and erosion Compaction, alteration of the structure and Reduction of water retention capacity	Reduction of erosion risk Maintenance of soil porosity Maintenance of water retention capacity	Soil disturbance (S_{dis})
Carbon management	Loss of organic matter Reduction of water retention capacity	Increase in soil carbon stock Maintenance of water retention capacity	Regeneration of the SOM (R_{som})
Copper management	Terrestrial eco-toxicity due to copper contamination	Reduction of copper contamination risk	Protection from copper eco-toxicity (C_{tox})
Nutrients management	Deficiency or excess of nitrogen Deficiency or excess of phosphorus Deficiency or excess of potassium	Optimal nitrogen balance Optimal phosphorus balance Optimal potassium balance	Nutrient Use Efficiency (N_{eff})
Biodiversity management	Loss of arthropods and biological quality Loss of the bacterial microbiota Loss of fungal communities	Maintenance or increase of arthropod diversity Maintenance or increase of bacterial diversity Maintenance or increase of fungal diversity	Protection of biodiversity (P_{bio})

$$S_{dis} = \frac{\widetilde{E}_{res} + \widetilde{T}_{red}}{2} \tag{2}$$

In order to assess the soil disturbance, the impact was evaluated in terms of erosion resistance and reduction of tillage intensity, including the consideration of the effects of tillage frequency and the potential consequences of soil compaction on its structure. The cover and management factor (C_m) from the RUSLE equation was used (Renard, 1997) to determine erosion resistance. As noted by other authors (Lamastra et al., 2016), the C_m factor can be easily employed to reflect the effect of cropping and management practices on erosion rates, while the other factors of the RUSLE equation are more closely related to specific soil characteristics rather than management options.

Here, factor C_m is determined according to equation (3).

$$C_{management} = C_{tillage} \times C_{residues} \times C_{cover} \tag{3}$$

The sub-factor $C_{tillage}$ was calculated according to equation (4). Here, $F_{inter\text{-}row}$ and F_{row} represent the surface fractions of inter-row and row areas, while $\mu\ TI_{inter\text{-}row}$ and $\mu\ TI_{row}$ are the arithmetic means of tillage intensity for inter-row and row areas, based on values proposed by the ORUSCAL (Orchard RUSle CALibration) model, which is derived from a calibration of RUSLE2 developed for tree crops like vineyards (Biddoccu et al., 2020).

$$C_{tillage} = F_{inter\text{-}row} \times \mu\ TI_{inter\text{-}row} + F_{row} \times \mu\ TI_{row}. \tag{4}$$

As proposed by the study conducted by Panagos et al. (2015), which obtained C-factors for tree crops such as vineyards based on the calibration of soil cover fractions deriving from satellite images, the sub-factor $C_{residues}$ was calculated according to equation (5), where $F_{residues}$ represents the fraction of the inter-row area subjected to organic residue redistribution (such as vine prunings and dead vegetation).

$$C_{residues} = (0.88 \times F_{residues}) + (1 - F_{residues}) \tag{5}$$

Finally, the cover crop sub-factor was calculated according to equation (6), where $F_{crop\text{-}cover}$ is the fraction of the inter-row area managed with cover crops.

$$C_{cover} = (0.80 \times F_{crop\text{-}cover}) + (1 - F_{crop\text{-}cover}) \tag{6}$$

The reduction in soil tillage intensity was calculated for each year using the Soil Tillage Intensity Rating (STIR) method developed by the USDA. STIR is a numerical index that represents the type and severity of disturbance caused by tillage operations. The STIR value incorporates the type, speed, depth and degree of disturbance caused by tillage management decisions. The STIR is the sum of the STIR values of individual field operations (Claassen et al., 2018). Both “erosion resistance” and “reduction in soil tillage intensity” values take into account tillage intensities; however, they consider somewhat different aspects. In the former case, soil cover is also considered, while in the latter case, both intensity and frequency of passes are taken into consideration. As other assessments suggest (Triviño-Tarradas et al., 2020), both indicators are considered in this study. The maximum thresholds of the C-factor observed in European vineyards (Panagos et al., 2015) were used to

Table 2
Normalization phase of the variables included in the indicators, encompassing the minimum (Min), maximum (Max), and optimum (Opt) levels of each indicator.

