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Pesticide use in vineyards is affected by semi-natural habitats and organic farming share in the landscape

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ABSTRACT

Reducing pesticide use in agricultural landscapes involves understanding the environmental drivers that affect pesticide application and its subsequent effect on pests. Landscape diversification has been found to benefit natural enemies of pests that may lead to lower pest pressure, but its effect on pests and pesticide use, in particular, remains unclear. We investigated how the proportion of organic farming and semi-natural habitats in the landscape affect pesticide use in conventional and organic vineyards based on 22 pairs of vineyards selected along landscape gradients. We quantified both insecticide and fungicide use by farmers as vineyards are heavily sprayed against insect pests and pathogens. Our study indicates that the share of organic farming in the total vineyard area and the proportion of semi-natural habitats in the landscape influence pesticide use. We found a tendency for insecticide use to increase with the share of vineyards under organic farming in the landscape, both in organic and conventional fields. Fungicide use followed the same pattern but only in conventional fields. Significant increases in pesticide use due to a higher share of organic farming were small, rarely exceeding 14% of the treatment frequency index. Notably, our results revealed contrasted effects of the proportion of semi-natural habitats on pesticide use between organic and conventional farming. Landscapes with a higher proportion of semi-natural habitats tended to increase fungicide use in conventional fields while insecticide use tended to decrease in organic fields. Our results demonstrate that designing landscapes that limit pesticide use should consider farming practices and semi-natural habitats within the landscape to favour beneficial effects on pest control while minimising potential adverse effects.

1. Introduction

Over the last decades, agricultural landscapes in Europe have undergone considerable changes with significant negative impacts on the environment, mainly due to an increase of cultivated areas and fragmentation of semi-natural habitats accompanied by an intensification in the use of agrochemical products per hectare (Tilman et al., 2001, 2002; Schreinemachers and Tipraqsa, 2012). Therefore, today's agriculture faces the challenge of maintaining high commodity production levels while simultaneously reducing the use of agrochemical inputs, such as pesticides (Desneux et al., 2007; Aktar et al., 2009; Geiger et al., 2010; Tilman and Clark, 2014; Goulson et al., 2015).

The solution to this problem requires a paradigm switch from industrial agriculture, mainly concerned with yield maximisation, to multifunctional agricultural landscapes in order to maximise the benefits of multiple ecosystem services on the farmland (Scherr and McNeely, 2008). To design innovative cropping systems with a lower reliance on pesticides, we need to understand the drivers of pesticide use in agricultural landscapes. Previous studies identified multiple drivers operating across several scales, including the farmers' behaviour towards risks (e.g. Ecobichon, 2001; Jallow et al., 2017), public policies (e.g. Hillocks, 2012; Osteen and Fernandez-Cornejo, 2013) and the fields' surrounding landscape (Paredes et al., 2021). While the effects of farmers' behaviours and public policies on pesticide use have been explored (Gong et al., 2016; Finger et al., 2017), very little attention has been given to the landscape's effects (see Paredes et al., 2021).

If we assume that pesticide use in a field depends on pest pressure, the landscape related effects on pesticide use should depend on

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landscape effects on pests. The amount of semi-natural habitats, the composition of the crop mosaic, and the type of farming practices operated by farmers can directly or indirectly affect pest populations (Bianchi et al., 2006; Gardiner et al., 2009; Rusch et al., 2010; Chaplin-Kramer et al., 2011). Landscapes with more semi-natural habitats generally harbour more abundant and diverse communities of natural enemies that might provide higher pest control services (Bianchi et al., 2006; Rusch et al., 2016), suggesting lower pesticide use levels in such landscapes. However, reported effects of semi-natural habitats on pest abundance are inconsistent (Chaplin-Kramer et al., 2011; Veres et al., 2013; Tscharntke et al., 2016; Karp et al., 2018). Moreover, other landscape features, such as agricultural practices in the landscape, affect natural enemies and pests and may partly explain the variable effects of semi-natural habitats on pest control (Maalouly et al., 2013; Monteiro et al., 2013). For example, the proportion of organic farming in the landscape may benefit natural enemy communities, and biological control, but could also enhance pest abundances (Puech et al., 2015; Muneret et al., 2019b). The expected outcome of the increased area under organic farming thus depends on the balance between organic farming's positive and negative effects on biological pest control services and pest abundances (Petit et al., 2020). Lastly, local farming practices can modulate the effect of the landscape on biological control services (Chaplin-Kramer and Kremen, 2012; Petit et al., 2017). The significant use of pesticides at the local scale may cancel out the potential benefits of semi-natural habitats on biological pest control by impacting natural enemy communities (Desneux et al., 2007; Bommarco et al., 2011; Ricci et al., 2019), so that landscape effects may be stronger in low-sprayed or organic fields (Tscharntke et al., 2005; Martínez-Sastre et al., 2021). Consequently, the potential effects of landscape context on pesticide use are complex and unpredictable since they result from multiple interactions between various environmental variables operating on different spatio-temporal scales (Petit et al., 2020). Therefore, it is essential to analyse the effect of landscape context and landscape-level farming practices on pesticide use using real-world data to improve our ability to predict the consequences of large-scale changes in farming practices.

To our knowledge, the only study that investigated the effect of landscape composition on local pesticide use was performed by Paredes et al. (2021). They showed that insecticide use against the grapevine moth, *Lobesia botrana* (Denis & Schiffermüller), increased with the landscape's proportion of vineyards. Conversely, the increase in shrubland areas significantly decreased the use of insecticides in the vineyards. These results suggest that such habitats may reduce pest populations either directly (i.e., the habitat being less favourable for the pest) or indirectly (i.e., by favouring the presence of natural enemies). However, this study did not consider farming practices in the landscape. Considering the diversity of agricultural practices at different spatial scales could improve our understanding of landscape effects on pesticide use (Maalouly et al., 2013; Monteiro et al., 2013; Tscharntke et al., 2016; Muneret et al., 2018b).

Grapevine, *Vitis vinifera* L. (Vitaceae), is an economically important perennial crop. In France, this crop is heavily sprayed with up to four insecticide treatments and 30 fungicide treatments per year (Delière et al., 2016; Pertot et al., 2017). This very intensive management is known to have adverse effects on the environment and on human health (Provost et al., 2007) highlighting the urgent need for pesticide reduction in this agrosystem. For instance, insecticide and fungicide use as well as soil tillage intensity affect biodiversity and the level of key ecosystem services (Trivellone et al., 2012; Muneret et al., 2019a; Ostandie et al., 2021; Rusch et al., 2021). The main pests for insecticide treatments are the grapevine moths Eudemis *L. botrana* and Cochylis *Eupoecilia ambiguella* (Hübner), leafhoppers (Cicadellidae), particularly *Scaphoideus titanus* (Ball). The latter species is the primary vector of the flavescence dorée disease (caused by the phytoplasma *Candidatus Phytoplasma vitis*) leading to mandatory treatments. For fungicides, the main targets are downy mildew, *Plasmopara viticola* (Berk & Curtis) and powdery mildew *Erysiphe necator* (Schwein). Depending on their life-history traits, these insect pests and pathogens are expected to be affected differently by the landscape context (Jackson and Fahrig, 2012; Miguet et al., 2016).

