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RESEARCH ARTICLE

Apple pest and pathogen reduction in landscapes with large patch size and small area of orchards: a national-scale analysis

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Abstract
Context The composition and configuration of habitats in agricultural landscapes may determine crop damage resulting from pests or pathogens either by directly affecting their population dynamics or through indirect effects on their natural enemies.
Objectives The aim of this study was to assess the impact of landscape composition and configuration on the occurrence and damage caused by the codling moth and apple scab in apple orchards.
Methods Using monitoring data at the French national scale, we examined how the proportion of landscape area grown with orchards, the mean patch area of orchards, the share of organic orchards and the proportion of woodlands and grasslands affected the occurrence and damage of these two pests from 2015 to 2019 in approximately sixty apple orchards each year.
Results Landscapes with a higher proportion of orchards supported a higher occurrence of apple scab and earlier colonisation of codling moths. In addition, we found that codling moth damage decreased with increasing orchard patch area in the landscape. The proportion of seminatural habitats or organic farming in the landscape never significantly explained pest occurrence or damage.
Conclusions Our results clearly highlight the importance of considering the amount and spatial arrangement of the pests' and pathogens' host crops to understand their infestation levels. Our study calls for the territorial management of orchard distribution to limit pesticide use in apple orchards.

Keywords Agroecology · *Cydia pomonella* · Landscape agronomy · *Malus domestica* · *Venturia inaequalis*

Introduction

Understanding how environmental conditions affect pest populations in agricultural landscapes is the cornerstone of agroecological crop protection limiting the use of pesticides. While several environmental factors operating at multiple scales affect pest population dynamics, landscape structure and weather conditions are among the important factors (Zhang et al. 2018; Courson et al. 2022). Several aspects of landscape structure belonging to the composition or

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configuration of agricultural landscapes can directly and indirectly impact the abundance of insect pests and pathogens in crops (Plantegenest et al. 2007; Rusch et al. 2016; Martin et al. 2019; Delaune et al. 2021). First, increasing host crop area can directly enhance the population of pests or pathogens by providing them with more resources and breeding habitats or facilitating dispersal (Landis et al. 2000; Tscharntke and Brandl 2004; Plantegenest et al. 2007; Ratnadass et al. 2012). This facilitation can result from both the quantity of host crops and the increase in the size of the crop patches, creating more homogeneous landscapes with a high degree of crop connectivity (Martin et al. 2019). In addition, farming practices within crop mosaics affect pest and pathogen habitat quality (Rusch et al. 2010; Vasseur et al. 2013; Marrec et al. 2022). Organic farming, for instance, has been shown to host more biodiversity, including pests and natural enemies, in many crops (Muneret et al. 2018a; Samnegård et al. 2019). At the landscape scale, organic crops could thus act as reservoirs of both pests and their natural enemies, making the outcome of an increasing share of organic crops difficult to predict. Then, homogeneous landscapes with a low proportion of fragmented seminatural habitats tend to allow for greater and earlier immigration of insect pests due to reduced top-down control delivered by natural enemies (Tscharntke and Brandl 2004; Gagic et al. 2021). Indeed, seminatural habitats, such as grasslands or forests, provide resources, breeding sites and refuges for a large diversity of natural enemies of pests (Landis et al. 2000). Decreasing their proportion or connectivity at the landscape scale can thus reduce pest control services (Rusch et al. 2010; Chaplin-Kramer et al. 2011; Veres et al. 2013; Holland et al. 2017; Duflot et al. 2022). Moreover, seminatural habitats may act as a barrier to pathogens or pests with passive dispersal, thus reducing pest or disease outbreaks (Plantegenest et al. 2007; Ratnadass et al. 2012). Despite decades of research, the relative effects of these different aspects of landscape structure on pest or pathogen infestation levels in crops remain poorly understood, as they are rarely jointly analysed.

The explicit consideration of weather conditions is rare in studies of the effect of landscape structure on pests (but see Stack Whithney et al. 2016; Lacasella et al. 2017; Courson et al. 2022), although weather is a proximal driver of pest and pathogen population dynamics (Gregory et al. 2009; Newbery et al. 2016) and can interfere with landscape effects (Karp et al. 2018). For example, increased air humidity and precipitation can promote disease infestations by supporting pathogen dispersal and spore germination (Combina et al. 2005). In addition, increased temperature can promote insect pest infestations by increasing their development rate and possibly the number of generations of multivoltine species (Gilbert and Raworth 1996; Deutsch et al. 2018). The few studies that have investigated the combined effects of landscape structure and weather conditions on pests (Gutiérrez Illán et al. 2020; Courson et al. 2022) confirmed that both aspects can affect pest dynamics, and more studies integrating these two dimensions are needed to better manage pests.

Apple orchards are the dominant fruit crops in metropolitan France (46% of orchard area, in 2020, Agreste 2021). Apples are one of the most treated crops, with a treatment frequency index (TFI) of up to 35 in 2017 compared to 7 on wheat or 18 on potato that same year (Agreste 2020). In France, most fungicide treatments target the apple scab pathogen, and most insecticide treatments target the codling moth (Sauphanor et al. 2009; Graph'AGRI 2022, Agreste. agriculture.gouv.fr). Apple scab is caused by the fungus *Venturia inaequalis* (Cooke) G. Wint, which is specific to apple trees (Bowen et al. 2011). It is the most economically damaging disease in apple orchards (MacHardy et al. 2001). Decision support tools predicting the risk of apple scab infection are used by technical advisers and farmers to trigger fungicide treatments. They are mainly based on weather variables, such as temperature, humidity and rainfall (Rossi et al. 2001). The effect of landscape structure on apple scab infestations remains poorly documented, although spores may disperse among distant orchards (Aylor 1999).

The codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), is the most damaging insect pest of pome fruits, including apples and pears, in many temperate regions. Adults emerge in spring from overwintering larvae. Free neonate larvae penetrate into fruits, causing damage. At the end of their development, the larvae leave the fruit and, depending on temperature and photoperiod conditions, either pupate to produce the next generation or enter diapause (Riedl and Croft 1978). Models predicting codling moth phenology are used to trigger the first insecticide treatments that target first generation eggs and neonate larvae. These models are mainly based on temperature (Riedl et al. 1976; Welch et al. 1978; Boivin et al. 2005), with a minimum temperature required for codling moth development of approximately 10 °C (Sæthre and Hofsvang 2002; Gharehkhani 2010). In addition, as for apple scab, weather conditions can impact codling moth population dynamics. In general, rainfall is unfavourable (Zhao et al. 2015) because it increases larval mortality (Hagley 1972) and decreases oviposition (Hagley 1976). The landscape proportion of host crops was shown to affect codling moth abundance but with opposite directions of effect for intensive apple orchards (Ricci et al. 2009) and extensive cider orchards (Martínez-Sastre et al. 2021). The predation of sentinel codling moth eggs and larval parasitism were lower in apple orchards surrounded by a large area of conventional orchards (Maalouly et al. 2013; Monteiro et al. 2013). In addition, seminatural habitats tend to increase codling moth predation by natural enemies (Heath and Long 2019).

Using national-scale data, we aimed to assess the impact of landscape structure on the infestation levels of apple orchards by the apple scab and the codling moth and associated fruit damage, while controlling for weather conditions. We first hypothesised that increased overall orchard area, orchard patch size or orchard organic farming in the landscape would promote apple scab and codling moth infestations due to a large amount of crop resources. In addition, we expected that increasing the amount of seminatural habitats would reduce the abundance of apple scab and codling moths due to the barrier effect of woodlands or hedgerows and the beneficial effects of seminatural habitats on pests' natural enemies.

Materials and methods

Data collection

Pest data were retrieved from the Epiphyt database, an epidemiological surveillance database held by the French Ministry of Agriculture (in French, https://agriculture.gouv.fr/epidemiosurveillance-le-systeme-dinformation-epiphyt). Apple scab and codling moths were monitored from 2015 to 2019 according to standardised protocols based on observations of pests or damage to different plant organs from one to several times each year (Table S1). Data are available at the plot level. The observation plots are not precisely located, but their municipality is known. For each of the two main pests, i.e., apple scab and the codling moth, data are available from two observation protocols, each corresponding to a different period of the pest's life cycle. Plots were distributed all over France, except for the plots monitored for adult codling moths, which were located only in western France (Fig. 1).

Apple scab records

The first two variables that we retrieved from the database are the presence/absence of shoot damage in the plot and the date of first occurrence of shoot damage expressed as the number of days from the 1st of January. The data came from a single protocol based on the visual evaluation (presence or absence of damage) of 500 shoots per orchard at each observation date from April to June. On average, 113 ± 34 (standard deviation, SD) plots were monitored each year in a total of 169 municipalities. The date of first occurrence was only recorded when damage was present, which was the case for 40 ± 15 (SD) plots each year on average (Table 1). These two variables are associated with early pest abundance. The third retrieved variable was the presence/absence of fruit damage in the plot in June. These data were based on the visual assessment (presence or absence of damage) of 500 fruits (20 fruits per tree on 25 trees) in June (end of primary infection). On average, 77 ± 20 (SD) plots were monitored each year in a total of 150 municipalities (Table 1).

Codling moth records

The first retrieved variable was the date of first adult moth occurrence expressed as the number of days from the 1st of January each year. These data came from adult codling moth trapping using pheromones from April to October in a total of 60 municipalities. The date of first occurrence was only recorded for plots in which codling moth adults were captured, i.e., on average 32 ± 10 (SD) plots per year (Table 1). The second retrieved variable was the presence/absence of fruit damage by codling moth larvae in June when first-generation larvae were fully developed. These data came from the visual inspection of

