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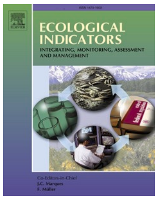

Original Articles

A multi-indicator approach to compare the sustainability of organic vs. integrated management of grape production

Castaldi Simona [a,*], Formicola Nicola [a], Mastrocicco Micol [a], Morales Rodríguez Carmen [b], Morelli Raffaella [c], Prodorutti Daniele [c], Vannini Andrea [b], Zanzotti Roberto [c]

[a] *Dipartimento di Scienze e Tecnologie Ambientali Biologiche e Farmaceutiche, Università Degli Studi Della Campania "Luigi Vanvitelli", via Vivaldi 43, 81100 Caserta, Italia*

[b] *Dipartimento per l'Innovazione nei sistemi Biologici, Agroalimentari e Forestali, Università Degli Studi Della Tuscia, via San Camillo de Lellis snc, 01100 Viterbo, Italia*

[c] *Unità Agricoltura Biologica, Centro Trasferimento Tecnologico, Fondazione Edmund Mach, Via E. Mach, 1 - 38098 San Michele all'Adige (TN), Italia*

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ABSTRACT

Sustainable agricultural practices are increasingly becoming a strategic asset for global and national environmental policies and economy. A big challenge is the selection of appropriate indicators to describe the complexity of the agroecosystem management. In the present work, the sustainability of grape production, in vineyard trials of Pinot blanc and Rhine Riesling, managed with integrated (INT) and organic management (organic, with cattle manure ORG1 and organic with green manure ORG2), was compared using a multi-indicator approach. The experiment was set in 2011 (1.5 ha in Trento, Italy) and carbon footprint (CF), nitrogen footprint (NF), water footprint (WF), soil microbial diversity (alpha diversity of bacteria, fungi, oomycetes communities) and soil C stock change, were evaluated in 2018. The CF was 0.213—0.227 kg CO_2-eq/kg in the INT, 0.144—0.168 kg CO_2-eq/kg in ORG1 and 0.134—0.147 kg CO_2-eq/kg in ORG2. The NF was around 1 g Nr/kg for the INT, 0.4 g Nr/kg for ORG1 and 0.5 g Nr/kg for ORG2. The WF, excluding the pesticides impact on grey water, was 666—708 L/kg for INT, 605—655 L/kg for ORG1 and 529—580 L/kg for ORG2. The impact of farming practices on soil microbial alpha diversity showed no significant difference among treatments for oomycetes and significantly higher indexes for fungi and bacteria in the ORG1, with INT and ORG2, being similar. No difference in bulk organic C were observed among treatments. Overall, the multi-indicator approach allowed to demonstrate that the organic management was more beneficial for most of the environmental spheres of the agroecosystem compared to integrated management, without affecting the grape yield.

1. Introduction

Food production is currently contributing, at unprecedented rates, to generate critical environmental pressures for the Earth system (Rockström et al., 2009; Willett et al., 2019) by modifying the atmospheric concentration of greenhouse gases (GHGs) (IPCC, 2019a), driving loss and degradation of ecosystem services and biodiversity (IPBES, 2019, Willett et al., 2019), releasing in the environment xenobiotics (Persson et al., 2022) and nutrient excess and consuming critical resources, like soil and water (Steffen et al., 2015).

Farming practices, significantly differ for their relative impact on natural resources and ecosystem services (Rockström et al., 2009; Poore and Nemecek, 2018; Willett et al., 2019) and a big effort is currently ongoing in EU to boost sustainability management in the agricultural sector (Farm to Fork strategy in European Commission, 2020). Multiple sustainability targets include climate change mitigation by GHG reduction (Climate Law Regulation (EU) 2021/1119) and C sequestration in vegetation and soil (Sustainable C cycle, COM(2921)800) as well as amelioration and preservation of soil biodiversity, health and overall agroecosystem quality (EU Soil Strategy 2030, COM(2021)699; EU Biodiversity Strategy for 2030, COM(2020)380, Zero Pollution Action Plan, COM(2021)400, Organic Action Plan, COM(2021)141). To measure and monitor these sustainability actions, reliable science-based indicators are required that valorise and capture the agroecosystem complexity (Zhang et al., 2007). Life Cycle Assessment (LCA) (ISO, 2006a) is the most used methodology to report multiple impacts of agroecosystems (Boschiero et al., 2023), with carbon footprint being one of its most known and diffused output on the market. However, as LCA

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* Corresponding author.
E-mail address: simona.castaldi@unicampania.it (C. Simona).

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main focus is on the use of materials, resources, energy and end-life of generated waste, it does not cover important site-specific aspects of agroecosystem sustainability, like those at the basis of the EU Soil Mission including conservation of soil C stocks, enhancement of soil biodiversity, prevention of erosion, increase of soil health, ecosystem biotic and abiotic quality (Zhang et al., 2007; Willett et al., 2019). This latter set of targets might be particularly relevant when organic farming systems are analyzed and compared to conventional systems. In fact, beyond a potentially lower intensity of multiple footprints extrapolated from LCA analysis (Boschiero et al., 2023, Chiriacò et al., 2022), organic farming is considered highly beneficial to soil health and to climate and C farming objectives, due to its higher potential of soil C accumulation or lower soil C losses (Gattingera et al., 2012; Goglio et al., 2015). On the contrary, an interesting open debate, with controversial evidences, is ongoing on the effect of organic farming, vs conventional farming, on soil microbial biodiversity (Lupatini et al. 2017; Zhang et al. 2019; van Rijssel et al., 2022). Increasing organic farming in EU is one of the strategic objectives of the EU Farm to Fork strategy (EC, 2020) and multicriteria approaches to investigate and demonstrate the sustainability of organic farming options would significantly contribute to boost both consumers and farmers confidence in organic production adoption.

Although, many indicators of impacts have been associated to food production and food systems (Chaudhary et al., 2018; Willett et al., 2019; Béné et al., 2019; Boschiero et al., 2023), the number of single studies concurrently reporting multiple indicators is significantly lower (Béné et al., 2019) and even lower is the comparative analysis for the organic farming sector. The most frequently available studies, comparing organic farming (OF) vs. conventional farming (CF), are based on LCA methodology. Boschiero et al. (2023) compared 77 pairwise LCA studies using 15 environmental impacts indicators (including climate change, ozone depletion, ecotoxicity, human toxicity, acidification, eutrophication, use of resources, water, and energy); Borsato et al. (2020) evaluated water and carbon footprint, an integrated indicator of vineyard management practices and an economic indicator (net income) to drive conclusions on vineyard OF and CF managements; Michos et al. (2018) used energy flow, carbon and water footprint to compare OF and CF in vineyards, kiwi and apple orchards; a complex multiple indicator model, RISE (Grenz et al. 2009), based on 57 sustainability parameters condensed into twelve indicators, was used in 10 paired studies in Poland by Berbeć et al. (2018). A vast literature exists on the effect of organic farming vs conventional farming on specific soil chemical, physical and biological parameters, but a synthesis is not generally associated to climate, water, nitrogen, energy and land footprint indicators.