Grapevine moths have a significant number of natural enemies ranging from parasitoids to bats and birds (Thiéry et al., 2018). Even though they are polyphagous species (Thiéry et al., 2018), *V. vinifera* remains their main host in vineyard-dominated landscapes (Maher and Thiéry, 2006). Downy mildew and powdery mildew may also depend on the amount of vineyards in the landscape. They are specialised obligate pathogens of the genus *Vitis* (Gessler et al., 2011) and genera of the Vitaceae family (Gadoury et al., 2012), respectively. Very few studies have explored the effects of the landscape context on vineyard insect pests and pathogens. In those studies, infestation by *L. botrana* was positively correlated with vineyard area (Van Helden et al., 2008; Paredes et al., 2021) and was negatively correlated with shrubby areas (Paredes et al., 2021). On the other hand, downy mildew and powdery mildew infestation seemed not to depend on the proportion of semi-natural elements or organic farming in the landscape (Muneret et al., 2018a). Different landscape features could thus impact grapevine moths and pathogens because of their different life-history traits and dispersal abilities.

In the present study, we investigated the effects of the landscape context on pesticide use in vineyards and evaluated if these effects differ between conventional and organic fields. More specifically, we analysed the relative effects of semi-natural habitats and the proportion of organic farming in the landscape on pesticide use. We hypothesised that: (i) Landscapes with a higher proportion of semi-natural habitats use less insecticides at the field scale because of higher levels of biological pest control and lower amounts of host crops; (ii) Landscapes with a higher proportion of organic farming increase the use of insecticides and fungicides at the field scale due to lower efficiency of practices to control pests and pathogens in organic farming; (iii) The effects of the landscape context on pesticide use are modulated by the type of farming system at the field scale with the landscape context expected to contribute more to pesticide use in organic than in conventional fields.

2. Materials and methods

2.1. Study site and design

The study was carried out in 2015 and 2018 in the Bordeaux area, southwest of France, in a region dominated by vineyards (44°48′N, −0°14′W). Between January and October, daily precipitation was higher in 2018 than in 2015 averaging 2.4 ± 1.2 mm and 1.9 ± 0.9 mm respectively in the study area. Daily temperatures were similar with 15 ± 6 °C for both years (SAFRAN data, 8 km grid).

The system studied consisted of a total of 22 different pairs of fields (Table A) that consisted of one field under organic farming and one under conventional agriculture (18 pairs in 2015 and 17 pairs in 2018, with 13 pairs in common between 2015 and 2018). Five pairs surveyed in 2015 were not surveyed in 2018 due to field uprooting, conversion to organic farming or retirement of winegrowers. Among the 13 pairs in common between 2015 and 2018, we changed four fields by selecting another field in the close surroundings to obtain the same cultivar (i.e., Merlot) within a field pair (Table A). Pairs were selected along two uncorrelated landscape gradients: a gradient of the proportion of semi-natural habitats and a gradient of the proportion of organic farming in a landscape of one-kilometre radius around the centroid of each vineyard. The semi-natural habitats were composed of grassy and wooded habitats. This design allowed us to disentangle the effects of the proportion of semi-natural habitats and the proportion of organic farming in the landscape on pesticide use in organic and conventional farming systems. All vineyards were commercial vineyards.

Landscape gradients were calculated based on land use digitised using ArcGIS 10.1 (ESRI) in 2015 and QGIS (version 3.10) in 2018.

Digitisation was carried out using the PIGMA database (https://portail.pigma.org/), orthophotos from the National Institute of Geographic and Forest Information (IGN, 2015), supplemented with field inspection and interviews of farmers about land-use and farming practices. The proportion of semi-natural habitats and the proportion of organic vineyards in the total vineyard area were calculated in five spatial extents ranging from a 200 to 1000 m radius around the centroid of the fields, every 200 m (Table 1). These extents were chosen to include both near neighbourhoods and large-scale effects and to check the consistency or variation of these effects with distance from the target field. The target field area was not included in landscape metrics calculation to avoid overestimating the proportion of vineyards, especially in the smaller spatial extents.

The proportion of semi-natural habitats was negatively and significantly correlated to the proportion of vineyards, the dominant crop in our study region (Pearson correlation from −0.69 to −0.93 depending on spatial extent, Fig. A supplementary material). Therefore, the proportion of semi-natural habitats is a good indicator of the ratio between crop and non-crop habitats in the landscape. The share of organic farming in the vineyard area was neither correlated to the proportion of vineyards nor the proportion of semi-natural habitats (Fig. A). Also, the share of organic farming in the vineyard area was correlated with the proportion of organic vineyards in the landscape (Fig. A).

2.2. Quantifying pesticide use

Pesticide use was characterised by three complementary variables: the treatment frequency index (TFI), the date of the first spraying and the spraying duration (Table 2). The TFI is an index used for calculating pesticide pressure and comparing alternative pesticide uses for different systems (Lechenet et al., 2014). The TFI was calculated for each targeted pest (grapevine moths, downy mildew and powdery mildew) using the treatment application schedules collected from the farmers on all registered products. It was set to 0 in the absence of spraying. Since flavescence dorée leafhopper is subject to mandatory treatments decided by public policies, we did not include insecticide use against this pest in our analyses. The recommended dose was retrieved from the French government database (https://alim.agriculture.gouv.fr/ift/ visited on the 18 february 2020). Active ingredients sprayed in conventional and organic fields differed to a large extent. The active ingredients most used against grapevine moths were the indoxacarb, and a chlorantraniliprole/ thiamethoxam mixture in conventional vineyards, and spinosad and *Bacillus thuringiensis* in organic vineyards. Copper, a fosetyl/metiram mixture or potassium phosphonates were sprayed against downy mildew in conventional vineyards, whereas only copper was used in organic vineyards. Finally, sulphur was sprayed in conventional and organic vineyards against powdery mildew.

