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Biodiversity conservation, ecosystem services and organic viticulture: A glass half-full

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ABSTRACT

Organic farming is a promising but still debated option to ensure sustainable agriculture. However, whether organic farming fosters synergies or mitigates tradeoffs between biodiversity, ecosystem services and crop production has rarely been quantified. Here, we investigate relationships between multitrophic diversity (14 taxa above and belowground), yield, natural pest control and soil quality (14 proxies of ecosystem services) in organic and conventional vineyards along a landscape gradient. Organic farming enhanced biodiversity and pest control, but decreased wine production. Compared to conventional systems, multitrophic diversity was 15 % higher, and pest control services were 9 % higher in organic systems, while wine production was 11 % lower. Regardless of management type, we found a strong tradeoff between wine production and pest control, but not between wine production and biodiversity. The landscape context was not a strong moderator of organic farming effects across taxa groups and ecosystem services, but affected specific taxa and ecosystem services, especially natural pest control. Our study reveals that wine production and biodiversity conservation do not necessarily exclude each other, which implies the existence of a safe operating space where biodiversity and wine production can be combined. We conclude that organic farming can contribute to improve the sustainability of viticulture, but needs to be complemented by management options at the local and landscape scales in order to fully balance biodiversity conservation with the simultaneous provision of multiple ecosystem services.

1. Introduction

A main strategy to limit biodiversity loss is to transform food production systems and reconcile biodiversity conservation with agricultural production (IPBES, 2019). In agricultural ecosystems, biodiversity provides numerous ecosystem services with cascading positive effects on production (Dainese et al., 2019). Agroecological management consists in harnessing ecological processes and aims to promote synergies between biodiversity conservation and ecosystem services (Bommarco et al., 2013; Seufert and Ramankutty, 2017; Winter et al., 2018). However, tradeoffs between agricultural production and biodiversity conservation may hamper the wide implementation of agroecological practices (Knapp and van der Heijden, 2018). Understanding the conditions that foster synergies and mitigate tradeoffs between crop production, biodiversity conservation and ecosystem services provision in agroecosystems is necessary to transform agricultural systems and halt the current global biodiversity loss (Bennett et al., 2009; Bommarco et al., 2013).

Designing multifunctional agroecosystems that can simultaneously maintain biodiversity and multiple ecosystem services is thus a major goal for agroecology, and multidimensional studies provide crucial information for stakeholders and land-use managers (Allan et al., 2014;

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Bennett et al., 2009; Birkhofer et al., 2018; Byrnes et al., 2014; Giling et al., 2019; Manning et al., 2018; Mouchet et al., 2017; Sirami et al., 2019). Using multifunctionality indices can reveal the simultaneous impact of management options across a range of taxa and ecosystem services (Allan et al., 2014; Byrnes et al., 2014; Manning et al., 2018), and offer major insights into the tradeoffs and synergies between ecosystem services and biodiversity conservation (Bennett et al., 2009; Mouchet et al., 2017). However, most multifunctional studies have so far dealt with few ecosystem types, and narrow range of taxa groups and ecosystem services (Garland et al., 2020; Sirami et al., 2019). To date, knowledge is particularly limited regarding agroecosystems and how agroecological practices might modulate such tradeoffs and synergies (Herzog et al., 2019; Wittwer et al., 2021).

Organic farming, often considered as a prototype for agroecological management, is being widely implemented at the global scale. For instance, in its recent Green Deal, the European Union targets 25 % of its farmland under organic farming by 2030. Yet, the environmental performances of organic farming are still debated (Brühl et al., 2022; Seufert and Ramankutty, 2017; Tscharntke et al., 2021). Evidence generally indicate multiple positive effects of organic farming on local biodiversity (Bengtsson et al., 2005; Hole et al., 2005; Tuck et al., 2014) and ecosystem services such as natural pest control, pollination, or carbon sequestration (Gattinger et al., 2012; Kennedy et al., 2013; Muneret et al., 2018a), but negative effects on crop yields (Seufert et al., 2012; Wittwer et al., 2021). In addition, the magnitude of organic farming effects on different taxa, and different ecosystem services can widely differ (Ostandie et al., 2021; Seufert et al., 2012; Wittwer et al., 2021). While synergies between biodiversity and ecosystem services like natural pest control and pollination are expected (Dainese et al., 2019), tradeoffs between biodiversity and agricultural production have been repeatedly observed (Geiger et al., 2010; Green et al., 2005). In organic systems, lower yields are often associated with higher biodiversity levels compared to conventional farming systems (Gabriel et al., 2013). Addressing if organic farming can enhance synergies and minimize tradeoffs between biodiversity and ecosystem services would bring major insights to resolve the debate about its potential to reconcile agricultural production with biodiversity conservation. This is especially the case in perennial agroecosystems that remain understudied compared to annual systems, but could show different responses to organic farming (Muneret et al., 2018a; Seufert et al., 2012).

Perennial crops such as vineyards are particularly interesting to investigate synergies and tradeoffs between biodiversity and ecosystem services (Rusch et al., 2022). Wine is often a luxury product, with a particular focus on product quality rather than on quantity. This is an important distinction with annual crops, where tradeoffs between biodiversity and crop yield have been investigated (Gabriel et al., 2013). Nevertheless, vineyards increasingly suffer from decreased yields due to the combined influence of extreme climatic and pathogen outbreak events (Hong et al., 2020; Wolkovich et al., 2018). Even though increasing yield is not necessarily the objective, maintaining yield in the current and future global change context is a key challenges for viticulture (Rusch et al., 2022). This justifies further investigation of tradeoffs between wine production, biodiversity and ecosystem services using yield as a proxy. In addition, perennial crops such as vineyards hold the potential to host a wide range of organisms because they are less often disturbed than annual crops, especially in the large areas between vine rows (i.e. inter-rows) (Bruggisser et al., 2010). However, vineyards are also very intensively managed, and represent one of the most pesticide-dependent crop in Europe (Rusch et al., 2022; Winter et al., 2018). Organic vineyards can suffer from high levels of pathogen and pest infestations and often rely on large amounts of non-synthetic pesticides (especially the fungicides sulphur and copper) with documented negative impacts on non-target organisms (Karimi et al., 2021; Pertot et al., 2017). Furthermore, the management of inter-row vegetation is an important driver of biodiversity and ecosystem services in vineyards (Winter et al., 2018), that does not necessarily differ between organic and conventional systems. Indeed, both organic and conventional vineyards increasingly establish and maintain inter-row vegetation cover and diversity, at least in parts of the vineyards, to limit soil erosion, increase soil fertility and trafficability, and conserve biodiversity. These major differences imply that the positive effects of organic farming on biodiversity and regulating ecosystem services observed in arable systems may not necessarily be transferred to viticulture, and that different synergies and tradeoffs profiles between wine production, biodiversity and ecosystem services can be expected.

