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Less field-level insecticides, but not fungicides, in small perennial crop fields and landscapes with woodlands and organic farming

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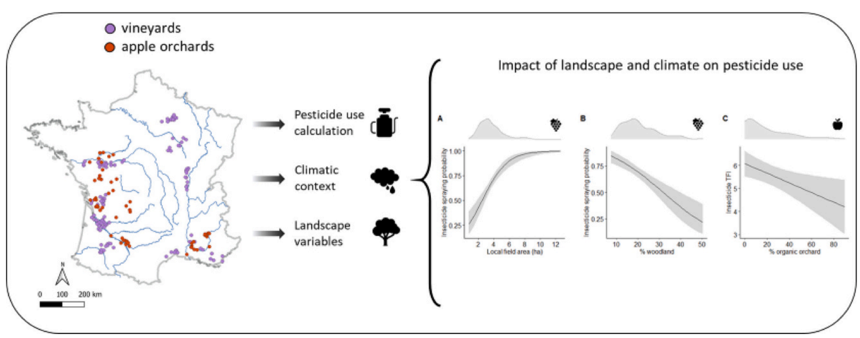
HIGHLIGHTS

- The effects of landscape context on pesticide use in perennial crops remains poorly investigated
- Pesticide use was monitored in 64 apple orchards and 138 vineyards from 2014 to 2019 and related to landscape composition
- Insecticide use was lower in vineyards for small fields or wooded landscapes and in orchards within many organic orchards
- Fungicide use was mainly affected by humid and warm weathers and not by landscape context
- Landscape-scale management options can help reduce insecticide use in agricultural landscapes

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: A large body of evidence suggests that landscape management may limit the use of pesticides in agricultural systems. However, this hypothesis is largely based on studies about biological pest control service, and the effects of landscape context on pesticide use remain poorly investigated.
OBJECTIVE: Here, we investigated how the proportion of host crops and semi-natural habitats affected the local use of fungicides and insecticides in the most treated crops in France, i.e., apple orchards and vineyards.
METHODS: Using pesticide use information at the national level from 64 apple orchards and 138 vineyards monitored between 2014 and 2019, we investigated how local field size, several aspects of landscape context (proportion of host crops, share of organic host crop, proportion of woodlands and grasslands) as well as the weather context affect the frequency, timing and diversity of local fungicide and insecticide use.
RESULTS AND CONCLUSIONS: Our results highlight that landscape-scale management could reduce the use of insecticides in agricultural landscapes. In vineyards, a lower use of insecticides was observed in small fields or landscapes composed of a high proportion of woodlands, while in orchards a lower local use of insecticides was found in landscapes with a high share of organic orchards. Fungicide use was mainly affected by the weather context in both apple orchards and vineyards, with more fungicide use in humid and warm weather. However,

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effects of vineyard size and grassland proportion on the date of the first spray suggest that these two variables may impact pathogen spatial dynamics, a topic that needs further investigations.
SIGNIFICANCE: Landscape-scale management options highlighted in our study may contribute to the design of functional agricultural landscapes minimising pesticide use.

1. Introduction

Pesticides help to reduce crop losses but have major negative effects on the environment and human health (Desneux et al., 2007; Perry, 2008). Thus, it is crucial to identify the main drivers of pesticide use while investigating alternatives to maintain crop productivity and food security. Two main drivers affect pesticide use: (i) pest infestation levels determined by biophysical factors such as climate (Delcour et al., 2015), farming practices (Lechenet et al., 2016) or landscape context (Delaune et al., 2021), and (ii) farmers' decisions and behaviours affected by pest pressures, risk aversion (Möhring et al., 2020) and socio-economic factors such as public policies (Bakker et al., 2021). Despite the current urgency to reduce pesticide use, we currently lack a good understanding of how biophysical factors in general, and landscape context in particular, affect pesticide use in agricultural landscapes (Gagic et al., 2021; Nicholson and Williams, 2021; Paredes et al., 2021).

Landscape structure may affect multiple facets of pesticide use depending on its direct and indirect effects on pest populations. Direct effects of landscape structure on pest populations are mediated by the availability of resources and certain functional traits of pest species such as dispersal abilities (Martin et al., 2019; Delaune et al., 2021). Indirect effects of landscape structure on pests are mediated by the activity of natural enemies, and also depend on their dispersal abilities and life-cycle characteristics (Martin et al., 2019). A high host crop area in the landscape may for instance increase pests' fitness through high resource availability (Delaune et al., 2021) leading to large pest populations, a high flow of pests colonising crop fields and more pesticide applications at the field scale (Paredes et al., 2021). Alternatively, high amounts of host crops in the landscape may dilute pest populations (Thies et al., 2008). Additionally, semi-natural habitats such as grasslands or woodlands are sources of natural enemies in the landscape and support biological pest control in crop fields (Bianchi et al., 2006; Sarthou et al., 2014; Rusch et al., 2016). Therefore, increasing the amount of semi-natural habitats may promote earlier control of pests by natural enemies and limit the growth rate of pest populations, possibly delaying or attenuating pesticide use. While these direct and indirect effects of landscape context on pests have been highlighted, their relative importance in driving pest population dynamics and pesticide use remains largely unknown.

Despite the large body of evidence highlighting the effect of landscape context on pests and their natural enemies, recent syntheses revealed a high context-dependency in this relationship (Tscharntke et al., 2016; Karp et al., 2018). This context-dependency may result from the hidden landscape heterogeneity driven by farming practices, particularly pesticide use, which may modify landscape composition effects (Vasseur et al., 2013; Karp et al., 2018; Ricci et al., 2019). Landscape-level farming practices may modulate pest population dynamics through changes in habitat quality. Organic farming limiting the use of pesticides supports biodiversity and could enhance natural enemy activity with beneficial effects on pest infestation levels (Muneret et al., 2018). However, decreasing the overall level of pesticide applications may also increase pest pressure over time. The balance between pest infestation levels and natural enemy activities to a decreasing level of control provided by pesticides remains hardly predictable. The few studies that explored the impact of landscape-level pesticide use on local pesticide use indicate inconsistent effects (Muneret et al., 2018; Etienne et al., 2022) and thus require further investigation.

Abiotic parameters such as temperature, humidity or wind are other major factors shaping pest population dynamics and pesticide use (Delcour et al., 2015). For instance, increased air humidity and temperature can favour pathogen and pest infestations by improving dispersal or development (Combina et al., 2005; Nelson et al., 2013; Deutsch et al., 2018). Moreover, several decision support systems used by farmers only consider weather conditions to assess the risk of pest or pathogen pressure (Boivin et al., 2005; Delière et al., 2015). However, such weather variables are rarely considered in large-scale studies analysing how landscape structure affects pest populations (Karp et al., 2018). These co-variables may potentially modulate or even mask landscape effects on pesticide use.