The mean TFI (± SD) per treatment was less than 1 for the two pathogens: downy mildew [0.26 ± 0.21 and 0.22 ± 0.18 in organic fields (respectively 2015 and 2018) and 0.78 ± 0.38 and 0.73 ± 0.32 in conventional fields (respectively 2015 and 2018)] and powdery mildew [0.48 ± 0.29 and 0.39 ± 0.20 in organic fields (respectively 2015 and 2018) and 0.84 ± 0.38 and 0.70 ± 0.33 in conventional fields (respectively 2015 and 2018)]. Downy and powdery mildew TFIs were positively correlated in 2015 (Pearson $R = 0.72$, $p < 10^{-6}$) and 2018 (Pearson $R = 0.48$, $p = 4 \times 10^{-3}$). The date of the first spraying was expressed in Julian days for each pest. The date of the first downy mildew spray was strongly correlated with the date of the first powdery mildew spray in 2015 (Pearson correlation, $R = 0.89$, $p < 10^{-11}$) and 2018 (Pearson correlation, $R = 1$, $p < 10^{-16}$).

The spraying duration was calculated as the difference between the Julian day of the last and first spraying. This index provides information about the duration of pest infestation. The spraying duration against downy mildew was positively correlated with the spraying duration against powdery mildew in 2015 (Pearson $R = 0.45$, $p = 0.007$) and 2018 (Pearson $R = 0.44$, $p = 0.01$).

Table 1
Proportions of semi-natural habitats and organic farming among vineyards over the landscape depending on spatial extents and years (mean ± standard deviation and range [min, max]).

	Semi-natural habitats		Landscape organic farming	
Spatial extent (m)	2015	2018	2015	2018
200	0.11 ± 0.11 [0.00, 0.35]	0.12 ± 0.12 [0.00, 0.51]	0.40 ± 0.23 [0.00, 0.86]	0.39 ± 0.27 [0.00, 0.86]
400	0.19 ± 0.14 [0.00, 0.50]	0.19 ± 0.15 [0.02, 0.52]	0.36 ± 0.17 [0.00, 0.68]	0.36 ± 0.20 [0.01, 0.67]
600	0.24 ± 0.18 [0.00, 0.67]	0.24 ± 0.17 [0.01, 0.68]	0.33 ± 0.16 [0.08, 0.67]	0.33 ± 0.16 [0.01, 0.67]
800	0.26 ± 0.20 [0.01, 0.73]	0.27 ± 0.17 [0.01, 0.73]	0.29 ± 0.13 [0.06, 0.55]	0.29 ± 0.14 [0.00, 0.56]
1000	0.27 ± 0.21 [0.01, 0.75]	0.27 ± 0.16 [0.00, 0.72]	0.27 ± 0.13 [0.04, 0.46]	0.27 ± 0.12 [0.00, 0.45]

2.3. Pest monitoring

The protocol differed slightly between years. In 2015, each taxon was counted on 30 vine stocks, four times between May and September. The pests were counted on four to six rows located between the field's 5th and 15th rows. Sampling started 10 m from the borders or other sampled vines. On each vine stock, we recorded the occurrence of downy mildew and powdery mildew on three randomly selected leaves and the number of larval nests of grapevine moths on three randomly selected grape bunches (Muneret et al., 2018a).

In 2018, each taxon was counted on 25 vine stocks per field distributed on five plots spaced 15 m apart (three plots on one row and two plots on one row at 15 m) over two counting sessions in June and July. On each vine stock, we recorded the occurrence of downy mildew, and powdery mildew on four randomly selected leaves during the two sessions. Sampling was done more than 10 m from the borders or other sampled vines. The number of larval nests of grapevine moths was recorded on four randomly selected grape bunches during the second counting session.

2.4. Statistical analyses

2.4.1. Model description

To analyse the effects of farming systems (organic vs conventional agriculture) and the landscape context (proportion of semi-natural habitats, *SNH*, and the share of organic farming in the total vineyard area, *L.OF*) on pesticide use (*TFI*, first spraying and spraying durations), we developed generalised linear mixed models (GLMM) in a Bayesian framework. Parameters were estimated for each spatial extent and each pest independently. The TFI variable was transformed into a presence/absence variable for each field in the case of the grapevine moth due to the low occurrence of spraying against this pest (Table 2). We therefore did not analyse the date of the first spraying and spraying duration against this pest. We assumed that this presence/absence variable followed a Bernoulli distribution and we used a logit link function in the GLMM. For pathogens, TFI, first spraying date, and spraying duration were assumed to follow a Gaussian distribution since it had better residuals than the others tested (Poisson and negative binomial for spraying duration). For downy mildew, infestation data were centred and scaled for each year to consider differences in sampling protocols. The proportion of semi-natural habitats and the share of organic farming in the total vineyard area were centred and scaled within each spatial extent to compare results between spatial extents. A Gaussian random effect was defined on each pair of fields to account for potential dependencies due to the local context.

The resulting model for the grapevine moth is:

Table 2
Summary of treatments and of pest infestations in conventional (Conv.) and in organic (Org.) fields depending on the year (2015 and 2018). Ratio of the sprayed over total fields, treatment frequency index (TFI, mean ± standard deviation), first spraying date (Julian day from the first January, mean ± standard deviation), spraying duration (number of days, mean ± standard deviation) and pest infestation. * Infestation by the grapevine moth is provided as the number of larval nests per grape bunch (mean ± standard deviation). Downy and powdery mildew infestations are presented as the percentage of the affected leaves (mean ± standard deviation). Spraying duration against grapevine moth is not provided because of the low number of treatments.

Target pest/pathogen	Farming system	Year	Sprayed/ total	TFI	First spraying	Spraying duration	Infestation*
Grapevine moth	Conv.	2015	10/18	1.32 ± 0.49	188 ± 26	/	0.01 ± 0.02
	Conv.	2018	3/17	1.78 ± 1.35	178 ± 13	/	0.02 ± 0.08
	Org.	2015	5/18	1.42 ± 0.53	208 ± 23	/	0.01 ± 0.01
	Org.	2018	3/17	1.67 ± 0.58	226 ± 4	/	0.01 ± 0.02
Downy mildew	Conv.	2015	18/18	8.23 ± 2.74	123 ± 6	104 ± 12	4 ± 3
	Conv.	2018	17/17	9.98 ± 3.00	115 ± 6	105 ± 11	39 ± 23
	Org.	2015	18/18	4.66 ± 1.46	120 ± 3	101 ± 11	6 ± 6
	Org.	2018	17/17	5.58 ± 1.70	115 ± 3	99 ± 11	41 ± 22
Powdery mildew	Conv.	2015	18/18	6.50 ± 1.71	123 ± 6	84 ± 19	0
	Conv.	2018	17/17	5.97 ± 1.53	115 ± 6	83 ± 14	0
	Org.	2015	17/18	4.53 ± 1.99	119 ± 5	83 ± 16	0
	Org.	2018	16/17	4.78 ± 2.08	115 ± 4	77 ± 12	0

$$
\begin{aligned}
&Y_i \sim Bern(\pi_i),\\
&logit(\pi_i) = \alpha^1{}_{y(i)} + \alpha^2_{k(i)} + SNH_i(\alpha^3 + \alpha^5{}_{y(i)} + \alpha^6{}_{k(i)}) + L.OF_i(\alpha^4 + \alpha^7{}_{y(i)} + \alpha^8{}_{k(i)}) + \epsilon_{p(i)},\\
&\epsilon_{p(i)} \sim N(0, \sigma).
\end{aligned}
$$