To contribute to the ongoing debate on the organic farming sustainability, we analyzed and compared grape production in vineyard trials (Pinot blanc, Rhine Riesling) managed with integrated and organic management, using a multi-indicator approach, based on the most relevant impacts of agriculture on the planetary systems (Willett et al., 2019) and relevant to EU policy targets. We selected the *carbon footprint (CF)*, relevant for climate change (IPCC, 2019a) and EU climate neutrality targets (Regulation EU, 2021), the *nitrogen footprint (NF)*, i.e. the "leakage" amount of reactive nitrogen (Nr) into the environment, relevant to key environmental impacts, including climate, eutrophication, biodiversity changes, acid rain, coastal 'dead zones' (Galloway et al., 2003, 2008); the *water footprint (WF)* relevant to water agricultural management, evapotranspiration balance, water withdrawal and water pollution (Hoekstra et al., 2011; ISO, 2014); *soil microbial diversity,* strongly linked to soil and plant health and functionality, resilience and crop productivity (Cordovez et al., 2019; Xiong and Lu, 2022), with soil microbiota including beneficial, neutral and pathogenic microorganisms the balance of which is significantly affected by land management practices (Xiong and Lu, 2022); *soil carbon*, relevant to soil health (Grilli et al., 2021) as well as to C farming and climatic objectives (Goglio et al., 2015).

Table 1
Farming management practices in the three experimental vineyard treatments (INT, ORG1 and ORG2).

	Actions	Farming management		
		INT	ORG1	ORG2
Mechanical treatment	Suckering	x	x	x
	Leafing	x	x	x
	Shredding pruning	x	x	x
	Harrowing		x	x
	Green manure			x
	Grass mowing	x	x	x
	Mineral fertilization	x		
	Compost sprinkling		x	
	Plant protection	x	x	x
	Chemical weeding	x		
Fertilization	Mineral fertilization	x		
	Composted manure		x	
	Biodynamic preparation			x
	Green manure			x
	Grassing	x	x	x
	Foliar coverage	x	x	x
	Pruning residues	x		
Chemical treatment	Pesticides	x		
	Inorganic pesticides	x	x	x
	Herbicide	x		
Farming waste material	Vineyard plant	x	x	x
	Fertilizers packaging	x		
	Plant protection packaging	x	x	x
	Herbicides packaging	x		

The different indexes were evaluated singularly to compare the pro and cons of the different management strategies for each specific impact, and where also combined into a multi-indicator sustainability index (SI), using a rating and weighting procedure based on the Analytical Hierarchy Process-AHP method (Saaty, 1977; 1980), one of the most used approaches of multi-criteria decision analysis for evaluating and ranking alternatives in socio-economic and environmental studies (Ramanathan, 2001; Eakin and Bojórquez-Tapia, 2008; Busico et al., 2019; Kazakis et al., 2019; Kumar and Pant, 2023).

2. Materials and methods

2.1. Site characteristics and farming managements

The study sites located in the experimental area of the Fondazione Edmund Mach (46° 11′ 44″ N, 11° 08′ 12″ E, 236 m a.s.l) at San Michele all'Adige (Trento, Italy), were characterized by a well-drained calcareous loamy soil, with sub alkaline pH (7.8–7.9) and an terrain inclination of 6 %. The average annual precipitation was about 1034 mm, with an average daily temperature of 22.9 °C during the hottest month of July and 1.0 °C during the coldest month of January. The vineyard trials started in 2011, in an area previously treated with integrated management (Morelli et al., 2022). From 2011 to date, three distinct farming managements were carried out, organized in six randomized blocks of about 0.25 ha each: an integrated management (INT, DPI, 2016) where mineral fertilizers were used; an organic management with cattle manure fertilization (ORG1); an organic management with green manure fertilization (ORG2). All organic practices were performed according to Reg. UE 834/2007. The farming practices and managements applied in the three systems are reported in Table 1. Each management was applied to two vineyard cultivations, Pinot blanc and Rhine Riesling, on plots of 0.25 ha replicated two times per each management for each cultivar, for a total of 1.5 ha of experimental vineyard. In each plot, the vineyard was organized with a planting system of 2.8 m x 0.5 m (simple pergola trentina trellis system). The materials used to create the vineyard structure were the same for each plot and are listed in Table S1. The vegetative and yield parameters were measured at technological grape ripeness from 2016 to 2018, in ten replicates per cultivar and thesis (Morelli et al., 2022).

2.2. Multiple indicators for sustainability assessment

The selected indicators, carbon footprint (CF), nitrogen footprint (NF), water footprint (WF), diversity of microbial communities (alpha diversity indexes of bacteria, fungi, oomycetes communities) and soil C accrual, were evaluated on the three management systems using as reference year 2018, 7 years since the setup of the experimental trials. The grape productivity, as well as the data used to evaluate the three footprints, were collected for 3 years (2016–2018) to provide a more robust average of the management systems, while parameters related to the soil system, organic C and microbial biodiversity, were analysed on soil sampled in spring 2018. To evaluate the C stock change data were also compared with baseline values measure at the beginning of 2012.

The footprint indexes are expressed both as product-based (1 kg of grape) and land-based (1 ha of vineyard). The former functional unit is the most typically used to communicate information on the food impact intensity (to managers of the food systems, consumers), whereas the latter provides information on the management impact on the land. Soil C accrual and biodiversity cannot be expressed per unit of product, but they integrate the footprints information on the quality level of the environmental management of the farming system. The normalization used in the rating and weighting procedure applied to each indicator in the combined index, translates the values of each indicator into a-dimensional classes, where the quality of the indicator rather than its unit of measure is compared.

2.2.1. The carbon footprint (CF)

The CF (ISO, 2018) of a product is defined as the total amount of carbon dioxide equivalent (CO_2-eq) released into the environment along the supply-chain and is based on LCA methodology in accordance with the requirements specified in ISO 14067 (ISO, 2018); ISO 14001 and ISO 14040 (ISO, 2006a), and ISO 14044 (ISO, 2006b). An attributional approach "cradle to farm gate" was applied to the experimental vineyards, divided by farming management and grape variety. The production and transport of raw materials, field operations, direct and indirect N_2O soil emissions, end-life of structural materials of the vineyard and waste materials, were included in the system boundary. From a spatial point of view, the system boundary coincided with farming management, while in terms of time dimension, it coincided with the annual cycle of vineyard production. SimaPro v9.3.0.3 software was used for the LCA analysis. Data used for the Life Cycle Inventory (LCI) (Table 1) were collected directly on site through measurements, interviews, and field record books and, when not available, conservative data were derived from international databases or reports, handbooks of agriculture, or calculated using appropriate models. The indirect loads due to production and transport activities of the materials were estimated using the databases Eco invent 3.8 and Industry data 2.0. The estimates of diesel and lubricant consumption for field operations (Table S2), based on the use of a diesel-powered isodiametric orchard tractor Carraro 75 HP, were taken from Ribaudo (2017) and from the hectare/crop table for fuel consumption of the Autonomous Province of Trento (TEC, 2016). Direct loads due to tractor combustion were estimated consulting the EMEP/EEA air pollutant emissions inventory guidebook 2019 (Ntziachristos and Samaras, 2019). For the operation of irrigation, a consumption of electricity (Table S2) was estimated as 0.239 KWh/m^3 of pumped water (average depth of pumping of 48 m) (WFLDB, 2020). External N inputs, (Table S3) included NPK 12–12-17, mature cow manure, applied in alternate years, N fixed by herbaceous leguminous plants incorporated in the soil. The biogenic direct and indirect N_2O emissions, as well as NO_3^- leaching were estimated with a IPCC Tier 1 approach (IPCC, 2006, ref. IPCC, 2019b, equ. S7-S10), while the Tier 2 of the EMEP/EEA (2019) methodology was applied to estimate NH_3 volatilization (equ. S5-S10). The packaging data, related to the chemical used for field operations, were directly measured (Table S4). Waste materials for one year of cropping cycle included packaging waste and the yearly fraction of the end-life materials used to create the vineyard plant (Table S1). LCIA was carried out using the method IPCC 2021 (SimaPro v9.3.0.3), with the impact category of Global Warming Potential 100 (GWP 100), based on AR6 (GWP of 273 for N_2On, 29.8 for CH_4 by fossil origin and 27.2 for non-fossil origin).