The success of organic farming in promoting biodiversity and associated services depends on environmental conditions such as the landscape context (Batáry et al., 2012; Muneret et al., 2018b; Tscharntke et al., 2012). While farming practices act as local filters on communities, larger-scale processes also shape biodiversity and ecosystem services due to metacommunity dynamics involving recolonization from the surrounding landscape (Leibold et al., 2004; Tscharntke et al., 2005). Several habitats such as grasslands or woodlands provide resources and refuges for a wide range of organisms and can therefore act as source habitats in the landscape (Landis et al., 2000; Rusch et al., 2010). Dispersal from such source habitats to crops motivated by several ecological processes such as spillover, resource complementation or supplementation, allow species to maintain locally at sites that otherwise would not support them (Dunning et al., 1992; Leibold et al., 2004; Rusch et al., 2010). Depending on species dispersal abilities, the amount and spatial configuration of such habitats in the landscape can thus affect local biodiversity and might strongly modify the local effect of farming practices (Beaumelle et al., 2021; Garibaldi et al., 2021; Martin et al., 2019; Muneret et al., 2018b; Ratto et al., 2021; Tscharntke et al., 2012). The presence of semi-natural habitats at the landscape scale can thus foster the positive effect of organic farming practices, while their absence can impede the beneficial effects from biodiversity-friendly practices due to a lack of recolonization potential (Muneret et al., 2019a; Winqvist et al., 2011). Such interactions between organic farming and the landscape context remain poorly understood at the scale of multiple taxa groups and of multiple ecosystem services (Birkhofer et al., 2018; Felipe-Lucia et al., 2020), and have been rarely investigated in perennial agroecosystems such as vineyards.

Here we investigate the potential of organic farming to reconcile the simultaneous provision of multiple ecosystem services while limiting negative impacts on biodiversity in vineyards. We address how organic farming affects the diversity and abundance of 14 taxonomic groups below- and above-ground (soil bacteria and fauna, plants, ground-dwelling and foliage arthropods, birds, butterflies, bees, and syrphids), and 14 proxies of three key ecosystem services in vineyards (wine production, natural pest control and soil quality and fertility). We evaluate how organic management influences tradeoffs and synergies between wine production, biodiversity, pest control and soil services compared to conventional management in 38 vineyards located along a wide landscape gradient (Muneret et al., 2018b; Ostandie et al., 2021). We further investigate if the proportion of semi-natural habitats, and distance to nearest semi-natural habitats modulate organic farming effects on biodiversity and multifunctionality.

2. Methods

2.1. Study design

We conducted the study in southwestern France near Bordeaux (44°48′N, − 0°14′W), in a region dominated by vineyards with a temperate oceanic climate (Fig. S1). We created a gradient of landscape complexity by selecting 19 landscapes with a range of proportions of semi-natural habitats. In each landscape, we selected two vineyards under conventional versus organic management in order to test for interactive effects between farming systems and landscape structure (Muneret et al., 2018b; Ostandie et al., 2021). Organic vineyards had all been under organic management for at least 6 years prior to data collection. Data collection and field samplings were conducted in 2019.

2.2. Local management

Vineyards were not irrigated, they were mostly cultivated with Merlot variety ($n = 31$ vineyards) and most of them ($n = 28$) tilled the soil every other inter-row, the other inter-row being vegetated (see the full description in Supplement A. and Table S1). We retrieved detailed information about farming practices (tillage and mowing frequencies, pesticide use) based on interviews with the farmers. Vegetation management in inter-rows involved several tillage and mowing operations per year in organic and conventional vineyards (Table S1). Conventional vineyards often used herbicides underneath the vines (but not in inter-rows) for weed control (Table S1). Although pesticide spraying frequencies were similar in both farming systems (Table S1), organic and conventional systems differed in terms of the number and type of active ingredients sprayed (Fig. S2). While organic vineyards received on average 3 distinct active substances, conventional received 15. Organic vineyards only used copper- and sulphur-based fungicides, while conventional vineyards used a range of synthetic and non-synthetic substances to control fungal pathogens. Importantly, due to mandatory treatments to control the vector of the quarantine disease flavescence dorée in this region, insecticides were also used in 9 of the 19 organic vineyards and the mean insecticide spraying frequencies was thus similar in organic and conventional (2 sprays per year). Insecticides used in organic vineyards against the vector of the flavescence dorée disease were certified for organic farming systems (pyrethrins and pyrethroids). Principal component analysis (PCA) of farming practices revealed the differences between organic and conventional systems, mainly driven by the number of active ingredients and total amounts of applied insecticides and herbicides (Fig. S2). Based on this separation between farming systems, and on our research question about the potential of organic farming to promote multifunctionality in vineyards, we focused on comparing organic and conventional vineyards, instead of testing the effects of specific management practices.

2.3. Landscape context

Our landscape gradient ranged from 2 % to 62 % of semi-natural habitats in a radius of 500 m around each vineyard (Table S2). Semi-natural habitats were composed of forests (from 0 % to 44 %), grasslands (0–40 %) and hedgerows (0–1 %). There was a strong negative correlation ($r = -0.9$, $p < 0.001$) between the proportions of semi-natural habitats and of vineyards (22–79 %) in our landscapes (Fig. S2). Only 7 landscapes out of 19 included other crops than vineyards (from 0.1 % to 15 %). We calculated several metrics of landscape composition (proportion of each land-use type) and configuration (edge density, mean patch size and distance to the nearest semi-natural habitat) using QGIS 2.18.1 and the R package sf (Pebesma, 2018). Edge density ranged from 0.03 to 0.06 m per landscape circle. The mean patch size of semi natural habitats ranged from 1106 to 80,445 m^2, while that of vineyards ranged from 4742 to 11,732 m^2. The distance to the nearest semi-natural habitat ranged from 14 to 243 m (Table S2).

We used PCA to identify landscape metrics summarizing landscape composition and configuration in our systems (Fig. S2). Several landscape metrics were highly correlated, in particular edge density and the proportion of semi-natural habitats (Fig. S2). Based on the results, and on previous studies in our systems (Beaumelle et al., 2021; Muneret et al., 2018b; Ostandie et al., 2021), we used the proportion of semi-natural habitats and the distance to nearest semi-natural patch as two main proxies summarizing landscape composition and configuration, respectively. These two landscape metrics were not correlated ($r = -0.04$, $p = 0.82$), and reflected the study design that involved a gradient of semi-natural habitats in the landscape.

2.4. Multitrophic diversity

We sampled 14 taxonomic groups across all 38 vineyards in 2019. Taxa groups were selected to span a wide range of trophic levels, functional roles and living compartments: aerial biodiversity (birds, butterflies, bees and syrphids); vine foliage arthropods (spiders, Coleoptera, Heteroptera, and Auchenorrhyncha (leafhoppers, spittlebugs, treehoppers and planthoppers)), ground-dwelling arthropods (ground beetles and spiders), plants, and below-ground biota (Collembola, earthworms and soil bacteria). Detailed sampling methodologies are presented in the Supplement D.

