Received: 20 April 2017 | Accepted: 23 October 2017
DOI: 10.1111/1365-2664.13034

RESEARCH ARTICLE

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

Deployment of organic farming at a landscape scale maintains low pest infestation and high crop productivity levels in vineyards

Lucile Muneret | Denis Thiéry | Benjamin Joubard | Adrien Rusch

[1]INRA UMR 1065 Santé et Agroécologie du Vignoble, ISVV, Université de Bordeaux, Bordeaux-Sciences-Agro, Villenave d'Ornon Cedex, France

Correspondence
Adrien Rusch
Email: adrien.rusch@inra.fr

Funding information
Region Aquitaine; Agence Française pour la Biodiversité; Ecophyto & the French National Foundation for Research on Biodiversity

Handling Editor: Ailsa McKenzie

Abstract

1. Organic farming is a promising way to reduce pesticide use but increasing the area under organic farming at the landscape scale could increase pest infestations and reduce crop productivity. Examining the effects of organic farming at multiple spatial scales and in different landscape contexts on pest communities and crop productivity is a major step in the ecological intensification of agricultural systems.
2. We quantified the infestation levels of two pathogens and five arthropod pests, the intensity of pesticide use and crop productivity in 42 vineyards. Using a multi-scale hierarchical design, we unravelled the relative effects of organic farming at both field and landscape scales from the effects of semi-natural habitats in the landscape.
3. At the field scale, pest communities did not differ between organic and conventional farming systems. At the landscape scale, increasing the area under organic farming did not increase pest infestation levels.
4. Three out of seven pest taxa were affected both by local farming systems and the proportion of semi-natural habitats in the landscape. Our findings revealed that the proportion of semi-natural habitats reduced pest infestation for two out of seven pest taxa.
5. Organic vineyards had much lower treatment intensities, very similar levels of pest control and equal crop productivity levels.
6. *Synthesis and Applications*. Our results clearly indicate that policies promoting the development of organic farming in conventional vineyard landscapes will not lead to greater pest and disease infestations but will reduce the pesticide treatment intensity and maintain crop productivity. Moreover, the interactions between semi-natural habitats in landscape and local farming practices suggest that the deployment of organic farming should be adapted to landscape contexts.

KEYWORDS
biological pest control, conventional farming, landscape complexity, organic farming, pathogens, pest community, pesticide use, Treatment Frequency Index, vineyard, yield

1 | INTRODUCTION

The intensification of agriculture that started 60 years ago in industrialized countries has had several negative impacts that limit the sustainability of food production systems. Although it has been successful in meeting the growing demand for food, such an intensification jeopardizes the environment and long-term production goals, as well as human health (Foley et al., 2011). Profound modifications to agricultural systems, such as reducing agrochemical dependency, while maintaining crop productivity (Tscharntke, Clough, et al., 2012), are thus needed.

Managing habitat diversity at different spatio-temporal scales is a promising way to limit pest pressure and reduce pesticide use in agroecosystems (Letourneau et al., 2011). Diversification schemes reduce pest populations through (1) the direct bottom-up effects of resource diversification on pest populations, mediated by physical or chemical confusion, that limit plant host localization; or (2) the indirect top-down effects of diversification on pests, mediated by natural enemies that benefit from alternative hosts or prey, pollen, nectar, refuges or micro-habitats in more diverse environments (Letourneau et al., 2011). Taking multiple scales into account, from the field to the landscape, is of major importance to understand pest population dynamics, natural enemy activity and the level of biological control (Chaplin-Kramer, O'Rourke, Blitzer, & Kremen, 2011; Rusch, Valantin-Morison, Sarthou, & Roger-Estrade, 2010).

Organic farming at the field scale and landscape complexity (i.e. the amount of semi-natural habitats in the landscape) are among the key management options for diversifying the environment and potentially limiting pest pressure (Bengtsson, Ahnström, & Weibull, 2005; Chaplin-Kramer et al., 2011). However, the relative effects of these variables at multiple spatial scales on pest communities and crop productivity remain poorly explored. It has been proposed that landscape complexity may nonlinearly modify the effects of local field management on biodiversity and ecosystem services, such as pest control (Concepción, Díaz, & Baquero, 2008). This suggests that organic farming at the field scale would have a maximized effect in landscapes of intermediate complexity, while it would have a minimal effect in extremely simplified or extremely complex landscapes. However, studies exploring this hypothesis yielded contrasting results (Birkhofer et al., 2016; Winqvist et al., 2011).

In addition, most of the studies on pest or natural enemy communities have focused on the role of semi-natural habitats rather than that of farming system at the landscape scale. Few studies have demonstrated the multi-scale effects of organic farming on biodiversity nor illustrated potential interactions between organic farming at the local and landscape levels (Gabriel et al., 2010; Inclán et al., 2015). However, how organic farming at the landscape scale modulates its benefits at the local scale remains unclear. Moreover, most of the studies examining the effects of organic farming at the landscape scale focus on biodiversity and little is known about pest abundances (but see Gosme, De Villemandy, Bazot, & Jeuffroy, 2012). On the one hand, we could hypothesize that a greater proportion of organic farming at the landscape scale would promote the diversity and abundance of natural enemies, enhance biological control and limit pest abundance. One the other hand, we could postulate that fields under organic farming may benefit from reduced pest pressure at the landscape scale owing to pesticide use in landscapes with a high proportion of conventional farming ("the chemical umbrella effect"). Thus, scale-dependent processes and the interplay between farming practices and semi-natural habitats on pest communities need to be investigated.

Despite the increased use of pesticides world-wide, crop losses owing to pests can still be substantial suggesting mixed effects of pesticide on crop productivity (Oerke, 2006). Evidence of the counterproductive effects of pesticide use have been reported in the literature (Bommarco, Miranda, Bylund, & Björkman, 2011; Settle et al., 1996), and highlight that, surprisingly, the relationships between pest pressure, pesticide use and crop productivity are poorly documented. Moreover, studies quantifying crop damage and productivity loss owing to pests mostly consider single species, although crop plants are attacked by multiple species that can interact (Gagic et al., 2016). Thus, it remains difficult to predict crop losses resulting from a large pest community because (1) both synergistic and antagonistic effects of multiple pest attacks on plant performance exist (Stephens, Srivastava, & Myers, 2013); and (2) relationships between pest communities and crop damage are highly context-dependent (Savary, Teng, Willocquet, & Nutter, 2006). It is thus of major importance to investigate how pest communities affect crop productivity if we intend to reduce pesticide use in agroecosystems.