Table 2
Meteorological data input, average annual temperature (T_{AVG}), humidity (U), sunshine (S), wind (W) and rainfall (P)), averaged for the period 2016–2018, used in CROPWAT software, derived from the meteorological station of San Michele all'Adige (TN).

Months	T_{AVG} (°C)	U (%)	W (km/h)	S (h)	P (mm)
Jan	1.8	70.9	5.8	5.1	28.6
Feb	5.6	68.5	7.0	6.3	81.5
Mar	9.8	61.6	8.5	8.2	74.6
Apr	14.2	58.5	10.1	10.0	65.3
May	17.0	66.7	8.3	11.2	98.4
Jun	21.2	65.5	8.7	12.5	118.0
Jul	23.3	65.3	9.1	11.5	124.2
Aug	23	66.8	8.9	10.3	116.8
Sep	18.7	71.4	7.2	8.7	54.3
Oct	13.2	74.6	6.0	7.1	119.9
Nov	7.4	78.9	5.9	5.3	100.2
Dec	2.1	72.8	4.8	5.0	52.5
Average	*13.1*	*68.4*	*7.5*	*8.4*	*1034.3*

2.2.2. The nitrogen footprint (NF_P)

The NF of grape production reported in this study refers to the total amount of reactive nitrogen (Nr) released into the environment because of farm management (Galloway et al., 2014) and is reported per unit of grapes (1 kg) (equ. S3-S4). It excludes the N in the grapes that is removed from the agroecosystem. Being referred to one unit of produced grape, NF represents a fraction of what is generally defined as the N footprint of human consumption, which includes both the production and consumption phases in the overall calculation (Leach et al., 2012). To estimate the total amount of Nr, data used for LCA calculations were also used to extract direct and indirect, abiotic and biogenic production of N species, biologically, photochemically and/or radiatively active, such as N_2O, NO_3^-, NO_2^-, NH_3 and NH_4^+. For the final quantification of Nr using LCA, a dedicated module was created to aggregate Nr data coming from different N sources.

2.2.3. The water footprint (WF)

The three components of the WF, green water, blue water, and grey water, were estimated as follows. The green water footprint (green WF), i.e., the water from precipitation that is stored in the root zone of the soil and evaporated, transpired, or incorporated by plants (Hoekstra et al., 2011), was estimated as the sum of the green water calculated for each month, u_g (mm/month) included in the cropping cycle (equ. S11-S15). The value $u_{g,}$ equal to the minimum between effective rainfall P_{eff} and crop evapotranspiration ET_c (Hoekstra et al., 2011), was estimated for both the vine plants and for the grass layer, the latter being characterized by different management cycles and species in the three tested systems. For each system, the total u_g value represented the sum of u_g of the two different plant covers. P_{eff} and ET_c were calculated using FAO CROPWAT v8.0 software. The ET_C is the product of the potential evapotranspiration (ET_0, $_{mm}$/d) of the crop and $K_{C,}$ the crop coefficient. ET_0 calculation in CROPWAT is based on the Penman-Montheith Equation and required the following climatic data: average annual temperature (T_{AVG}), humidity (U), sunshine (S), and wind (W), which were derived from the local meteorological station (Table 2).

The K_C value for vines and grass, as well as the other parameters required to run CROPWAT (Table S5), were derived from Allen et al. (1998). The P_{eff}, calculated using CROPWAT, was estimated as equal to $P_{eff} = P_t$ x (125–0.2 x P_t)/125 based on the USDA Soil Conservation Service (SCS) methodology, when $P_t \leq 250$ mm, with P_t representing the total monthly rainfall. The blue water footprint (blue WF) is the surface or groundwater that is evaporated, incorporated into a product or taken

Table 3
Impacts and weights used to identify the scores defining the 5 classes of the sustainability index.

	Impact class (I)					Weight (W)	Sustainability index (SI) classes scores				
Indicator	V.L.	Low	Medium	High	V.H		1	2	3	4	5
C footprint	1	2	3	4	5	0,45	0,45	0,9	1,35	1,8	2,25
W footprint	1	2	3	4	5	0,29	0,29	0,58	0,87	1,16	1,45
Soil C	5	4	3	2	1	0,14	0,70	0,56	0,42	0,28	0,14
N footprint	1	2	3	4	5	0,08	0,08	0,16	0,24	0,32	0,40
Biodiversity	5	4	3	2	1	0,04	0,20	0,16	0,12	0,08	0,04
Total Sustainability score per class							**1,72**	**2,36**	**3,00**	**3,64**	**4,28**

from one body of water and returned to another, or returned at different time (Hoekstra et al., 2011, equ. S16). In the experimental sites, only emergency irrigation was used on a few occasions during the summer, with a total amount which was almost irrelevant compared with green water. The grey water footprint (grey WF) is an indicator of the water volume needed to dilute a pollutant load that reaches a water body so to reach a pollutant concentration within the national water quality standards (Franke et al., 2013). The methodology to calculate the grey WF (Franke et al., 2013, equ. S17-S19) considers the pollutant load (L) entering a water body, the maximum acceptable concentration (C_{max}) (Directive EU 2020/2184) and the natural background concentration of the chemical in the receiving water body (C_{nat}). The estimated pollutant load was first multiplied for a scalar (0–1) to consider the effect of the application method on the reduction of available pollutant for dispersion into the environment (Franke et al., 2013). In case of diffuse sources of water pollution, like the use of pesticides and fertilizers in agriculture, it is assumed that only a fraction (α) of the pollutant released in the field reaches freshwater bodies. The α value was derived following the methodology of Franke et al. (2013). The pollutants considered for the grey WF analysis used in the field trials were pesticides, herbicides and nitrogen and phosphate from fertilization (Table S9).

2.2.4. Microbial biodiversity

For the present study the alfa biodiversity of three main microbial groups, bacteria, fungi and oomycetes, was analysed and the Shannon-Wiener diversity index (Shannon and Weaver, 1949) was chosen as the main index to be included in the integrated multi-indicator; the Faith phylogenetic diversity index (Faith, 1992) and the Pielou index of evenness (Pielou, 1966) were also estimated to discuss the biodiversity results.