Indicator	Normalized variable	Original indicator	Min value	Max value	Opt value	Normalization
S_{dis}	$\widetilde{E}_{res}$: Erosion resistance	Cover and management factor (Panagos et al., 2015)	0.00	3.45	0.00	$1 - \frac{C_{m_i}}{3.45}$
	$\widetilde{T}_{red}$: Soil tillage intensity reduction	Soil Tillage Intensity Rate (Claassen et al., 2018)	0.00	80	0	$1 - \frac{T_{redi}}{80}$
R_{som}	$\widetilde{IMO}$	IMO Organic Matter Indicator (Bockstaller et al., 1997)	0.00	10	10	$\frac{IMO_i}{10}$
C_{tox}	$\widetilde{I}_w$	Copper terrestrial ecotoxicity (Viveros Santos et al., 2018)	0.00	53.69	0.00	$1 - \frac{I_{w_i}}{53.69}$
N_{eff}	$\widetilde{Nit}$	Nitrogen Use Efficiency (Oenema, 2015)	0.00	1.00	0.70	$1 - \frac{\lvert Nit_i - 0.70\rvert}{0.70}$
	$\widetilde{Pho}$	Phosphorus Use Efficiency	0.00	1.00	0.70	$1 - \frac{\lvert \mathrm{Pho}_i - 0.70\rvert}{0.70}$
	$\widetilde{Pot}$	Potassium Use Efficiency	0.00	1.00	0.70	$1 - \frac{\lvert \mathrm{Pot}_i - 0.70\rvert}{0.70}$
P_{bio}	$\widetilde{QBS}_{ar}$	QBS-ar (Parisi et al., 2005)	0.00	6.00	6.00	$\frac{QBS_{ari}}{6.00}$
	$\widetilde{R}_{bac}$	Bacteria richness	0.00	2353	2353	$\frac{OTUs_{baci}}{2077}$
	$\widetilde{R}_{fun}$	Fungal richness	0.00	293	293	$\frac{OTUs_{fun_i}}{293}$

Table 3
Descriptive statistics of data useful for calculating the indicator for soil management (S_{dis}).

Viticultural practice	Working hours (h)				Intensity coeff.[a]	Modifier coeff. [b]	% of surface disturbed
	2014 baseline	2015	2019	2021			
Harrow	50	41	56	107	0.65	0.7	83 %
Row chisel	200	34	91	100	0.8	0.8	17 %
Subsoiling	0	18	22	18	0.8	0.7	83 %
Mowed cover crop	53	40	0	64	0.7	0.4	83 %
Cultivated manually	7	0	144	98	0.65	0.7	17 %
Other	284	228	273	183	0.65	0.15	83 %

[a] Intensity coefficient (erosion) obtained from Biddoccu et al. (2020).
[b] Modifier coefficient (tillage intensity rate) obtained from.

normalize the erosion resistance indicator. For the soil tillage intensity reduction indicator, the USDA maximum value of 80 for conservation tillage management was considered (NRCS, 2022).

Organic matter indicator. The indicator relating to the ability to regenerate soil organic matter (SOM) is equal to the normalization of the Organic Matter Indicator (OMI) proposed by Bockstaller et al. (1997). The OMI assesses the effect of farming systems on the evolution of the SOM. The calculation of the indicator is based on the comparison of organic matter inputs through manure and crop residues with the recommended input levels, which are designed to maintain a satisfactory level of SOM in the long term. These levels were obtained using the Hénin-Dupuis model (Mary and Guérif, 1994) for various classes of clay and limestone soil content. The OMI indicator ranges from 0 to 10, where 7 is an optimal value (Bockstaller et al., 1997). However, the potential excess of nutrient inputs is considered in the Nutrients Use Efficiency indicator. A normalization with an optimal value of 10 was used in this study, where only the organic matter input was considered in this indicator.