Individuals were identified to the nearest possible taxonomic level depending on the group considered (species (birds, butterflies, spiders, plants, ground beetles, Collembola and earthworms), genus (pollinators), family (Coleoptera, Heteroptera, Auchennorrhyncha), or operational taxonomic units (OTU) for soil bacteria). We calculated for each group in each vineyard, the mean abundance and total species, genus, family or OTU richness across all sampling units (Figs. S3, S4). We use the term taxa richness throughout, although the richness of the different groups was based on different taxonomic ranks. Such discrepancies are inevitable given the wide range of organisms considered here. Using different taxonomic ranks should have little effects on our results, because we addressed the response of each group separately, and of multitrophic diversity indices calculated with the standardized richness of each group as explained below.

We evaluated multitrophic diversity through two multidiversity indices that were based on the richness or abundance of the 14 taxa groups (Allan et al., 2014; Sirami et al., 2019). For each index, we calculated three metrics: average of z scores, average of variables standardized by the maximum, and number of groups exceeding a threshold of 70 % of their maximum richness or abundance across the 38 vineyards (Byrnes et al., 2014). We chose a 70 % threshold, but also explored other thresholds that showed similar patterns in response to farming systems (Fig. S7). The three multidiversity indices were strongly correlated (correlations between indices ranged from 0.77 to 0.99, with $p < 0.001$), and gave similar results (Fig. S6). In the following, we thus report only the results of the average standardized richness or abundance, with a standardization by the maximum observed value (Byrnes et al., 2014).

We also calculated a weighted multitrophic diversity index giving equal weight to the richness of four compartments (below-ground, ground-dwelling, foliage and aerial). Weighted and unweighed indices were highly correlated with $r = 0.99$, and gave similar results in terms of organic farming and landscape effects. This was probably linked to the even number of taxa groups among different compartments: below-ground ($n = 3$ groups), ground-dwelling ($n = 3$), foliage ($n = 4$), and aerial groups ($n = 4$). Here, we only report the results for the unweighed multitrophic diversity indices.

2.5. Multifunctionality

We evaluated the levels of three important ecosystem services in vineyards: wine production, natural pest control and soil quality and fertility. We selected them based on previous reviews of ecosystem services in vineyard systems (Paiola et al., 2020; Winkler et al., 2017; Winter et al., 2018). Each service was measured using several proxies or ecosystem functions (see the detailed methodology in Supplement D) and raw data in Fig. S5). For wine production, we used yield (hl of wine produced per hectare), and leaf chlorophyll content (a proxy of grapevine performance) (Taskos et al., 2015). Leaf chlorophyll content reflects grapevine N status, which is crucial for plant vigour, yield, and wine quality (Verdenal et al., 2021). Evaluating wine production is complicated by the fact that many winegrowers aim at producing high quality wines rather than maximising yields. This is not the case in our study system however, and evaluating wine yield together with vine N status combines two important aspects of production that winegrowers are concerned about. Yield and leaf chlorophyll contents were not correlated ($r = 0.14$, $p = 0.4194$). Here, we did not include measurements of grape quality due to the difficulty to standardize quality across different vine varieties, but we acknowledge that it is an important aspect to consider in future studies. For soil quality and fertility, we measured soil C and N contents, soil enzymes involved in C (glucosidase), N (urease), and P (phosphatase) cycling (Benitez et al., 2006), as well as decomposition rates using the tea bag method (litter decomposition rate (k), and labile litter stabilization (S factor, indicating long term dynamics)) (Keuskamp et al., 2013). For pest control services, we evaluated natural pest control potential (i.e. natural pest control without the release of biocontrol agents), by integrating pest predation rates, lack of pathogen damage and lack of pest damage based on different proxies. We measured predation rates of one of the main insect pests of grape, the European grapevine moth (*Lobesia botrana*) based on sentinel prey card, using eggs, pupae and predation marks on model caterpillars. Natural enemies of *L.botrana* in our systems include spiders, harvestmen, rove beetles, lacewings, ants, earwigs and parasitic wasps (Muneret et al., 2019b; Papura et al., 2020; Rusch et al., 2015, 2016). Vertebrates such as bats and birds also participate in the natural pest control of grape berry moths (Charbonnier et al., 2021; Thiéry et al., 2018). Finally, our index for pest control services also included proxies related to pest and pathogen infestation levels on leaves and grapes (mildew, oidium, botrytis, black rot, and *L. botrana*).

For each ecosystem service category, we calculated a multifunctionality index summarizing the response across the different proxies considered (Byrnes et al., 2014). We then calculated an overall multifunctionality index by giving an equal weight to each service independently of the number of proxies they were measured with. This avoided that a service measured by many proxies would be given more weight into the analysis. The overall multifunctionality was thus the average of the three, standardized, service-specific indices. Note that we used the response of pathogen and pest damage for the analysis of individual ecosystem services, but we transformed these variables to a negative scale (namely the lack of damage: $Y = 1 – \text{damage}$), for the calculation of multifunctionality indices. As for multitrophic diversity, we compared different multifunctionality indices using different standardizations and thresholds. For threshold-based indices, we chose a 70 % threshold that provided a better distribution than other thresholds, but all thresholds exhibited similar patterns in response to organic farming (Fig. S7). Threshold-based and averaging indices were highly correlated ($r = 0.66 - 0.97$, $p < 0.001$) and gave similar results (Fig. S6). Thus, we present only the results of multifunctionality indices averaging proxies or functions standardized by the maximum in the main text (Allan et al., 2014; Byrnes et al., 2014).

2.6. *Statistical analysis*

2.6.1. *Interactive effect of organic farming and landscape composition and configuration*

We tested the main and interactive effects of farming systems, landscape composition and configuration using linear mixed effect models. Models included a random effect of the site (landscape) to account for dependence between pairs of vineyards located in the same landscape. The following full model was tested across the richness and abundance of individual taxa groups, the individual proxies of ecosystem services, and the multitrophic diversity and multifunctionality indices:

$$Y \sim \mathtt{FarmingSystem\ x\ LandscapeComposition} \\ + \mathtt{FarmingSystem\ x\ LandscapeConfiguration} + 1|\mathtt{Site}.$$

With *Y* the response variable, *FarmingSystem* a two-level factor (organic or conventional farming), *LandscapeComposition* and *LandscapeConfiguration* as continuous variables: the proportion of semi-natural habitats, and distance to nearest semi-natural patch, respectively. We analysed the effect of organic farming by comparing response variables in organic vineyards versus in conventional vineyards: the intercepts in our models were thus the conventional systems. Given our main objective to test the effects of the farming system while accounting for the potential modulating effect of the landscape context, our analysis focuses on landscape metrics at a 500 m radius around each plot. We acknowledge that landscape effects on our response variables may depend on the spatial scale considered. Therefore, we also calculated the proportion of semi-natural habitats (forests and grasslands) at 1000-m scale, that ranged from 2 % to 61 % and was highly correlated with that at 500 m ($r = 0.996$, $p < 1e\text{-}16$). We ran sensitivity analyses to investigate landscape composition effects on biodiversity variables at a larger scale (1000 m). The results were identical with the main analysis, except for Coleoptera richness (Table S12). This is in line with previous results showing strong relationships between landscape characteristics at 500 and 1000 m in our study systems, and similar impact on natural enemies and pest control services (Muneret et al., 2018b). Other studies also have concluded that landscape characteristics at 500 m described well communities of larger organisms such as birds in our study systems (Barbaro et al., 2017; Bosco et al., 2021).