In this study, we investigated the relative effects of farming systems and semi-natural habitats at multiple spatial scales on pest communities (hereafter, pests refer to both arthropod pests and pathogens) and crop productivity levels in vineyards. We selected viticulture as a model system because it is highly dependent on pesticides and is subjected to a diverse pest community. Using an experimental design in which pairs of organic and conventional farming fields were selected along two orthogonal landscape gradients (proportion of semi-natural habitats and proportion of organic farming), we were able to unravel the relative effects of these variables on pest communities and crop productivity. We hypothesized that pest infestations would be greater in organic than in conventional fields because organic farmers cannot use curative pesticides unlike conventional vine growers. We also hypothesized that the local effects of organic farming on pest infestation would be further modulated by the landscape context. We expected, on average, greater pest infestations in landscapes with a high proportion of organic farming compared with landscapes containing a high proportion of conventional farming but lower pest infestations in landscapes with a high proportion of semi-natural habitats compared with landscapes containing a low proportion of semi-natural habitats. Finally, we hypothesized that crop productivity would directly depend on the level of pest infestation.

2 | MATERIALS AND METHODS

2.1 | Study sites and design

Our study sites were located within a vineyard-dominated region (44°81′N, −0°14′W) of the Bordeaux area in southwestern France.

This is a major wine production area with ~138,000 ha of vineyards, and it receives about 16 pesticide treatments a year per unit area (Agreste, 2013). Our study system consisted of 21 pairs of organic and conventional fields (42 fields) selected along two orthogonal landscape gradients: one of semi-natural habitats and one of organic farming (Table S1, Figure S1). The spatial scale used for calculating landscape variables and selecting sites was a 1,000 m radius around each field. We only included organic vineyards that had been converted for at least 5 years (on average 11 years since the conversion; Table S1). This design allowed for the unravelling of farming system effects at the local scale as well as the effects of the proportions of semi-natural habitats and organic farming at the landscape scale. The average distance between the two fields of a given pair was 125 m. In addition, landscape variables were calculated at three other spatial scales: 250-, 500- and 750-m radii around each field using ArcGIS 10.1 (ESRI). Independence among landscape variables was maintained at all scales.

2.2 | Studied pest taxa

Seven pest taxa, including five arthropod pests and two pathogens, were regularly quantified over four periods between May and September 2015. All pest taxa were counted on 30 vine stocks at each time period. We counted pests on four to six vine rows located between the 5th and 15th closest vine rows of the paired fields. Sampled vine stocks were more than 10 m from the edge or any other sampled vine stock. On each vine stock, the trunk, three leaves (the first one at the head, the second in the middle of the vegetation and the third at the base) and three grape clusters (randomly chosen) were carefully inspected in the field. On each plant, the occurrence of mealybugs (Pseudococcidae) on trunks, downy mildew (*Plasmopara viticola*), black rot (*Guignardia bidwellii*), mite galls (*Colomerus vitis*), phylloxera galls (*Daktulosphaira vitifoliae*) and leafhopper larvae (Cicadellidae) on leaves, and larval nests of the grape moths (*Lobesia botrana* and *Empoecilia ambiguella*) on grape clusters were recorded. Most of the sampled leafhoppers (>95%) belonged to the species *Empoasca vitis* and the most abundant mealybug species were *Parthenolecanium corni* (>95%) and *Pulvinaria vitis* (<5%). Botrytis bunch rot (*Botrytis cinerea*) and powdery mildew (*Erysiphe necator*) occurred on leaves and grape clusters, but the occurrence was so low that they were not included in our analyses. We surveyed these pests because they are the main taxa attacking grapevines in our study region. Downy mildew, black rot, leafhoppers and grape moths are the major pests, while phylloxera, mites and mealybugs are considered minor pests (Delière et al., 2016; Pertot et al., 2017). No economic threshold has been identified for most of vineyard pests but if more than 5% of the clusters are attacked by grape moths or more than 30% of the leaves are attacked by pathogens, then yield loss is highly probable in this region (Savary, Delbac, Rochas, Taisant, & Willocquet, 2009; Thiéry & Moreau, 2005; L. Delière, pers. comm.). In addition to pest occurrence and abundance, we calculated pest community richness and evenness using Pielou's index at the field scale to analyse how pest communities (sensu lato) respond to farming systems and semi-natural habitats. Assuming that organic farming is more beneficial to pests than conventional farming, we expected greater pest richness and evenness levels in organic compared with conventional fields.

2.3 | Measurements of pesticide use intensity, crop vigour and crop productivity

The 42 vineyards were managed as usual by 38 different farmers. We collected data on pesticide applications for each field by interviewing the vine growers and calculating the Treatment Frequency Index (TFI) for all pesticides following the formula:

$$\mathrm{TFI} = \sum_{i=1}^{n} {}^{\mathrm{Appl.dose}}/_{\mathrm{Recom.dose}},$$

where n indicates the number of treatments, Appl. dose indicates the applied dose per hectare and Recom. dose indicates the recommended dose per hectare (Haldberg, Verschuur, & Goodlass, 2005; Jørgensen et al., 2008; OECD, 2001). The TFI is a well-known index used to assess pesticide pressure at different scales and to compare pesticide use intensity across different contexts (Jørgensen et al., 2008). It is easy to calculate and allows the aggregation of very different substances to measure overall pesticide pressure. However, it is not an index of toxicity because it does not discriminate between pesticides with different environmental toxicity levels. In the surveyed fields, 86% of the pesticides targeted downy mildew and oidium, 6% were insecticides against grape moths and leafhoppers, 4% were herbicides and the remaining were aimed at Botrytis (2%). We also assessed crop vigour using the Normalized Difference Vegetation Index obtained from ground-based measurements with a Greenseeker leaf colour analyser (N-Tech Industries, Ukiah, CA, USA and Oklahoma State University, Stillwater, OK, USA) once at the end of August 2015 along a 50-m transect per field. The mean crop vigour per field was then divided by the number of vine stocks along this transect to eliminate the effect of vine stock density on the crop vigour score.

Crop productivity was estimated a few days before harvest by counting the number of grapes on 20 randomly chosen vine stocks and by weighing 25 randomly chosen grapes on different vine stocks. Crop productivity per hectare was calculated by multiplying the average number of grapes per vine stock by the average grape weight and the vine stock density per field.