Apple orchards and vineyards are among the most treated crops globally and reducing pesticide use has become necessary to protect both human health and the environment. Most pesticides in these systems are used against fungi and insect pests with an average treatment frequency index (TFI index, which represents the number of reference doses applied per hectare) of about 35 per year for apple orchards and 12 to 15 per year for vineyards in France (Agreste, 2018). In addition to high levels of pesticide use in those systems, there is also a major variability in pesticide use between or within regions indicating different pest or pathogen pressures due to diverse environmental contexts and different farmers' strategies to manage pests and pathogen pressures (Mailly et al., 2017). Despite major issues related to pesticide reduction in those systems, the environmental variables explaining the mean and the variability of pesticide use in agricultural landscapes remains largely unexplored.

This study evaluated the impact of landscape composition and the climate context on fungicide and insecticide use in apple orchards and vineyards focusing on pesticides that are most harmful to biodiversity and the environment. We tested three hypotheses about how landscape composition could affect the pesticide use in those systems: (H1) Higher amounts of host crops in the landscape would increase pesticide use, both fungicides and insecticides, due to higher resource availability for pests and pathogens that benefit their fitness. (H2) Higher amount of host crops under organic farming in the landscape increases pesticide use due to higher pest or pathogen risks in organic crops. (H3) Conversely, higher amounts of semi-natural habitats would decrease insecticide use due to the expected beneficial effects of such habitats on natural enemies and the top-down control of pests they support.

2. Materials and methods

2.1. Data collection

Pesticide use information was collected within the DEPHY-farm network. This national network comprises farms involved in the French ECOPHYTO program that aim to reduce pesticide use. Fruit and vine growers involved in the network are committed to implement farming practices and to reach a given target of pesticide-use reduction. Here, each combination of farm, crop (here vineyard or apple orchards), farming practices and objective of pesticide use reduction is referred as a cropping system. Within a farm, the same cropping system can be implemented to one or more fields. Pesticide use is recorded in the Agrosyst database for each cropping system each year.

Pesticide use data for 64 apple orchards and 138 vineyard cropping systems were extracted from the Agrosyst database. These cropping systems were all conventional systems located in 54 municipalities in the South and the West of France for orchards and 127 municipalities distributed throughout France for vineyards (Fig. 1). Annual data were recorded between 2014 and 2019 and included cropping systems

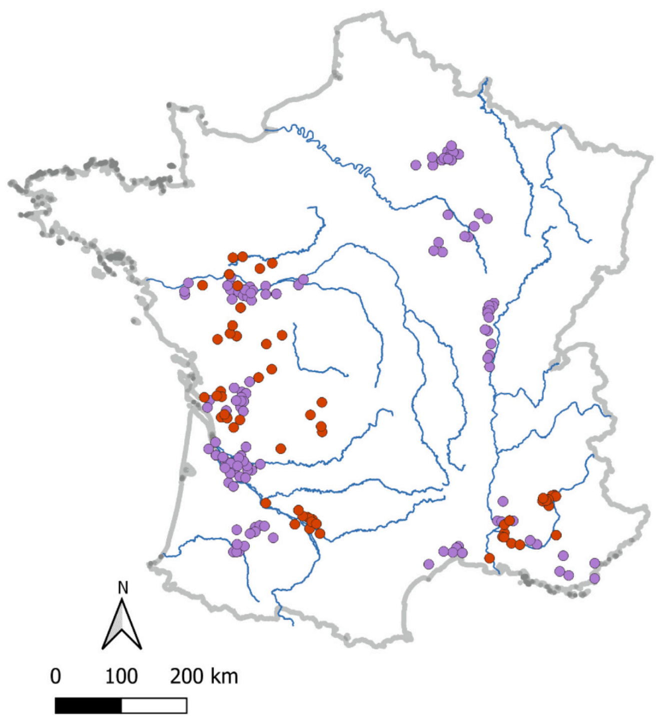

Fig. 1. Map of continental France with locations of the municipalities of the study cropping systems for apple orchards (red) and vineyards (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

monitored between three and six consecutive years.

2.2. *Indicators of pesticide use*

Pests considered in our analyses were pathogenic fungi and oomycetes, as well as insects with an agronomic pest status. In apple orchards, the main targeted pests include apple scab [*Venturia inaequalis* (Cooke) G. Winter] and powdery mildew [*Podosphaera leucotricha* (Ellis & Everh.) ES Salmon] as disease agents and the codling moth [*Cydia pomonella* (L.)] and the rosy apple aphid [*Dysaphis plantaginea* (Passerini)] as insect pests. In vineyards, the main targeted pests include downy mildew [*Plasmopara viticola* (Berk. & MA Curtis) Berl. & De Toni)] and powdery mildew [*Erysiphe necator* (Schwein)] as disease agents and grape berry moths [*Eupoecilia ambiguella* (Hübner) and *Lobesia botrana* (Denis & Schiffermüller)] and a leafhopper vector of the Flavescence dorée disease [*Scaphoideus titanus* (Ball)] as insect pests.

We characterized the field level pesticide use in each cropping system each year by calculating the Treatment Frequency Index (TFI also named STI, Sattler et al., 2007, equivalent to the number of treatments if these had been sprayed at the full recommended doses over the all-field area, supplementary material, Eq. S1), the first day of spraying, and the active ingredient diversity. These indicators were calculated independently for fungicides and insecticides. The dose and area sprayed were retrieved from the Agrosyst database. The recommended dose was retrieved from the French government database (Ministry of Agriculture and Food 2020, https://alim.agriculture.gouv.fr/ift/, March 2020). Pesticides characterized as 'biocontrol' in the database were excluded from calculations because of their supposedly limited impact on non-target organisms and the environment. Products based on copper or spinosad were thus included although their usage was approved under organic agriculture. Each recommended dose is attached to a particular target pest/disease or product (fungicides and insecticides). When the farmers had specified more than one target pest or no target pest for the treatment in the Agrosyst database, the higher recommended dose for this pesticide on that crop was used (i.e. 22% and 7% of the treatments for apple orchards or for vineyards). For 9% (apple orchards) and 3% (vineyards) of the treatments, we could not locate the pesticide in the official databases for 2020. For apple orchards, we searched the last recommended dose for the previous years until 2014. In the end, only 1% of the treatments did not link to a recommended dose. As most treatments in the dataset corresponded to a TFI of 1 (59% of insecticides and 51% of fungicides in apple orchards and 58% of insecticides and 32% of fungicides in vineyards), all treatments with no specified target pest were arbitrarily allocated a TFI of 1. Partial TFIs were calculated by summing only the fungicide (TFI_f) or only the insecticide (TFI_i) treatments. The first spraying day was the first date indicated in the database for a given year, expressed in Julian days. The first spraying day was recorded independently for fungicides and insecticides. The diversity of active ingredients was the number of active ingredients sprayed in a given cropping system each year. This information is complementary to the TFI, which sums-up different active ingredients. The diversity of active ingredients was also calculated independently for fungicides and insecticides. While TFI provides comparable treatment frequency information across cropping systems, the first spraying day indicates pest or pathogen infestation precocity. Moreover, the diversity of active ingredients may reflect pest diversity and farmers' strategies to manage resistance and environmental impacts.

