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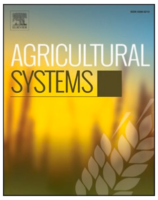

Climate and landscape composition explain agronomic practices, pesticide use and grape yield in vineyards across Italy

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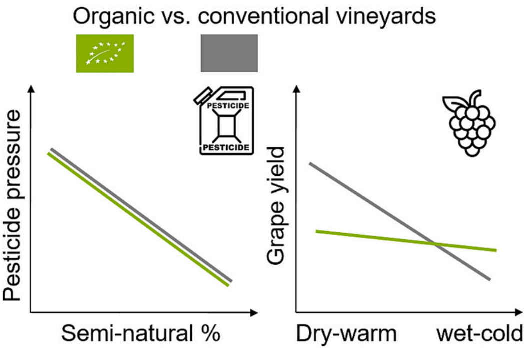
HIGHLIGHTS

- We compared conventional and organic vineyards along climate and landscape gradients.
- Most agronomic practices did not differ between conventional and organic vineyards.
- In both systems, climate and landscape were strong predictors of agronomic practices, pest management and yield.
- Pesticide environmental impact decreased with increasing temperature and semi-natural areas in both systems .
- Yield difference between organic and conventional farming depends on climate.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Worldwide, organic farming is being promoted as one of the main alternatives to intensive conventional farming. However, the benefits of organic agriculture are still controversial and need to be tested across wide environmental gradients.
Objective: Here, we carried out an observational study to test how agronomic practices, pest management, environmental impact and yield of conventional and organic vineyards changed along wide climatic and landscape gradients across Italy.
Methods: We used a block design with 38 pairs of conventional and organic vineyards across Italy.
Results and conclusions: Most agronomic practices did not differ between conventional and organic vineyards. By contrast, landscape composition and climate were strong predictors of management in both systems. First, increasing semi-natural areas around the vineyards reduced pesticide pressure and related environmental impacts, but was also associated with lower yield. Second, irrespective of the farming system, a warm and dry climate was associated with reduced fungicide pressure. Conventional farming had a yield gain of 40% in cold and wet climate compared to organic but the yield gap disappeared in the warmest regions.
Significance: In both farming systems, we observed a large variability in management practices that was mainly explained by climate and landscape composition. This large variability should be considered when evaluating the benefits and drawbacks of different farming systems under contrasting environmental contexts.

1. Introduction

Vineyards are often intensively managed and are one of the most agrochemical dependent crops in Europe (Rusch et al., 2021). As the main alternative to intensive conventional farming, the EU agricultural policy has been long promoting organic agriculture. The new European Green Deal sets the target of allocating 25% of agricultural land to organic farming by 2030, due to its expected positive effects on biodiversity and associated ecosystem services (Bengtsson et al., 2005; Tuck et al., 2014). However, the assessment of the potential ecological impact and the economic profitability of organic vs. conventional farming is still controversial, particularly in perennial crops such as grape (Debuschewitz and Sanders, 2022; Tscharntke et al., 2021), with recent studies showing that the expected benefits of organic vineyards for biodiversity are rather small (Beaumelle et al., 2023; Reiff et al., 2023). Depending on the environmental and socio-economic context, there might be large variability in management and yield within both organic and conventional vineyards that makes it difficult to generalise their benefits and drawbacks.

By definition, there are several important practices that differ between organic and conventional vineyards. One key difference is the ban of synthetic inputs in organic agriculture, such as synthetic pesticides, and mineral fertilisers. Nowadays, negative effects of synthetic agrochemicals on human health and non-target organisms are well documented, and decreasing their use is a key target to achieve sustainable viticulture (Mailly et al., 2017; Perry, 2008; Pertot et al., 2017; Siviter and Muth, 2020; Suma et al., 2009). However, even if they are usually associated with lower persistence (Geissen et al., 2021), alternatives to synthetic pesticides can also have negative environmental impacts. For example, in vineyards, high inputs of copper and sulphur-based products, the most used organic fungicides, can negatively affect aboveground (Möth et al., 2023; Reiff et al., 2023) and below-ground biodiversity and associated ecosystem services (Ostandie et al., 2021). In addition, in organic viticulture, herbicides are banned but the soil can still be tilled with detrimental effects on multiple taxa (Brambilla and Gatti, 2022; Griesser et al., 2022; Nascimbene et al., 2012; Winter et al., 2018). Hence, even if organic viticulture is expected to promote environmental sustainability compared to conventional agriculture (Froidevaux et al., 2017; Puig-Montserrat et al., 2017), results are sometimes controversial (Beaumelle et al., 2023), and the potential differences might be context dependent, changing across wide environmental gradients.