2.4 | Statistical analyses

We used generalized linear mixed models (GLMMs) with Poisson error distributions to investigate the effects of farming systems and the landscape context on the level of infestation for each pest taxa. The response variables used in the models were the number of leaves or trunks infested with mealybugs, mites, downy mildew, black rot or phylloxera and the total number of leafhoppers or grape moths counted per field (n = 166 for each pest except grape moths for which n = 125).

We used a multimodel inference approach to test our hypotheses and evaluate the support from the data for three competing set of models of increasing complexity. For each response variable, we started with a first set of models, M0, that included four explanatory variables, “field age”, “field size”, “vine trunk density” and “crop vigour”, which were considered as potential confounding variables. Then, we selected a set of best models using the Akaike information criteria corrected for small sample size (AIC_c). Models that were within the range of two AIC_c units of the lowest AIC_c score were considered as the best set of models and were used to estimate the mean effects and confidence intervals of each predictor variable using model averaging (Grueber, Nakagawa, Laws, & Jamieson, 2011). To account for the study design, we always added the “field pairs” (21) and the “sampling date” (4) as two crossed random effects. GLMMs were corrected for overdispersion by including an observation-level random effect. Significant local covariates (i.e. with a high relative importance and a confidence interval significantly different from zero) retained at this step were then used as the basic model structure in the two other sets of competing models. The following set of models, M1, included previously selected “local covariates” and “local farming system” as explanatory variables. This step enabled the testing of our hypothesis that pest populations could benefit from organic farming at the local scale. The last step of our modelling procedure, M2, included significant local covariates selected at M0, the local farming system and landscape variables (i.e. “the proportion of organic farming” and “the proportion of semi-natural habitats”) at a given scale. We added interaction terms between the local farming system and both landscape variables in M2. We decided to always use “local farming system” in M2 as it allowed us to test our hypotheses on the modulation of the effects of local farming systems by landscape context. Four different sets of competing models were considered independently using landscape variables calculated at four different spatial scales (250, 500, 750 and 1,000 m). At each step (M0, M1 and M2), we used the same averaging approach and the same random structure as previously described. For every response variable and for each top model at each step, we calculated the marginal R^2 values and conditional R^2 values to assess the amount of variance explained by the best model (i.e. that having the lowest AIC_c; Nakagawa & Schielzeth, 2013). Following Schielzeth (2010), we standardized all explanatory variables, with mean equal to 0 and standard deviation equal to 0.5 before modelling.

Additionally, to determine which level of model complexity, and indirectly which spatial scale, was the most important for explaining our response variables, we recalculated the Akaike weights among all of the models from the six different sets (i.e. M0, M1 and M2 at four spatial scales) obtained for a given response variable. Using this approach, we estimated the relative importance of each level of complexity for a given response variable. The sum of the Akaike weights (“Sum Wi”) of the models obtained at a given level of complexity provided the model’s probability of being a top model at all scales.

The same modelling strategy was used to analyse how pest richness, pest evenness, total TFI and crop productivity responded to our environmental variables using linear mixed models (LMMs) for pest richness and Poisson GLMMs for other response variables ($n = 166$, $n = 166$, $n = 42$ and $n = 38$, respectively). In addition, we examined the effects of pest infestations on crop productivity using LMMs. The average pest infestations of the seven taxa were included as explanatory variables and the “field pairs” as a random factor.

Diagnostic residual plots of all full models were confirmed using the DHARMa package (Hartig, 2017). Spatial autocorrelation in the residuals were explored using variograms, and no spatial autocorrelation was detected. Collinearity among predictors was assessed for each full model using the variance inflation factor, and the values were all close to 1.

All analyses were performed using R software (R Core Team, 2016) and the packages “lme4” (Bates, Mächler, Bolker, & Walker, 2014) and “MuMIn” (Bartoń, 2016).

3 | RESULTS

3.1 | Relative effects of the farming system and landscape context on each pest taxa

On average, 20.33% (*SD* = 17.13), 4.7% (*SD* = 9.35), 12.31% (*SD* = 9.45) and 4.47% (*SD* = 7.18) of leaves were infested with mites, phylloxera, black rot and downy mildew, respectively. On average, 13.15% (*SD* = 18.86) of trunks per field were infested with mealybugs, 8.44% (*SD* = 9.33) with leafhoppers and 1.72% (*SD* = 3.19) with grape moths. Approximately, 40% of the fields were subjected to a level of pest attack that could lead to yield loss. At the population level, we found that only mealybugs, phylloxera and mites responded to farming systems and semi-natural habitats at multiple scales. Black rot, downy mildew, leafhoppers and grape moths did not respond to any local or landscape variables (see Tables S2–S5). Among the local covariates, the crop vigour as assessed by the Normalized Difference Vegetation Index was never retained as a significant variable. At the landscape scale, the proportion of organic farming was never retained as a significant variable explaining pest infestations.

3.1.1 | Mealybugs

Models including local covariates, the local farming system and landscape variables had the highest probability of being among the best sets of models (Table 1). In particular, models fitted using landscape variables at the 250-m scale had the highest probability (Sum $Wi_{\text{M2 at 250 m}} = 0.41$) to appear as top models among all models fitted at all scales. Model averaging of models fitted at this spatial scale indicated that local farming system, vine stock density, and proportion of semi-natural habitats were all included in the top models (each relative variable’s importance was equal to 1; Table 1). Mealybug infestation was greater in organic fields, increased with vine trunk density and decreased with the proportion of semi-natural habitats ($R^2_m = 0.15$; $R^2_c = 0.62$; Table 1). We did not find any significant interactions among the local farming system and landscape variables (Figure 1a). Results of the multimodel inferences at other spatial scales were consistent with these results.