For each crop and pesticide class (fungicides or insecticides), TFI, first spraying date, and active ingredient diversity were significantly correlated (all $p < 0.003$), except for the first spraying date and the diversity of fungicides in vineyards that were not significantly correlated (supplementary material, Fig. S1).

2.3. *Landscape context*

Land use maps were created by combining (i) the French Land Parcel Identification System (RPG, a geographical database designed for the registration of parcels from farmers within the framework of the Common Agricultural Policy), which provides information about the type of crop grown and grassland (temporary or permanent) in each field from 2015 to 2019, and (ii) the BD TOPO® (v2 2017, IGN, French National Geography Institute), which provides information about the forests, orchards and vineyards. These maps were used to characterise the landscape context. The *alm* package (Allart et al., 2021) combined these two landscape databases, prioritising the RPG, which was informed each year. All resulting orchards and vineyards smaller than 0.01 ha were considered artefacts of the procedure and were removed from the map.

The exact coordinates of each cropping system in a municipality were not available in the Agrosyst database. We thus retrieved 2 to 517 (mean 74) orchard fields per municipality for apple cropping systems and 4 to 675 (mean 128) vineyard fields per municipality for vineyard cropping systems (supplementary material, Table S1). Then, the mean area of orchard (respectively vineyard) fields, and the proportions of orchards (resp. vineyards), grasslands and woodlands were calculated in a 2000 m radius buffer zone centered around each retrieved orchard or vineyard field. Within each municipality and each crop, the average of land-cover proportions over all buffer zones was considered to describe landscape composition surrounding orchards (resp. vineyards) cropping systems from that municipality. Note that, at landscape level, the exact information about the crop grown in orchards was not available. However, available information indicates that apple orchards were generally the majority and represented 39 ± 8% of orchards (Fig. S2).

Depending on the year 3% to 26% of the orchard cropping system municipalities did not comprise organic orchards and 28% to 40% of the vineyard cropping system municipalities did not comprise organic vineyards (Table S1). For the other municipalities, data on the area of organic orchards or vineyards was unavailable if there were less than three organic farms to protect farmers' privacy. Therefore, we had to estimate the area of organic crops for these municipalities. For this purpose, and for each year, we divided the total area of organic orchards or vineyards in the department (territorial authority grouping together several municipalities) where these municipalities were located by the number of organic farms with orchards or vineyards in the same department. We thus obtained the average area of an organic farm in the department and we used this value to estimate the area of orchards or vineyards under organic farming at the municipality level (i.e. in 45% of the apple cropping system x year combinations and in 32% of the vineyard cropping system x year combination). Evaluation of this procedure on municipalities with more than three organic farms indicated that this procedure was robust in predicting the area of organic farming, although there was variation among municipalities (Fig. S3).

Orchards were mainly surrounded by woodland, followed by grassland and orchards (Table 1). Vineyards were mainly surrounded by vineyards, followed by woodland and grassland (Table 1). The area of organic farming increased for both crops from 2014 to 2019. It doubled for orchards and increased by 50% for vineyards (Table 1). Some landscape variables were significantly correlated, although with low R values ($R < 0.3$, Fig. S4).

2.4. Weather data

The interpolated meteorological dataset of Meteo-France (SAFRAN) was used to describe the weather context for each cropping system and year. Weather data are provided for 64 km^2 mesh grids over the French territory. The mean daily rain and snow, minimum, maximum and mean daily temperatures, wind speed, air humidity, soil wetness index, evapotranspiration, mean daily streaming and mean daily radiation were averaged per mesh for each cropping period (November year n-1 to end October year n) using the data from 2013 to 2019. The November to October period was chosen to account for the winter conditions experienced by pests. Each cropping system was associated with the weather cell containing the centroid of its municipality.

To summarise these weather contexts for each cropping system, we used a principal component analysis on weather variables and retrieved the coordinates of each cropping system on the principal component analysis (PCA) first two axes (R software 3.5.0—package FactoMineR). For apple orchards (Fig. 2), the first principal component of the PCA (PC1) was positively correlated with temperature and negatively correlated with rainfall and while the second principal component (PC2) was positively correlated with humidity and negatively correlated with radiation and evapotranspiration. For vineyards (Fig. 2), PC1 was positively correlated with temperature, evapotranspiration and radiation and negatively with humidity. Finally, PC2 was positively correlated with rainfall.

2.5. Statistical analyses

Generalised linear models (glmer function, lme4 package, Bates et al., 2014) were used to investigate how weather variables and landscape context affect pesticide use (using TFI, first spray and active ingredient diversity - see below for details about model fitting for each dependent variable). We performed independent models for orchards and vineyards and for fungicide and insecticide use for each crop. For each model, fixed effects were the proportion of orchards (respectively vineyards), grassland, woodland and organic farming, the coordinates on the PC1 and PC2 of weather variables, and local field size. In addition, the number of years since each cropping system entered the DEPHY network size was added as a fixed effect because farmers joining the DEPHY network aim to gradually reduce their use of pesticides. Lastly, because of the strong positive correlation between the diversity of active ingredients and TFI, we included the TFI as a covariate in the model explaining the diversity of active ingredients. We thus aimed to consider landscape effects on the component of diversity that did not depend on the value of the TFI. Local field size and landscape variables were z-transformed to facilitate comparisons of their effects (Grueber et al., 2011). The cropping system identity was included as a random effect in all models except for insecticides in vineyards (see below) to consider repeated measures on the same cropping system.

Following analyses of model residuals (see below), dependent variables were assumed to follow a Gaussian distribution except for insecticides in vineyards. Due to a large number of vineyard cropping systems that had a null insecticide TFI (about $^1/_3$ of the cropping systems), the first insecticide spraying date and the diversity of active insecticide ingredients could not be analysed. Instead, the presence/absence of insecticides (binary response) was analysed with a Binomial error distribution. With this distribution, the fitted model estimates the effects of landscape and weather on the probability of spraying insecticide. Due to the very low variability in insecticide spraying probability within a cropping system, random effects associated to cropping system identity could not be estimated and were not included in this model.