$$R_{som} = OMI \tag{7}$$

Terrestrial eco-toxicity impact indicator. Among the active ingredients permitted in organic farming, copper is one of the most closely monitored due to its high eco-toxicity for soil fauna communities (Beaumelle et al., 2023; Goritschnig et al., 2024). Its persistence in the soil and widespread use in organic agriculture raise concerns about potential effects on soil health. Copper toxicity is particularly high in acidic soils with low organic matter content, where its bioavailability is greater (Karimi et al., 2021). The terrestrial eco-toxicity impact score (PAF·m^3·day·kg of grapes^{-1}) was used to assess protection from copper eco-toxicity (C_{tox}), considering the characterization factors (CFs) proposed by Viveros Santos et al. (2018). These factors account for both farming systems and the distribution of copper in the soil within the reference vine-growing area. The CFs for copper terrestrial eco-toxicity were obtained using the spatial resolution of the soil mapping units from the HWSD. The distribution was geochemically modelled using WHAM 6.0 (Windermere Humic Aqueous Model), a model that enables geochemical speciation. WHAM 6.0 is utilized by USEtox to calculate CFs that consider metal speciation based on freshwater chemistry for aquatic eco-toxicity (Gandhi et al., 2010). The terrestrial eco-toxicity impact score I_W (PAF·m^3·day·kggrapes^{-1}) was therefore calculated according to Equation (5), where m_W represents the amount of copper released into the soil per kilogram of grapes (kg Cu·kggrapes^{-1}), and CF_w is the characterization factor for copper terrestrial eco-toxicity (PAF·m^3·day·kgCu^{-1}) in the reference vine-growing area.

$$I_w = m_w \cdot CF_w \tag{8}$$

In order to calculate m_w, the amount of copper released into the soil from the active ingredients of phytosanitary products used was considered according to the Product Category Rules (PCR) manual for arable and vegetable crops (EPD International, 2023). For the C_{tox},the maximum value, representing the worst-case scenario, was determined based on an applied copper content of 6 kg/ha, which is considered the threshold necessary to prevent the disruption of soil biological functions (Karimi et al., 2021). The corresponding territorial characterization factor was based on the highest value calculated for vineyards in the vine-growing area of “Lombardy” as calculated by Viveros Santos et al. (2018).

$$C_{tox} = \widetilde{I_w} \tag{9}$$

Nutrient Use Efficiency Indicator. The indicator for nutrient use efficiency (N_{eff}) was determined as the arithmetic mean of three normalized nutrient-related sub-indicators: nitrogen ($\widetilde{Nit}$), phosphorus ($\widetilde{Pho}$) and potassium ($\widetilde{K}$). For each nutrient, the non-normalized variable refers to the ratio between the nutrient input and output, based on the principle of nutrients mass balance (Oenema (2015). This involves considering nutrient input and nutrient output for the calculation: nutrient output/nutrient input. Based on the proposal by Oenema, 2015 concerning Nitrogen Use Efficiency (NUE), the normalization of N_{eff} was carried out considering 0.7 as the optimal value. This ideal value falls between the risky limits of 0.9, which poses risks due to soil mining effects, and 0.5, which poses risks due to excess nitrogen. The same criterion was applied to phosphorus and potassium.

$$N_{eff} = \frac{\widetilde{Nit} + \widetilde{Pho} + \widetilde{Pot}}{3} \tag{10}$$