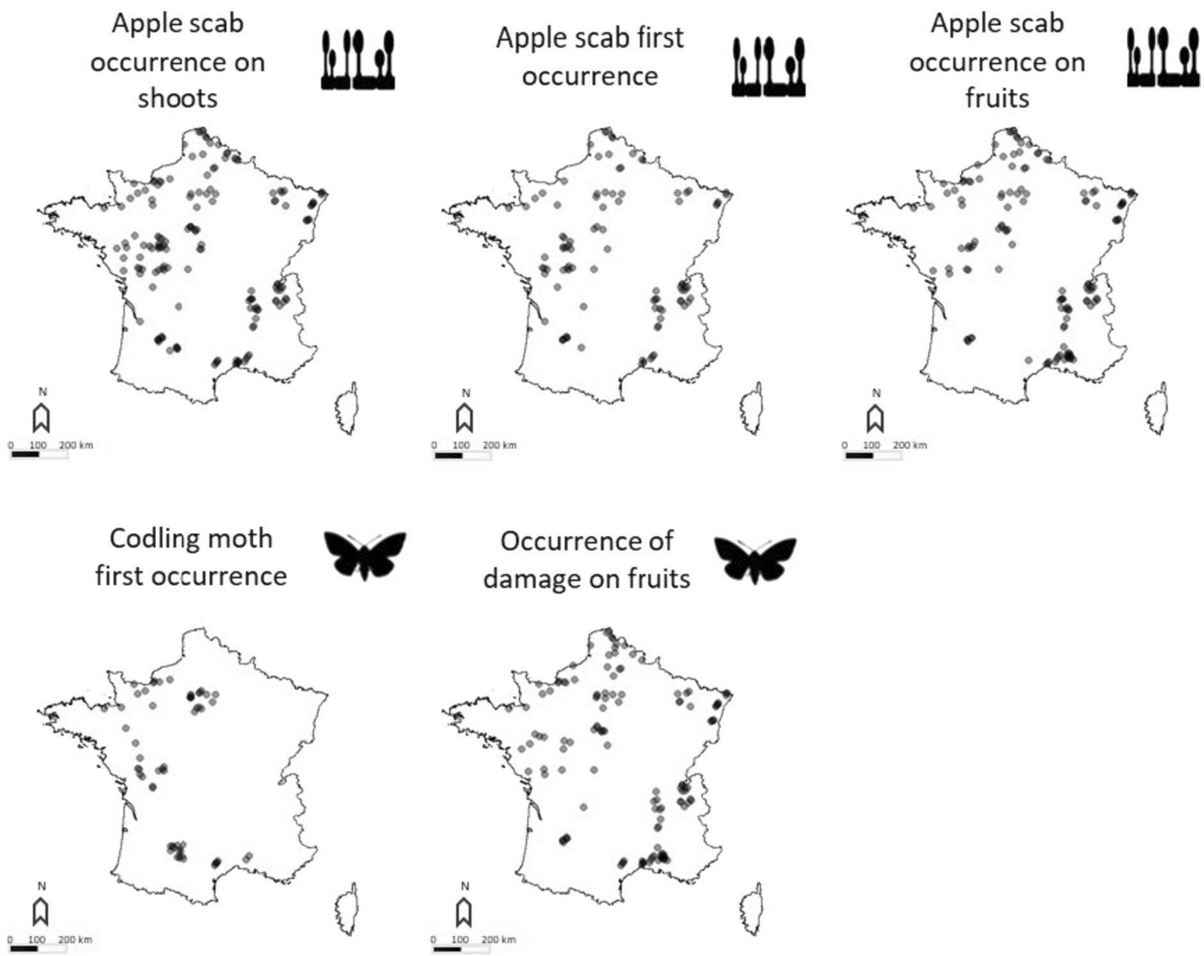

Fig. 1 Locations of municipalities of monitored plots in France. Locations are provided for each observation protocol independently for the apple scab and the codling moth

Table 1 Structure of the data retrieved from the Epiphyt database: number of plots and corresponding municipalities (between parentheses) each year

Year	Apple scab			Codling moth	
	Occurrence on shoots	First occurrence on shoots	Occurrence on fruits	First adult occurrence	Occurrence of damaged fruits
2015	165 (88)	63 (58)	50 (44)	32 (24)	56 (48)
2016	61 (56)	26 (25)	73 (57)	13 (13)	70 (49)
2017	121 (95)	38 (36)	104 (80)	37 (31)	107 (78)
2018	121 (92)	49 (46)	95 (76)	35 (28)	95 (72)
2019	95 (62)	23 (22)	64 (45)	41 (30)	74 (45)

500 fruits per orchard (20 fruits per tree on 25 trees). Data were available for a total of 151 municipalities. On average, 80 ± 18 (SD) plots were monitored per year (Table 1).

Weather data

To describe the weather context of each plot each year, we used the interpolated meteorological dataset of Météo-France (Safran). This dataset contains estimated weather information for France based on 8 km × 8 km grid cells. Many weather variables are available, among which we retrieved daily relative humidity, rainfall and temperature (average and minimum values). For each year from 2015 to 2019, to associate the pest data with weather variables, the centroid of the municipality in which each Epiphyt plot was located was associated with the corresponding grid cell.

Weather variables used in statistical models seeking to explain pest occurrence were selected based on their expected effect on the pest life cycle. For both pests, the following variables were thus selected: proportion of days with rainfall, average relative humidity and average temperature. For data on pest or damage occurrence, these weather variables were calculated every year, starting from the first day when the average temperature was 10 °C until the last day of the last month of the corresponding protocol. For data on the day of first occurrence, the weather variables were calculated from the first day with a mean temperature of 10 °C to the day of occurrence. Temperature and rainfall were slightly correlated (R = 0.54, Figure S1).