3.1.2 | Mites

Models fitted using local covariates, the local farming system and landscape variables at the 250-m scale had the highest

TABLE 1 Model selection table for models explaining mealybug infestations in vineyards. The table reports the explanatory variables selected, estimates, confidence intervals (2.5%–97.5%) and the relative importance of each level of model complexity (M0, M1 and M2). M0 only considered local cofounding variables; M1 considered the retained local covariates from M0 as well as the local farming system (organic or conventional); and M2 considers previous variables as well as landscape variables. For M2, only model outputs of the most important spatial scale (identified by the sum of Akaike weights normalized across each spatial scale) are indicated in the table. For each level of model complexity, R^2 marginal and R^2 conditional are reported. R^2 values were calculated using the best models at each scale. The sum of the Akaike weight normalized across each spatial scale (Sum Wi) provided the probability of a given level of complexity to appear in the top models

Models	Explanatory variables selected	Estimates	Confidence intervals	Relative variable importance
M0 (R^2_m = 0.06; R^2_c = 0.6; sum Wi < 0.01)	Field age	−0.33	−0.83 to 0.01	0.81
	Vine trunk density	0.86	0.29–1.42	1
	Field size	0.08	−0.15 to 0.74	0.28
	Crop vigour	−0.04	−0.73 to 0.31	0.17
M1 (R^2_m = 0.08; R^2_c = 0.61; sum Wi = 0.03)	Vine trunk density	0.72	0.15–1.29	1[a]
	Local farming system: Conventional	0.46	0.14–0.78	1[a]
M2 at 250 m (R^2_m = 0.15; R^2_c = 0.62; sum Wi = 0.41)	Local farming system	0.49	0.15–0.84	1
	Vine trunk density	0.72	0.18–1.26	1
	Proportion of semi-natural habitats	−0.8	−1.49 to −0.11	1
	Proportion of organic farming	0.16	−0.35 to 1.25	0.36

[a] Only one best model selected here.

probability of being top models among all models fitted at all scales (Sum $Wi_{M2\ at\ 250\ m}$ = 0.99). Model averaging at this scale showed that the proportion of leaves infested with mite galls increased with field age and decreased with trunk density, field size and the proportion of semi-natural habitats in the landscape (each relative variable's importance was equal to 1; R^2_m = 0.44; R^2_c = 0.87; Table 2). This model also revealed a significant interaction between the local farming system and the proportion of semi-natural habitats. This indicated that mite infestations were greater in conventional fields than in organic fields in landscapes with a low proportion of semi-natural habitats, while there was no difference in mite infestation levels between organic and conventional farming in landscapes with a high proportion of semi-natural habitats (Figure 1b, Table 2).

3.1.3 | Phylloxera

Models fitted using local covariates, the local farming system and landscape variables calculated at the 1,000-m scale had the highest probability (Sum $Wi_{M2\ at\ 1{,}000\ m}$ = 0.98) of being top models among all models fitted at all scales. Model averaging of models fitted at 1,000 m indicated that phylloxera infestations decreased with field age and that the effect of the local farming system on phylloxera infestation was dependent of the proportion of semi-natural habitats (each relative variable's importance was equal to 1; R^2_m = 0.25; R^2_c = 0.72; Table 3). This interaction indicated that the level of phylloxera infestation was greater in organic fields than in conventional fields but only in landscapes with a high proportion of semi-natural

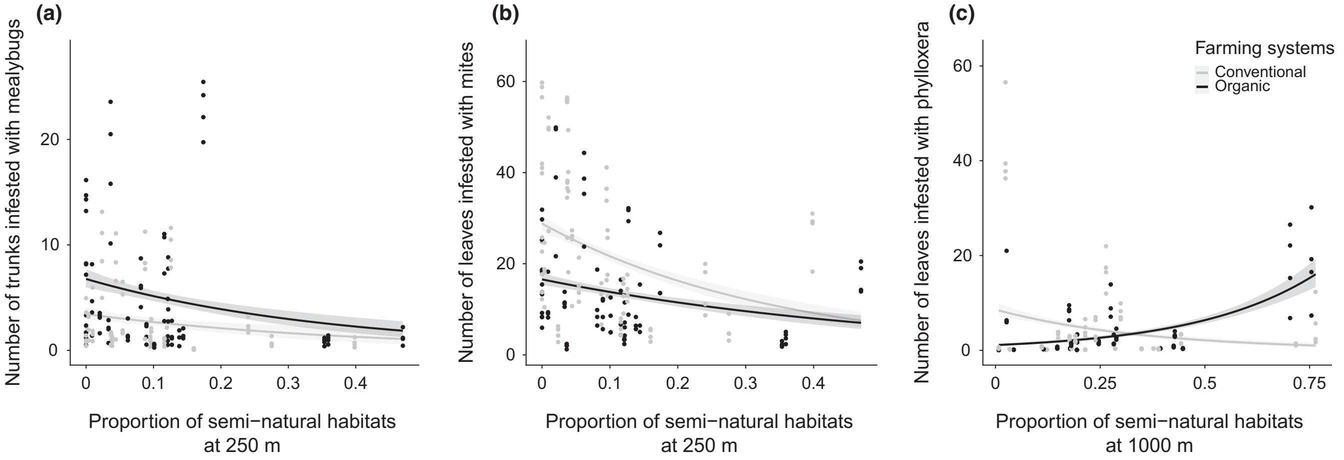

FIGURE 1 Responses of mealybugs (a), mites (b) and phylloxera (c) to the interactions between local farming systems and the proportion of semi-natural habitats at two different spatial scales (250 m or 1,000 m)

TABLE 2 Model selection table for models explaining mite infestations in vineyards. All models, explanatory variables, estimates, confidence intervals and relative importances that are reported in this table have been obtained using the same procedure as the data reported in the Table 1. See the legend in Table 1

Models	Explanatory variables selected	Estimates	Confidence intervals	Relative variable importance
M0 ($R^2_m = 0.17$; $R^2_c = 0.63$; sum Wi < 0.01)	Field age	0.81	0.51–1.10	1
	Vine trunk density	−0.41	−0.74 to −0.08	1
	Field size	0.47	−0.77 to −0.18	1
	Crop vigour	0.03	−0.22 to 0.45	0.3
M1 ($R^2_m = 0.19$; $R^2_c = 0.65$; sum Wi < 0.01)	Field age	0.63	0.33–0.92	1
	Local farming system: Conventional	−0.44	−0.64 to −0.23	1
	Vine trunk density	−0.19	−0.61 to 0.02	0.63
	Field size	−0.4	−0.68 to −0.11	1
M2 at 250 m ($R^2_m = 0.44$; $R^2_c = 0.87$; sum Wi = 0.99)	Vine trunk density	−0.38	−0.69 to −0.13	1
	Field age	0.69	0.48–0.98	1
	Field size	−0.5	−0.79 to −0.28	1
	Local farming system: Conventional	−0.19	−0.36 to 0.02	1
	Proportion of semi-natural habitats	−1.48	−2.04 to −1.07	1
	Proportion of organic farming	−0.08	−0.72 to 0.42	0.27
	Local farming system:proportion of semi-natural habitats	0.5	0.22–0.95	1

habitats. The opposite was found in landscapes with a low proportion of semi-natural habitats (Figure 1c).