First, the choice of agricultural practices and their intensity might change depending on landscape composition and configuration. For example, in vineyards, pesticide use usually declines with increasing cover of semi-natural habitats in the surrounding landscape (Paredes et al., 2021; Rusch et al., 2017). As semi-natural areas provide food and refuge sites to predators and parasitoids, landscapes with a high proportion of semi-natural habitats usually provide higher pest control services and/or lower pest pressures (Bianchi et al., 2006; Rusch et al., 2016). Landscape configuration, e.g. average field size, is also emerging as a predictor of pesticide use across multiple crops, although its effects are often idiosyncratic (Gagic et al., 2021; Marini et al., 2023; Rosenheim et al., 2022). Finally, also yield and economic profits often depend on landscape composition and configuration. Even though landscape effects on vineyard pesticides and pests are often reported, to our knowledge, no study tested yet the effect of landscape composition and configuration on grape yield and profits. However, organic profits seem to be greatest in landscapes characterized by small fields for winter wheat and multiple crops (Batáry et al., 2017; Smith et al., 2020).

Both conventional and organic farming practices are also expected to be affected by weather and general climate. For most crops, climate is an important driver of the risks of both pathogen (Gessler et al., 2011) and pest damage (Courson et al., 2022). In particular, grapes are highly susceptible to several fungal diseases, and rainfall and humidity usually enhance both the development and the sporulation of mildews increasing the infection risk (Carroll and Wilcox, 2003; Fernández-González et al., 2013). By contrast, the severity of powdery mildew (*Erysiphe necator* Schwein) responds to temperature with a unimodal relationship (Caffarra et al., 2012; Trecate et al., 2019). Besides fungal diseases, one of the major grape pests is the grapevine moth, *Lobesia botrana* Den. & Schiff, that increases the number of generations per year under warming temperatures (Martín-Vertedor et al., 2010). Hence, plant protection strategies in vineyards are expected to change along climatic gradients (Reineke and Thiéry, 2016). In addition to climate's effect on pests, inter-row soil management and vegetation cover are also affected by temperature and rainfall due to the direct effect of weather conditions on water availability and vegetation growth (Biddoccu et al., 2020; Wittwer et al., 2023). However, a few studies considered the effect of climate on both conventional and organic farming, in particular in viticulture across large geographical gradients (but see (Etienne et al., 2023)).

Here, we tested how conventional and organic agronomic practices, pest management, environmental impact associated with the use of pesticides, and yield changed in contrasting landscapes and climates across Italy. Italy is the first wine-producing country globally and vineyards are distributed across a wide climatic gradient from cold Alpine to warm Mediterranean regions (Gismondi, 2020). Using a block design, we selected 38 pairs of conventional and organic vineyards along statistically independent gradients in landscape composition and climate. Specifically, we tested the effect of the local management (conventional vs. organic), the cover of semi-natural habitats in the surrounding landscape and climatic variables on agronomic practices, the environmental impact of plant protection products, and grape yield.

2. Methods

2.1. Study area and site selection

We selected 38 landscapes across the whole Italian peninsula (Fig. 1a). Landscapes were chosen along two statistically independent gradients: a climatic gradient related to the latitudinal variation and a landscape composition gradient, ranging from areas dominated by agriculture to mostly natural areas (see climatic and landscape variables). The minimum distance between landscapes was 4 km, while the most distant landscapes were >1000 km apart. In each landscape, we selected a pair of vineyards, consisting of one organic and one conventional vineyard (for a total of N = 76 vineyards) (Fig. 1b). Organic vineyards were all managed according to EU standards. The vineyards belonging to a pair were geographically close, with a maximum distance of approximately 1 km between each other (mean distance within pair = 0.85 km ± 0.55 SD, i.e. standard deviation). In addition, each pair of vineyards had the same red grape variety (except for one pair with a white variety). The pair block design allowed us to standardize the comparison and minimize the ecological and socio-economic diversity. Mean elevation of the 76 selected vineyards was 246 m above sea level ± 195 SD and mean slope = 5.947 ± 7.12 degrees. The most common grape variety was Merlot (N = 13) (Fig. S1). Selected vineyards showed ten different training systems: *Alberello* or *Goblet* (N = 6), *Cappuccina* or *Double arched cane* (N = 4), *Double spurred cordon* (N = 9), *Geneva double curtain* (N = 2), *Guyot* (N = 22), *Pergola* (N = 3), *Double Pergola* (N = 2), *Spurred cordon* (N = 13), *Sylvoz* (N = 9), *Tendone* (N = 4). Among all vineyards, 22 pairs shared the same training system, while 16 showed different ones.