The estimate of biodiversity was based on a metagenomics analysis applied to composites soil samples, one for each plot obtained from 3 replicated cores (0–20 cm). Total DNA was extracted from sieved (2 mm) fresh soil (0.33 g) (MoBIO Power Soil DNA Isolation kit, MoBIO Laboratories, Inc., CA, USA). The DNA concentrations were quantified with a Qubit dsDNA BR Assay kit (Thermo Fisher Scientific Inc., MA, USA), before amplification. Additionally, three mock communities (Oomycetes, Fungi, and Bacteria) were created by pooling DNA from a pure culture of different species and used as controls, processed in the same way as the samples. For the PCR amplification procedure of DNA see supplementary information. Paired-end sequencing was carried out on an Illumina MiSeq sequencer (2x300 bp) by Genesupport SA (Plan-les-Ouates - Switzerland). The pipeline reported by Morales-Rodriguez et al., (2019) was used for the analysis of Illumina results (details in supplementary information). Alpha diversity indexes were calculated with QIIME2 program (Caporaso et al., 2010). Differences among managements were estimated for each alpha diversity index by Kruskal-Wallis one way analysis of variance, followed by Dunn's test for multiple pairwise comparison, where necessary. Null hypotheses were rejected in all cases when $P < 0.05$. This analysis was done using Prism 8 (Graph Pad Software, San Diego, CA, USA).

2.2.5. Soil C stock

To estimate the soil C accrual, data sampled in 2018 were compared with baseline data sampled in 2012. In 2018, four soil cores (0–20 cm depth) were sampled in each plot together with samples for bulk density. Total organic carbon (TOC) was measured on air-dried, sieved (<2 mm) and grinded (<0.2 mm) soil, and it was calculated as the difference between total carbon, measured by elemental analyser CN equipped with a TCD detector, and inorganic carbon determined by volumetric method (Morelli et al., 2022). The soil C stock change (t C ha^{-1} yr^{-1}) was calculated empirically, by direct difference of soil C stocks in 2012 and 2018. Soil C stocks were estimated as the product of the content of SOC in the fine soil (%) for the bulk density measured at the same sample depth, corrected for possible rock fragment presence.

2.2.6. The multi-indicator sustainability index (SI) and the Analytical Hierarchy Process-AHP method

For the evaluation of the sustainability index (SI), a rating and weighting procedure was used based on the Analytical Hierarchy Process-AHP method (Saaty, 1977; 1980). First, a preliminary ranking was assigned to each indicator based on the following criteria: a. the relevance of the indicator for critical environmental pressures set as priority goals in international and EU policies, b. the criticality of the indicator for local resources depletion/degradation, c. science-based evidence and strength connecting the indicator to the "health and sustainability" status of agroecosystem. Based on these three criteria the five indicators were ranked as follows, from 1 (higher priority) to 5 (lower priority): 1. C footprint, 2. water footprint, 3. soil C accrual, 4. N footprint, 5. biodiversity (Shannon index). The C footprint and water indicators (water footprint, blue water), generally rank first and second in most studies dealing with food sustainability and agriculture impacts (Chaudhary et al., 2018; Béné et al., 2019). Soil C sequestration is very important for soil quality and health (Grilli et al., 2021) and climate mitigation, however less robust evidence is available to generalize the effect of different managements on C sequestration rates (IPCC, 2006, 2019b). The N footprint reflects pressures generated by N use in agriculture, for which significant scientific evidence exists (Gu et al., 2023), but much less data are available to compare and rank agro-products based on their N footprint. We ranked biodiversity last not because it was considered of minor importance but because, referring to soil microbial biodiversity studies, no univocal and strong scientific evidence exists yet that demonstrates the level of microbial community biodiversity considered "healthy" for an agronomic system. The ranking was then used as input in the following analysis using the Analytical Hierarchy Process method (Saaty, 1980), which provided the weights of the 5 indicators. The measure of each indicator was determined by prioritizing and ranking the variables in a pairwise comparison scale, and then defining a linear hierarchy of importance among the factors (Saaty, 1980). The consistency ratio (CR), CI/RI, where RI is the random index and CI is the consistency index, was used to check the consistency of the application (Saaty, 1977). The weights, obtained for each indicator, are reported in Table 3.

For each indicator five *impact classes* were identified and the range of indicators' values for each "impact" class was created using data

Table 4
Average yield (±1 st.dev.) of the two grape types (Pinot blanc and Rhine Riesling) analyzed over three years (2016–2018), n = (30 per thesis per year).

Vineyard	Average yield (Tons/ha)		
	INT	ORG1	ORG2
Pinot blanc	13.54 ± 5.51	14.12 ± 5.40	14.23 ± 6.00
Rhine Riesling	12.28 ± 4.00	13.22 ± 4.49	13.10 ± 3.84

reported in literature (Table S10). The “impact”scores were assigned a class value from 1 to 5 for those parameters where less is better (less GHG emitted, less water lost, less reactive N released) or from 5 to 1 for those parameters where more is better (more soil C accrual, more biodiversity). Classes of Impacts were represented in banding colours, from dark green (most sustainable option) to red (less sustainable option) (Table 10).

The sustainability index (SI) was calculated as: $SI = .\sum_{1=5}^{i} W_i \times I_i$

where Wi is the “weight” of each indicator (i) obtained with the AHP method, which is multiplied for Ii, its “impact class value” (Table 3).

The five classes of the “sustainability index” (SI), estimated with this approach, have the following values, ***class 1*** $x < 1.72$, ***class 2*** $1.72 < x < 2.36$, ***class 3*** $2.36 < x < 3$, ***class 4*** $3 < x < 3.36$, ***class 5*** $x > 3.64$ (Table 3). Each SI class was associated to a banding color going from the most sustainable class 1 to the least sustainable option, class 5 red.

3. Results and discussion

3.1. Effect of management on grape yield

Yield plays an important role in the use of “footprint” indicators when they are expressed per unit of product, as is often the case. This is particularly relevant when comparing conventional and organic farming, as the latter is generally considered to provide lower yields. This difference can vary from an average of 20 %, as reported by Seufert et al. (2012) in a *meta*-analysis study carried out mostly in developed countries, to around 5 % under favourable climatic and edaphic conditions combined with optimized management (Willer and Kilcher, 2011). In this study, no statistical difference (One-Way ANOVA, $P > 0.05$) was found among the grape yields of the three investigated managements within each grape variety (Table 4). The yield of grapes varied between 9.8 and 16.7 tons/ha depending on the treatment, year and cultivar (Morelli et al., 2022).

The similar yield values, obtained for INT and ORG, could be explained by the very high degree of naturalness applied in all the managements including INT, which also made use of permanent grass and minimal use of machinery in favour of manual treatments (e.g., topping, pruning, tying, shoot management, leaf removal, etc.). Furthermore, the high sustainability of the vineyard made it possible to achieve a low impact of diseases on the grapes (powdery mildew, downy mildew and rot). Carrying out the practice of thinning in all the trials was essential to allow compliance with the grape growing regulations, which set yield limits of 15 and 14 tons/ha, respectively for DOC Pinot blanc and Rhine Riesling wines. This similarity in yield allowed a better appreciation of the difference in footprint due to the management impact alone (Chiriacò et al., 2022).

3.2. Carbon footprint

The grape CF values (kg CO_2eq/kg), as well as the total GHG/ha (kg CO_2eq/ha), were in the order INT > ORG1 > ORG2 for both cultivars (Fig. 1, Table S6-S8).