Residuals were checked for normality, variance homogeneity and strong departure from linearity using residual diagnostic plots with the DHARMa package (Hartig and Lohse, 2020). The following variables were log-transformed to reach normality and variance homogeneity: bird, ground beetle, foliage Coleoptera and Heteroptera richness; the abundance of earthworms, syrphids, bees, ground dwelling spiders, foliage Auchenorrhyncha and Heteroptera; soil C, phosphatase activity, predation rates of pupae, pathogen and pest damage; and the index of agricultural production and of overall multifunctionality. We added a small constant before log-transformation that was set to `1 - min(Y)` so that the minimum value would be 0 on a log scale. For pathogen damage and pest damage however, we set the constant to 10^{-3} and 10^{-6}, respectively. Bubble plots of the residuals versus their spatial coordinates, and variograms both showed no particular spatial correlation.

We evaluated the main effects of landscape composition and configuration, and their interactive effects with farming systems across our response variables, using Wald type Chi square tests on full models (Tables S3, S6, S9). We quantified the effects of organic farming on the different taxa groups and functions/proxies based on comparisons to conventional systems, using standardized coefficients from full models. Detailed model results are given in the supplement (Tables S4, S7, S10), along with the magnitude of the effects based on percent changes in organic compared to conventional vineyards (100 × Organic/Conventional) (Tables S5, S8, S11). As our results may be influenced by multiple testing given the wide range of response variables considered, we calculated adjusted p-values using the FDR method (Benjamini and Hochberg, 1995), and used an arbitrary threshold of 0.2 following Le Provost et al. (2021). Given the limitations of p-value adjustments (Bender and Lange, 2001), we interpreted our results in light of the simultaneous magnitude of the effects (percent changes), associated p-value and adjusted p-value.

2.6.2. *Synergies and tradeoffs with wine production*

In a second step, we tested if biodiversity, pest control services, and soil quality/fertility services were related to wine production, and if organic farming modulated these relationships. For that, we fitted the same model structure as above, and added a relationship with the wine production index (Production), in interaction with the farming system. This way potential synergies or tradeoffs with agricultural production were derived while accounting for our study design:

$$Y \sim \mathtt{FarmingSystem\ x\ LandscapeComposition} \\ + \mathtt{FarmingSystem\ x\ LandscapeConfiguration} \\ + \mathtt{FarmingSystem\ x\ Production} + 1|\mathtt{Site}.$$

Response variables (*Y*) were the indices of multitrophic diversity (richness- and abundance-based), or of ecosystem services (indices of pest control, and soil quality/fertility services). We checked the model residuals as reported above and we evaluated the significance and direction of the relationship with production based on Wald type Chi-square and likelihood ratio tests (Tables S13, S14). Although we use a linear relationship approach with production as explanatory variable, we are not implying that production has causal effect on the response variables. Instead, we used linear relationships approach to explore if synergies and tradeoffs between wine production, biodiversity and ecosystem services differed in organic and conventional systems (Bennett et al., 2009; Mouchet et al., 2014).

As tradeoffs with wine production levels can represent obstacles to the wide development of agroecological practices, we here focused on relationships between wine production and biodiversity or ecosystem services, but we also report and found no tradeoffs between biodiversity, pest control and soil services (Fig. S11).

3. Results

3.1. Interactive effects of organic farming and landscape context on multitrophic diversity and ecosystem services

Organic farming effects on taxa richness ranged from negative to positive depending on the group considered (Fig. 1A, Tables S3, S4, S5), but most taxa were positively affected and multitrophic diversity was significantly higher in organic than conventional vineyards (Fig. 1B). Earthworm and ground beetle richness were significantly lower in