For the downy and powdery mildew, the model is as follows:

$$
\begin{aligned}
&Y_i \sim N(\mu_i, \tau),\\
&\mu_i = \beta^1{}_{y(i)} + \beta^2_{k(i)} + SNH_i(\beta^3 + \beta^5{}_{y(i)} + \beta^6{}_{k(i)}) + L.OF_i(\beta^4 + \beta^7{}_{y(i)} + \beta^8{}_{k(i)}) + \epsilon'_{p(i)},\\
&\epsilon'_{p(i)} \sim N(0, \sigma').
\end{aligned}
$$

Where *i* denotes the vineyard field, *p(i)* is the pair of fields to which it belongs, *y(i)* is the year it was observed, and *k(i)* is the farming system on that field. Note that since α^6, α^8, β^6 and β^8 depend on the farming system, the models include the farming system*SNH* and farming system*L.OF* interactions. For identifiability reasons, α^1, α^5, α^7, β^1, β^5 and β^7 were fixed at 0 for the first year. Similarly, α^6, α^8, β^6 and β^8 were fixed at 0 for conventional farming. Thus, parameter values are interpreted respectively to the fixed levels.

Moreover, except for powdery mildew that was not detected in our field survey, the same models were fitted by adding each pest's infestation as a covariate. This made it possible to quantify the relative effects of the pests' presence on pesticide use in addition to the effects of previously tested variables.

2.4.2. Model implementation

Normal prior distributions (N(0, 1000)) for all α and β parameters were used, while uniform prior distributions (U(0,10)) were defined on all the standard deviation terms. The model parameters were estimated in a Bayesian framework using the JAGS 4.3.0 software (Plummer, 2017). Three Monte Carlo Markov Chain (MCMC) of 20,000 iterations were simulated. The first 10,000 iterations were discarded as a burn-in period, and the remaining 10,000 iterations were thinned every 10 iterations for inference. Chain convergence was checked using the shrink factor (a measure of the ratio between variability between chains and variability within each chain). It was acceptable for all of the parameters ($R < 1.1$, Gelman et al., 2014). Moreover, we assessed model fit with a Bayesian posterior predictive check based on a comparison of observed and predicted TFI (Kéry, 2010). The spatial structure of the residuals of the different models at each spatial extent was explored with the Moran's I and no significant structure was detected except for models on TFI and spraying duration against downy mildew. In these two cases, the coordinates of the field's centroid (latitude and longitude) were added in the models as covariates. Effects were considered strong enough to be discussed when credibility intervals [10%–90%] did not overlap 0 (for a year or pesticide use) or did not overlap between farming systems (organic and conventional). Herein, we provide posterior medians of parameters along with the 0.1 and 0.9 posterior quantiles. Predicted relative effects of a given landscape variable were also assessed by computing how much pesticide use was decreased or increased when the value of this landscape variable was modified from its minimum to its maximum value.

Analyses were performed using R version 3.6.1 with the rjags (Plummer, 2019) and coda (Plummer et al., 2006) packages.

3. Results

3.1. Pesticide use in conventional and organic vineyards

A small proportion of fields were sprayed with insecticides against grapevine moths (Table 2). The probability of spraying insecticides was higher in 2015 than in 2018. The probability was also higher in conventional than organic fields (Table 3 and B).

All fields were sprayed against downy mildew. The average TFI against downy mildew was higher in conventional than organic fields. However, in contrast to insecticides, fungicide use against downy

Table 3
Parameter estimates (Median with 80% credibility interval) for the effects of the 'year', the farming system' and the coordinates of the field's centroid (X: latitude and Y: longitude; for TFI and spraying duration on downy mildew) in the models relating pesticide use to year, farming system, X, Y (if relevant) and landscape variables. Results are provided for the 1000 m spatial extent, and values for other spatial extents are provided in Table B. The year 2015 was taken as the reference (estimate = 0).

Pesticide use	Target	Year 2018	Org.	Conv.	X	Y
Spraying probability	Grapevine moth	**−2.46 [− 3.94,− 1.26]**	−1.50 [− 2.87,− 0.52]	−0.08 [− 1.07,0.84]	/	/
TFI	Downy mildew	**0.17 [0.08, 0.26]**	1.69 [1.61, 1.77]	2.18 [2.1, 2.26]	−0.03 [− 0.11, 0.06]	**0.06 [0, 0.13]**
	Powdery mildew	0.00 [−0.14, 0.13]	1.57 [1.45, 1.69]	1.95 [1.83, 2.06]	/	/
First spraying	Grapevine moth	/	/	/		
	Downy mildew	**−6.07 [− 7.47, − 4.52]**	120 [119,122]	122 [120,123]	/	/
	Powdery mildew	**−5.55 [−7.38, − 3.83]**	120 [118,121]	121 [120,123]	/	/
Spraying duration	Grapevine moth	/	/	/	/	/
	Downy mildew	−0.39 [− 3.39, 2.62]	100 [97,103]	104 [101,107]	**5.24 [2.13, 8.65]**	−0.23 [− 2.69, 2.30]
	Powdery mildew	**−4.24 [− 7.70, − 0.71]**	82 [78,85]	85 [81,88]	/	/

Org: organic farming, Conv: conventional farming and TFI: Treatment Frequency Index. Estimates are bold when the [quantile 0.1, quantile 0.9] interval does not overlap 0.

mildew was higher in 2018 than in 2015 (Table 3 and B) with higher TFIs and earlier spraying in 2018. This observation is consistent with the higher infestation level in 2018 (Tables 2 and 3 and B). Spraying duration was nevertheless similar between farming systems and between years. In addition, the models revealed spatial effects for TFI and spraying duration, the former increasing with longitude and the latter with latitude (Table 3 and B).

The proportion of fields sprayed against powdery mildew was also substantial, but pesticide use against powdery mildew was less than against downy mildew, particularly in conventional fields. Average first spraying dates against powdery mildew were very close to those of downy mildew, and spraying durations were approximately 20 days shorter. As for downy mildew, the TFI against powdery mildew was higher in the conventional fields. The main difference with downy mildew concerns the between-year pattern, in which infestation levels were very low both years, and TFIs were similar between years although spraying durations were lower in 2018, particularly in organic fields (Tables 2 and 3 and B).