Variance inflation factors were below 2 for all models, confirming the low levels of multicollinearity between independent variables (Zuur et al., 2010). Model residuals were inspected for dispersion using a quantile-quantile (QQ) plot of standardised residuals and for uniformity and outliers using a plot of residuals versus predicted values. Associated statistical tests were also performed with the DHARMa R package (Hartig, 2019). Moreover, spatial autocorrelation in the residuals of each model was explored using variograms, and no spatial autocorrelation was detected. Standardised residuals were also plotted against regions where the cropping systems were located to detect potential unaccounted-for effects. Graphs for significant effects and partial

Table 1
Mean [min, max] landscape proportions of orchards (Orchard) or vineyards (Vineyard), grassland (Grassland), woodland (Woodland), organic orchards among orchards (Organic orchards), organic vineyards among vineyards (Organic vineyards), and mean [min, max] estimated area of orchard or vineyard fields (respectively, Orchard field area and Vineyard field area) per municipality. Except for Organic orchards and Organic vineyards, landscape maps of 2015 were used for 2014. See text Table S1 for details on variable calculation.

Crop	Year	Orchard	Grassland	Woodland	Organic orchards	Orchard field area (ha)
Apple	2014	9.32 [0.22, 28.08]	20.39 [1.05, 55.08]	25.09 [9.49, 43.78]	12.78 [0, 75.33]	2.58 [0.92, 6.85]
	2015	8.99 [0.22, 28.08]	19.01 [1.05, 55.08]	24.33 [9.49, 43.78]	10.53 [0, 53.28]	2.61 [0.92, 6.85]
	2016	10.49 [0.22, 29.45]	15.33 [0.86, 54.29]	22.34 [6.14, 43.81]	18.77 [0, 81.24]	2.57 [0.92, 6.78]
	2017	8.13 [0.22, 30.59]	13.97 [0.47, 41.07]	22.39 [6.10, 54.64]	17.87 [0, 73.13]	2.65 [1.12, 6.94]
	2018	8.36 [0.20, 31.78]	12.89 [0.74, 33.29]	21.95 [6.11, 56.23]	20.86 [0, 74.22]	2.62 [1.11, 6.51]
	2019	8.01 [0.18, 32.85]	11.58 [0.19, 35.39]	22.03 [7.44, 56.21]	25.48 [0, 87.37]	2.68 [1.08, 6.71]
Crop	Year	Vineyard	Grassland	Woodland	Organic vineyards	Vineyard field area (ha)
Vineyard	2014	29.55 [1.53, 68.06]	5.61 [0.23, 23.15]	24.40 [7.30, 63.24]	10.62 [0, 87.28]	3.84 [0.77, 11.54]
	2015	29.35 [1.53, 68.06]	5.43 [0.23, 23.15]	23.76 [7.30, 63.24]	10.06 [0, 93.08]	3.80 [0.77, 11.54]
	2016	28.53 [0.65, 68.06]	5.09 [0.12, 22.95]	23.21 [7.34, 64.08]	9.81 [0, 88.28]	3.77 [0.84, 12.83]
	2017	27.23 [0.65, 76.28]	5.39 [0.10, 31.37]	23.14 [4.56, 63.96]	12.68 [0, 99.19]	3.63 [0.78, 12.84]
	2018	27.20 [0.64, 76.32]	5.46 [0.10, 32.67]	22.58 [4.48, 61.00]	13.21 [0, 82.99]	3.65 [0.69, 10.62]
	2019	25.30 [1.18, 76.47]	6.09 [0.10, 32.48]	22.31 [4.50, 61.17]	15.50 [0, 81.34]	3.52 [1.15, 9.10]

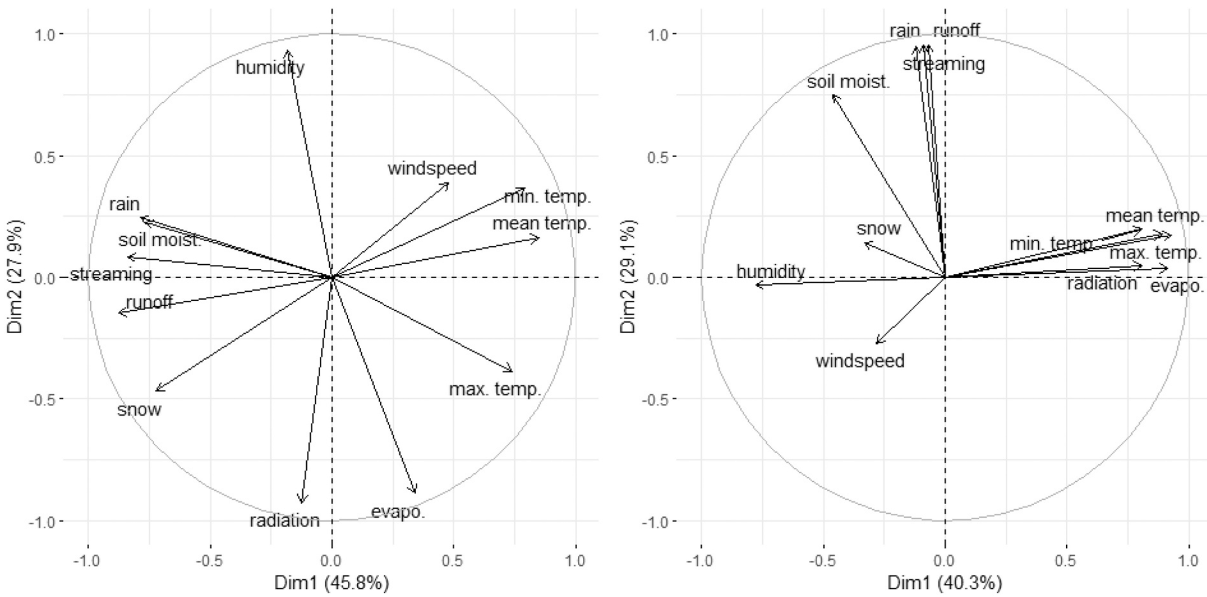

Fig. 2. Correlation circle of Principal Components Analysis (PCA) on the weather variables for apple orchard (left) and vineyards (right). "snow": Solid precipitation (daily accumulation 06–06 UTC) in mm, "rain": Liquid precipitation (daily accumulation 06–06 UTC) in mm, "streaming": Effective rainfall (daily accumulation) in mm, "mean temp.": Temperature (daily average) in °C, "min. Temp": Minimum temperature of the 24 hourly temperatures in °C, "max. Temp": Maximum temperature of the 24 hourly temperatures in °C, "windspeed": Wind (daily average) at 10 m in m.s-1, "radiation": Visible radiation (daily accumulation) in J.m-2, "evapo.": Potential evapotranspiration (Penman-Monteith formula) in mm, "humidity": Relative humidity (daily average) in %., "soil moist.": Soil moisture index (daily average 06–06 UTC) in %., "runoff": Runoff (daily accumulation 06–06 UTC) in mm.

residuals were obtained with the effects (Fox et al., 2016), visreg (Breheny et al., 2020) and ggplot2 (Wickham et al., 2016) R packages.