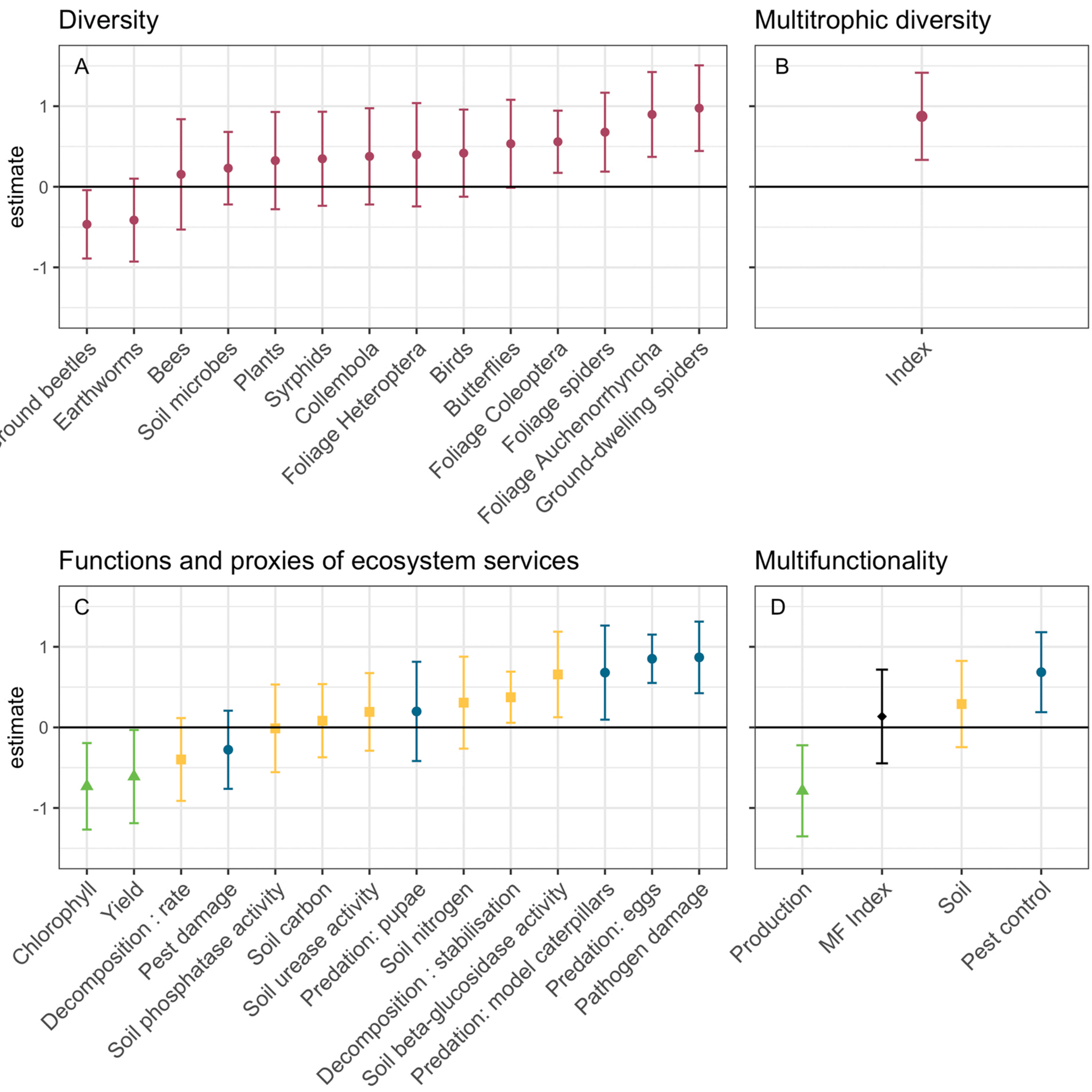

Fig. 1. Effect of organic farming on biodiversity and ecosystem services. Estimates are the standardized coefficients of the difference between organic and conventional vineyards as predicted from linear mixed effect models with landscape composition and configuration as covariates for (A) taxa richness of different groups, (B) index of multitrophic diversity, (C) proxies of three ecosystem services (agricultural production (green), soil quality/fertility (orange) and natural pest control (blue)), and (D) indices of multifunctionality for each ecosystem service, and across the three services: multifunctionality index (MF). Positive estimates indicate that the response variable is higher in organic than in conventional systems, while negative estimates indicate the response variable is lower in organic than conventional systems. Error bars are 95 % confidence intervals, significant effects of organic farming are indicated by error bars not overlapping with zero. We analysed pathogen and pest damage individually, but multifunctionality indices incorporated lack of damage (1 - damage) to reflect the direction of pest control services.

organic vineyards (19 % and 30 % lower respectively, Table S5), while the richness of ground-dwelling spiders and foliage arthropods (spiders, Coleoptera and Auchenorrhyncha (leafhoppers, spittlebugs, planthoppers and treehoppers)) were 36–51 % higher (Table S5). The richness of aerial groups (birds, butterflies and pollinators), plants, foliage Heteroptera, soil bacteria and Collembola tended to be higher in organic vineyards (from 5 % to 39 %, Table S5), but differences were not statistically significant. In terms of abundance, responses also differed according to the taxa (Fig. S8, Tables S6, S7, S8). Ground-dwelling spiders, foliage Auchenorrhyncha, and soil bacteria were significantly more abundant in organic fields (by 86 %, 63 % and 14 % respectively, Table S8), while the abundance of other groups varied non-significantly in direction and magnitude (Fig. S8, Table S6). In contrast with richness-based multitrophic diversity, multitrophic abundance did not differ significantly in organic versus conventional vineyards, although a positive trend was detected (Fig. S8).

The landscape context was not a main driver of multitrophic biodiversity and its response to organic farming (Table S3). Landscape composition (% semi-natural habitats) mostly affected the richness or abundance of aerial biodiversity groups: across the 14 groups considered, only birds, butterflies and syrphid were affected by landscape composition. While butterfly richness and abundance increased with the proportion of semi-natural habitats, it was the opposite for birds and syrphids (Tables S3, S6, S4, S7). Landscape composition modulated the response of foliage spider and Coleoptera richness to organic farming (interaction Table S3). Indeed, foliage spider richness decreased with increased proportion of semi-natural habitats in conventional vineyards, but increased with semi-natural habitats in organic farms (Fig. S9). In contrast, foliage Coleoptera richness increased with semi-natural habitats only in conventional vineyards (Fig. S9). Landscape configuration (distance to nearest semi-natural habitat patch) had no significant effect on multitrophic diversity (Table S3). In conventional vineyards, the richness of earthworms and foliage Coleoptera and the abundance of ground-dwelling spiders decreased with increasing distance to the nearest semi-natural habitat in conventional vineyards, but the opposite pattern was found in organic vineyards (Fig. S9).

Organic farming practices affected the levels of most ecosystem functions and services considered in various directions and magnitudes (Fig. 1C, Tables S9, S10, S11). The overall multifunctionality index across ecosystem services was not significantly affected by organic farming, but profiles of ecosystem functions and services differed between organic and conventional farming systems (Fig. 1D). Pest control services and agricultural production exhibited opposite responses to organic farming. While the pest control index was higher, the production index was significantly lower in organic compared to conventional vineyards. Indeed, organic systems had lower yields (16 % lower compared to conventional) and chlorophyll contents (6 %), higher pathogen damage (190 %), but higher pest predation rates (eggs and model caterpillars, 23 % and 93 %, respectively) than in conventional vineyards (Fig. 1C, Table S11). Insect pest damage levels were very low, independently of the farming system, with half of the plots exhibiting zero damage (Fig. S5). The soil quality and fertility index did not differ significantly between organic and conventional vineyards (Fig. 1D). Indeed, most of the soil quality proxies were similar in both farming systems, and only soil glucosidase activity and the labile litter stabilisation factor (S) were significantly higher in organic vineyards (Fig. 1C).

Landscape composition, but not configuration, modulated pest control services response to organic farming (Table S9, Fig. S9). We found that the index of pest control services increased with the proportion of semi-natural habitats in organic vineyards, but decreased with semi-natural habitats in conventional vineyards (Fig. 2). We found a 10 % increase in pest control index between 0 % and 60 % of semi-natural habitats in organic vineyards, versus 21 % decrease in conventional vineyards (Table S11). Predation of model caterpillars showed a similar pattern (Table S9, Fig. S9), with a predicted 187 % increase from 0 % to 60 % of semi-natural habitats in organic, and 126 % decrease in conventional vineyards. Those interactions were marginally significant (Tables S10). Landscape variables had little detectable effects on other