Depending on the year, the proportion of rainy days varied from 0.44 to 0.60, with an average humidity from 70.4 to 79% and an average temperature from 8.9 to 13.1 °C in municipalities where apple scab was observed (supplementary material, Table S2). The proportion of rainy days varied from 0.40 to 0.63, with an average humidity from 67.8 to 80.9% and an average temperature from 8.4 to 13.4 °C in municipalities in which codling moths were observed (Table S2).

Landscape context

The landscape was characterised at the municipality level. The average area of a municipality was 2776 ± 3242 ha (mean ± SD). Maps were created by combining; (i) the French parcel identification system (RPG, a geographic database for registering crop in farmers' parcels under the Common Agricultural Policy), which provided information on the type of crop or grassland (temporary or permanent) in each parcel from 2015 to 2019; and (ii) BD TOPO® (v2 2017 IGN, Institut Géographique National), which provided spatial information on woodland, orchards and vineyards. Land cover information from these two databases was combined by intersecting their spatial elements (polygons) using the R package *alm* (Allart et al. 2021). In situations where the two databases provided different land covers for a single polygon, priority was given to the RPG, which land cover is filled in every year (see for detail, Allart et al. 2021). Adjacent polygons with similar land covers were then merged. Small remaining orchard polygons of less than 0.01 ha were considered as artefacts of the combination process and were erased. Then, the proportion of area covered with orchards, woodland and grassland as well as orchard fragmentation (i.e., here, average area of an orchard patch) were calculated within each municipality (Table S2). Note that information was not available about the crops grown in orchards. However, data for districts (French "département", administrative entity grouping several municipalities) in which the monitored plots were located indicate that apple orchards were generally the majority, representing (mean ± SD) 44 ± 11% of orchards (Figure S2).

To determine the area of orchards under organic management in each municipality, we used the 2015–2019 data provided by the French Agency for the Development and Promotion of Organic Agriculture (https://www.agencebio.org/). When fewer than three farms were organic in a municipality, only the number of farms, and not area, was available because of statistical secrecy. There were organic orchards in 26 to 70% of the municipalities with study plots, depending on the year and retrieved pest variable (Table S3). Municipalities with only one or two organic farms represented 35 to 74% of the municipalities with organic orchards, depending on the year and retrieved variable (Table S3). We extrapolated the area of orchards under organic management for these municipalities. For this purpose, we used data available at the district level. For each year, we estimated the area of organic orchards per farm by dividing the area of organic orchards in each district by the number of organic farms in that district. Then, we used this area to estimate the area of organic orchards at the municipality level taking into account the number (1 or 2) of organic farms (see also Etienne et al. 2023). The results of this procedure, which was evaluated on municipalities with more than three organic farms, showed that, on average, the estimated areas under organic farming were aligned with the actual areas. However, there was some variation in the results among municipalities (Figure S3).

For the municipalities in which apple scab was monitored, the proportion of area grown with orchards was low, with mean values of 3.2 to 7.8% (mean orchard area of 1.7 to 2.4 hectares), depending on the year. Over the course of the study, the proportion of organic orchards increased from 10.9 to 34.4% of the orchard area. The proportion of grassland ranged from 9.6 to 16.5%, and the proportion of woodland ranged from 17.0 to 26.6%. In the municipalities where the codling moth was monitored, the proportion of area grown with orchards was also low, with mean values of 2.2 to 8.1% (mean orchard area of 1.8 to 3.1 hectares). Over the course of the study, the proportion of organic orchards increased from 6.1 to 33.8% of the orchard area. The proportion of grassland ranged from 6.3 to 17.2%, and the proportion of woodland ranged from 20.4 to 36.1%. For each year and protocol, some landscape variables were significantly correlated although with low R values ($|R| < 0.2$, Figure S1). The proportion of area grown with orchards, in particular, was not significantly correlated with the mean orchard patch area ($R = -0.04$), indicating that different proportions of area grown with orchards did not correspond to particular spatial distributions of orchards (i.e., orchards clustered in large patches or distributed in numerous isolated patches). Correlations between landscape and weather variables were weak ($|R| < 0.3$, Figure S1).

Statistical analyses

Statistical analyses were conducted using Rstudio software (R version 3.6.1, R Core Team 2022). They aimed to relate pest or damage data measured at the plot level with landscape and weather variables attached to the plot's municipality. A generalised linear mixed model with a binomial distribution was used to analyse the variation in the probability of pest or damage occurrence, while a linear mixed model was used to analyse the log-transformed date of first pest occurrence. The fixed independent variables in the models described the landscape and weather contexts, and a random 'municipality' effect was included to account for the fact that there were multiple plots within the same municipality. The fixed landscape variables included the proportion of area grown with orchards, the proportion of orchard area with organic management, the proportion of area with grassland, and the proportion of area with woodland, as well as the average size of an orchard patch in the municipality. The weather variables included the proportion of days with rainfall, the average humidity, and the average temperature over the period of observation for each specific pest and observation protocol. Variance inflation factors (VIFs) were calculated for all models. The proportion of days with rainfall and humidity were found to be collinear (VIF > 2); thus, only the proportion of days with rainfall was retained in the final models. The number of records per plot was included as a fixed variable in all models to account for variability due to this factor.