Biodiversity indicator. As highlighted by several authors, soil arthropod communities serve as valuable bioindicators of changes in soil properties and the impact of human activities (Ghiglieno et al., 2021; van Straalen, 1998). Bacteria and fungi play a crucial role in various ecological processes within the soil, contributing to its fertility and the maintenance of its characteristics (Belda et al., 2025; de Menezes et al., 2017). Given their ecological importance, this study considers biodiversity protection (P_{bio}) in terms of soil arthropods and microorganisms (fungi and bacteria). The indicators is the arithmetic mean of the normalized versions of the biological soil quality index (QBS_{ar}) (Parisi et al. (2005), the Fungal richness (R_{fun}) and Bacteria richness (R_{bac}). For assessing arthropod biodiversity, QBS-ar index values were normalized using the Soil Quality Classes proposed by Parisi for Northern Italy (Parisi et al., 2003). These classes increase in score from 0 to 6, where a score of 6 indicates higher QBS-ar values associated with the presence of Proturans and eu-edaphic groups (eco-morphological index greater than 20). In order to assess bacterial and fungal biodiversity, microbial diversity values, defined as the richness of Operational Taxonomic Units (OTUs), were normalized by identifying a maximum achievable limit for their respective microbial groups. The maximum values of OTUs were determined for the reference area, based on over 200 samplings carried out in managed vineyards in Franciacorta, a viticultural area in northern Italy, which was chosen as the case study.

$$P_{bio} = \frac{\widetilde{QBS_{ar}} + \widetilde{R}_{fun} + \widetilde{R}_{bac}}{3} \tag{11}$$

2.3. Contextualization of the case study and data collection

The case study was conducted in a 2.98-ha Pinot Noir vineyard at Guido Berlucchi, a farm located in Franciacorta, a grape-growing area in northern Italy. The vineyard planting density is spaced 2 m inter-row and 0.8 m between vines, with 0.2 m on each side considered for the tilled surface area along the row. The indicators were applied using data collected by the farm for the years 2014 (baseline), 2015, 2019, and 2021. Table 3 shows the types of viticultural practices, their intensity coefficient (erosion) and modifier coefficient (tillage intensity rate), as defined by Biddoccu et al. (2020) and Claassen et al. (2018) respectively, and used to calculate the S_{dis} indicator.

All indicators were calculated for each year, except for the S_{fun} and S_{bac} indicators, which cover2019 and 2021 only. For 2014; 2015, the biodiversity protection indicator was determined only with the QBS_{ar}, as data relating to the OTUs richness for fungi and bacteria were not available. Management of the inter-row area was carried out over various years, as reported in Table 4.

The grape yield considered for all years covered by the study was 12 tons per hectare, which is the actual production of the vineyard in the years covered by the study and corresponds to the maximum limit set by the Franciacorta Controlled and Guaranteed Denomination of Origin (DOCG) production regulation (see Table 5). The average consumption of nutrients has been considered based on the production level, as proposed by Fregoni (1981). In order to include biological nitrogen fixation (BNF) in assessing the $\widetilde{Nit}$ indicator, the BNF values (kg ha^{-1}) proposed by Vasconcelos et al. (2020) for the legumes in the functional mix used as green manure were utilized. More specifically, the proposed mix had a total contribution of 134.73 kg/ha. A gradual release and nitrogen mineralization was considered in order to account for the controlled input over 4 years (Kebede, 2021). As required for the R_{som} indicator (Bockstaller et al., 1997)., the calculation of nutrient efficiency also considered the mean organic fertilizer input from the 4 preceding cropping years, given that organic fertilizers release nutrients slowly (Niedziński et al., 2021) and fertilizations are not carried out every year. Regarding copper for calculating the indicator C_{tox}, the metal copper applied per year has been considered, taking into account the fraction applied to the soil (EPD International, 2023). The active ingredients and quantities of products applied in the different years are reported in Table 6.

In order to assess the $\widetilde{QBS}_{ar}$ indicator, a cubic soil sample (10 × 10 × 10 cm) was placed in a Berlese–Tüllgren funnel under a 60W incandescent bulb. This setup prompted the soil arthropods to migrate towards the moist part of the sample, away from the light, and fall through the funnel into a preserving solution (alcohol and glycerol). The extracted arthropods were then classified to determine the QBS-ar index. In order to determine the OTUs, the amplicon sequencing of the bacterial 16S rRNA gene and fungal ITS, total DNA was extracted from 1 g of soil and amplicon sequencing was performed using Illumina MiSeq as described in Marasco et al. (2022).