The highest contribution to the total GHG emissions came from the use of fuel and energy (37 %-52 %) and materials necessary for the vineyard plant structure (29 %-39 %) (Fig. 1). Mineral fertilization and chemicals accounted for about 32 % in the INT, only 8 % in ORG1 and 20 % in ORG2. A lower use of external materials reduced the waste generated in ORG1 and ORG2 and the GHG emissions associated to its end-life. Overall, the GHG emissions associated with organic managements were 24 % – 31 % lower than those estimated for the integrated treatment, when reported per land basis (ha). This GHG saving is comparable with results for “vegetable” and “fruit” typologies reported by Chiriacò et al. (2022), who analysed 41 food items from 27 peer-reviewed studies, comparing the CF of the food produced in paired experiments of organic versus not organic (mostly conventional) management. In absolute terms, the measured emissions from the three systems were below the 50th percentile of values reported in Chiriacò et al. (2022) for organic management. The CF of the INT grape was 0.213 and 0.227 kg CO_2-eq/kg of grapes, 0.144 and 0.168 kg CO_2-eq/kg grape in ORG1 and 0.134 and 0.147 kg CO_2-eq/kg of grapes in ORG2, for Pinot and Riesling cultivars, respectively. Using the 3 years of observation for each cultivar as replicates for statistical analysis, no difference was observed among treatments considering the overall C footprint. Only GHG emissions per unit of grapes associated to fertilizer and chemical use were statistically higher in the INT treatment compared to ORG1 and ORG2 (Table S6). The biggest contribution to the CF came from the use of fossil fuels and energy as well as from the vineyard plant set up, for all the treatments (Fig. 1). The latter is characterized by concrete posts that are still commonly used in this production sector. The most relevant difference between INT and ORG (1 and 2) was associated with the different fertilizers used and chemicals for pest control. INT made specific use of mineral fertilizers, which significantly contribute to GHG emission during both phases of industrial production (abiotic) and field application (biogenic emissions). The contribution of agricultural wastes treatment to total CF was negligible (below the 1 %

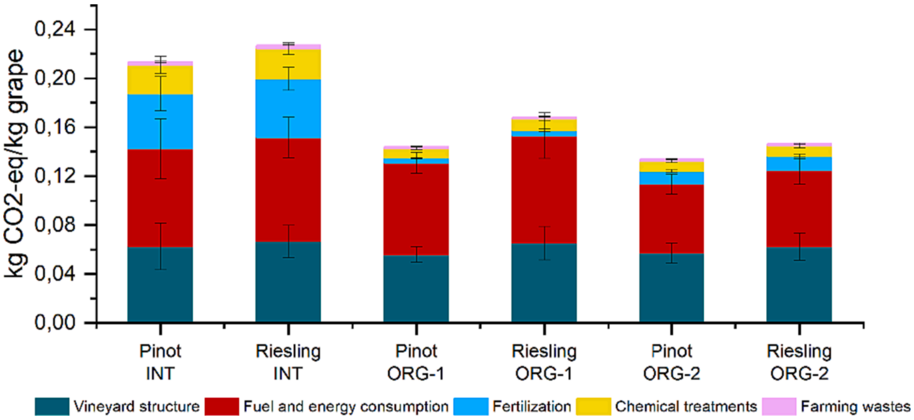


Fig. 1. Carbon footprint of grapes (kg CO_2eq./kg of product) estimated for the integrated (INT) or organic farming (ORG1 and ORG2) managements, applied in the experimental vineyard trials. For statistical differences see Table S6.

Table 5

Nr associated to each phase of the life cycle of grape production reported as land-based (kg Nr/ha) and product-based (g Nr/kg grape) for the three treatments (INT, ORG1 and ORG2) and two cultivars (Pinot blanc and Rhine Riesling). Different letters in apex indicate significant differences among treatments (INT, ORG1 and ORG2) (One Way ANOVA, $P < 0.01$, Holm-Sidak test for multiple comparisons).

Farming management		Vineyard structure	Fuel and electricity consumption	Fertilization	Chemical treatments	Farming wastes	Total
	kg Nr/ha						
INT	Mean	0.097	0.011	12.7	0.373	0.003	13.2
ORG1	Mean	0.097	0.011	5.9	0.113	0.002	6.1
ORG2	Mean	0.097	0.009	7.1	0.111	0.003	7.4
Pinot blanc		g Nr/kg grape					
INT	Mean	0.0075^{a}	0.0008^{a}	0.993^{a}	0.0292^{a}	0.0002^{a}	1.031^{a}
ORG1	Mean	0.0068^{a}	0.0008^{a}	0.409^{b}	0.0079^{b}	0.0002^{a}	0.425^{b}
ORG2	Mean	0.0069^{a}	0.0006^{a}	0.509^{b}	0.0079^{b}	0.0002^{a}	0.525^{b}
Rhine Riesling		g Nr/kg grape					
INT	Mean	0.0081^{a}	0.0009^{a}	1.057^{a}	0.0310^{a}	0.0003^{a}	1.097^{a}
ORG1	Mean	0.0079^{a}	0.0009^{a}	0.478^{b}	0.0092^{b}	0.0002^{a}	0.497^{b}
ORG2	Mean	0.0076^{a}	0.0007^{a}	0.558^{b}	0.0087^{b}	0.0002^{a}	0.575^{b}

Table 6

ETc, Peff, green water and green water footprint (L/kg grape) reported for the grapes of the cultivars under three managements (INT, ORG1 and ORG2). There is no statistical difference among treatments for each wine variety (One Way ANOVA, $P > 0.05$).

Farming management	ETc mm/ha	Peff mm/ha	Green water mm/ha	L/ha	Year	**Green WF - Pinot** L/kg grape	**Green WF - Riesling** L/kg grape
INT	817.2	873.4	817.2	8.17E + 6	2016	860.2	605.3
					2017	567.5	833.9
					2018	489.3	600.9
					Mean	**639.0**	**680.0**
					SD	195.5	133.3
ORG1	817.2	873.4	817.2	8.17E + 6	2016	664.4	548.5
					2017	523.8	763.7
					2018	563.6	583.7
					Mean	**583.9**	**632.0**
					SD	72.4	115.5
ORG2	713.5	873.4	713.5	7.13E + 6	2016	517.0	454.4
					2017	575.4	654.6
					2018	432.4	561.8
					Mean	**508.3**	**556.9**
					SD	71.9	100.1

cut-off value). Overall, the CF of the grapes were in the range, and below the mean value, of CF values reported for grapes in the Petersson et al. (2021) CF database (mean: 0.33 kg CO2eq/kg, range: 0.15–0.88 kg CO_2eq/kg). Considering the sole organic theses, the CF was significantly lower than the Q1 (0.27 kg CO_2eq/kg) value of the 15 studies reported by Petersson et al. (2021).

3.3. Nitrogen footprint

The Nr associated to one ha of land treated with organic management was between 44 and 55 % (Table 5) lower than Nr estimated for the INT management. Around 96 % of the estimated Nr derived from fertilizer application, while the other processes contributed for less than 1 %, except for chemical treatment application in the INT management. The NF of grapes in the INT management (1.03–1.10 g Nr/kg) was significantly higher than NF measured for ORG1 (0.42–0.50 g Nr/kg) and ORG2 (0.52–0.57 g Nr/kg). These values are lower than the lowest NF value of 2 g Nr/kg product reported for sugar beet, fruits and vegetables, and potatoes by Leip et al. (2014), who analysed 14 food categories in EU27 at country level. As also reported by Leip et al. (2014), the most

Table 7

ETc, Peff, blue water and blue water footprint (L/kg grape) reported for the grapes of the cultivars under three managements (INT, ORG1 and ORG2). There is no statistical difference among treatments for each wine variety (One Way ANOVA, $P > 0.05$).