Model residuals were inspected for dispersion using a quantile−quantile (QQ) plot of standardised residuals, as well as for uniformity and outliers using a plot of residual versus predicted values. Associated statistical tests were performed with the *DHARMa* R package (Hartig 2019). Moreover, ROC curve analyses (Hoo et al. 2017) were performed on binomial models to assess the fit of the models with data (*PRROC* package, Grau et al. 2015). The areas under the ROC curve (AUC) indicated good model fits, with values ranging between 0.92 and 0.94 for binomial models. Graphs for significant effects and partial residuals were obtained with the *effects* (Fox et al. 2016), *visreg* (Breheny et al. 2020) and *ggplot2* (Wickham et al. 2016) R packages. Spatial autocorrelation was explored on residuals for each year using variograms (*variog* function *geoR* package, Diggle and Ribeiro 2007) and no spatial autocorrelation was detected. Moreover, standardised residuals were plotted against the region in which the municipality was located and the study year to detect potential unaccounted-for temporal or spatial effects. Residuals did not depend on the region and appeared to depend on the year only for the model analysing the first codling moth occurrence (Figure S4). Thus, a random 'year' effect was added in that model. Results were unchanged, and residuals did not depend on the year anymore. Results of this specific model are presented in Figure S6.

Results

The occurrence of scab on shoots was, on average, higher than that on fruits, but occurrence frequencies were highly variable between and within years (as shown by a large standard deviation). The lowest scab occurrence was in 2019 (25% on shoots and 17% on fruits), and the highest occurrence was in 2015 on shoots (up to 60%) and 2018 on fruits (up to 39%) (Table 2). The day of first apple scab occurrence on shoots did not vary much between years (between the 138th and 142nd day on average), except for the year 2016 when it was approximately ten days later. The day of first moth occurrence was more variable than the day of first apple scab occurrence, ranging from Day 140 in 2016 and 2017 to Day 155 in 2019. The occurrence of codling moth damage reached 43% in 2017 and was between 18 and 29% in the other years. The number of records per plot did not significantly affect the dependent variables, with the exception of apple scab occurrence on shoots, where an increase in the number of records on the plot significantly increased the probability of apple scab occurrence (Fig. 2).

Landscape effects on scab infestation were generally not significant. Only scab occurrence on shoots increased with the proportion of area grown with orchards (Fig. 2). The probability of scab occurrence on shoots increased from 0.30 to 0.83 when the proportion of area grown with orchards increased from almost 0 to 30% (Fig. 3). Landscape effects were more often significant on codling moths than on apple scab (Fig. 2). The first codling moth occurrence was earlier in landscapes supporting a higher proportion of area grown with orchards. This effect reached 25 days when the orchard proportion increased from almost 0 to 40% (Fig. 3). In addition, an increased size of orchard patches from less than 1 to 14 ha decreased the probability of damage to apples from 0.30 to 0.02 (Fig. 3).

Weather conditions did not affect apple scab or codling moth occurrences but affected their phenology. Earlier apple scab occurrence and later occurrence of adult moths were related to a yearly increase in both the proportion of days with rainfall and the average temperature (Fig. 2).

Discussion

Inconsistent effects of landscape structure on pest infestations have been previously reported, possibly due to covariables not being taken into account or variability in climatic conditions (Chaplin-Kramer et al. 2011; Karp et al. 2018). Here, we investigated how several aspects of landscape structure related to host crop and seminatural habitats surrounding orchard plots affected the two main apple pests at the French national level while taking into account weather effects. Our results clearly confirmed that weather conditions prominently affect both pests. Among landscape variables, we found that only orchard-related metrics significantly affected pest infestations, but that both composition and configuration of orchards had an effect on pests. Apple scab occurrence on shoots increased, and the first codling moth adults occurred earlier in orchard plots located in landscapes with a large proportion of area grown with orchards. Furthermore, the occurrence of codling moth damage decreased in landscapes with large orchard patches. Unexpectedly, we found no effects of seminatural habitats on pest or on damage occurrence.

We expected positive effects of the proportion of landscape area grown with orchards on infestation levels of both pests. Our results partially confirmed

Table 2 Occurrence (mean ± standard deviation) and date of first occurrence (in number of days from 1st January) according to the pest per plot each year

Year	Apple scab			Codling moth	
	Occurrence on shoots	First occurrence on shoots	Occurrence on fruits	First adult occurrence	Occurrence of damaged fruits
2015	0.60 ± 0.49	142.32 ± 12.29	0.38 ± 0.49	147.88 ± 35.67	0.29 ± 0.46
2016	0.43 ± 0.50	151.92 ± 17.02	0.29 ± 0.46	140.36 ± 14.85	0.23 ± 0.42
2017	0.31 ± 0.47	141.20 ± 22.82	0.27 ± 0.45	140.1 ± 26.30	0.43 ± 0.50
2018	0.40 ± 0.49	138.51 ± 19.13	0.39 ± 0.49	153.7 ± 24.04	0.26 ± 0.44
2019	0.24 ± 0.43	138.04 ± 17.31	0.17 ± 0.38	155.22 ± 32.08	0.18 ± 0.38