3.2 | Relative effects of the farming system and semi-natural habitats on the pest community

For pest community evenness, models fitted with landscape variables calculated at the 250-m scale had the highest cumulated probability of being top models (Sum $\text{Wi}_{\text{M2 at 250 m}} = 0.45$; Table S6). Field age, vine trunk density and the proportion of semi-natural habitats were included in the top models fitted at the 250-m scale (Table S6). Pest community evenness increased with vine trunk density and with the proportion of semi-natural habitats in the landscape, while it decreased with field age (each relative variable's importance was equal to 1; $R^2_m = 0.19$; $R^2_c = 0.32$; Table S6). Our multimodel inference approach showed no evidence of any effects caused by other local or landscape variables. Additionally, there were no effects of the farming system and semi-natural habitats at multiple spatial scales on the pest taxa richness.

3.3 | Crop productivity and management intensity

Crop productivity was not affected by the local covariates, local farming system or any landscape variables. On average, organic fields produced 11.01 t (*SD* = 4.07) of grape per hectare, while conventional fields produced on average 10.90 t (*SD* = 3.58) of grape per hectare, which highlighted the similar production levels between organic and conventional systems (Figure 2a). Surprisingly, crop productivity was not affected by any pest infestations of any taxa despite variabilities in pest infestations among fields (Table S7). Finally, the total TFI was lower in organic than in conventional fields but was not affected by the landscape composition at any scale. On average, the total TFI was twofold lower in organic than in conventional fields (Figure 2b).

4 | DISCUSSION

To our knowledge, this is the first study investigating how infestations with multiple pest taxa respond to both organic farming and semi-natural habitats using a multiple scale design with orthogonal landscape factors. Contrary to our initial hypotheses, the pest community did not differ at the field scale between organic and conventional farming systems. Additionally, the proportion of organic farming in the landscape was never an important variable for explaining pest infestations. Finally, our study showed that three out of seven pest species responded to local farming systems and semi-natural habitats in the landscape. Nevertheless, it illustrated the importance of considering both farming practices and landscape context when studying pest dynamics.

Contrary to expectations, the pest community did not differ between organic and conventional fields. Additionally, increasing the organic farming area in the landscape (within the range explored in our study design) did not lead to greater pest infestations. Our results contradict previous results from two theoretical studies investigating the effects of the spatial arrangement of organic farming in the landscape (Adl, Iron, & Kolokolnikov, 2011; Bianchi, Ives, & Schellhorn, 2013). Both studies showed that the deployment of organic farming at the landscape scale could increase pest outbreaks. However, these studies assumed that chemical control was less effective, or even absent, in organic fields compared with conventional ones, which is not the case

TABLE 3 Model selection table for models explaining phylloxera infestations in vineyards. All models, explanatory variables, estimates, confidence intervals and relative importances that are reported in this table have been obtained using the same procedure as the data reported in the Table 1. See the legend in Table 1

Models	Explanatory variables selected	Estimates	Confidence intervals	Relative variable importance
M0 (R^2_m = 0.07; R^2_c = 0.66; sum Wi < 0.01)	Field age	−1.11	−1.74 to −0.46	1
	Crop vigour	−0.22	−0.99 to 0.13	0.51
	Vine trunk density	−0.08	−1.15 to 0.52	0.24
	Field size	−0.06	−0.88 to 0.37	0.24
M1 (R^2_m = 0.07; R^2_c = 0.66; sum Wi < 0.01)	Field age	−1.11	−1.76 to −0.47	1
	Local farming system: Conventional	−0.04	−0.54 to 0.25	0.31
M2 at 1,000 m (R^2_m = 0.25; R^2_c = 0.72; sum Wi = 0.98)	Field age	−1.12	−1.54 to −0.67	1
	Local farming system: Conventional	−0.36	−0.63 to −0.10	1
	Proportion of organic farming	0.71	−0.09 to 2.51	0.58
	Proportion of semi-natural habitats	0.72	−0.34 to 1.79	1
	Local farming system:proportion of semi-natural habitats	1.82	1.37–2.27	1

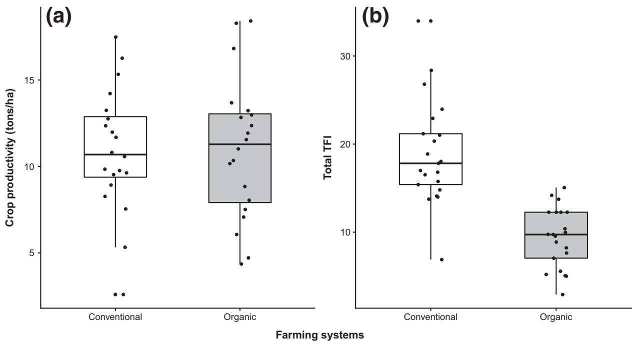

FIGURE 2 Effects of local farming systems (conventional or organic) on (a) crop productivity (t/ha) and (b) the total Treatment Frequency Index (TFI)

here. Our survey of farming practices showed that organic growers were using organic pesticides to control pests, as indicated by an average total TFI of approximately 9 for organic fields, while they obtained similar levels of crop productivity. Furthermore, our results are in line with two empirical studies that showed no evidence of greater pest pressure in cereal fields and orchards as the amount of area under organic farming in the landscape increased (Gosme et al., 2012; Ricci et al., 2009).

Three out of the seven surveyed pest taxa responded to the proportion of semi-natural habitats in the landscape. Both mealybug and mite infestations decreased as the proportion of semi-natural habitats in the landscape increased. Similarly, the phylloxera abundance decreased with the proportion of semi-natural habitats in the landscape but only in conventional fields. This negative effect of landscape complexity on pest infestations may be explained by two complementary hypotheses: (1) direct effects of landscape composition on pest dynamics and (2) indirect effects of landscape composition on pests through top-down control by natural enemies (Rusch et al., 2010; Veres, Petit, Conord, & Lavigne, 2013). Direct effects of landscape complexity on pest dynamics include limited pest dispersal owing to the direct barrier effects of unsuitable habitat types, such as semi-natural habitats, and reduced pest sources in more complex landscapes that support lower proportions of host plant (Avelino, Romero-Gurdián, Cruz-Cuellar, & Declerck, 2012; Kuefler, Hudgens, Haddad, Morris, & Thurgate, 2010; Plantegenest, Le May, & Fabre, 2007; Summerville, 2004). Indirect effects of landscape complexity on pests are caused by the presence of key resources for natural enemies (Landis, Wratten, & Gurr, 2000). The increased availability of semi-natural habitats in the landscape enhances the diversity and abundance of natural enemies and, in turn, the biological control of pests (Chaplin-Kramer et al., 2011; Letourneau, Jedlicka, Bothwell, & Moreno, 2009; Rusch et al., 2016).