Farming management	Chemicals treatments water L/ha	Irrigation water L/ha	Blue WF L/ha	Year	**Blue WF - Pinot** L/kg grape	**Blue WF - Riesling** L/kg grape
INT	3.30E + 4	2.40E + 5	2.73E + 5	2016	28.8	20.2
				2017	19.0	27.9
				2018	16.4	20.1
				Mean	**21.4**	**22.7**
				SD	6.5	4.5
ORG1	3.40E + 4	2.40E + 5	2.74E + 5	2016	22.3	18.4
				2017	17.6	25.6
				2018	18.9	19.6
				Mean	**19.6**	**21.2**
				SD	2.4	3.9
ORG2	3.36E + 4	2.40E + 5	2.74E + 5	2016	19.9	17.4
				2017	22.1	25.1
				2018	16.6	21.6
				Mean	**19.5**	**21.4**
				SD	2.8	3.8

Table 8
Grey water and grey water footprint (L/kg grape) reported for the grapes of the cultivars under three managements (INT, ORG1 and ORG2).

Farming management	Pollutant	Grey water m3/ha	Year	**Grey WF - Pinot** liters/kg grape	**Grey WF - Riesling** liters/kg grape
INT (Scenario with pesticides)	Potassium phosphonate	7.92E + 5	2016	8.34E + 4	5.87E + 4
			2017	5.50E + 4	8.08E + 4
			2018	4.74E + 4	5.82E + 4
			Mean	**6.19E + 4**^{a}	**6.59E + 4**^{a}
			SD	1.89E + 4	1.29E + 4
INT (Scenario w/o pesticides)	NPK 12–12-17	73.5	2016	7.74	5.45
			2017	5.11	7.50
			2018	4.40	5.41
			Mean	**5.75**^{b}	**6.12**^{b}
			SD	1.76	1.20
ORG-1		18.4	2016	1.49	1.23
			2017	1.18	1.72
			2018	1.27	1.31
			Mean	**1.31**^{c}	**1.42**^{c}
			SD	0.16	0.26
ORG-2		19.7	2016	1.43	1.26
			2017	1.59	1.81
			2018	1.20	1.55
			Mean	**1.41**^{c}	**1.54**^{c}
			SD	0.20	0.28

relevant contribution came from N leaching, run-off and ammonia volatilization, therefore, mitigation measures aimed at reducing not only N inputs but also the aforementioned processes might further reduce the Nr footprint of grapes.

The N investment factor (NIF) of grapes, defined as the quantity of new reactive N required to produce one unit of N in the grapes, varied in our case between 0.5 and 0.6 Nr/kg N for the ORG treatments and 1.3–1.4 kg Nr/kg N for the INT treatment. In all cases NIF was, as expected, lower than NIF reported for N reach plant-based products like pulses (1–2 kg N/kg N) and much lower than NIF of animal products like beef (15–20 kg N) (Leip et al., 2014).

3.4. *Water footprint (WF)*

The three components of WF, green, blue and grey WF, calculated for the grapes of the three treatments and two cultivars are reported in Table 6, 7 and 8, respectively. The green WF varied between 508.3 and 680 L/kg grape, with the mean value estimated for the three years decreasing in the order INT > ORG1 > ORG2, although the difference among treatments was not statistically significant.

This is to be expected, as greening with grass was present in all the three systems with similar plant density (Morelli et al., 2022). Rainwater was sufficient to satisfy crop requirements thus requiring limited emergency irrigation resulting in a very low blue WF of 19.7–22.5 L/kg grape, with no significant difference among treatments or cultivars (Table 7).

The biggest difference was found analyzing the grey WF (Table 8). When only fertilization and nutrient inputs were considered in the evaluation of the potential water pollution generated by the three

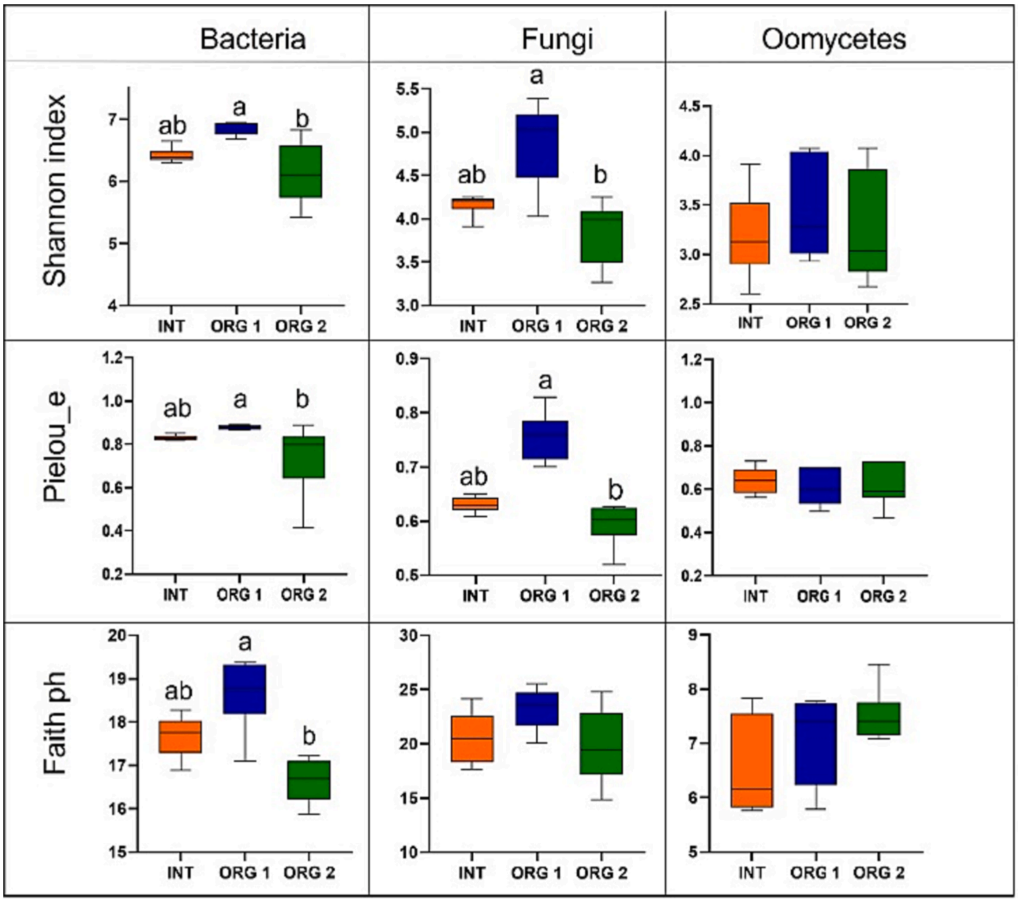


Fig. 2. Alpha diversity indexes of soil microbial communities. Shannon index, Pielou's evenness index and Faith's phylogenetic diversity indexes calculated from the metagenomics data of Bacteria, Fungi, and Oomycetes for integrated (INT) and organic (ORG 1 and ORG2) managements of experimental vineyard trials. Difference letters indicate significant difference, Dunn's test; $P < 0.05$.

management, the grey WF was generally quite low (1.31–6.12 L/kg) due to the relatively low amount of fertilizer added to the vineyard treatments, compared with other cultivations. The INT grey WF was significantly higher than the grey WF of ORG1 and ORG2, which did not significantly differ.