All analyses were also performed with landscape variables calculated at a 1000 m radius buffer to assess the robustness of the results. As results were very similar, considering both significant factors and the direction of effects (Fig. S5), we only present results for the 2000 m buffer in the main text.

3. Results

Fungicides were sprayed in all orchards, except for one in 2017, and vineyards. Insecticides were also sprayed in all orchards but only in 54% to 68% of vineyards, depending on the year. The average TFI for fungicides (TFI_f) was approximately four times greater than the average TFI for insecticides (TFI_i) for both crops, as was the diversity of active ingredients (Table 2). This diversity of active ingredients increased with

Table 2
Mean pesticide use in apple orchards and vineyards: number of sprayed cropping systems among all cropping systems, fungicide (TFI_f) and insecticide (TFI_i) treatment frequency indices, the first day of spraying (First spray) and active ingredient diversity (Diversity). Values represent mean ± SD (standard deviation) calculated only on sprayed cropping systems per year.

		Fungicide				Insecticide			
Crop	Year	Sprayed/total cropping systems	TFI_f	First spray	Diversity	Sprayed/total cropping systems	TFI_i	First spray	Diversity
Apple orchard	2014	19/19	20.88 ± 10.65	67.53 ± 19.52	9.32 ± 3.33	19/19	5.76 ± 2.02	80.37 ± 7.91	6.32 ± 2.16
	2015	21/21	20.38 ± 9.49	73.29 ± 24.69	9.71 ± 3.04	21/21	6.53 ± 2.20	85.29 ± 10.76	6.95 ± 2.60
	2016	33/33	18.67 ± 8.49	68.94 ± 18.77	10.33 ± 2.94	33/33	6.28 ± 2.07	80.33 ± 7.51	6.85 ± 2.48
	2017	59/60	18.77 ± 8.10	62.00 ± 14.91	11.75 ± 3.76	59/60	6.01 ± 1.99	73.98 ± 8.59	6.58 ± 2.20
	2018	57/57	17.86 ± 7.73	66.46 ± 18.91	11.98 ± 4.15	57/57	5.31 ± 1.08	85.95 ± 9.75	5.75 ± 2.05
	2019	53/53	19.02 ± 8.41	62.13 ± 13.59	12.75 ± 4.60	53/53	5.26 ± 1.78	73.83 ± 8.43	5.81 ± 1.82
Vineyard	2014	75/75	8.46 ± 3.13	120.23 ± 12.15	12.17 ± 4.90	51/75	1.76 ± 0.81	167.96 ± 21.37	2.10 ± 1.19
	2015	80/80	7.69 ± 3.05	125.16 ± 8.05	11.45 ± 4.83	53/80	1.71 ± 0.90	171.04 ± 15.77	1.98 ± 1.03
	2016	93/93	9.11 ± 3.76	121.41 ± 13.91	13.94 ± 5.35	58/93	1.61 ± 0.89	170.95 ± 20.03	2.14 ± 1.16
	2017	131/131	7.56 ± 3.06	120.63 ± 11.31	12.34 ± 4.95	80/131	1.73 ± 0.96	165.5 ± 19.49	2.22 ± 1.24
	2018	125/125	9.01 ± 2.87	119.94 ± 7.32	14.26 ± 4.43	73/125	1.94 ± 1.29	164.42 ± 15.89	2.25 ± 1.27
	2019	74/74	6.62 ± 3.06	121.81 ± 12.77	11.82 ± 4.61	40/74	1.88 ± 1.12	165.5 ± 33.92	1.98 ± 1.17

the TFI in all models (Fig. 3). As expected, TFI_i in orchard cropping systems and TFI_f in vineyard cropping systems significantly decreased with the number of years since the cropping systems entered the DEPHY network. In contrast, the diversity of fungicide active ingredients in orchards and vineyards increased with the number of years in the network (Fig. 3).

3.1. Local field area effects

Pesticide use in orchards did not depend on the local field area (Fig. 3). In contrast, in vineyards, fungicide spraying started earlier, and insecticide spraying probability increased in larger fields (Figs. 3 and 4). An increase in vineyard field area of 1.5 ha was associated with a one day earlier application of the first fungicide spray (Fig. 4A). Similarly, an increase in vineyard field area from 2 to 12 ha was associated with an