Table 4
Description of the inter-row management practised during the study years.

Year	Inter-row management
2014 (baseline)	Spontaneous grassing year-round, periodic mowing
2015	Spontaneous grassing year-round, periodic mowing, autumn subsoiling
2019	Sowing functional grassing mixture, termination of cover cropping with rolling, autumn subsoiling. Composition of the cover crop mixture: fava bean (*Vicia faba* L.), common vetch (*Vicia sativa* L.), pea (*Pisum sativum* L.), Egyptian clover (*Trifolium alexandrinum* L.) and red clover (*Trifolium pretense* L.)
2021	Spontaneous grassing year-round, periodic mowing, autumn subsoiling

Table 5
Description of nutrient inputs and the quantity of copper applied during the study years.

Vineyard inputs	2014	2015	2019	2021
Nitrogen[a] from organic fertilizers (kg ha^{-1})	198.07	177.24	332.28	250.47
Phosphorus[a] from organic fertilizers (kg ha^{-1})	44.74	40.04	75.06	56.58
Potassium[a] from organic fertilizers (kg ha^{-1})	142.27	127.31	238.67	179.91
Metallic copper from copper-based fungicides (kg ha^{-1})	5.15	3.47	4.18	3.60

[a] Content of N, P, K derived from the analysis of the organic fertilizer used.

Table 6
Results of individual indicators and their respective sub-indicators across the different study years.

Indicator	2014	2015	2019	2021
$\widetilde{E}_{res}$	0.852	0.841	0.843	0.844
$\widetilde{T}_{red}$	0.842	0.759	0.561	0.671
S_{dis}	0.847	0.800	0.702	0.758
R_{som}	0.900	0.806	1.000	1.000
C_{tox}	0.968	0.978	0.977	0.980
$\widetilde{Nit}$	0.967	0.919	0.436	0.546
$\widetilde{Pho}$	0.666	0.744	0.397	0.527
$\widetilde{Pot}$	0.354	0.161	0.981	0.699
N_{eff}	0.662	0.608	0.605	0.590
$\widetilde{QBS}_{ar}$	0.500	0.500	0.833	0.833
$\widetilde{R}_{bac}$	*NA*	*NA*	0.631	0.801
$\widetilde{R}_{fun}$	*NA*	*NA*	0.631	0.751
P_{bio}	0.500	0.500	0.699	0.795

3. Results and discussion

3.1. Trend of individual indicators over the study years

The Soil disturbance S_{dis} indicator obtained as the arithmetic mean of erosion resistance $\widetilde{E}_{res}$ and soil tillage intensity reduction $\widetilde{T}_{red}$. Throughout the study, $\widetilde{E}_{res}$ remained consistently high, though a slight decline was noted after 2014, likely due to shifts in soil management. That year marked the only instance in which subsoiling was not performed in the inter-row - a high-intensity tillage practice - suggesting its role in maintaining earlier values. This trend was even more pronounced in $\widetilde{T}_{red}$, which exhibited a sharp decrease as tillage operations and tractor traffic intensified in subsequent years. The impact was particularly evident in 2019 when, despite maintaining functional cover cropping throughout the season without mowing, frequent tillage for seeding preparation and manual cultivation for weed control and row management contributed to further reductions. As some authors have already underlined, the intensity and frequency of tillage have a significant impact on soil organic carbon (Haddaway et al., 2016) and contribute to soil compaction, which negatively affects hydrological processes (Capello et al., 2019). Despite very low $\widetilde{T}_{red}$ values, particularly in 2021 and 2019, the cover cropping accounted for in the $\widetilde{E}_{res}$ calculation helps offset the S_{dis} indicator. As observed by various authors (Morvan et al., 2014; Stanchi et al., 2021), grass cover, especially permanent cover cropping, significantly reduces soil erosion, while tractor passes accelerate it. Some authors have found that conventional tillage in vineyards increases runoff and soil erosion, while grass cover can reduce these effects by over 60 % (Biddoccu et al., 2017). The S_{dis} indicator, therefore, reflects an overall positive management approach, even in years with higher tillage intensity, thanks to the adoption of cover crops in the vineyard.