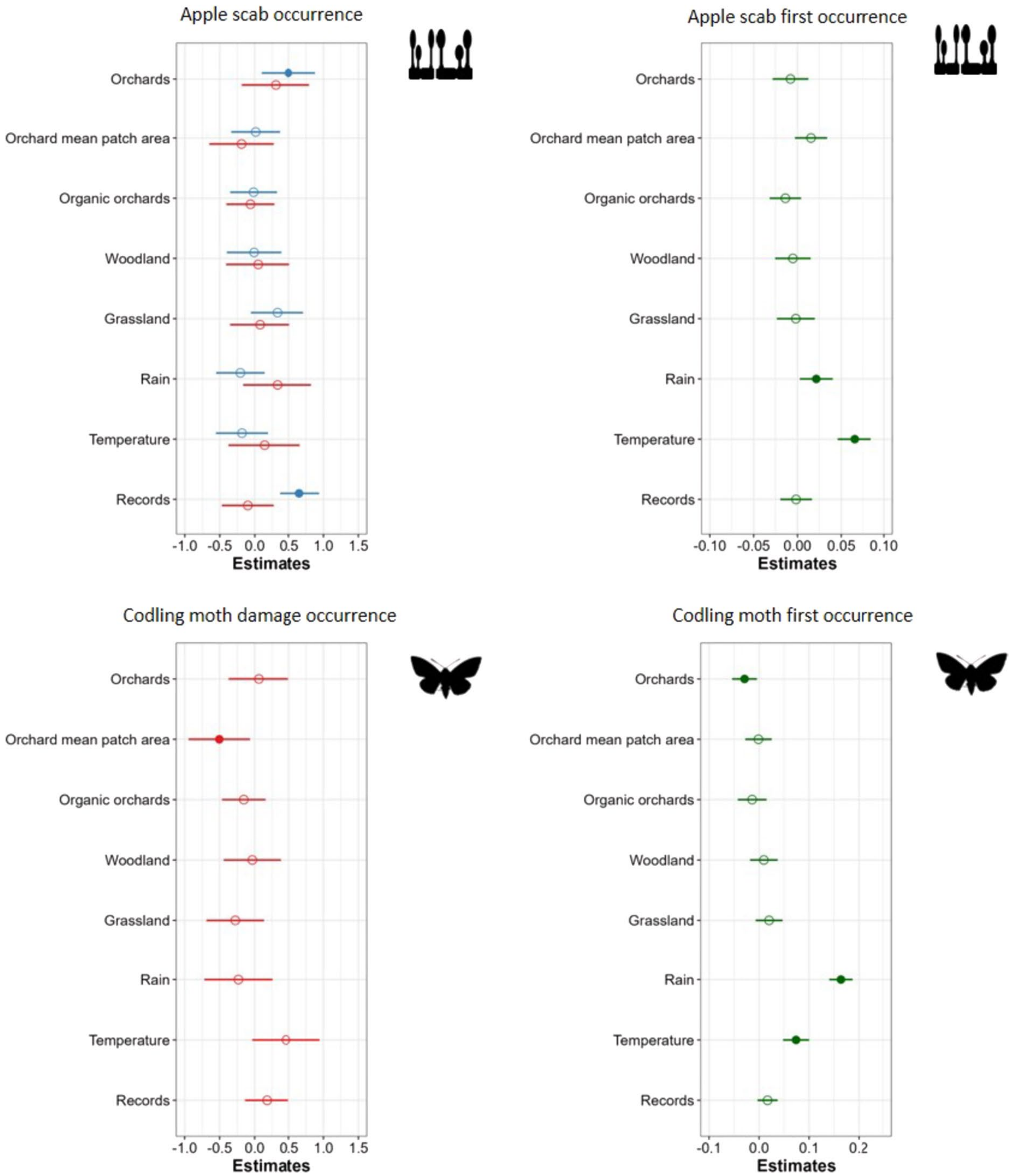

Fig. 2 Estimates of the effects of landscape and weather factors on apple scab (top panels) and codling moth (bottom panels) infestations. Upper left panel: occurrence of apple scab on shoots (blue) and on fruits (red); upper right: date of first apple scab occurrence on shoots; bottom left: occurrence of codling moth damage on fruits; bottom right: date of first adult moth occurrence. Solid dots represent a significant effect ($p<0.05$). Orchard, woodland and grassland: proportion of municipality area with orchard, woodland and grassland respectively; orchard mean patch area: mean of orchard patch areas in the municipality; organic orchards: proportion of orchard area with organic management in the municipality. Rain: proportion of days with rainfall; Temperature: mean temperature; Records: number of yearly records on the plot. All landscape variables were calculated at the municipality level