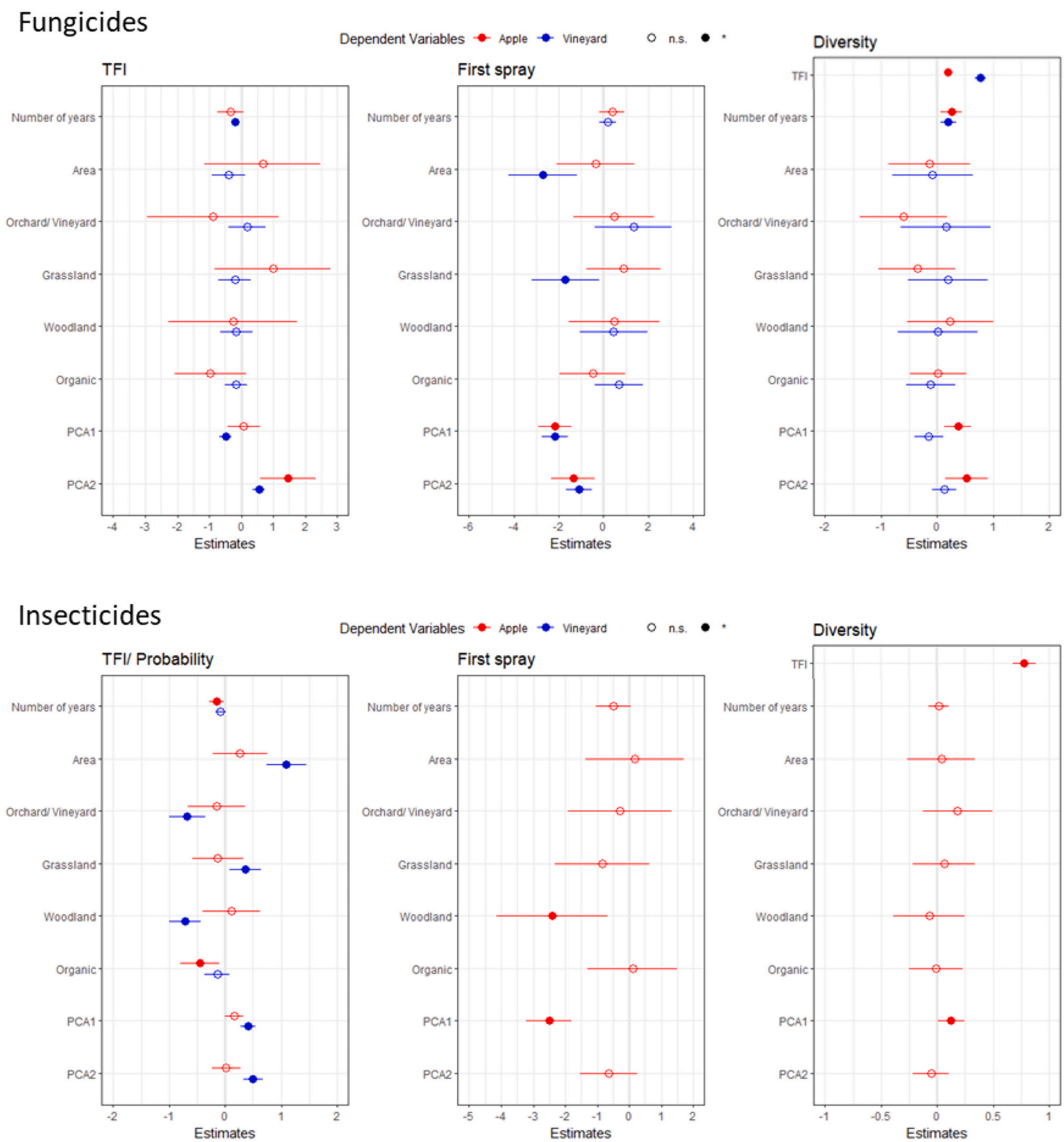

Fig. 3. Estimates of the effects of local, landscape and weather factors on pesticide use (fungicide in the first line and insecticide in the second line) in apple orchards and vineyards (fungicide or insecticide TFI and spraying probability (TFI/Spraying probability, left panel), the first day of spraying (First spray, middle panel) and active ingredient diversity (Diversity, right panel)). Full dots indicate a significant effect ($p < 0.05$). Number of years: number of years since joining the DEPHY network; Area: local field area; Organic: organic orchards among orchards (Apple model) or organic vineyards among vineyards (Vineyard model), see text for variable calculation; PC1 and PC2, respectively refer to coordinates of the study fields on the principal components 1 and 2 of the PCA on the weather variables.

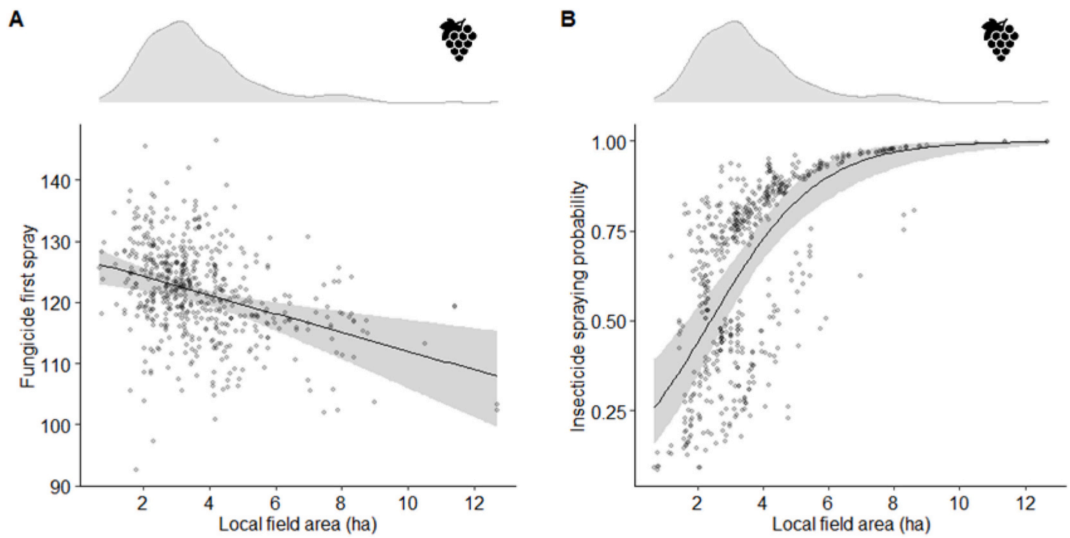

Fig. 4. Relationships between the first fungicide spraying day in vineyards (A) or the insecticide spraying probability in vineyards (B) and the local field area. The density plot above the relation plot represents the density of the local field area. The midline represents the model's estimate, and the grey area is the standard error. Points show the partial residuals, i.e. the residuals left after accounting for the effects of all other independent variables in the model. Plots were obtained with the 'effects' (Fox et al., 2016), 'visreg' (Breheny et al., 2020) and 'ggplot2' (Wickham et al., 2016) R packages.

increase in insecticide spraying probability from 30% to almost 95% (Fig. 4B).

3.2. Landscape composition effects

Landscape effects were more often significant for insecticides than fungicides and concerned one or more land uses, depending on the type of response variable.

3.2.1. Fungicide use

None of the landscape variables significantly affected any fungicide use variables in apple orchards (Fig. 3). In vineyards, spraying began approximately one day earlier when grassland proportion in the landscape increased by 2% (Figs. 3 and 5A).

3.2.2. Insecticide use

Both the TFI_i (for orchards), spraying probability (for vineyards) and the timing of spraying were affected by landscape variables, while insecticide diversity was not. In apple orchards, the TFI_i decreased when a higher proportion of orchard area was under organic farming, and spraying began earlier in landscapes with a higher proportion of woodland (Fig. 3). However, these effects were of moderate magnitude: The TFI_i decreased by approximately two units when organic farming increased from 0% to 80%, a value seldom found in the data (Fig. 5B); spraying began approximately one week earlier when the proportion of woodland in the landscape increased from 0% to 50% (Fig. 5C). In vineyards, the spraying probability decreased with increasing proportions of vineyards and woodlands in the landscape and increased with grasslands (Fig. 5D-F). These three effects were nonlinear. The negative effects of vineyards and woodlands, for which spraying probability decreased from 0.87 to 0.23 and 0.84 to 0.22 when their respective proportions increased from 5% to 75% and from 5% to 50% (Fig. 5D and F), were the strongest. Finally, spraying probability increased from 0.62 to 0.88 when grassland proportion increased from 5% to 35% (Fig. 5E).

3.3. Effects of the weather context

3.3.1. Fungicide use

Humidity and temperature were the two main drivers of fungicide use in apple orchards and vineyards (Fig. 3). In orchards, the TFI increased under humid weathers (positive PC2 coordinates, Fig. 2) and spraying was delayed due to cold temperatures (negative PC1 coordinates). Since temperature and rainfall were negatively correlated, spraying was delayed in rainy weathers (negative PC1 coordinates). Fungicide active ingredient diversity in apple orchards increased with humidity (positive PC2 coordinates) and warm temperatures (positive PC1 coordinates). Unsurprisingly, the TFI increased in humid, relatively cold (negative PC1 coordinates) and rainy (positive PC2 coordinates) weathers in vineyards. The first spraying was delayed in cold and humid weathers but applied ahead of schedule with increased rainfall.