As to the regeneration of the SOM R_{som} indicator, the years in which organic matter input was deemed insufficient or excessive are penalized. Higher values were observed in 2019 and 2021, indicating an improvement, despite organic fertilization being consistent in previous years. Like the original organic matter indicator (Bockstaller et al., 1997), the R_{som} indicator assesses the effect of agricultural practices on the evolution of soil organic matter (SOM), taking into account multi-year organic fertilization. In addition to having a positive impact on vine health and grape quality (Mulotto et al., 2022), organic fertilization improves soil health and boosts soil fauna and microbial activity in particular (Wang et al., 2022; Zhou et al., 2022).

The protection from copper eco-toxicity C_{tox} indicator considers the potential impacts due to the application of copper. In organic farming, the use of non-synthetic products such as mineral-based fungicides like copper or sulfur is allowed. Unlike sulfur, whose environmental impact is considered very low (Spruijt-Verkerke et al., 2004), residues from copper-based fungicides can alter soil pH, lead to nutrient deficiencies and, most importantly, cause toxicity to soil biota (Akinnifesi et al., 2006; Wightwick et al., 2013). The C_{tox} indicator shows slightly lower values in 2014 and relatively stable values in the following study years. This is to be expected, as the pressure from *Plasmopara viticola* was particularly high in 2014 in the area covered by the study. Nevertheless, the indicator reveals high performance across all the study years, highlighting how copper-based disease management in the study context was not penalized according to the indicator. By including the characterization factors derived from Viveros Santos et al. (2018), the area-specific factors, such as copper complexation with soil organic matter (SOM), are taken into account. Copper has a high affinity for organic matter (Matar et al., 2015), which affects its bioavailability and, consequently, its potential toxicity to soil fauna and microorganisms.

The nutrient use efficiency N_{eff} indicator shows relatively consistent trends over the years covered by the study, although there are differences in individual nutrients, such as nitrogen, where lower values can be observed in 2019 and 2021. Fluctuations can be attributed to several factors, primarily differences in fertilization inputs and dosages, as well as the influence of legume cover cropping in 2019, which contributed to biological nitrogen fixation. To optimize nutrient efficiency, particularly for nitrogen, fertilization doses should also be adjusted based on nutrient inputs from legume cover cropping. In general, inputs exceeded outputs, except for potassium in 2014 and 2015, where inputs were lower. It should be noted that the yield limit set by production regulations does not account for any excess production per plant, which may be removed through green harvesting. Therefore, the years in which inputs exceeded outputs relative to the set limit are considered years with excess nutrients. Improving nutrient use efficiency is crucial to enhancing both productivity and sustainability. Strategies adopted to achieve this result include appropriate dosing, the use of effective sources, as well as optimal timing and application methods (Baligar and Fageria, 2015). It is also important to consider the mineralization rates of nutrients, particularly nitrogen, in organic amendments. The release of mineral nitrogen from organic fertilizers greatly depends on the cultivation substrate, temperature, humidity and the nature of the fertilizer, ranging from 10.7 % to 71.3 % of the applied fertilizer nitrogen (Cannavo et al., 2022). Regarding excesses, proper management of phosphorus and nitrogen is required to limit the risks of eutrophication (Haque, 2021). Although the potential role of potassium in eutrophication is considered minimal (Leentvaar, 1980), an excess or deficiency of potassium in agricultural systems can lead to long-term sustainability issues with soil resources, thereby compromising agricultural production (Öborn et al., 2005). Adequate potassium input is essential to maintaining soil health (Das et al., 2019). In this case, the indicator aggregation was based on an equally weighted average of the three nutrients. A potential further development could involve weighting the nutrients based on their importance for production or the risk associated with potential environmental impacts. Additionally, a more detailed monitoring of nutrient release over time should be considered.