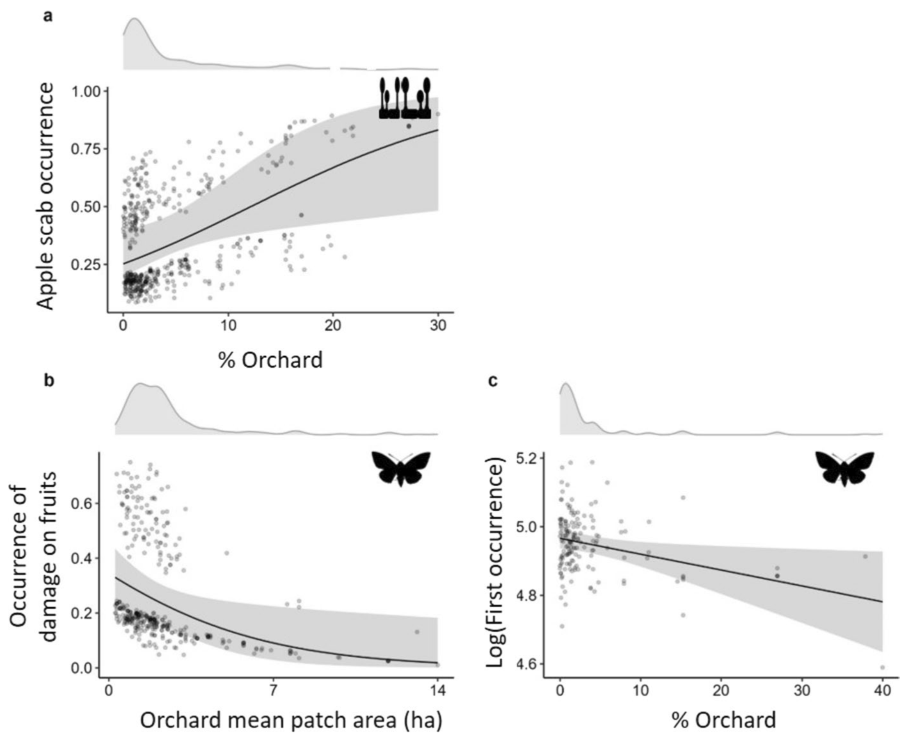

Fig. 3 Relationship between pest occurrence and landscape variables: **a** apple scab occurrence on shoots and proportion of landscape area grown with orchard, **b** codling moth damage occurrence on fruits and mean patch area of orchard in the landscape and **c** log of the date of first codling moth occurrence (in number of days) and proportion of landscape area grown with orchards. The density plot above the graph represents the density of the landscape variable. The line represents the model estimate, and the shaded area represents its standard error. The partial residuals, which represent the residuals after accounting for the average effects of all other independent variables in the model, are depicted by dot plots in each panel. Graphs were generated using the *effects*, *visreg* and *ggplot2* R packages (Fox et al. 2016; Wickham et al. 2016; Breheny et al. 2020). Landscape variables were calculated at the municipality level

this hypothesis: the first occurrence of codling moths was earlier, and the probability of apple scab occurrence on shoots was higher with an increasing proportion of landscape area grown with orchards. These two significant relationships are consistent with the extension of the resource concentration hypothesis to the landscape scale, which states that landscapes with large areas of host crops promote agricultural pest loads by increasing their amount of resources and reducing their dispersal costs (O'Rourke and Petersen 2017). They are also consistent with studies that point to the importance of host crop area in explaining pest densities, both in annual (Delaune et al. 2021) and perennial crops (Ricci et al. 2009; Martínez-Sastre et al. 2021; Paredes et al. 2022). The two variables that responded to orchard area indicate that landscape-scale orchard area affects early pest populations. In contrast, variables corresponding to later observations, such as codling moth and apple scab damage on fruits, were not significantly affected. Such timing suggests that landscape-scale orchard area promotes early field colonisation. This interpretation is in line with the fact that long-distance dispersal of apple scab spores and its consequences for in-field contamination by spores emitted by distant fields were formerly demonstrated by modelling studies (Aylor 1999). Similarly, adult codling moths emerge in spring from overwintering larvae and at least part of the population is able to fly long distances (Schumacher et al. 1997); thus earlier adult occurrence in traps may also reflect a larger landscape level abundance.

Relationships between host crop area and pest abundance are complex and may show opposite trends (Ricci et al. 2009; Delaune et al. 2021; Martínez-Sastre et al. 2021; Paredes et al. 2022). For apple orchards, in particular, opposite effects of host crop area on pests may come from differences in landscape-level pesticide intensity. Large areas of intensively treated host crops tend to reduce pest populations (Ricci et al. 2009) whereas an opposite effect is observed when host crops are extensive (Martínez-Sastre et al. 2021). We investigated this question by considering the share of organic orchards. We found no effect of this variable, contrary to our initial hypothesis. This absence of effect is consistent with former results obtained at a smaller spatial scale (Ricci et al. 2009) and concur with results on grapevines (Muneret et al. 2018b) and arable crops (Gosme et al. 2012). Farmers manage pests with a diversity of practices in organic apple orchards (Marliac et al. 2016). Some organic orchards are grown with apple cultivars that are resistant or tolerant to apple scab (Holb 2007). In addition, effective treatments against codling moths based on granuloviruses are available. They can be complemented by netting systems to protect apple orchards against the codling moth, especially in areas where codling moth populations have become resistant to the granulovirus (Marliac et al. 2016). It is therefore possible that, although pest damage is generally greater in organic orchards (Simon et al. 2017; Samnegård et al. 2019), organic orchards are not a source of codling moth or apple scab for other orchards. This result should, however, be taken with caution given that the share of organic orchards in municipalities was approximated based on higher level administrative information for part of the data (see material and methods). Furthermore, we could explore only a restricted range of variation for this variable because most orchards were conventional in the study landscapes.