Mealybugs, mites and phylloxera were also affected by local farming systems, either alone or through interactions with the proportion of semi-natural habitats in the landscape. Mites and phylloxera were the two taxa that supported our hypothesis predicting that the effects of the local farming system on pest infestation would be modulated by the proportion of semi-natural habitats in the landscape. In very simple landscapes, mites and phylloxera infestations were lower in organic than in conventional fields, while in complex landscapes, the infestation levels were either similar or greater in organic than in conventional fields. This illustrates how the landscape context can modulate the effect of local farming systems on pest infestations. However, our results seem to not corroborate the intermediate landscape complexity hypothesis that stated that organic farming would be more effective in enhancing ecosystem services, such as biological control, in intermediate landscapes than in simple and complex landscapes (Tscharntke, Tylianakis, et al., 2012). Phylloxera infestations were greater in organic fields than in conventional fields but only in complex landscapes. Thus, processes other than top-down control by natural enemies might be involved and other covariates related to bottom-up processes may explain this pattern. Despite the negative effect of semi-natural habitats, infestations by mealybugs were always greater in organic than in conventional vineyards suggesting that organic vineyards could be highly beneficial to mealybugs. Indeed, mealybugs are favoured by the tillage, the presence of Formicidae and a decreased exposure to synthetic pesticides (Daane et al., 2012; Mgocheki & Addison, 2010; Muscas et al., 2017).

Pest taxa that responded to the landscape context were affected by the proportion of semi-natural habitats at two different spatial scales: the 250-m (for mealybugs and mites) and the 1,000-m radii (for phylloxera). The most important scale explaining species abundance can be interpreted as the scale at which a given species perceives and interacts with the landscape and can be used for management issues (Jackson & Fahrig, 2012). This scale of response depends on functional attributes, such as the dispersal ability, of the species and on the structure of the landscape itself. The most important scales found in our study for these three pest taxa are consistent with available information on their dispersal abilities (Forneck, Anhalt, Mammerler, & Griesser, 2015; Grasswitz & James, 2008). Moreover, our results corroborate those of recent studies in perennial crops in which the beneficial effects of semi-natural habitats on pest control were greatest at relatively small spatial scales (<250 m radius) (Henri et al., 2015; Thomson & Hoffmann, 2013).

Pest pressure at the community level tends to be limited in complex landscapes mainly owing to the negative effect of landscape complexity on mites. Downy mildew, black rot, leafhoppers and grape moths were not affected by the proportion of semi-natural habitats in the landscape. Overall, these findings are consistent with the conclusions of two recent meta-analyses that found no clear trend in the response of pest abundance to the proportion of semi-natural habitats in the landscape, despite the strong positive effects of landscape complexity on natural enemies and biological control (Chaplin-Kramer et al., 2011; Veres et al., 2013). One possible explanation is that farming practices, and pesticide use in particular, may have hidden the effect of landscape context on pest populations (Tscharntke et al., 2016; Veres et al., 2013). Indeed, the four pest taxa that did not show any response to farming practices or landscape context are the main targets of pesticide use in both organic and conventional vineyards. This strongly suggests that both farming systems used effective control strategies that masked potential effects. Second, the thematic resolution, as well as the spatial extent, used to characterize our landscapes might differ from the actual functional roles of the habitats and from the scale of response of the given pest species (Jackson & Fahrig, 2012). The most relevant scale of observation corresponds to the mean dispersal distance of the species being studied (Gilligan, 2008; Jackson & Fahrig, 2012). Thus, the lack of landscape context effect for the four major pests might also result from a too narrow scale of observation, especially for pathogens that disperse by wind over long distances (Fontaine et al., 2013).

Finally, our study demonstrated that organic vineyards have TFIs that are twofold less important than those of conventional vineyards having similar levels of pest infestations and equal productivity levels. The TFI is clearly a proxy for treatment intensity and is not a measure of environmental impact. However, increasing the amount of organic farming at the landscape scale should decrease treatment intensity without modifying pest pressure or crop performance in the given context of our study. Our results are consistent with a recent study on arable crops in which the reduction of pesticide use did not affect crop productivity or economic performances (Lechenet, Dessaint, Py, Makowski, & Munier-Jolain, 2017). Studies regarding the agronomic consequences of organic farming expansion should also consider crop quality.

4.1 | Synthesis and applications

Reducing pesticide use, while not altering crop productivity and quality, is a major challenge for agroecologists. Our study demonstrates that organic farming can be used as an agri-environmental scheme to achieve this goal in vineyard agroecosystems that heavily depend on synthetic pesticides. Increasing the area of organic farming in the landscape did not lead to greater pest pressure but reduced treatment intensity and maintained crop productivity. However, the long-term effects of organic inputs largely used in organic farming such as sulphur and copper should be investigated in vineyards. Moreover, our results further illustrate how proportions of semi-natural habitats in the landscape can modulate the local effects of farming systems on pest infestations by some taxa. These results highlight the importance of taking into account landscape composition to optimize farming system allocation and limit pest pressure. Our study has important implications for both practitioners and policymakers concerned with the ecological intensification of farming systems and land-use planning. However, future research is still needed to explore potential threshold effects when there is a much greater proportion of organic farming in the landscape. Moreover, the relative effects of the spatial composition and configuration (e.g. connectivity) of organic farming on pest pressure and biological pest control remain largely unknown and require further investigation.

ACKNOWLEDGEMENTS

We are grateful to Arthur Auriol, Emilie Vergnes, Laura Arias, Lionel Druelle, Pascale Roux, Olivier Bonnard, Sylvie Richard-Cervera, Isabelle Demeaux, Lisa Le Postec, Lionel Delbac and Gilles Tarris for their technical help. We also thank the 38 grapevine growers for allowing us access to their vineyards and Lesley Benyon, PhD, from Edanz Group for editing a draft of this manuscript. The research was funded by the Region Aquitaine (REGUL project) and the Agence Française pour la Biodiversité, joint call Ecophyto & the French National Foundation for Research on Biodiversity (SOLUTION project). This research is also part of the cluster of Excellence Cote.