The Protection of biodiversity P_{bio} indicator shows variability, with lower values in 2014 and 2015. In these years, the indicator only considered the $\widetilde{QBS}_{ar}$. Even when analyzing the $\widetilde{QBS}_{ar}$ values exclusively, 2014 and 2015 still show lower values. With a higher H′ index value for bacteria and a lower H′ index value for fungi, there is a slight contribution to the reduction of the averaged indicator in 2019 and 2021 compared to the assessment based solely on $\widetilde{QBS}_{ar}$ for the same years. The years with lower $\widetilde{QBS}_{ar}$ values also show lower scores, partly due to the absence of some groups (deep soil-living organisms), such as Protura, which are more sensitive to variations in soil environment and better adapted to life in the soil (Parisi et al., 2003; Wahsha et al., 2012). Although, in this case, as a "measured indicator", it is not possible to assess direct associations between the effects of individual practices on biodiversity, various authors (Karimi et al., 2020; Winter et al., 2018) have highlighted that organic viticulture practices, such as cover cropping, organic fertilization and the addition of pruning wood, can improve diversity and activity of soil microorganisms. In contrast, soil tillage, lack of cover and mineral fertilization can harm them. The reduced use of copper-based products in organic viticulture enhances yield and environmental sustainability without compromising grape quality, while simultaneously improving soil biodiversity (Storchi et al., 2022). This aspect has already been accounted for by the C_{tox} indicator.

3.2. Integrated assessment of individual indicators and MISQ

A synthesis of the variations in the contributions of individual indicators are shown in the multi-year doughnut chart on the left in Fig. 2. Higher values are recorded in the last two years of management for the P_{bio} and R_{som} indicators. A slight improvement was also observed in C_{tox}, although it was limited. While the values of N_{eff} are variable, higher values of S_{dis} are observed in the earlier years of the study, where fewer operations were conducted. As observed, the addition of organic matter in vineyards and long-term use of manure increase soil microarthropod biodiversity and abundance (Ghiglieno et al., 2020; Kautza et al., 2002). Organic fertilization can also enhance the complexity of microbe-microfauna ecological associations (Suleiman et al., 2019). Some authors have observed greater diversity and stability in arthropod communities in vineyards managed with spontaneous vegetation compared to those managed with tillage or sown vegetation (Gonçalves et al., 2020). However, other studies suggest that soil properties and climatic conditions often have a greater influence on the movement and presence of soil arthropods (Xin et al., 2018). Cover crops in vineyards can generally increase beneficial arthropod populations and reduce harmful ones, potentially benefiting integrated pest management programs (Vogelweith and Thiéry, 2017). Sowing legume-rich mixtures can improve the structure of the soil microbial community (Moreno et al., 2021). Additionally, organic carbon and nitrogen deposits in the soil increase through mixed cover crops of grasses and legumes in vineyard agroecosystems, thereby improving nitrogen availability and reducing soil erosion (Ball et al., 2020). Selecting functional aspects in artificial cover cropping can positively impact biotic activity and lead to a more significant overall improvement compared to the use of spontaneous vegetation (Tang et al., 2022). As observed by some authors (Messiga et al., 2015), the combination of legume-based cover crops and soil amendments can, depending on the conditions, provide a supply of soil mineral nitrogen and available phosphorus comparable with that of fertilized treatments, while also improving the chemical and biological properties of the soil and overall soil quality under the pedoclimatic conditions of the vineyards. The right side of Fig. 2 shows the trend of the MISQ integrated indicator, obtained from the geometric mean. A rising trend can be observed in the surveyed scenario, with values higher in 2019 and 2021. The MISQ provides a synthetic overview of the individual indicators' trends, but it remains essential to monitor their evolution over time. Comparing different years allows for a better