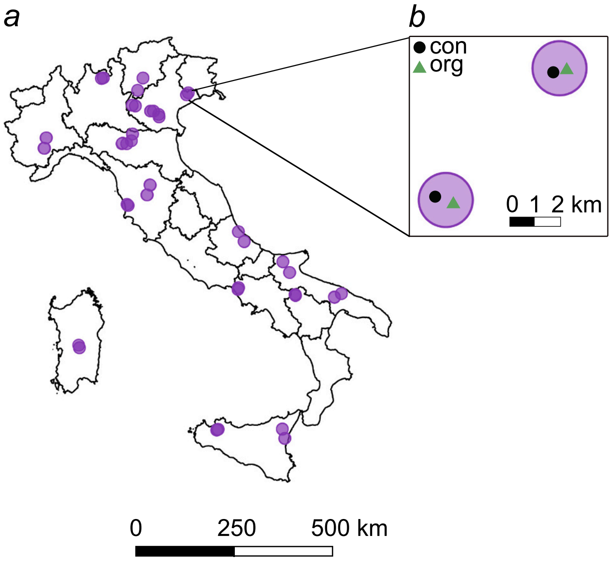

Fig. 1. A) study area with the 38 landscapes selected along the Italian peninsula; b) example of two landscapes, each one consisting in a pair of one conventional and one organic vineyard. Con = conventional and org = organic.

2.2. Farm management survey

To gather information about the local management of each vineyard, farmers were interviewed through a face-to-face questionnaire. Questionnaires comprised 20 standardized questions on the main agronomic practices, such as agronomic inputs, plant protection, vegetation management, and on grape yield (Table S1, S2). To account for inter-annual variability, farmers were asked to answer all questions referring to average practices across the last 5 years (2018–2022). To quantify pesticide pressure, we used the Treatment Frequency Index (TFI), a commonly used index for calculating pesticide pressure to compare alternative pesticides across different systems (Etienne et al., 2022; Lechenet et al., 2014). The TFI allows the aggregation of very different substances to measure overall phytosanitary pressure but it does not measure pesticides' impact. The TFI takes into account the number of treatments, the dose applied relative to the recommended reference dose, and the proportion of the treated area, following this formula:

$$TFI = \frac{application\ rate}{recommended\ dose} \times \frac{treated\ area}{total\ area}$$

Application rate corresponds to the dose sprayed per product (kg ha^{-1} $year^{-1}$). To consider the minimum environmental impact possible, we defined as the recommended dose the lowest application dose which is indicated for a given crop. We retrieved information on the lowest recommended dose from products' registered labels in the website of the Italian Department of Health and Social Care (http://www.fitosanitari.salute.gov.it/fitosanitariws_new/FitosanitariServlet). The TFI is equal to the number of treatments if these had been sprayed at the full recommended doses over the whole field. We calculated insecticide and fungicide TFI separately, using the treatment application records collected from the farmers on all registered products. The overall TFI per vineyard was calculated as the sum of the TFI for each fungicide and/or insecticide application performed and it was set to 0 in the absence of spraying.

2.3. Climatic variables

Based on the GPS coordinates of each vineyard, we extracted, from the nearest weather station, data on the mean annual rainfall (mm) and annual temperatures (°C) over a period of 30 years (1971 to 2000), to characterize the climatic variables around each vineyard. We selected this temporal range because it was available for all weather stations. We calculated the mean annual temperature and mean annual rainfall throughout the 30-year period. The mean annual temperature recorded from 1971 to 2000 ranged from approximately 10 °C in Sondrio (c. 300 m a.s.l.) to 17 °C in Palermo (34 m a.s.l.), while the gradient of mean annual rainfall from approximately 495 to 1294 mm. Local temperatures in monitored vineyards were standardized at sea level using data from the closest weather station and considering an adiabatic lapse rate of 0.6 °C per 100 m. We derived the elevation (m a.s.l.) of each vineyard from a high-resolution national digital elevation model (DEM) (25 × 25 m).

2.4. Landscape variables

We quantified landscape composition metrics considering a buffer of 1 km radius around each vineyard. We used the program Google Earth Pro 7.3.4.8642 to manually draw polygons around each patch, using satellite pictures taken in 2022 for all landscapes, except for two dating from 2021 and 2020. We then classified each patch depending on the land-use type (six habitat classes: urban areas, annual crops, forests, grasslands, vineyards and other perennial crops), and transformed the polygons into a raster file with a 1 m resolution using the R package “raster” (Hijmans, 2023). We calculated the area belonging to each class using the R packages “landscapemetrics” (Hesselbarth et al., 2019). We summed forest and grassland area to calculate the overall semi-natural area, ranging from 0 to 77%.

2.5. Environmental impact associated with pesticide use

To assess the environmental impact associated with pesticide use, we calculated the potential environmental impact (EI), by multiplying the amount of fungicide, insecticide or herbicide used (kilograms of active ingredient per hectare) by the Environmental Impact Quotient (EIQ) (Cross and Edwards-Jones, 2011; Gallivan et al., 2001; Kovach et al., 1992). The EIQ is a scoring system that evaluates all types of pesticides for their potential negative impact on farmworkers, consumers, and the environment (Kovach et al., 1992). We extracted EIQs from the dataset of Cornell University’s College of Agriculture and Life Sciences (Eshenaur et al., 2020; Kovach et al., 1992) (Table S3). For 7 active ingredients (i.e., *Ampelomyces quisqualis*, cerevisane, D-limonene, myclobutanil, pyriofenone, taufluvalinate and *Trichoderma viridae*), we did not find info on the associated EIQs and, therefore, we excluded them from the analysis. However, except for D-limonene, they were used only once per vineyard at very low quantities (mean quantity = 0.43 kg ha $^{-1}$). Concerning D-limonene, it is considered to pose minimum risk for humans and the environment (Kim et al., 2013). In addition, when pesticide quantity (kg ha $^{-1}$) was not reported (N = 12 fungicides and 1 insecticide), we used the mean quantity reported for the same active ingredient by all other farmers to calculate the EI. The only used herbicide was glyphosate, and we considered all farmers to apply the optimal dose per hectare in vineyards, i.e., 3 kg ha $^{-1}$, as we did not have info on the applied dose for each vineyard. Finally, to obtain a measure of fungicide, insecticide and herbicide impact for each vineyard, we summed the so obtained EIs.