Our results support the idea that not only landscape composition but also landscape configuration affects pest infestations. Indeed, in addition to the landscape composition effects explained above, we found a lower occurrence of fruit damage caused by codling moths in orchards located in landscapes with large orchard patch areas. Two ecological mechanisms possibly explain the negative trend between crop patch area and pest abundance. The first stems from dispersal limitation. Based on a simulation study, Edwards et al. (2018) found that grouping fields of annual crops could limit the abundance of dispersal-limited pests because pests cannot build-up populations in the most central fields. Dispersal limitation, however, is unlikely to affect codling moths that can fly over long distances (Schumacher et al. 1997). Furthermore, codling moths overwinter on apple tree trunks or in orchard soil and do not need to colonise orchards every year. The second mechanism is dilution. Negative trends between pest population and crop patch area can be observed when a constant number of pests is distributed over a range of crop areas and the pest becomes locally less abundant as the crop area increases (Zaller et al. 2008a, b). Dilution is expected for actively dispersing specialised pests. Dilution may be responsible for the pattern observed in fruit damage: mated codling moth females can fly over long distances (Schumacher et al. 1997), and, although females tend to cluster their eggs on nearby trees, they may also disperse them among distant trees within orchard patches (Franck et al. 2011; Margaritopoulos et al. 2012), possibly to avoid within-fruit larval competition (Ferro and Harwood 1973; Jackson 1982). Lastly, it is possible that fruit damage was affected by early insecticide treatments that specifically target neonate larvae. The observed trend could then have resulted from less efficient pest management in isolated orchards, either because these orchards are less central to the farm, or because pests colonise more easily isolated orchards, not suffering on their movement from insecticides sprayed in neighbouring orchards (Ricci et al. 2009).

The absence of effects of seminatural elements, whatever the pest, was unexpected given our hypotheses. Such cases are also often reported in global syntheses (Chaplin-Kramer et al. 2011; Veres et al. 2013; Karp et al. 2018; Martin et al. 2019; Rosenheim et al. 2022). One explanation is that seminatural habitats might also act as reservoirs of pests (Tscharntke et al. 2016). This is unlikely here given the host specificity of the codling moth and apple scab. Another explanation is related to the absence of natural enemies or the limited resources for natural enemies in seminatural habitats (Tscharntke et al. 2016). Such an explanation is likely for apple scab for which, to our knowledge, no natural enemy has yet been reported. However, it is less likely for the codling moth since the presence of seminatural elements has been shown to increase predation of codling moths in orchards (Heath and Long 2019), the abundance of a predatory spider (Lefebvre et al. 2016) and possibly promote its primary parasitoids (Maalouly et al. 2013). However, the scale of the effect of seminatural habitats considered by these studies was smaller than in the present study, and it is possible that small-scale analyses are necessary to detect the effects of seminatural habitats on pest populations (Begg et al. 2017).

Considering data at the national level made it possible to explore a large gradient of weather conditions and landscapes. However, because this dataset was not originally compiled for scientific purposes, there were a few limitations. First, we had to strongly simplify the dataset (e.g., modelling the probability of occurrence rather than abundance of pests) to account for differences in data monitoring along years or regions. This likely reduced the ability of our analysis to detect landscape effects but increased its robustness. Second, landscape characteristics may covary with weather conditions. To address this possible bias, we included weather variables in the models. These variables, as expected, impacted pests, particularly their date of first occurrence, but none was found to strongly covary with landscape variables (Figure S1 and low model variance inflation factors) indicating that we were able to disentangle weather and landscape effects. Third, we could have overlooked some regional features that impacted pest populations (e.g., different farm structures or apple cultivars). However, residual variations in our models were homogeneous among the French regions, suggesting that this was not the case, except for the date of first scab occurrence, for which we found no landscape effect (Figure S4). Last, no information on pesticide treatments was available in the Epiphyt database. First insecticide treatments against the codling moth are triggered early in season, after first adults are caught in traps, but before fruit damage. Similarly, fungicide treatments against apple scab are based on observation of early scab symptoms on shoots and according to rainy weather conditions. It is likely that these treatments early in the season have affected later recording of pest and pathogen occurrences. Variation in pesticide treatments among orchards may thus explain that we found the landscape to affect early observations, but not later ones. Despite these limitations we acknowledge that such large datasets initially built for advising farmers also contain precious information that nicely complete more classic information provided by empirical studies usually performed in landscape ecology (e.g., several fields surveyed along landscape gradients). Analysing such datasets makes it possible to explore the variability of landscape-scale effects in multiple climatic contexts and appears to be a step forwards in the direction of building predictive models to anticipate pest outbreaks.

Conclusion

Our results indicate that the main driver of pest dynamics in apple orchards was the composition and the configuration of orchards themselves in the landscape, rather than the quantity of seminatural elements. In particular, we found indications that the area grown with orchards affected early in-field colonisation and that the orchard mean patch area affected fruit damages. Our results therefore call for a territorial management of orchards to limit pest pressure and pesticide use in apple orchards. The management choices, however, should be adapted to the local context, focusing on the most problematic pests, as our results indicate that pests do not all respond similarly to the orchard spatial distribution. In addition, other aspects such as biodiversity conservation or ecosystem services delivery should be included in such territorial management as they may respond differently to changes in landscape composition and configuration (Martin et al. 2019). In the context of a necessary reduction in the use of pesticides, our study further indicates no specific impact of an increase in the area under organic agriculture, but it should be noted that the explored range of area grown organic remained low.

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Declarations

Competing interests 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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