Correlations between pesticide use variables indicate that, for the two pathogens, farmers who sprayed earlier also generally sprayed longer (negative correlation between first day of spraying and spraying duration for 2015: Pearson correlation, $R = -0.53$, $p = 0.001$ for downy mildew and $R = -0.10$, $p = 0.02$ for powdery mildew and, in 2018: $R = -0.42$, $p = 0.02$ for downy mildew; not significant for powdery mildew: $R = -0.24$, $p = 0.2$). In general, farmers who sprayed earlier also increased pesticide pressure (positive correlation between first day of spraying and TFI for 2015: Pearson correlation, $R = 0.45$, $p = 0.01$, only for powdery mildew, and in 2018: $R = 0.42$, $p = 0.02$ for downy mildew and $R = 0.57$, $p < 0.001$ for powdery mildew; not significant for downy mildew in 2015: $R = 0.17$, $p = 0.34$). However, TFI and the spraying duration were not significantly correlated.

3.2. Effects of semi-natural habitats on pesticide use

The effects of semi-natural habitats in the landscape on pesticide use were variable between targeted pests, farming systems, and years. There was a tendency, nevertheless, for insecticide use to decrease and for fungicide use to increase with increasing amounts of semi-natural habitats.

The probability of spraying against grapevine moths was more affected by the proportion of semi-natural habitats in organic than in conventional fields. In general, the probability of spraying decreased with the proportion of semi-natural habitats in organic fields for both years although the spatial extent at which effects are detected vary (the effect being significant respectively from 400 m to 1000 m in 2015 and from 800 m to 1000 m in 2018 (Fig. 1)). The most considerable estimated effect in 2015 was at the 800 m spatial extent in 2015 and at 1000 m in 2018. The probability of spraying in organic fields in 2015 and 2018 decreased by an estimated value of 0.88 when the proportion of semi-natural habitats increased from 10% to 73% and 0% to 73% respectively. In addition, our analyses revealed that the probability of spraying against grapevine moths increased at the 200 m spatial extent in organic fields in 2015 by an estimated value of 0.69 when the proportion of semi-natural habitats increased from 0% to 35%. The effect was only significant, and in the opposite direction, in conventional fields in 2018 at the 400 m spatial extent.

Overall, fungicide use against downy mildew tended to increase with the proportion of semi-natural habitats in the landscape in conventional fields and mainly at small spatial extent, from 200 m to 400 m. This increase reached an estimated maximum of 0.49 TFI in 2015 (i.e., 6% of its observed value) when the proportion of semi-natural habitat at 400 m increased from 0% to 50%. The downy mildew TFI in organic fields was never affected by the proportion of semi-natural habitats at any spatial extent. The effect of the proportion of semi-natural habitats was less clear for the first day of spraying, but our analyses indicated a tendency for earlier spraying in conventional fields in landscapes supporting more semi-natural habitats (Fig. 1). Finally, the spraying durations in organic fields decreased with the proportion of semi-natural habitats although the spatial extent mediating this effect varied between years (600 m in 2015, and from 200 m to 1000 m in 2018) (Fig. 1). This decrease reached an estimated value of 20.9days in 2018. Our analyses indicated a tendency for longer spraying duration in conventional fields in 2015, at the 200 m spatial extent.

Fungicide use against powdery mildew, especially TFI and the first day or spraying were not strongly affected by the proportion of semi-natural habitats. The TFI against powdery mildew tended to increase with the proportion of semi-natural habitats at the smallest spatial extent (i.e., 200 m) but only in 2018 and for both farming systems (Fig. 1). Moreover, our analyses indicated a tendency for earlier spraying in conventional fields in 2015 at the 200 m spatial extent in landscapes supporting more semi-natural habitats (Fig. 1). The spraying duration for powdery mildew showed a decreasing response to the proportion of semi-natural habitat with spatial extent in conventional fields. It increased with the proportion of semi-natural habitats mainly at spatial extents lower than 400 m and decreased with the proportion of semi-natural habitats at 1000 m in 2015. This increase reached 45.1 days when the proportion of semi-natural habitats within 200 m increased from 0% to 35% whereas the decrease at 1000 m reached 13.9 days when the proportion of semi-natural habitats increased from 1% to 75%. In addition, we observed for downy mildew, that the spraying duration increased with the proportion of semi-natural habitats in organic fields in 2015 at the 400 m spatial extent and in 2018 at the 600 m spatial extent.