2.6. Data analysis

To compare conventional and organic farming across climatic and landscape gradients, we tested the effect of landscape composition, and climatic factors on: 1) inter-row width (m), 2) annual frequency of inter-row mowing, 3) annual frequency of inter-row tilling, 4) annual amount of N used as fertilizer treatments (either organic or conventional) (kg ha^{-1} year^{-1}), 5) irrigation application (yes or no), 6) fungicide Treatment Frequency Index (TFI), 7) insecticide Treatment Frequency Index (TFI), 8) employment of mating disruption techniques (yes or no), 9) total Environmental Impact (EI) calculated by the sum of fungicide, herbicide and insecticide EIs, and 10) mean grape yield (t ha^{-1}).

First, we checked for collinearity between all fixed factors: semi-natural area (%), slope (degrees), mean temperature (°C), and mean rainfall during the growing season (mm) (Fig. S2). Mean yearly temperature and mean growing season rainfall were highly negatively correlated (Pearson correlation coefficient $r = -0.79$, $p < 0.001$), and semi-natural area (%) and slope (degrees) were positively correlated (Pearson correlation coefficient $r = 0.42$, $p < 0.001$). We therefore excluded rainfall and slope from further analyses. For all models, Variance Inflation Factors (VIFs) were smaller than 2, indicating low multicollinearity.

Then, we fitted eight generalized linear mixed models using the R package “glmmTMB”(Magnusson et al., 2017), with inter-row width, mowing frequency, tilling frequency, N fertilization, fungicide TFI, insecticide TFI, pesticide EI, and mean grape yield as response variables. For each model, we used management (conventional or organic), semi-natural area, and temperature as fixed effects and vineyard pair ID as random intercept. We also included the interactions between management and semi-natural area, and management and temperature, and removed non-significant interactions one-by-one with a backward deletion procedure ($p > 0.05$). We log-transformed mowing frequency, tilling frequency, N fertilization, fungicide TFI, insecticide TFI, pesticide EI and grape yield to improve linearity and to achieve a normal distribution of the residuals. To examine whether they were normally distributed, residuals of all models were visually checked using the R package “car” (Fox et al., 2012). Moreover, to exclude the effect of the training system on mean grape yield, we run an additional model on a subset of data consisting only in the vineyard pairs sharing the same training system (N = 22), testing the effect of management (conventional or organic), semi-natural area, and temperature on mean grape yield.

For binary response variables, we fitted generalized linear mixed models assuming a binomial distribution and using vineyard pair ID as random intercept with the following response variables: irrigation application and employment of mating disruption techniques. We included the interactions between management and semi-natural area, and management and temperature, and removed non-significant interactions one-by-one with a backward deletion procedure ($p > 0.05$). Residuals were visually checked using the R package “DHARMa” to confirm that they were uniformly distributed (Hartig, 2019).

Finally, to evaluate the goodness-of-fit of our models we computed marginal and conditional R^2 using the function r.squaredGLMM in the R package “MuMIn” (Bartoń, 2023).

3. Results

3.1. Agronomic practices

Inter-row width and the probability of irrigation decreased with increasing area of semi-natural cover (Figs. 2a, b, Table S4). Mowing frequency decreased in warm-dry climates, while tilling frequency increased with increasing temperature and with increasing area of semi-natural cover (Figs. 2d, e, f, Table S4). In addition, inter-row width, irrigation probability, mowing and tilling frequency were not affected by management type (conventional vs. organic). By contrast, N fertilization was jointly affected by management type (conventional vs. organic) and temperature; i.e. conventional farmers used a higher amount of N fertilizer and it decreased in landscapes with large semi-natural areas, while the amount used in organic vineyards remained constant (Fig. 2c, Table S4).