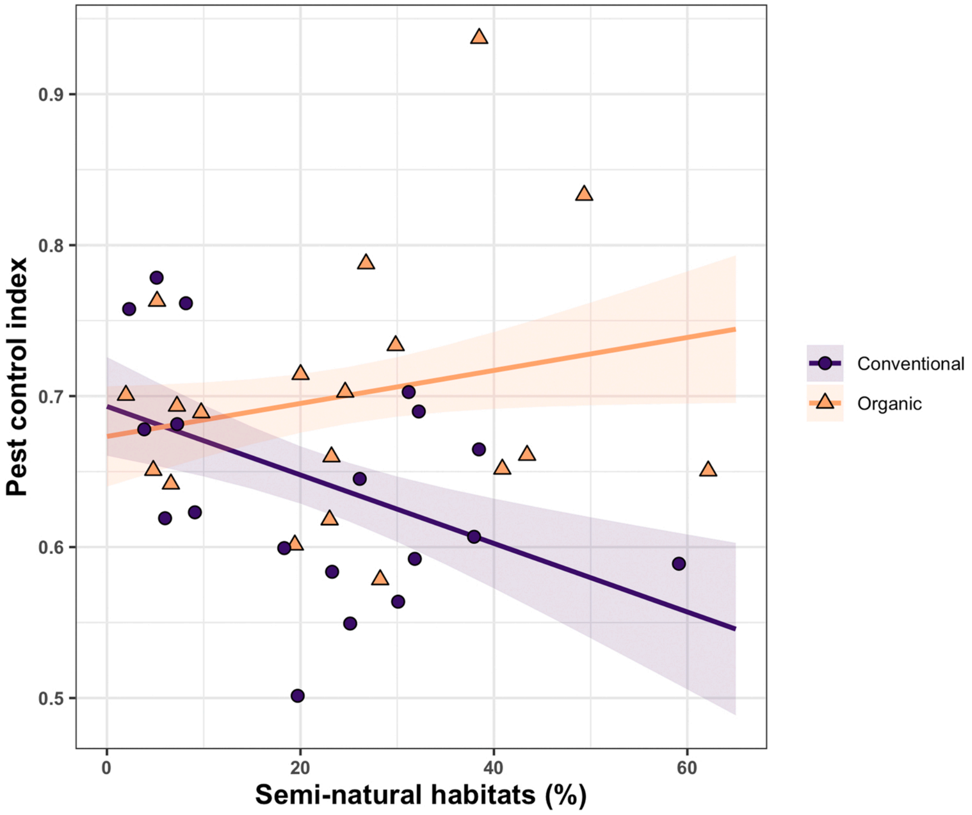

Fig. 2. Landscape composition modulated pest control services response to organic farming. Pest control index integrates pest predation rates (eggs, pupae and model caterpillars), lack of pathogen, and lack of pest damage by averaging their standardized values in each vineyard. Proportion of semi-natural habitats (grasslands, forests, hedgerows) in a 500-m radius around each vineyard. Lines represent the predicted slopes and standard errors from mixed effect models with other explanatory variables kept constant (see Tables S4, S7, and S10 for full model results).

functions and proxies of ecosystem services. Only soil urease activity and the litter stabilization factor decreased with the proportion of semi-natural habitats and the distance to semi-natural habitats, respectively (Tables S9, S10).

3.2. *Tradeoffs between biodiversity, ecosystem services, and wine production*

We found no evidence for a tradeoff between multitrophic diversity and wine production (combined yield and chlorophyll contents responses) (Fig. 3A). Organic farming was associated with higher levels of multitrophic diversity and lower levels of agricultural production (Fig. 1), but there was no relationship between biodiversity and production, neither across nor within farming systems (Fig. 3A, Table S13). Instead, we found that vineyards with the highest indices of multitrophic diversity and production comprised both organic and conventional vineyards (Fig. 3A, Fig. S13 A). Multitrophic abundance showed similar results and was not significantly related with the wine production index (Fig. S10, Table S13).

In contrast, our analysis revealed a strong tradeoff between pest control and wine production (Fig. 3B). This negative relationship was similar across and within farming systems, as there was no significant effect of organic farming on the slope of this relationship (Table S13). Reversely, the index of soil quality/fertility was not related to the wine production index, and organic farming system did not affect this relationship (Fig. 3C).

In order to account for differences in yield due to different vine varieties, terroirs and regulated production limits, we further evaluated synergies and tradeoffs using the proportion of the production goal achieved instead of the production index, as a sensitivity analysis (Fig. S12). Winegrowers have an initial production goal (target yield) depending on regulated limits (maximum permitted yield), and vine varieties. We fitted similar models using the ratio of yield achieved versus expected, instead of the production index. We found similar results, except for the pest control index, which was negatively related with the production index in the main analysis, but not with the percentage of target yield achieved. This discrepancy was probably due to a negative correlation between target yield and pest control index ($cor = -0.4$, $p = 0.001$), indicating that vineyards aiming for the highest yields may exhibit intensive practices detrimental to pest control services (e.g. insecticide use).

We finally conducted an analysis to identify local and landscape management variables associated with simultaneous high levels of multitrophic diversity and wine production. For that, we created a binary index taking the value 1 when both indices of multitrophic diversity and of wine production were above the mean, zero otherwise (Fig. S13 A). Using logistic regression with a binomial distribution of the index against key local and landscape variables in our study sites (frequencies of tillage, spraying and mowing operations, total amounts of fungicides and insecticides, and proportion of semi-natural habitats), we found that none of the main local management variables and landscape characteristics explained the probability to reach simultaneously high biodiversity and production levels (Fig. S13 B-H).

4. Discussion

The urgent need to design multifunctional agricultural landscapes able to maintain biodiversity and commodity production calls for a better understanding of agroecological management effects on multiple dimensions including biodiversity, ecosystem services and their relationships (synergies and tradeoffs) (Herzog et al., 2019; Paiola et al., 2020; Seufert and Ramankutty, 2017). Our study demonstrates that compared to conventional farming, organic farming positively affected the richness of multiple trophic groups and levels of natural pest control, a key ecosystem service, in perennial systems. In contrast, wine production was lower in organic than conventional systems. While this result could imply a tradeoff between production and biodiversity and associated services, we found instead no significant relationship between biodiversity and production either within or across farming systems. Producing wine while simultaneously maintaining biodiversity across trophic levels thus appears compatible, but organic farming alone is not a guarantee to reach that end. Indeed, synergies and tradeoffs between biodiversity and ecosystem services were similar in both farming systems. Organic farming did not foster synergies between wine production and biodiversity, nor mitigated tradeoff between wine production and pest control services. A strong tradeoff between production levels and natural pest control services both across and within farming systems, illustrated that even in organic vineyards, farming practices increasing wine production elicit detrimental effects on a key biodiversity-mediated ecosystem service. Nevertheless, our results indicated that landscape complexity can foster the positive effects of organic farming on pest control services. Future work with higher sampling size could explore if combining semi-natural habitats and organic management can alleviate the tradeoff between wine