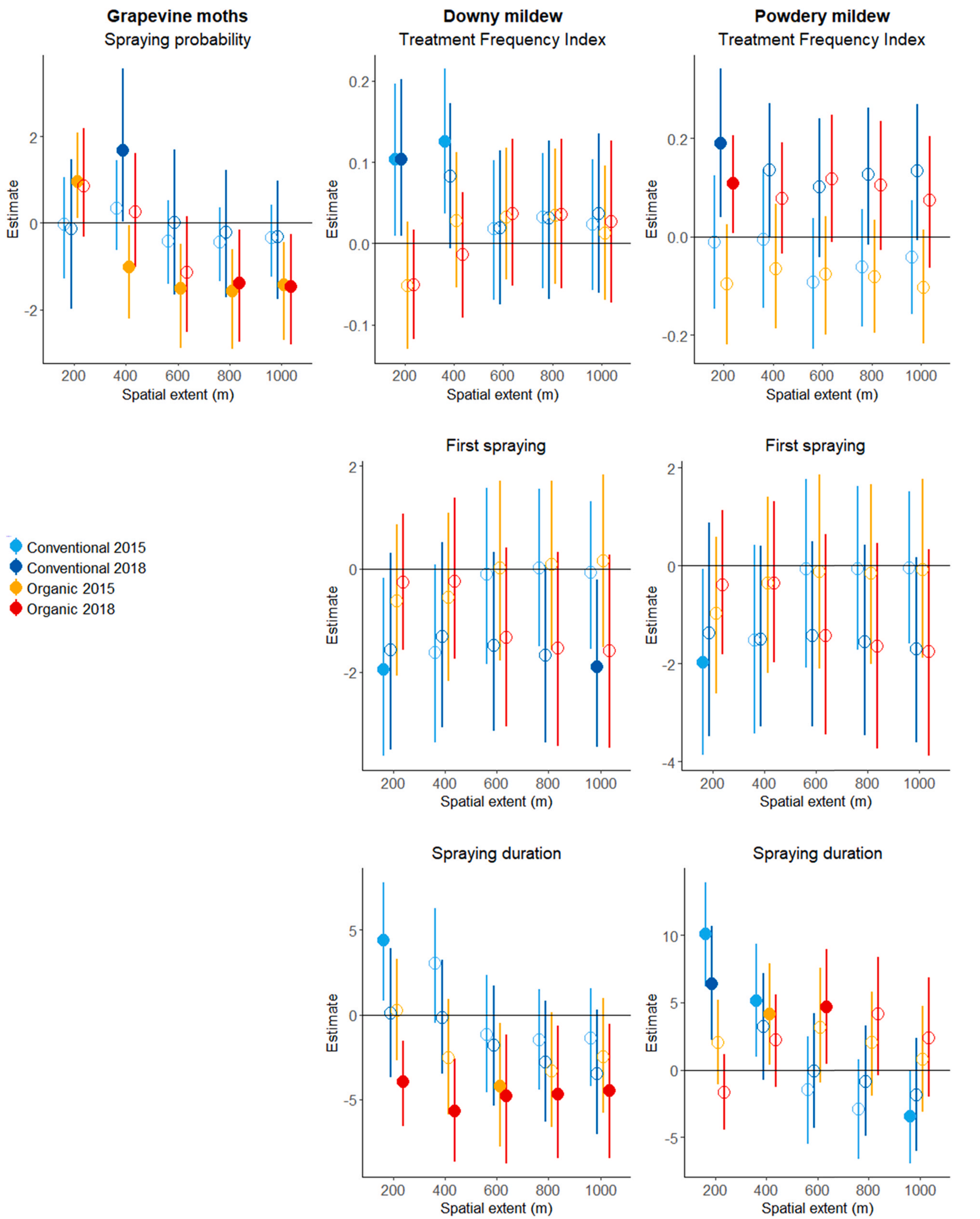

Fig. 1. Estimates of the effects of the proportion of semi-natural habitats in the landscape (median and 80% credible intervals) on the probability of spraying insecticide against grapevine moths (left panel) as well as on the Treatment Frequency Index (TFI), the first day of spraying (First spraying) and the spraying duration against downy mildew (middle panel) and powdery mildew (right panel) according to farming systems (Conventional or organic farming), years and spatial extent. Insecticides are used against grapevine moths, while fungicides are used against downy and powdery mildew. Full dots indicate that the 80% credible interval does not overlap 0.

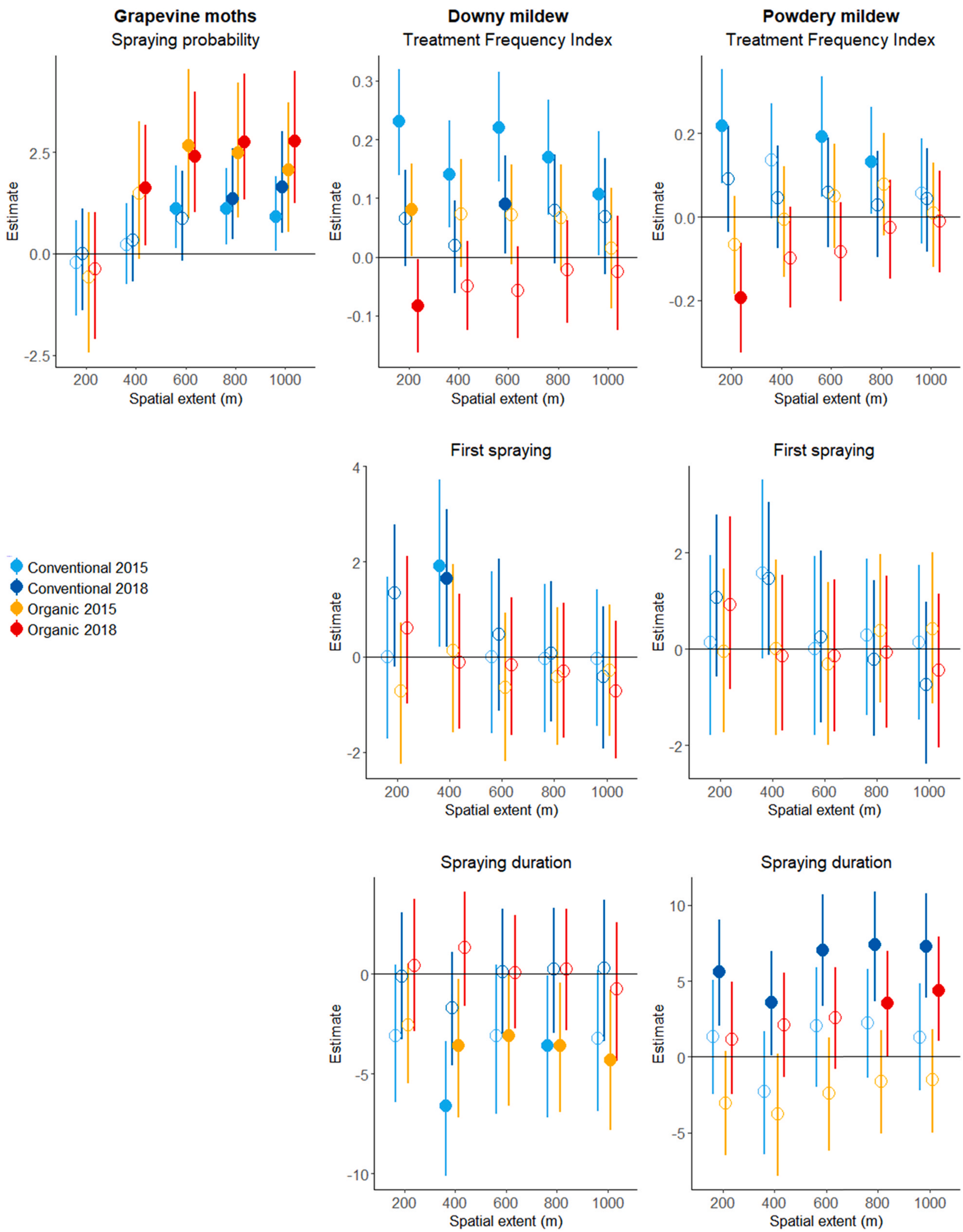

Fig. 2. Estimates of the effects of the proportion of vineyards under organic farming (median and 80% credible intervals) on the probability of spraying insecticide against grapevine moths (left panel) as well as on the Treatment Frequency Index (TFI), the first day of spraying (First spraying) and the spraying duration against downy mildew (middle panel) and powdery mildew (right panel) according to farming systems (Conventional or organic farming), years and spatial extent. Insecticides are used against grapevine moths, while fungicides are used against downy and powdery mildew. Full dots indicate that the 80% credible interval does not overlap 0.

3.3. Effects of the share of organic farming in the total vineyard area on pesticide use

There was an overall tendency for insecticide use to increase with the share of vineyards under organic farming, both in conventional and organic fields. Fungicide use also tended to increase with the share of organic farming, but mainly in conventional fields.