When, however, also the chemical treatments were added in the evaluation, the very low limits posed by EU regulation (Directive EU 2020/2184) for synthetic organic chemical concentration in water raised the grey WF of INT from 5.7 to 6.12 L/kg to 65,900 L/kg of grape (Table 8, Table S8). These stringent thresholds assigned to organic pesticides lead to very high WF values in conventional and integrated managements (Borsato et al., 2018).

Although in the panorama of reported values of food WF this high value might seem surprising, we have to consider that the majority of publications, reported for large scale analysis, mainly considered pollution derived from fertilizer application (Mekonnen and Hoekstra, 2011; Hoekstra, 2017), due the more robust data that can be found for fertilizer use and application, compared with the extremely high uncertainty associated to identification of pesticides applied and leaked into the environment. Additionally, while green and blue WF represent indeed a real flux of water and provide also a measure for potential water loss and use in the system which can be concretely used for water management planning, the grey WF is rather a concept which gives an order of magnitude of the potential water polluting effect of a process or management and assimilation capacity of the water bodies, as the exact dilution of a chemical in fresh water depends on the hydrogeology of the system/s analyzed. If we hence report the WF excluding pesticide impact, the analyzed total WF was on average 666 and 708 L/kg grapes for INT (Pinot and Riesling), 605 and 655 L/kg for ORG1 (Pinot and Riesling), and 529 and 580 L/kg for ORG2 (Pinot and Riesling). These values are in the range of values previously reported for grapes (506–608 L/kg Mekonnen and Hoekstra, 2011). It however, relevant to consider that adding pesticides in the calculation dramatically changes the level of WF.

3.5. *Microbial biodiversity*

After bioinformatic treatment of the data, a total of 1311 OTUs were used for downstream analyses, 110 oomycete OTUs, 634 fungal OTUs, and 567 bacteria OTUs. Rarefaction curves of all taxa reached an asymptote and showed saturation, indicating that the sampling size was acceptable and suggesting that most of the biodiversity of the samples was detected (data not shown). The Oomycetes group did not show any significant difference among treatments, for any of the three alpha diversity indexes (Fig. 2). The Shannon index (*H*), that indicates the diversity of species in a particular community, showed the highest value for the bacteria, followed by fungi and oomycetes. For both, fungi and bacteria, H was significantly higher in ORG1 ($H = 9.67$; $P < 0.05$) compared with ORG2 and INT (which did not differ), the difference being more evident for fungi ($H = 8.6$; $P < 0.05$). No effect of management on evenness was found in this study in the oomycetes group, while for both fungi and bacteria ORG1 was significantly higher than ORG2 and similar to INT. Bacteria showed higher evenness followed by fungi and oomycetes (Fig. 2).The Pielou's evenness measures how the species are evenly distributed in a community, with low evenness values indicating an uneven distribution with high densities of only few opportunistic species and higher evenness generally indicating higher community stability.

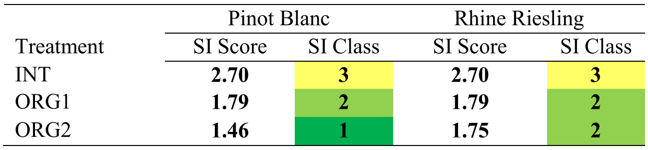
The third index, the Faith's Phylogenetic index (*pd*), a measure of biodiversity based on phylogeny (the tree of life) showed the highest *pd* values in ORG1, higher in the fungal group, slightly lower for bacteria and very low for oomycetes. Although not statistical difference was observed, the fungal *pd* value increased in the order ORG2 < INT < ORG1 ($19.79 < 20.59 < 23.28$). For the bacterial community the *pd* order was ORG2 < INT < ORG1 ($16.66 < 17.67 < 18.64$) and was always significantly different ($H = 10.48$; $P < 0.05$) (Fig. 2). Generally, high Faith's Phylogenetic index values suggests a stable ecosystem with many different niches and low competition (high richness and evenness), whereas lower values indicate systems with few potential niches where only a few species dominate (low richness and evenness). The.

Table 9
Total soil organic C in the studied vineyard soils (median, minimum, maximum, first – Q_1 – and third – Q_3 – quartile). No statistically significant was evidenced between year 2012 and 2018 (Kruskal-Wallis text, $p \leq 0.05$) for the same management.

Farming management	Year	SOC ($g\ kg^{-1}$ d.w.)	Min – Max ($g\ kg^{-1}$ d.w.)	Q_1 - Q_3 ($g\ kg^{-1}$ d.w.)
INT	2012	23.2	22.0—27.8	22.6—25.5
	2018	23.8	20.9—35.4	22.3—29.6
ORG1	2012	20.3	19.7—24.4	20.0—22.3
	2018	22.3	18.0—26.1	19.7—24.7
ORG2	2012	21.2	15.1—26.7	15.4—26.7
	2018	21.5	18.6—26.1	19.4—24.4

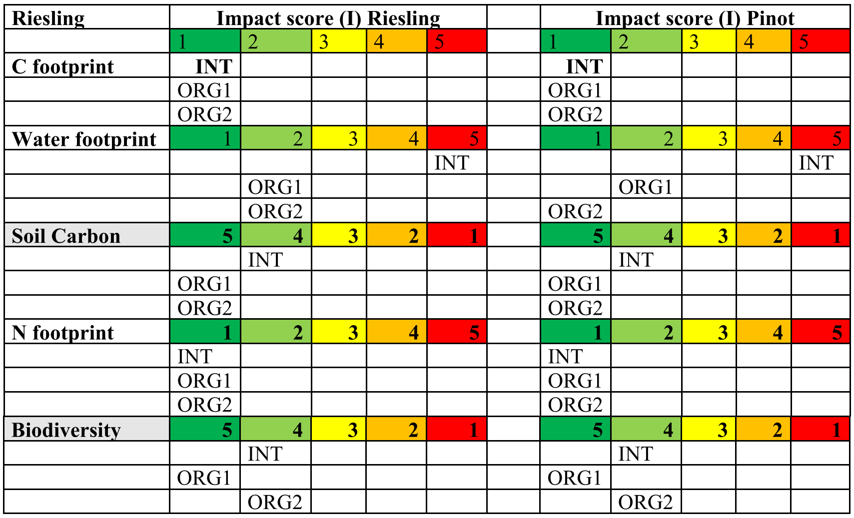
There is evidence that soil biodiversity confers stability to stress and disturbance, although the mechanisms are not yet fully understood (Brussard et al., 2007). Fertilization management has been found to influence soil microbial communities in agroecosystems (Zhang et al., 2020). Hartmann et al. (2015), analysing the response of the bacterial and fungal communities to more than two decades of organic vs conventional farming management, using a high-throughput pyrosequencing approach on ribosomal markers, found that organic farming increased soil microbial richness but the effect was visible only where conventionally managed soils received exclusively mineral fertilization, whereas the difference became smaller when conventionally managed soils were under an integrated fertilization scheme. This result might be coherent with the level of biodiversity observed in this study in the INT management, often like ORG2, as also in the INT management a permanent cover of grass was maintained over the years. ORG1 presented the highest biodiversity indices and hence it might be hypothesised that cattle manure had a positive effect of soil microbiome. Although cattle manure can be used in grapevines as organic fertilizer, to our knowledge, information about soil microbial communities of vineyards treated with cattle manure fertilization is limited. Composted chicken, cow, and sheep manure applied alone or in combination with plant growth-promoting bacteria were found a promising tool for the management of phytoparasitic nematodes, enrichment of free-living nematodes and predacious nematodes and for the improvement of plant growth and grapevine yield by El-Ashry (2021). Bacterial diversity in tea plantations treated with cow manure fertilization was found to be significantly higher than in soils treated with chemical fertilization by Zhang et al. (2020). The cow manure was found to increase soil pH, nitrogen, available potassium and organic matter respect to the unfertilized soil or fertilized with urea (Zhang et al., 2020). Soil pH indeed is a critical factor for bacterial diversification and exerted a strong influence on the structure of soil microbial communities (Zhalnina et al., 2015). Soil organic matter is considered a factor influencing the microbial community composition (Zhang et al., 2017) and cattle manure could provide rich carbon sources to promote the activity of soil microorganisms. Also, soil available potassium has been found to have positive effect on soil microbial community composition (Yan et al., 2020). Unexpectedly, addition of green manure (mix of Poaceae 47 %, Fabaceae 40 %, and Brassicaceae 13 %) in ORG2 did not seem to lead to an increase in soil microbial alpha diversity indices. Previous studies with greening management, in conditions similar to ORG2, showed that bacterial alpha diversity was significantly higher compared to soils fertilized with organic fertilizer or treated with biodynamic management, whereas no differences were found in fungal communities among treatments (Longa et al., 2017). However, more studies would be needed to drive general conclusions.