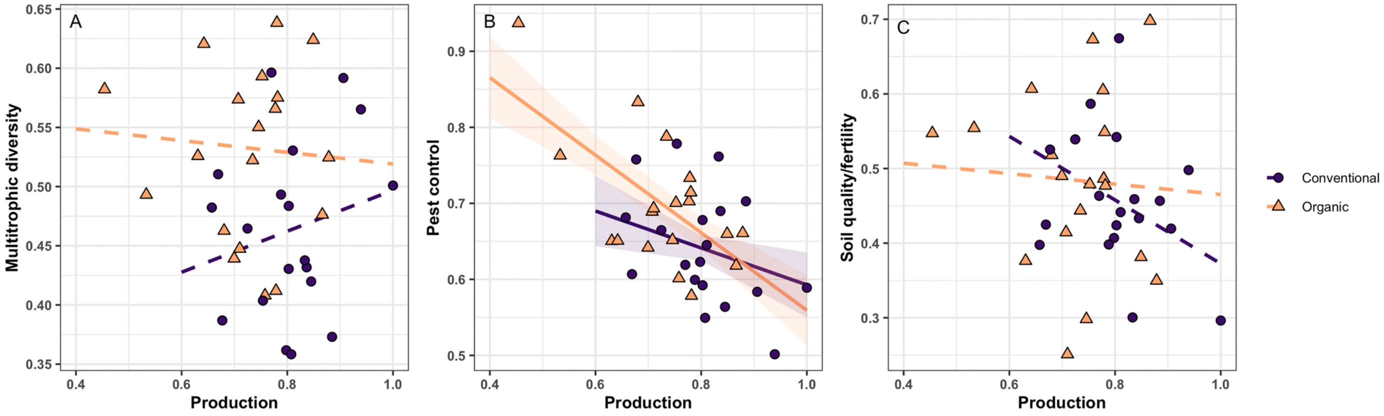

Fig. 3. Relationships between wine production, multitrophic diversity and ecosystem services were similar in organic and conventional farming systems. Production index is the average standardized wine yield (hl/ha) and vine performance (chlorophyll content) of each vineyard. Multitrophic diversity index (A) is based on the richness of 14 taxa (birds, plants, arthropods, soil fauna and microbes); pest control index (B) integrates pest predation rates (eggs, pupae and model caterpillars), lack of pathogen, and lack of pest damage; and soil quality/fertility index (C) is based on soil C, N contents, soil enzymes activities (glucosidase, urease and phosphatase) and litter decomposition and stabilization rates. Lines are slopes predicted by linear mixed effect models that also included landscape composition and configuration effects (solid line: $p < 0.05$; dashed line: $p > 0.05$). Slopes were independent of the farming system (non-significant interactions; see detailed model results Table S13).

production and pest control by enhancing the latter without impacting production levels. Taken together, these results reveal that organic management can improve the environmental performances of perennial crops such as vineyards, but that further management options at both local and landscape scales will be needed to better balance biodiversity and ecosystem services.

4.1. Organic farming enhances multitrophic diversity and pest control services, but not multifunctionality

We found that organic farming generally benefited multiple taxa simultaneously from below-ground to aerial compartments. As a result, multitrophic diversity was higher in organic than conventional vineyards, expanding the findings of previous syntheses to the case of perennial crops (Bengtsson et al., 2005; Tuck et al., 2014). Organic farming exerted contrasted effects on the richness and abundance of different taxa, probably due to taxa-specific responses to different agricultural practices (Bruggisser et al., 2010; Ostandie et al., 2021). For example, organic farming clearly benefited spider communities, in line with previous studies in similar systems (Bosco et al., 2022; Kolb et al., 2020; Muneret et al., 2018b; Ostandie et al., 2021), while ground beetles and earthworms exhibited lower richness in organic vineyards. Decreases in taxa richness in response to organic farming practices could be due to their sensitivity to higher applications of non-synthetic fungicides in organic systems (Karimi et al., 2021). It is also possible that those ground-dwelling and belowground organisms were negatively affected by higher tillage intensities in organic systems (Tsiafouli et al., 2015). Here, although tillage frequencies were only slightly higher in organic compared to conventional fields, Ostandie et al. (2021) reported that higher surfaces under tillage in organic vineyards explained decreases in the abundance of multiple taxonomic groups in our study system.

In contrast, organic farming did not enhance simultaneously the three key ecosystem services we investigated, and multifunctionality was thus similar in organic and conventional vineyards (Herzog et al., 2019; Ostandie et al., 2021). Organic farming is generally associated with reduced yields in various cropping systems including perennial crops (Katayama et al., 2019; Seufert et al., 2012). Here, such a yield gap was associated with pathogen damage levels, that were almost twice as high in organic than in conventional vineyards. Higher pathogen damage in organic vineyards are commonly reported, notably due to the lower efficiency of fungicides approved for organic viticulture (van Bruggen and Finckh, 2016). Conversely, our results confirmed the positive effects of organic farming on pest control services highlighted by a recent global meta-analysis (Muneret et al., 2018b). In organic systems, higher potential predation rates of an important vineyard pest were consistent with the observed positive effects on natural enemies (e.g. on foliage spiders richness) and probably linked to lower levels of pesticides (Geiger et al., 2010; Muneret et al., 2019a). Here, organic and conventional fields differed markedly in terms of the number of active ingredients sprayed. It is possible that the use of a wider range of substances in conventional farming systems resulted into stronger detrimental effects on natural pest control by affecting a wider range of natural enemies through direct toxic and sublethal effects, as well as indirect effects mediated by species interactions (Rillig et al., 2019). In terms of soil services however, our results indicated limited benefits of organic farming. Out of seven proxies, only soil glucosidase activity and labile litter stabilization significantly differed between farming systems. While organic farming generally aims to safeguard soil quality (Gattinger et al., 2012), here such positive effects may have been limited by intensive practices in organic vineyards (Ostandie et al., 2021). High levels of non-synthetic fungicides can indeed alter soil biota (Karimi et al., 2021), which is in line with the lack of positive effects of organic farming on earthworms, springtails and soil microbes reported here.

Together, our results highlight the contrasted effects of organic farming on multiple agronomic and environmental dimensions. While organic farming may be a first step to reach multifunctionality by enhancing biodiversity and natural pest control in vineyards, it appears inefficient to simultaneously promote biodiversity along with the three key ecosystem services considered here.

4.2. Synergies and tradeoffs between biodiversity and services are not affeted by organic farming

Our analysis further showed that achieving high wine production levels and maintaining the richness of multiple taxa groups is compatible. The absence of a relationship between agricultural production and multitrophic diversity is somehow surprising given that intensive practices, detrimental to biodiversity, often underlines high yields and production levels (Geiger et al., 2010). Many studies in annual crops have demonstrated tradeoffs between production and biodiversity conservation (Kleijn et al., 2009; Smith et al., 2020; Steffan-Dewenter et al., 2007). Despite high pesticide application rates, perennial crops are less often disturbed compared to annual crops and can offer a long-term provision of key resources for several species (Bruggisser et al., 2010; Rusch et al., 2016). Indeed, in other perennial systems such as agroforests, the richness of multiple taxa groups did not decrease with yield (Clough et al., 2011).