The probability of spraying against grapevine moths increased with the share of organic farming in the total vineyard, both in organic and conventional fields. In organic fields, this effect was significant starting from the 400 m extent in 2018 and 600 m in 2015. Similarly, it was significant in conventional fields from the 600 m spatial extent in 2015 and from 800 m in 2018 (Fig. 2). The largest increases were observed in 2018. The probability of spraying was estimated to increase by 0.99 in the organic fields and by 0.89 in the conventional fields when the share of organic in the total vineyard within 1000 m increased from 0% to 45%.

The TFI against downy mildew increased with the share of organic farming in the total vineyard area but mainly in conventional fields (in 2015 for all spatial extents, in 2018 at the 600 m spatial extent) and less so in organic fields (only in 2015 at the 200 m spatial extent) (Fig. 2). However, the effect was moderate. An increase of the TFI of up to 0.94 (i. e., 11% of the observed TFI) was observed when the share of organic farming in the total vineyard area within 200 m increased from 0% to 86%. The TFI against downy mildew in organic fields in 2018, in contrast, tended to decrease with the share of organic farming but only at the 200 m spatial extent. These variations in TFI could not be explained by an effect on the first day of spraying since this variable was little affected by the share of organic farming in the total vineyard area and only in conventional fields. Finally, spraying duration in 2015 decreased with the share of organic farming at the 400 m and 800 m spatial extents in conventional fields and from 400 m to 1000 m in organic fields. The spraying duration decreased by up to an estimated 24.3 days in conventional fields when the share of organic farming within 400 m increased from 0% to 50% and 15.7 days in organic fields when the share of organic farming within 1000 m increased from 1% to 75%.

As for downy mildew, the TFI against powdery mildew increased with the share of organic farming in vineyards in conventional fields in 2015. Effects were significant for the 200 m, 600 m and 800 m spatial extents (Fig. 2). The TFI increased by a maximum of 0.89 (i.e., 14% of the observed TFI) when the share of organic farming in the vineyard within 200 m increased from 0% to 92%. In addition, as for downy mildew, the TFI in organic fields decreased with the share of organic farming in 2018 but only at the 200 m spatial extent. The share of vineyards under organic farming did not affect the first spraying date (Fig. 2). In contrast, it had a strong positive effect on the spraying duration for both organic and conventional fields in 2018 (Fig. 2). That year, the spraying duration increased by up to an estimated of 16 days in organic fields when the share of organic farming in the vineyard within 1000 m increased from 0% to 45% and by an estimated 26.6 days in conventional fields when the share of organic farming within 800 m increased from 0% to 56%.

3.4. Modelling pesticide use with landscape variables and pest infestation levels

When pest infestation level was added to the model explaining pesticide use with landscape variables, the effects were roughly the same. The estimates of landscape effects changed in few cases but the direction of the effects remains largely similar (Fig. B and C, supplementary materials). Local effects, in particular, were similar to those observed in the models without the pests (Table C, supplementary materials). First spraying was earlier when the proportion of leaves infected with downy mildew increased (Table C, supplementary materials).

4. Discussion

Our study shows for the first time that the proportion of semi-natural habitats in the landscape and the share of organic farming in the total vineyard area influence several aspects of pesticide use at the field scale, revealing contrasted landscape effects between farming systems. We show that landscapes with a higher proportion of semi-natural habitats tend to increase the probability of spraying insecticides against grapevine moths and the level of fungicide use against pathogens in conventional fields. In such landscapes, this increase in fungicide use was accompanied by a longer spraying duration, particularly on powdery mildew. Conversely, landscapes with a higher proportion of semi-natural habitats were found to decrease the probability of spraying against grapevine moths in organic fields. These results partially confirmed our initial hypotheses since they suggest variable effects of semi-natural habitats on pesticide use depending on the type of farming practices at the field scale. In accordance with our hypotheses, our results also indicate that the probability of spraying against grapevine moths increased with the share of organic farming in the total vineyard area. Similarly, the increase in the share of organic farming in the total vineyard area led to a low increase in fungicide use, but this was mainly detected in conventional fields.

4.1. Impact of semi-natural habitats on pesticide use

We hypothesised that a higher amount of semi-natural habitats in the landscape would lead to a decrease in insecticide use at the field scale due to greater biological pest control levels and fewer pest sources (i.e., patches of host plant) (Hogg and Daane, 2010; Barbaro et al., 2017; Wilson et al., 2017; Thiéry et al., 2018; Papura et al., 2020). Our results are consistent with this hypothesis but only in organic fields from the 400 m spatial extent. Our analysis revealed the opposite in conventional fields in 2018, where landscapes with higher amounts of semi-natural habitats within 400 m increased the probability of spraying insecticide. However, it should be noted that 2018 was a low-infestation year for the grapevine moth and that only a small fraction of the fields had been sprayed against this pest in 2018, contrary to 2015. Our results for 2015, when the infestation level of the grapevine moth was higher, are consistent with the results of Paredes et al. (2021), that showed that the insecticide use against *L. botrana* was indeed lower in vineyards surrounded by more shrublands. Therefore, our study suggests that the expected beneficial effects of semi-natural habitats on limiting insecticide use might be modulated by the type of farming systems or by year-effects (e.g., variability in pest population levels or climatic conditions). This variability in the effects of semi-natural habitats on insecticide use highlights the need to investigate the interactions between landscape context and local management using time series and over large spatial scales for understanding the mechanisms shaping pesticide use in agricultural landscapes.

The tendency for positive effects of the proportion of semi-natural habitats in the landscape on the levels of fungicide treatments against pathogens was mainly observed in conventional fields. Such effect could come from micro-climatic effects that may favour the appearance and development of cryptogamic diseases. It may have only been detected in conventional fields because organic farmers have less flexibility in their use of fungicides given the limited authorized amount of copper sprayed in vineyards. Semi-natural habitats are known to foster milder local climates with lower temperatures and higher humidity at their edges (Fall et al., 2010; Faye et al., 2014; Sinha et al., 2015; Papanikolaou et al., 2017). Such local climatic conditions might be beneficial for the development of pathogens (Gessler et al., 2011; Gadoury et al., 2012). Higher local moisture may lead to earlier fungicide sprays, with the increase of semi-natural habitats at small spatial extents. However, because the proportion of semi-natural habitats was strongly inversely correlated with the area of vineyards in the landscape, our results may also indicate that fungicide use decreased with increasing vineyard area.

This result is unexpected since pathogen infestations are expected to increase with the amount of surrounding host crop (Carrière et al., 2014). Other aspects of landscape structure such as varietal landscapes or spatial configuration of host and non-host patches might also influence pesticide use. This possibility needs to be investigated with complementary experiments (Plantegenest et al., 2007). It is also possible that while microclimatic effects of semi-natural habitats are detectable at relatively small scales, host reservoir effects would only be detectable at larger scales than investigated in this study for downy and powdery mildew that disperse over long distances (Savage et al., 2012; Norros et al., 2014).