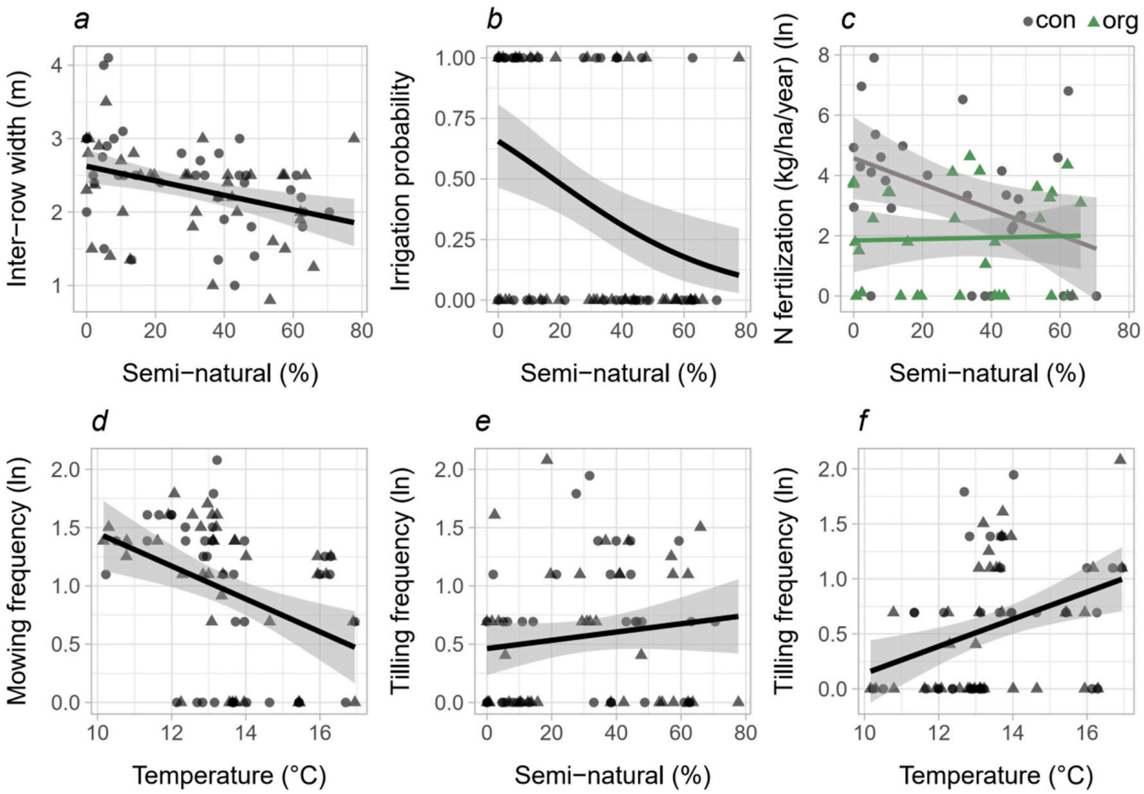

Fig. 2. The effects of semi-natural cover, temperature and the interaction between management and semi-natural cover on agronomic practices in the 76 vineyards. Points show values of conventional vineyards, while triangles of organic. Con = conventional, org = organic, and ln = natural logarithm. Figures show significant effects ($p \leq 0.05$). Displayed values are raw data, lines represent model estimates, and the shaded areas represent the 95% confidence intervals.

3.2. Pest management and associated environmental impact

The fungicide TFI decreased with increasing area of semi-natural cover and with increasing temperature (Figs. 3a, b, Table S4). By contrast, management type (conventional vs. organic) did not affect fungicide TFI (mean fungicide TFI for conventional = 24.21 ± 21.51 SD, for organic = 19.91 ± 16.05 SD). The insecticide TFI decreased with increasing semi-natural-areas, and it was not affected by the management type, or temperature (mean insecticide TFI for conventional = 1.82 ± 1.66 SD, for organic = 1.91 ± 2.65 SD), (Fig. 3c; Table S4). Finally, mating disruption techniques were adopted mainly in cold-wet climates and were not affected by management type (conventional vs. organic) or semi-natural cover (Fig. 3d; Table S4). Pesticide environmental impact showed a decreasing trend for with increasing semi-natural area (Fig. 3e, Table S4). Moreover, pesticide environmental impact decreased with increasing temperature (Fig. 3f).

3.3. Grape yield

Mean annual grape yield decreased with increasing semi-natural area (Fig. 4a, Table S4). In addition, there was a significant interaction between management type and temperature on grape yield, i.e., conventional management had higher yields than organic in cold-wet climates but lower in warm-dry climates (Fig. 4b). Considering only vineyard pairs sharing the same training system, yielded consistent results (Table S5).

4. Discussion

Our results highlight that climate and landscape contexts were better predictors of agronomic practices than conventional or organic management. Conventional and organic vineyards were on average managed similarly, but exhibited large variability. However, for both management types, increasing semi-natural areas reduced pesticide applications and the environmental impact associated with pesticide use. In addition, grape yields of conventional and organic vineyards responded differently to climate. Conventional vineyards provided higher yields than organic only in cold-wet climates, while a trend for an opposite pattern was found in warm-dry climates. Overall, we observed large variability that makes it difficult to generalise benefits and drawbacks of both agricultural systems.