Our results imply that vineyard management can be adapted to optimize simultaneously biodiversity and production, but that organic farming alone is not a guarantee to reach that end (Gabriel et al., 2013; Schneider et al., 2014; Tscharntke et al., 2021). Indeed, organic farming did not appear as an effective way to promote synergies between wine production and multitrophic diversity. Here, the lack of a tradeoff between production and biodiversity was independent of the farming system. Many conventional vineyards simultaneously achieved high levels of biodiversity and production. Indeed, conventional vineyards exhibited a range of agricultural practices, including extensive practices such as low pesticide inputs, mowing and tillage frequencies (Fig. S2). The regulation of organic farming practices currently mostly focus on banning synthetic pesticides and fertilizers, but reducing tillage, mowing and persistent non-synthetic pesticides can also strongly benefit multitrophic biodiversity (Tscharntke et al., 2021). This, along with our results, indicates that policy-makers involved in the regulation of organic farming should consider to include other key management practices in order to enhance biodiversity and ecosystem services in agricultural landscapes. Here, further analyses revealed no clear association between the key local and landscape characteristics of our study system and the probability of vineyards to reach simultaneously high biodiversity and production levels (Fig. S13). However, our study had a limited temporal scale, and future studies could now address the temporal dynamics of management effects and identify which environmental characteristics and management options lead to win-win scenarios for biodiversity and wine production.

Our study further shows a strong tradeoff between natural pest control and wine production independent of the farming system which is in line with Wittwer et al. (2021). This result suggests that intensive practices underlining higher yields and lower pest pressure may elicit detrimental effects on specific groups and processes such as natural enemies and natural pest control (Reiff et al., 2021). Yield and vine N status were indeed positively related to pesticide intensity and mowing frequency, which are known to be detrimental to predatory arthropods (Geiger et al., 2010). In addition, in the study region, both organic and conventional vineyards undergo mandatory insecticide treatments to control for the leafhopper vector of the flavescence dorée disease, and such treatments may have non-target effects on natural enemy communities (Castro et al., 2018). Such a tradeoff between production and pest control services might appear contradictory with the hypothesis that pest control services ultimately benefit agricultural production (Dainese et al., 2019). We note that it was pathogen damage that mostly limited wine production levels, while our pest control index primarily captured the regulation of insect pests that were less problematic that year (34 % of vineyards had signs of pest damage, while 97 % of vineyards had signs of pathogen damage). Yet, excluding the lack of pathogen damage as a proxy of the pest control index confirmed this significant tradeoff between wine production and natural pest control services (Fig. S14). Investigating such a tradeoff thus brings important insights into the factors controlling the relationships between key provisioning and regulating services in perennial agroecosystems. We show that organic farming practices do not mitigate tradeoffs between wine production and pest control services, despite having positive effects on pest control.

Our results finally point to the potential key role of the landscape context to specifically enhance pest control services without affecting yield. Indeed, we found no clear effect of landscape composition and configuration on the simultaneous provision of multiple agronomic and environmental dimensions at the spatial scales considered. Other landscape characteristics not included here, such as the spatial arrangement and amount of organic fields, or the simultaneous effect of multiple spatial scales on different taxa groups and ecosystem services should be considered in the future, as they could play important roles to maintain biodiversity and multiple ecosystem services in vineyard landscapes. Here, the proportion of semi-natural habitats and distance to the nearest semi-natural habitat only modulated the effects of organic farming on the richness or abundance of 4 out of 14 taxa groups, and on the levels of 2 out of 14 proxies of ecosystem services. Landscape composition particularly affected the response of taxa and functions linked to pest control services. Although such effects were marginally significant, communities of predator arthropods such as spiders, and pest predation rates have been found particularly prone to interactive effects between local practices and landscape context (Batáry et al., 2011; Beaumelle et al., 2021; Muneret et al., 2018b; Perrot et al., 2021; Tscharntke et al., 2012). Here, we found contrasting effects of the proportion of semi-natural habitats on pest control and natural enemy communities depending on farming systems, in line with previous studies (Karp et al., 2018; Muneret et al., 2018b; Ricci et al., 2019). Colonization processes from semi-natural habitats that offer alternative resources and habitats for natural enemies may explain the observed increase in pest control with increasing proportion of semi-natural habitats in organic vineyards (Muneret et al., 2018b, 2019a). In contrast, in conventional vineyards, intensive practices such as synthetic pesticide use may act as local filters limiting colonization processes, or even deterring natural enemies towards more friendly habitats. Such processes could explain the observed decrease in pest control with semi-natural habitats in conventional vineyards (Ricci et al., 2019). Our results thus indicated potential synergies between organic farming and landscape complexity at the spatial scales considered (Fig. S9). This highlights that while the landscape context is not a strong driver of multifunctionality and multitrophic diversity, it could be an important leverage to further improve the multifunctional performances of organic farming, by affecting pest control services specifically.

In conclusion, our results reveal that high biodiversity and wine production do not necessarily exclude each other. Organic farming promoted biodiversity and natural pest control and can thus contribute to reaching a “safe operating space” where biodiversity conservation and multiple ecosystem services provision can be combined in perennial agroecosystems. However, organic farming did not foster synergies nor mitigated tradeoffs between biodiversity and ecosystem services, and was associated with lower wine production levels. We conclude that organic farming alone will not suffice to reach multifunctionality, and highlight the need to complement organic farming with other solutions at both the local and landscape scales. Indeed, specific biodiversity-mediated services such as pest control may be negatively affected by practices underpinning high production levels in both organic and conventional systems. Our results suggest the landscape context could be key to mitigate that particular tradeoff, by affecting specifically natural pest control services. Our study thus brings important insights for designing multifunctional agroecosystems able to reconcile biodiversity conservation with agricultural production.

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

All data and R codes associated with this analysis can be accessed from GitHub (https://github.com/leabeaumelle/MultiBEFVineyardsManuscript) and are archived on Zenodo (https://zenodo.org/badge/latestdoi/472809233). Raw sequence data from Illumina were deposited in the Sequence Read Archive service of the NCBI database (https://www.ncbi.nlm.nih.gov/) (BioProject ID: PRJNA911566).

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Authors’ contributions

LB, AR, BG, EB, ME, SW, and JZ conceived the ideas and designed methodology. LB performed the analyses, and wrote the original draft. SW, ME, EB, JZ, and AR secured funding. SW, PT, ME, EB, JZ, AA, OB, YC, OF, BJ, SK, NO, and SRC collected the data. All authors contributed critically to the drafts.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108474.

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