3.3.2. Insecticide use

The TFI was not significantly affected by weather variables in apple orchards, and the first spraying was earlier in warmer and less rainy weathers (positive PC1 coordinates, Fig. 3). In vineyards, treatment probability increased with temperature (positive PC1 coordinates) and rainfall (positive PC2 coordinates, Fig. 3).

The same results were observed when the landscape within a 1000 m radius buffer was used instead of a 2000 m buffer. The only difference was for the weather synthetic variable PC1, which significantly affected the TFI for insecticide in apple orchards (Fig. S5).

4. Discussion

The landscape context significantly affected the frequency and the timing of pesticide use in apple orchards and vineyards. However, detected effects were not necessarily in the expected direction, and fungicide use was less affected by landscape composition than insecticide use. The main results of our study were, first, that overall pesticide use was not affected or decreased with increasing proportion of the host crop. Second, pesticide use in orchards was not affected by the share of organic orchards in the landscape and insecticide spraying probability in vineyards even decreased with the landscape share of organic vineyards. Third, we found little evidence for reduced pesticide use in landscapes harbouring more semi-natural habitats, while considering types of semi-natural habitats independently revealed that the probability of spraying insecticide in vineyards did decrease with the proportion of woodlands but increased with the proportion of grasslands in the landscape. Finally, insecticide spraying began earlier in orchards located in landscapes with a higher proportion of woodland and fungicide spraying began earlier in vineyards surrounded by a higher proportion of grassland.

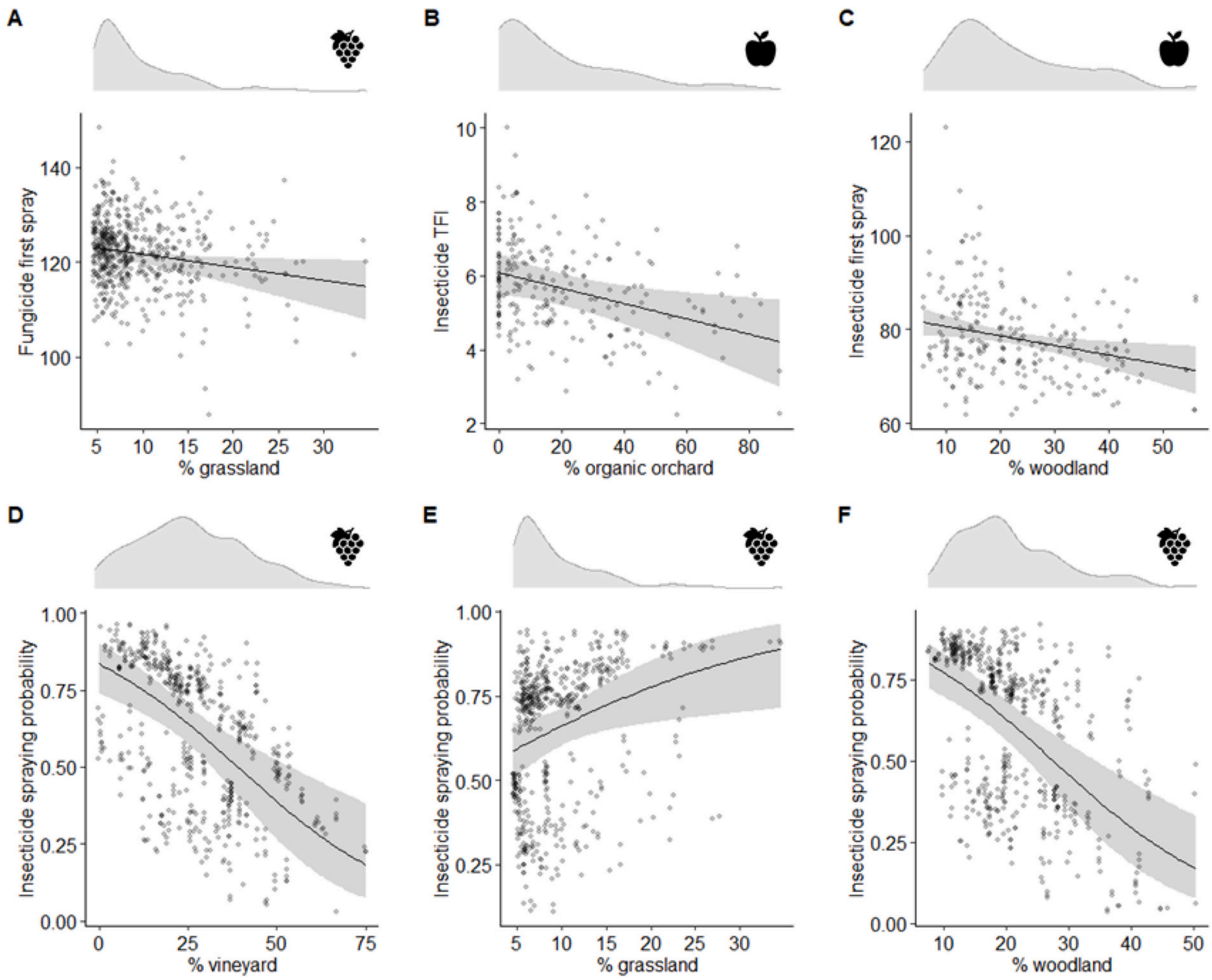

Fig. 5. Relationships between the first fungicide spraying day in vineyards and the proportion of grasslands in the landscape (A), insecticide TFI in apple and the proportion of organic orchards among orchards in the landscape (B), insecticide first spray and the proportion of woodlands in the landscape (C), insecticide spraying probability in vineyards and the proportion of vineyard in the landscape (D), the proportion of grasslands in the landscape (E), the proportion of woodlands in the landscape (F). The density plot above the relation plot represents the density of the landscape variable. The midline represents estimates of the models, and the grey area is the standard error. Points show the partial residuals, i.e. the residuals left after accounting for the effects of all other independent variables in the model. Plots were obtained with the 'effects' (Fox et al., 2016), 'visreg' (Breheny et al., 2020) and 'ggplot2' (Wickham et al., 2016) R packages.