4.1. Agronomic practices

Conventional farmers applied higher rates of N fertilization but all other considered agronomic practices did not differ between conventional and organic management. Higher inputs of N usually decrease plant diversity in the inter-row and soil biodiversity, even though vineyards usually show relatively low N fertilization compared to other crops (Gaigher and Samways, 2010; Nascimbene et al., 2013). However, in both systems, agronomic practices changed along climatic and landscape gradients. For example, inter-row width, N-fertilization in conventional vineyards, and the probability of irrigation decreased with increasing semi-natural cover, probably because landscapes with large cover of semi-natural habitats were more likely to be associated with steep and shallow soils (Fig. S2, Pearson's correlation between slope and semi-natural area $r = 0.42$, $p < 0.01$). Steep and shallow soils are usually difficult for agricultural machinery to access. In addition, the mowing frequency decreased in warm climates, while tilling frequency increased. The former result is related to the dry summer conditions that reduce vegetation growth, while the latter is caused by the traditional management of tilling the inter-row carried out in the Mediterranean regions to reduce potential competition for water between herbaceous plants and grape plants. High frequency of tillage mostly negatively

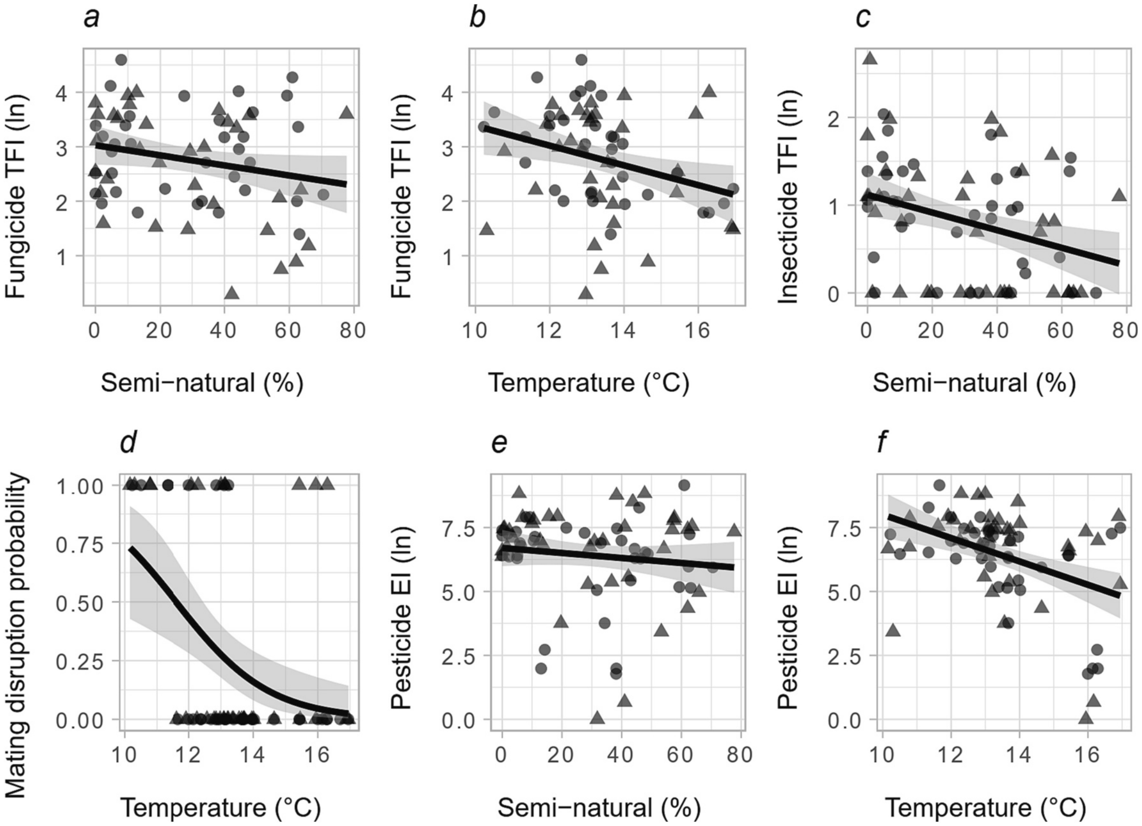

Fig. 3. The effect of semi-natural cover, temperature and the interaction between management and temperature on pest management and environmental impact. Points show values of conventional vineyards, while triangles of organic. TFI = treatment frequency index, EI = environmental impact, and ln = natural logarithm. EIs were calculated by multiplying the total amount of pesticide used (kilograms of active ingredient per hectare) by the Environmental Impact Quotient (EIQ) (Kovach et al., 1992). All figures show significant effects ($p \leq 0.05$), besides panel e showing a marginal significant effect ($p = 0.06$). Displayed values are raw data, lines represent model estimates, and the shaded areas represent the 95% confidence intervals.