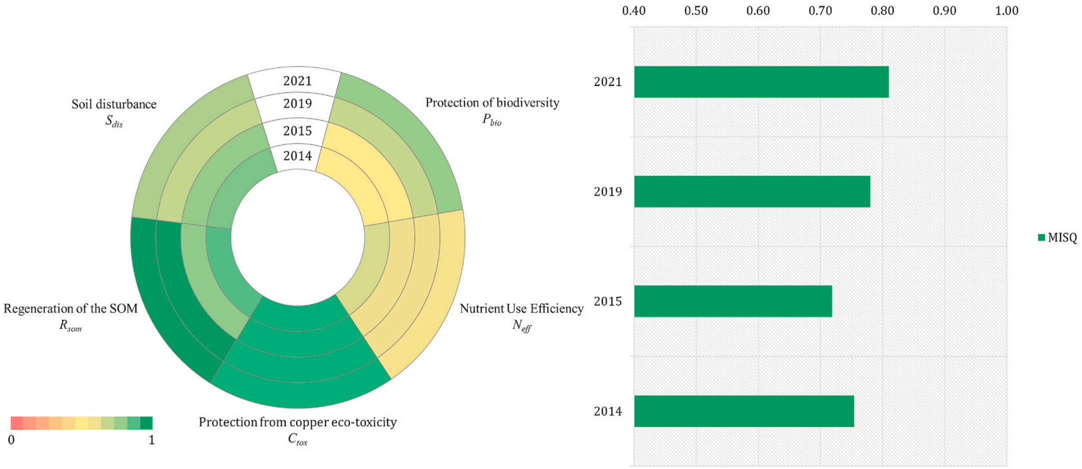

Fig. 2. a. A multi-year doughnut chart illustrates the trends of the MISQ indicators for each year. **b.** A bar chart shows the different values of the integrated indicator over the study years.

refinement of management strategies and an assessment of long-term effects. In addition to the integrated indicator value, a comprehensive analysis of individual parameters helps identify the most effective combinations of practices to maintain and enhance soil fertility, functionality, and biodiversity, and thus its overall quality.

4. Conclusions

Soil is a fundamental resource for viticulture and maintaining its functionality is essential to preservie soil health and optimize the ecosystem services it provides for production.

This study introduces an integrated indicator, the Management Impact on Soil Quality (MISQ) indicator, which provides a comprehensive assessment of the effects of organic viticulture practices on soil functions. Enhanced functionality has been observed in years when the biological community was supported through the optimized distribution of organic matter and the use of functional cover crops.

Measuring the sustainability of agricultural practices is a challenging task but is vital for developing localized strategies. The simplicity of the indicators used makes this tool applicable in various scenarios, thereby facilitating the development of effective management strategies that minimize a negative impact on soil functions. Furthermore, the indicator is expected to be adaptable for use in other studies, with its composition customized to fit specific research settings.

As previously mentioned, the MISQ proves particularly effective for intra-site and interannual evaluations, allowing for a precise analysis of the effects of viticultural management practices on soil quality. Given its structured approach, it would be valuable to explore its application in different contexts. However, caution is needed when considering initial conditions and, in order to ensure comparability across different scenarios, assessing the relative increase from a baseline may be a more suitable approach.

Expanding the applicability of the MISQ requires a deeper understanding of the relationships between soil types and their specific characteristics. While the indicator was developed for organic viticulture, adapting it to systems with different management practices would necessitate considering additional factors, such as incorporating other active ingredients beyond copper in the toxicity indicator.

The MISQ can serve as a functional tool for grape growers, contributing to the reduction of the environmental impact of viticultural practices on soil quality. Future research should focus on refining the indicator's adaptability to diverse agricultural contexts, ensuring it remains a reliable tool for assessing and improving soil quality under various management strategies.

CRediT authorship contribution statement

Isabella Ghiglieno: Writing – original draft, Methodology, Investigation, Conceptualization. **Luca Facciano:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Anna Simonetto:** Writing – original draft, Formal analysis, Data curation. **Daniele Daffonchio:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Ramona Marasco:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Sara Borin:** Formal analysis, Data curation. **Lorenzo Vergani:** Formal analysis, Data curation. **Leonardo Valenti:** Investigation. **Gianni Gilioli:** Writing – review & editing, Supervision.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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