AUTHORS' CONTRIBUTIONS

L.M., D.T. and A.R. conceived the work and designed the experiments; L.M., B.J. and A.R. collected the data; L.M. and A.R. analysed the data; L.M. and A.R. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.vv1t9 (Muneret, Thiéry, Joubard, & Rusch, 2017).

ORCID

Adrien Rusch http://orcid.org/0000-0002-3921-9750

REFERENCES

Adl, S., Iron, D., & Kolokolnikov, T. (2011). A threshold area ratio of organic to conventional agriculture causes recurrent pathogen outbreaks in organic agriculture. *Science of the Total Environment*, *409*, 2192–2197.

Agreste. (2013). Ministère de l'agriculture, de l'agroalimentaire et de la forêt – Agreste – La statistique, l'évaluation et la prospective agricole – Pratiques culturales dans la viticulture. http://agreste.agriculture.gouv.fr/enquetes/pratiques-culturales/pratiques-culturales-dans-la/.

Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H. F., & Declerck, F. A. (2012). Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. *Ecological Applications*, *22*, 584–596.

Bartoń, K. (2016). Package 'MuMIn'. Model selection and model averaging based on information criteria. R package version 1.15.11. http://CRAN.R-project.org/package=MuMIn

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823.

Bengtsson, J., Ahnström, J., & Weibull, A.-C. (2005). The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *Journal of Applied Ecology*, *42*, 261–269.

Bianchi, F. J. J., Ives, A. R., & Schellhorn, N. A. (2013). Interactions between conventional and organic farming for biocontrol services across the landscape. *Ecological Applications*, *23*, 1531–1543.

Birkhofer, K., Arvidsson, F., Ehlers, D., Mader, V. L., Bengtsson, J., & Smith, H. G. (2016). Organic farming affects the biological control of hemipteran pests and yields in spring barley independent of landscape complexity. *Landscape Ecology*, *31*, 567–579.

Bommarco, R., Miranda, F., Bylund, H., & Björkman, C. (2011). Insecticides suppress natural enemies and increase pest damage in cabbage. *Journal of Economic Entomology*, *104*, 782–791.

Chaplin-Kramer, R., O'Rourke, M. E., Blitzer, E. J., & Kremen, C. (2011). A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecology Letters*, *14*, 922–932.

Concepción, E. D., Díaz, M., & Baquero, R. A. (2008). Effects of landscape complexity on the ecological effectiveness of agri-environment schemes. *Landscape Ecology*, *23*, 135–148.

Daane, K. M., Almeida, R. P. P., Bell, V. A., Walker, J. T. S., Botton, M., Fallahzadeh, M., … Zaviezo, T. (2012). Biology and management of Mealybugs in Vineyards. *Arthropod Management in Vineyards* (eds N. J. Bostanian, C. Vincent & R. Isaacs), pp. 271–307. Dordrecht, the Netherlands: Springer.

Delière, L., Burgun, X., Lafond, D., Mahé, H., Métral, R., Serrano, E., … Pillet, E. (2016). Réseau DEPHY EXPE: Synthèse des résultats à mi-parcours à l'échelle nationale - filière Viticulture. Cellule d'Animation Nationale DEPHY Ecophyto. http://viticulture.ecophytopic.fr/sites/default/files/Synth%C3%A8se%20EXPE%20Viticulture.pdf.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337–342.

Fontaine, M. C., Austerlitz, F., Giraud, T., Labbé, F., Papura, D., Richard-Cervera, S., & Delmotte, F. (2013). Genetic signature of a range expansion and leap-frog event after the recent invasion of Europe by the grapevine downy mildew pathogen *Plasmopara viticola*. *Molecular Ecology*, *22*, 2771–2786.

Forneck, A., Anhalt, U. C., Mammerler, R., & Griesser, M. (2015). No evidence of superclones in leaf-feeding forms of Austrian grape phylloxera (*Daktulosphaira vitifoliae*). *European Journal of Plant Pathology*, *142*, 441–448.

Gabriel, D., Sait, S. M., Hodgson, J. A., Schmutz, U., Kunin, W. E., & Benton, T. G. (2010). Scale matters: The impact of organic farming on biodiversity at different spatial scales. *Ecology Letters*, *13*, 858–869.

Gagic, V., Riggi, L. G., Ekbom, B., Malsher, G., Rusch, A., & Bommarco, R. (2016). Interactive effects of pests increase seed yield. *Ecology and Evolution*, *6*, 2149–2158.

Gilligan, C. A. (2008). Sustainable agriculture and plant diseases: An epidemiological perspective. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *363*, 741–759.

Gosme, M., De Villemandy, M., Bazot, M., & Jeuffroy, M.-H. (2012). Local and neighbourhood effects of organic and conventional wheat management on aphids, weeds, and foliar diseases. *Agriculture, Ecosystems & Environment*, *161*, 121–129.

Grasswitz, T. R., & James, D. G. (2008). Movement of grape mealybug, *Pseudococcus maritimus*, on and between host plants. *Entomologia Experimentalis et Applicata*, *129*, 268–275.

Grueber, C. E., Nakagawa, S., Laws, R. J., & Jamieson, I. G. (2011). Multimodel inference in ecology and evolution: Challenges and solutions. *Journal of Evolutionary Biology*, *24*, 699–711.

Haldberg, N., Verschuur, G., & Goodlass, G. (2005). Farm level environmental indicators; are they useful? An overview of green accounting systems for European farms. *Agriculture, Ecosystems & Environment*, *105*, 195–212.

Hartig, F. (2017). DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models. https://cran.r-project.org/web/packages/DHARMa/index.html.

Henri, D. C., Jones, O., Tsiattalos, A., Thébault, E., Seymour, C. L., & Veen, F. J. (2015). Natural vegetation benefits synergistic control of the three main insect and pathogen pests of a fruit crop in southern Africa. *Journal of Applied Ecology*, *52*, 1092–1101.

Inclán, D. J., Cerretti, P., Gabriel, D., Benton, T. G., Sait, S. M., Kunin, W. E., … Marini, L. (2015). Organic farming enhances parasitoid diversity at the local and landscape scales. *Journal of Applied Ecology*, *52*, 1102–1109.

Jackson, H. B., & Fahrig, L. (2012). What size is a biologically relevant landscape? *Landscape Ecology*, *27*, 929–941.