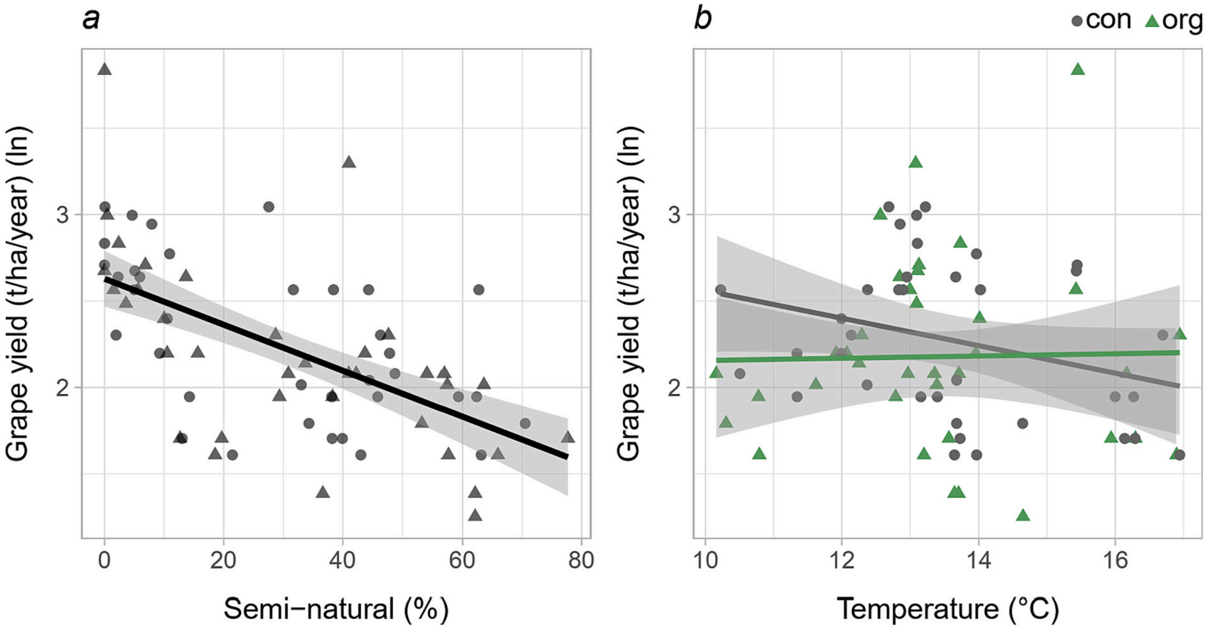

Fig. 4. The effect of semi-natural cover and the effect of the interaction between temperature and management on grape yield. Points show values of conventional vineyards, while triangles of organic. Con = conventional, org = organic, and ln = natural logarithm. Figures show significant effects ($p \leq 0.05$). Displayed values are raw data, lines represent model estimates, and the shaded areas represent the 95% confidence intervals.

affects soil arthropod and microbial diversity and associated ecosystem services, therefore, considering climatic effects on agronomic practices might be important for future research (Burns et al., 2016; Griesser et al., 2022; Nascimbene et al., 2012; Winter et al., 2018).

4.2. Pest management and associated environmental impact

TFIs of insecticides and fungicides were similar between the two farming systems. This supports the notion that, over the last years, organic farming has been increasingly intensified (Beaumelle et al., 2023; Etienne et al., 2022; Tscharntke et al., 2021). Natural pesticides usually need to be applied more often because of their low persistence, nevertheless these results points at some potential negative impacts also of organic viticulture on biodiversity, humans and the environment. Also natural pesticides can negatively impact non-target arthropods (Bahlai et al., 2010; Ostandie et al., 2021), and can pose risks for human health and the environment, especially copper- and sulphur-based products (Briffa et al., 2020). Interestingly, climatic and landscape factors explained pesticide pressure irrespective of local management. In vineyards surrounded by high semi-natural cover, pesticides were sprayed less frequently in both systems. Although biological control seems highly context-dependent (Karp et al., 2018; Tamburini et al., 2020), evidence has already emerged that, in vineyards, complex landscapes enhance the local availability of natural enemies (Etienne et al., 2022, 2023; Rusch et al., 2016). Understanding the effect of semi-natural areas on fungicides is more complex, albeit other studies have already reported the same pattern (Etienne et al., 2022). As expected, fungicide use decreased under warm-dry climates. This is consistent with the well-known fact that rainfall triggers disease development and that higher fungicide doses have to be applied in rainy compared to dry areas (Komárek et al., 2010). Besides predicting the intensity of pesticide pressure, landscape and climatic variables also had an effect on the environmental impact of fungicides, insecticides and herbicides. Pesticide impact on the environment decreased in warm-dry climates and with increasing semi-natural habitats, supporting the notion that natural habitats help reducing the use of large amount of and/or highly toxic pesticides (Park et al., 2015). Finally, it should be noted that our measure of environmental impact does not consider interactions between pesticide mixes. In our study, conventional farmers used a three times larger number of active ingredients than organic farmers, potentially increasing the risk of synergistic effects (Quintela and McCoy, 1998; Sgolastra et al., 2017; Tosi and Nieh, 2019).