4.2. Impact of organic farming in the landscape on pesticide use

Few studies have investigated the effects of an increased proportion of organic farming in the landscape on pest pressures and pesticide use levels (Muneret et al., 2018b). Different hypotheses about the effects of the expansion of organic farming on pesticide use can be formulated. Organic farming may favour biological pest control potential due to enhanced abundance and diversity of pests' natural enemies (Crowder et al., 2010; Muneret et al., 2018b). However, higher amounts of organic farming could also increase pest loads at the landscape scale due to less efficient pest control methods, at least temporarily, considering that beneficial effects of biological control may emerge over time.

Contrary to our hypothesis, we did not observe higher pest infestation levels in the organic fields, suggesting that pest control would be as efficient in organic as in conventional fields despite lower treatment frequency index. Additionally, Muneret et al. (2018a) in the same study region showed increased organic farming on the landscape did not affect local levels of grapevine moth or downy mildew infestations. It was therefore unexpected to find that the increase in the share of vineyards under organic farming (regardless of the vineyard area) tended to increase pesticide use, as observed from the probability of spraying against grapevine moths in both organic and conventional fields, the fungicide TFI in conventional fields (particularly in 2015) and the spraying duration in both farming systems for powdery mildew (in 2018). The opposite trend, however, was observed for the duration of treatment against downy mildew. One possible explanation for increased pesticide use is that, as the share of organic farming increases in the landscape, so does the probability that pests and pathogens were poorly controlled in some vineyards in the landscape, thus being a reservoir in years with intense pest pressure. This might come from lower efficiency of plant protection strategy in organic farming especially during conversion or the fact that organic farmers might have more issues to overtake pathogen epidemic when installed in a given field compared to conventional farmers (Merot et al., 2020). For instance, in 2018, some organic fields of the study area were not harvested due to weather conditions that made downy mildew epidemics out of control in those fields (pers. obs.). The very strong increase of spraying duration against powdery mildew with the share of organic farming that year suggests that landscapes with a higher share of organic farming modified disease dynamics and hosted clusters for a more extended period. This hypothesis, based on a higher heterogeneity of infestation levels in organic agriculture, deserves further investigation.

4.3. Relative importance of pest pressure versus other determinants of pesticide use

Altogether, our results may suggest that factors unrelated to actual pest pressure largely determine the level of pesticide use in vineyards. First, although the infestation levels for downy mildew varied between years, the level of pesticide use (here measured through the TFI) against this pathogen increased only by approximately two units in conventional fields and 0.5 units in organic fields between 2015 and 2018. Second, while some landscape effects were significant, they were moderate determinants of pesticide use. Semi-natural habitats and organic farming share affected fungicide TFIs by less than one unit for the highest effect size, corresponding to at most 14% of the total fungicide TFIs. Third, the distances of landscape effects were unexpectedly small relative to the pests and pathogens dispersal ability (Jackson and Fahrig, 2012). Grapevine moths have relatively small dispersal abilities (Schmitz et al., 1996; Sciarretta et al., 2008), while pathogens are expected to disperse over a more considerable spatial extent (Savage et al., 2012; Norros et al., 2014). Our analysis did not reveal highly contrasted scales of effects of landscape context on insecticide and fungicide uses. Landscape features affected both insecticide and fungicide use at similar spatial extents. However, it is also possible that the scales of our analysis did not sufficiently match the scale of dispersal of the insect pest and pathogens studied. For instance, the passive dispersal of pathogens may operate at a much larger spatial extent than the kilometre radius used in our study (Brown and Hovmøller, 2002). Assessing the effect of landscape structure at much larger scales might therefore reveal different effects on pesticide use. Lastly, our analyses indicate that pest infestation levels, when included in our models, did not affect pesticide use except for the powdery mildew.

Other factors besides pest pressure may be involved in the decision-making process of farmers. This might be particularly true in high-value crops such as the monitored vineyards. Although likely related to farmers' risk aversion, the farmers' decision-making process regarding spraying against pests and diseases is multifactorial and remains poorly understood (Carpentier, 2010; Aka et al., 2018; Raineau, 2018; Bakker et al., 2021). Our study did not aim at tackling this issue but instead investigated if the ability of landscape structure to shape pest and natural enemy abundance locally would impact pesticide use at the local scale. Therefore, we did not collect data about the risk aversion of farmers or even information they used in their decision-making process (Gong et al., 2016; Möhring et al., 2020a). However, including such information in our data analyses would make it possible to weigh the relative importance of the biophysical context compared to social or economic factors on pesticide use. Such an approach would provide valuable insights for advancing pesticide policies (Möhring et al., 2020b). Finally, as decision-making on pesticide use and reduction is becoming better understood (Raineau, 2018; Bakker et al., 2021), considering winegrowers' decisions would help better understand the landscape effects on pesticide use.

Furthermore, it would be interesting to explicitly analyse how pesticide use could affect or benefit biological pest control services provided by natural enemies. Indeed, for insect pests, pesticide use is partly influenced by pest infestations, which are affected by the activity of natural enemies. In addition, similar studies in other study-systems such as annual crops and in other regions are now needed to explore the variability of the detected landscape effects on pesticide use in other contexts. Lastly, studies integrating a larger temporal scale would provide a more robust estimation of landscape effects on pesticide use (Paredes et al., 2021). This study only considered a two-year dataset as regularly done in landscape-scale studies on pest populations (Karp et al., 2018). However, considering multiple years would make it possible to explore legacy of previous year infestation, meteorological contexts, capture cyclic dynamics and landscape effects that may emerge over time (Schellhorn et al., 2015; Nenzén et al., 2017; Zhao and Reddy, 2019).

5. Conclusions

Our study provides evidence that the landscape context affects the use of pesticide at the field scale. Although the effect sizes of landscape effects were small, our analysis revealed that landscapes with a high proportion of semi-natural habitats tend to increase the probability of spraying against insect pests and pathogens in conventional fields but not in organic fields. Thus, our study highlights that pesticide use is strongly affected by an interaction between the local and landscape scales, suggesting that such interactions must be considered to understand the potential ambivalent effects of landscape context on pesticide use. Moreover, independently of the effects of semi-natural habitats in the landscape, our results suggest that a higher proportion of organic farming in the landscape may enhance pest loads as insecticide and, to a lesser extent, fungicide use tended to be higher in such landscapes than in landscapes with a low proportion of organic farming. This result suggests that designing landscapes that would limit pesticide use should consider farming practices and semi-natural habitats that favour beneficial effects while minimising the negative ones. Elucidating the optimal structure of landscapes that limit pest infestations and pesticide use now appears to be a significant challenge for future research given the steep increase in organic farming in European landscapes and the intense societal pressure to reduce pesticide use.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.107967.

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