Jørgensen, L. N., Noe, E., Nielsen, G. C., Jensen, J. E., Ørum, J. E., & Pinnschmidt, H. O. (2008). Problems with disseminating information on disease control in wheat and barley to farmers. *European Jornal of Plant Pathology*, *121*, 303–312.

Kuefler, D., Hudgens, B., Haddad, N. M., Morris, W. F., & Thurgate, N. (2010). The conflicting role of matrix habitats as conduits and barriers for dispersal. *Ecology*, *91*, 944–950.

Landis, D. A., Wratten, S. D., & Gurr, G. M. (2000). Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology*, *45*, 175–201.

Lechenet, M., Dessaint, F., Py, G., Makowski, D., & Munier-Jolain, N. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants*, *3*, 17008.

Letourneau, D. K., Armbrecht, I., Rivera, B. S., Lerma, J. M., Carmona, E. J., Daza, M. C., … Trujillo, A. R. (2011). Does plant diversity benefit agroecosystems? A synthetic review. *Ecological Applications*, *21*, 9–21.

Letourneau, D. K., Jedlicka, J. A., Bothwell, S. G., & Moreno, C. R. (2009). Effects of natural enemy biodiversity on the suppression of arthropod herbivores in terrestrial ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, *40*, 573–592.

Mgocheki, N., & Addison, P. (2010). Spatial distribution of ants (Hymenoptera: Formicidae), vine mealybugd and mealybug parasitoids in vineyards. *Journal of Applied Entomoly*, *134*, 285–295.

Muneret, L., Thiéry, D., Joubard, B., & Rusch, A. (2017). Data from: Deployment of organic farming at a landscape scale maintains low pest infestation and high crop productivity levels in vineyards. *Dryad Digital Repository*, https://doi.org/10.5061/dryad.vv1t9

Muscas, E., Cocco, A., Mercenaro, L., Cabras, M., Lentini, A., Porqueddu, C., & Nieddu, G. (2017). Effects of vineyard floor cover crops on grapevine vigor, yield, and fruit quality, and the development of the vine mealybug under a Mediterranean climate. *Agriculture, Ecosystems & Environment*, *237*, 203–212.

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*, 133–142.

OECD. (2001). Environmental indicators for agriculture volume 3/2001. https://www.oecd.org/tad/sustainable-agriculture/40680869.pdf.

Oerke, E.-C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, *144*, 31–43.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M. S., … Anfora, G. (2017). A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. *Crop Protection*, *97*, 70–84.

Plantegenest, M., Le May, C., & Fabre, F. (2007). Landscape epidemiology of plant diseases. *Journal of the Royal Society Interface*, *4*, 963–972.

R Core Team. (2016). R: The R project for statistical computing. https://www.r-project.org/.

Ricci, B., Franck, P., Toubon, J. F., Bouvier, J. C., Sauphanor, B., & Lavigne, C. (2009). The influence of landscape on insect pest dynamics: A case study in southeastern France. *Landscape Ecology*, *24*, 337–349.

Rusch, A., Chaplin-Kramer, R., Gardiner, M. M., Hawro, V., Holland, J., Landis, D., … Bommarco, R. (2016). Agricultural landscape simplification reduces natural pest control: A quantitative synthesis. *Agriculture, Ecosystems & Environment*, *221*, 198–204.

Rusch, A., Valantin-Morison, M., Sarthou, J.-P., & Roger-Estrade, J. (2010). Biological control of insect pests in agroecosystems: Effects of crop management, farming systems, and seminatural habitats at the landscape scale: A review. *Advances in Agronomy*, *109*, 219–260.

Savary, S., Delbac, L., Rochas, A., Taisant, G., & Willocquet, L. (2009). Analysis of nonlinear relationships in dual epidemics, and its application to the management of grapevine downy and powdery mildews. *Phytopathology*, *99*, 930–942.

Savary, S., Teng, P. S., Willocquet, L., & Nutter, F. W. Jr (2006). Quantification and modeling of crop losses: A review of purposes. *Annual Review of Phytopathology*, *44*, 89–112.

Schielzeth, H. (2010). Simple means to improve the interpretability of regression coefficients. *Methods in Ecology and Evolution*, *1*, 103–113.

Settle, W. H., Ariawan, H., Astuti, E. T., Cahyana, W., Hakim, A. L., Hindayana, D., & Lestari, A. S. (1996). Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. *Ecology*, *77*, 1975–1988.

Stephens, A. E., Srivastava, D. S., & Myers, J. H. (2013). Strength in numbers? Effects of multiple natural enemy species on plant performance. *Proceedings of the. Royal Society of London B*, *280*, 20122756.

Summerville, K. S. (2004). Do smaller forest fragments contain a greater abundance of lepidopteran crop and forage consumers? *Environmental Entomology*, *33*, 234–241.

Thiéry, D., & Moreau, J. (2005). Relative performance of European grapevine moth (*Lobesia botrana*) on grapes and other hosts. *Oecologia*, *143*, 548–557.

Thomson, L. J., & Hoffmann, A. A. (2013). Spatial scale of benefits from adjacent woody vegetation on natural enemies within vineyards. *Biological Control*, *64*, 57–65.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., … Whitbread, A. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, *151*, 53–59.

Tscharntke, T., Karp, D. S., Chaplin-Kramer, R., Batáry, P., DeClerck, F., Gratton, C., … Zhang, W. (2016). When natural habitat fails to enhance biological pest control – Five hypotheses. *Biological Conservation*, *204*, 449–458.

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batary, P., … Westphal, C. (2012). Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological Reviews*, *87*, 661–685.

Veres, A., Petit, S., Conord, C., & Lavigne, C. (2013). Does landscape composition affect pest abundance and their control by natural enemies? A review. *Agriculture, Ecosystems & Environment*, *166*, 110–117.

Winqvist, C., Bengtsson, J., Aavik, T., Berendse, F., Clement, L. W., Eggers, S., … Bommarco, R. (2011). Mixed effects of organic farming and landscape complexity on farmland biodiversity and biological control potential across Europe. *Journal of Applied Ecology*, *48*, 570–579.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Muneret L, Thiéry D, Joubard B, Rusch A. Deployment of organic farming at a landscape scale maintains low pest infestation and high crop productivity levels in vineyards. *J Appl Ecol*. 2017;00:1–10. https://doi.org/10.1111/1365-2664.13034