These results contradict our assumption that pesticide use would increase with host crop area in the landscape because of higher pest load. A positive relationship between host crop area and pest load is expected for perennial crops. In these crops, pest populations exhibit low variation of local population abundance related to concentration/dilution effects associated with between-year variation in crop area (Delaune et al., 2021). Host crops can serve as permanent pest reservoirs, especially for specialist pests such as the codling moth or grapevine moth that overwinter within the field. Indeed, positive relationships were detected in perennial crops for the olive fly, the olive moth, but not the grapevine moth (Paredes et al., 2022). The results that (i) fungicide use did not significantly depend on the amount of host crop in the landscape, (ii) that insecticide spraying probability decreased in vineyards with the amount of vineyard in the landscape, while (iii) insecticide TFI in orchards was not affected by the proportion of orchards in the landscape were thus unexpected. One possible explanation could be the impacts of pesticide treatments at the landscape scale affecting pest population dynamics. While Martínez-Sastre et al. (2021) found a positive relationship between codling moth abundance in cider apple orchards and landscape area of these low intensive orchards, Ricci et al. (2009) found a negative relationship between codling moth abundance in high intensive dessert apple orchards and their landscape area, suggesting that landscape-level insecticide load reduced inoculum. Since vine is a high-value crop, a similar pattern may occur in French vineyards.

The insecticide treatment frequency in apple orchards decreased with the proportion of orchards under organic farming in the landscape, thus suggesting that landscape level farming practices may shape population dynamics and local pesticide use. This result possibly indicates a positive outcome of organic farming concerning the balance between the beneficial effect on pest control and pest loads. Organic apple growers in France use efficient pest control measures other than insecticides (e.g., pest exclusion nets or biocontrol products) and rely more on efficient prophylactic methods (e.g., early destruction of unharvested apples) than conventional growers (Simon et al., 2011). Organic orchards may thus not be a source of inoculum. Organic apple orchards also host more natural enemies (Samnegård et al., 2019) and higher levels of natural pest control (Monteiro et al., 2013). As previously observed in vineyards (Muneret et al., 2018, 2019), a high proportion of orchards under organic farming in the landscape may contribute to the control of insect pests in apple orchards. Our analyses, however, were limited by the need to estimate the landscape organic share for 54% of the apple orchard cropping systems over the six study years. Further investigations should bring more robust answers as organic farming expands and more data on organic farming area become available.

We initially expected similar effects of the proportion of grasslands and woodlands in the landscape on local pesticide use. However, grasslands and woodlands affected pesticide use differently, even though both host natural enemies of insect pests (Sarthou et al., 2014). Woody semi-natural elements, in particular, are supposed to be sources of natural enemies for orchards and vineyards due to their structural similarity with these crops and the fact that they host very similar canopy-dwelling arthropods that can directly feed on pests in perennial crops (Lefebvre et al., 2016; Thomson and Hoffmann, 2013). Consistent with this expected beneficial effect on woody habitats, we found that the probability of spraying insecticide in vineyards decreased with the proportion of woodlands. However, this beneficial effect was not found in orchards, suggesting that such effect highly depends on the pest species under study and their characteristics. Woody areas such as hedgerows have been found to favour apple tree colonisation by aphids (Simon et al., 2011) and reinforce mutualistic interactions with ants that protect aphids against predators and thus accelerate the development of the aphid colonies (Albert et al., 2017). This direct effect of woody areas on the timing of aphid infestation in orchards may account for earlier insecticide use in this system.

Contrary to our expectations, high proportions of grasslands in the landscape were not associated with lower use of pesticide in both systems. In orchards, pesticide use remained unaffected by variation in the proportion of grasslands in the landscape. In contrast, in vineyards located in landscapes with high proportions of grasslands, insecticide spraying probability increased, and fungicide spraying occurred earlier. These results suggest that grasslands may have supported host plants for pests or pathogens or that these open habitats may represent a favourable environment for dispersal and development. The polyphagous grape berry moth may have benefited from grasslands if host plants such as *Daphne gnidium*, *Ligustrum vulgaris*, *Rubus* sp. occupied these habitats (Thiéry, 2008). *Scaphoideus titanus* and downy and powdery mildew specialised in the *Vitis* genus might also have benefitted from wild *Vitis* plants in abandoned vineyards or similar habitats that may have been classified as grasslands (Kwame Adrakey et al., 2022). However, the spatio-temporal distribution of host plants for these species remains largely unexplored, and further investigations are needed to understand these correlations precisely.

Weather is known to have strong effects on pest dynamics, particularly their between year variability (Paredes et al., 2022). In agreement with our hypothesis, weather context was a strong driver of pesticide use: humidity and temperature increased fungicide application, likely promoting fungi proliferation (Combina et al., 2005). As expected, higher temperatures led to increased insecticide use because of the arthropod pests' higher fitness and faster development under warmer weather conditions (Boivin et al., 2005; Deutsch et al., 2018). Our results highlight the importance of considering these variables when investigating landscape effects that may be masked or overestimated without this joint consideration. Residual variations of our models were homogeneous among the French regions (Fig. S6), suggesting that weather accounted for most geographical differences and did not covary with singular regional landscape features.

In addition to landscape and weather effects, local field characteristics also affected pesticide use. First, and as expected, the number of years since the focal field was in the DEPHY network resulted in a decrease in the TFI, which is in line with the network's objective (Fouillet et al., 2022). The number of years in the DEPHY network mainly resulted in a reduction of insecticide use in apple orchards and a reduction of fungicide in vineyards. This latter reduction was mainly achieved by adjusting treatment doses in vineyards (Fouillet et al., 2022). Interestingly, we found that changes in fungicide use were accompanied by a diversification of the treatments, which could result from resistance management advice (REX, 2013). Second, increasing local field size consistently increased pesticide use in vineyards as larger fields were submitted to earlier fungicide first spray and had a higher probability of being sprayed with insecticides. These results suggest that larger field sizes allow higher and earlier pest immigration, as recently reported in cotton fields (Gagic et al., 2021). Reducing the use of pesticides by reducing the size of fields could represent a real cost saving opportunity for producers, even if it entails labour and transport costs (Gónzalez et al., 2007; Latruffe and Piet, 2014). This last result also highlights that other aspects of landscape structure, such as the spatial configuration of habitats, might be important to consider when investigating landscape effects on pesticide use.

5. Conclusion

Reducing pesticides in perennial crops such as orchards and vineyards is a major issue considering the high frequency of use in those crops and the negative impact on the environment that it entails. Our results revealed landscape composition effects on insecticide use in vineyards and apple orchards, and that the drivers of fungicide use were mainly related to the weather context. Notably, the results indicate that increasing landscape heterogeneity through organic farming, reduced field size and woodlands could attenuate insecticide use in perennial crops. Combining such landscape-scale management options with other tools such as decision-support systems or integrated pest management strategies should contribute to limit the use of pesticides in agricultural landscapes.

Declaration of Competing Interest

All research was conducted in accordance with applicable ethical guidelines. All authors approve its publication in your journal. We also declare that there are no conflicts of interest.

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.2022.103553.

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