Table 10
The Sustainability index (SI) calculated for each managements option for the two grape cultivars.



	Pinot Blanc		Rhine Riesling	
Treatment	SI Score	SI Class	SI Score	SI Class
INT	**2.70**	**3**	**2.70**	**3**
ORG1	**1.79**	**2**	**1.79**	**2**
ORG2	**1.46**	**1**	**1.75**	**2**

Table 11
Breakdown of the impact score class of each indicator, relative to each management, calculated for both cultivars.



Riesling	**Impact score (I) Riesling**						**Impact score (I) Pinot**				
	1	2	3	4	5		1	2	3	4	5
C footprint	**INT**						**INT**				
	ORG1						ORG1				
	ORG2						ORG2				
Water footprint	1	2	3	4	5		1	2	3	4	5
					INT						INT
		ORG1						ORG1			
		ORG2					ORG2				
Soil Carbon	**5**	**4**	**3**	**2**	**1**		**5**	**4**	**3**	**2**	**1**
		INT						INT			
	ORG1						ORG1				
	ORG2						ORG2				
N footprint	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**
	INT						INT				
	ORG1						ORG1				
	ORG2						ORG2				
Biodiversity	**5**	**4**	**3**	**2**	**1**		**5**	**4**	**3**	**2**	**1**
		INT						INT			
	ORG1						ORG1				
		ORG2						ORG2			

3.6. Soil quality

An average increase of soil C was observed in 2018 (Table 9) in all the treatments compared to 2012 (0.075, 0.25 and 0.037 g C kg^{-1} yr^{-1}, for INT, ORG21 and ORG2, respectively), corresponding to about 0.29, 0.97- and 0.15-Tons C ha^{-1} yr^{-1} (0–30 cm depth). The increase, however, was not statistically significant, hence it should be considered as a trend and additional years could be necessary to consolidate the treatment effect on soil C accrual. As no statistical difference was observed between treatments we calculated an average C sequestration rate of 0.47 Tons C ha^{-1} yr^{-1} for all the treatments.

Organic farming, as well as greening and increased organic inputs are considered as effective measures to improve soil C accumulation (Vicente-Vicente et al., 2016). However, it is generally recognized that especially in soils with a medium to good level of organic C, it may take several decades to observe a significant change in C content due to management (IPCC, 2006). Morelli et al. (2022), analysed the fractions of soil C with different stability on the same samples and reported a significant increase of the most stable fraction and the labile fraction in ORG 2, and only the labile organic C in ORG1. The stable fraction of soil organic C, resistant to acid hydrolysis, represents the most strongly protected fraction of soil C from microbial decomposition, is associated to the mineral component and is characterized by a long lifetime, all positive factors to contribute to C accrual in the ecosystem (Rovira and Vallejo, 2002; Mclauchlan and Hobbie, 2004; Hoosbeek et al., 2006; von Lützow et al., 2006).

3.7. Multi indicator comparison between integrated and organic management

The sustainability index calculated for the three management options of the two cultivars, Riesling and Pinot, (Table 10) showed that, considering the whole scenario of evaluated impacts, the sustainability level of both organic farming management systems was higher compared to the integrated management, but it also showed a quite good level of sustainability in the integrated treatment. For the latter, the major cause of class 3 (yellow) was to be attributed to the very high grey footprint associated to the use of organic pesticides (Table 11).

The available studies reporting comparisons of conventional vs. organic farming with multi-indicators approaches, provide supporting evidence for a better performance of organic systems, despite the generally lower yield. Boschiero et al. (2023), revising 77 paired case studies where impacts were evaluated with LCA methodology, concluded that organic systems had overall a better environmental performance than conventional ones for all the analysed LCAI categories, when reported on land basis, and only for climate change, ozone depletion, ecotoxicity and use of resources (i.e. abiotic, mineral and metal resources) when expressed as product-base. Fruit and nuts provided the most clear difference between systems, although a significant variability was observed within the same commodity depending on site characteristics and management (Boschiero et al., 2023). A crucial conclusion of their review, was that fundamental aspects of agricultural systems, such as biodiversity, soil organic carbon, impact on soil and land "are still rarely taken into account in LCA studies, despite the available evidence on the fundamental role that these aspects play in mitigating GHG emissions and in ensuring the resilience of food systems" and that scientific effort is needed to propose monitoring methodologies that include such neglected impacts in LCA farming studies.

An other positive result, based on multi-footprint approach on vineyards, is reported by Borsato et al. (2020), who included a multi-criteria descriptor of farming sustainability (VIVA) in their analysis and showed that organic management in viticulture gave better environmental performances results without economic losses. Michos et al. (2018) using three main indicators, energy efficiency of the farming systems, carbon and water footprint, on 15 vineyards, could not differentiate organic from integrated management, as results depended on the farm and specific managements applied.

Vanham et al. (2019) in their systematic review of multi-footprint studies, pointed out that “the footprint family is a flexible framework where particular members can be included or excluded according to the context or area of concern”. A comprehensive set of indicators is hence necessary to get this type of flexibility.

4. Conclusions

The integration of complementary footprints and indicators to assess environmental sustainability is recognised as fundamental for “comprehensive understanding of environmental issues, policy formulation and assessment of trade-offs between different environmental concerns” Vanham et al. (2019) to respond to Sustainable Development Goals (SDGs) and environmental planetary challenges. With a multi-indicator approach we showed that the organic management could be considered an important option in the analysed vineyard to increase the sustainability of grape production for the most important spheres of intervention necessary to stay within the limits of Earth sustainability planetary boundaries.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111297.

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