4.3. Grape yield

Conventional farming provided higher grape yield than organic farming only in cold-wet climates. While grape yield showed a 25% decrease in organic farms with warming temperatures, conventional yield decreased by 70%. Usually, poor yields coincide with warm and dry summers, which cause higher evapotranspiration rates and related crop stresses (Araujo et al., 2016; Camps and Ramos, 2012; Ramos and Martínez-Casasnovas, 2010). The overall lower level of fertilization in organic farming might provide a lower but more stable yield than conventional when environmental conditions are less favourable. This should be further investigated, as approaches of adaptation to climate change are currently lacking (Morel and Cartau, 2023). Besides the effect of climate, we found that grape yield decreased with increasing semi-natural areas in the surrounding landscape. This result might be linked to the correlation between large cover of semi-natural habitats and slope. Growing vines on steep slopes usually produce low yields due to reduced water supply and shallow soils. Finally, the reported large-scale variability in yield between pairs could also be explained by a variety effect, i.e., some wine varieties might be found only in particular environmental conditions, such as Syrah that can be grown only under warm climates (Fig. S1). An additional constrain to our results on productivity is that we could not take into account the effect of grafting and clone on yield.

5. Conclusions

Against our expectations, the overall agricultural inputs as well as the environmental impact associated with pesticides were similar between conventional and organic viticulture, indicating that some biodiversity and environmental risks associated with tilling, irrigation or pesticides could also be connected to organic farming, if intensively managed. Concerning vineyard productivity, we found that conventional vineyards provided higher yields than organic only in cold-wet climates, suggesting that organic vineyards might become more profitable under future climate warming. In addition, we showed that climatic and landscape factors are important predictors of vineyard pest management practices. For example, increasing semi-natural areas around a vineyard reduced pesticide applications irrespective of the management type. Hence, to achieve a less intensive and more sustainable grape production, future assessments should consider the climatic and landscape context and should explore the variability of both conventional and organic farming before recommending and supporting conversion from one system to the other.

CRediT authorship contribution statement

Costanza Geppert: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Mariana da Cruz:** Data curation, Writing – review & editing. **Alberto Alma:** Validation, Visualization, Writing – review & editing. **Lucia Andretta:** Validation, Visualization, Writing – review & editing. **Gianfranco Anfora:** Validation, Visualization, Writing – review & editing. **Donatella Battaglia:** Validation, Visualization, Writing – review & editing. **Giovanni Burgio:** Validation, Visualization, Writing – review & editing. **Vittoria Caccavo:** Validation, Visualization, Writing – review & editing. **Serena Giorgia Chiesa:** Validation, Visualization, Writing – review & editing. **Francesca Cinquatti:** Validation, Visualization, Writing – review & editing. **Arturo Cocco:** Validation, Visualization, Writing – review & editing. **Elena Costi:** Validation, Visualization, Writing – review & editing. **Ilaria D'Isita:** Validation, Visualization, Writing – review & editing. **Carlo Duso:** Validation, Visualization, Writing – review & editing. **Antonio Pietro Garonna:** Validation, Visualization, Writing – review & editing. **Giacinto Salvatore Germinara:** Validation, Visualization, Writing – review & editing. **Paolo Lo Bue:** Validation, Visualization, Writing – review & editing. **Andrea Lucchi:** Validation, Visualization, Writing – review & editing. **Lara Maistrello:** Validation, Visualization, Writing – review & editing. **Roberto Mannu:** Validation, Visualization, Writing – review & editing. **Enrico Marchesini:** Validation, Visualization, Writing – review & editing. **Antonio Masetti:** Validation, Visualization, Writing – review & editing. **Luca Mazzon:** Validation, Visualization, Writing – review & editing. **Nicola Mori:** Validation, Visualization, Writing – review & editing. **Giacomo Ortis:** Validation, Visualization, Writing – review & editing. **Ezio Peri:** Validation, Visualization, Writing – review & editing. **Guerino Pescara:** Validation, Visualization, Writing – review & editing. **Stefan Cristian Prazaru:** Validation, Visualization, Writing – review & editing. **Gianvito Ragone:** Validation, Visualization, Writing – review & editing. **Ivo E. Rigamonti:** Validation, Visualization, Writing – review & editing. **Marzia Cristiana Rosi:** Validation, Visualization, Writing – review & editing. **Giuseppe Rotundo:** Validation, Visualization, Writing – review & editing. **Patrizia Sacchetti:** Validation, Visualization, Writing – review & editing. **Sara Savoldelli:** Validation, Visualization, Writing – review & editing. **Pompeo Suma:** Validation, Visualization, Writing – review & editing. **Giovanni Tamburini:** Validation, Visualization, Writing – review & editing. **Giovanna Tropea Garzia:** Validation, Visualization, Writing – review & editing. **Lorenzo Marini:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103853.

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