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Reducing pest pressure and insecticide use by increasing hedgerows in the landscape

Emeric Courson [a], Benoit Ricci [a,b], Lucile Muneret [a], Sandrine Petit [a,*]

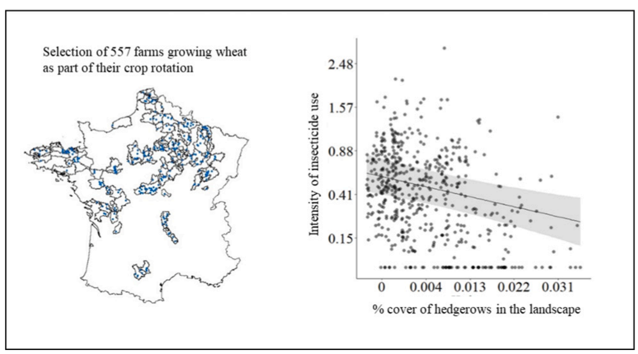
[a] Agroécologie, INRAE, Institut Agro, Univ. Bourgogne, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

[b] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France

HIGHLIGHTS

- Insecticide use across 557 French farms that included winter wheat in their crop rotation was examined
- Insecticide use increased with pest pressure and field size
- Pest pressure increased as the cover of hedgerows in the landscape decreased
- Increasing the landscape-scale cover of hedgerows from 1 % to 3 % halved insecticide use

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing pesticide use while maintaining agricultural production is a key challenge. Ecological theory predicts that landscape simplification is likely to increase insect pest outbreaks and limit their control by natural enemies, and this situation could boost insecticide use. Some studies have indeed detected that simpler landscapes were associated with higher insecticide use, but very few have demonstrated that this association is caused by landscape effects on pest abundance. Here, we analysed insecticide use and pest pressure in response to landscape simplification across 557 arable farms across France. Accounting for potentially confounding covariates, we found that lower cover of hedgerows in the landscape, but not semi natural areas, were associated with higher on-farm insecticide use. We also found that greater hedgerow coverage was associated with lower aphid pest pressure. Specifically, increasing the landscape-scale cover of hedgerows from 1 % to 3 % meant that insecticide use was halved. These findings suggest that restoring hedgerow cover at the landscape scale should be targeted in order to speed-up the ecological intensification of agriculture.

1. Introduction

Pesticides are a cornerstone of crop productivity under the dominant agriculture paradigm (Popp et al., 2013) but scientific evidence has accumulated on their detrimental impacts on human health (Kim et al., 2017), biodiversity and associated ecosystem services (Geiger et al.,

* Corresponding author.
E-mail address: sandrine.petit-michaut@inrae.fr (S. Petit).

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2010; Sánchez-Bayo and Wyckhuys, 2019). A primary option to reduce pesticide use is the adoption of alternative, non-chemical practices that alleviate pest pressure, such as intercropping or the diversification of the crop sequence (Petit et al., 2020; Van der Werf and Bianchi, 2022). Increasing attention is also being paid to the landscape context of individual fields (Meehan et al., 2011). Landscape simplification, i.e. the loss of non-crop habitats and the increasing size of crop patches, can be associated to increased pesticide use (Meehan and Gratton, 2015; Nicholson and Williams, 2021; Malaj and Morrissey, 2022). Such association could simply reflect the farm level economy, e.g. spraying a larger field costs less and protects a larger share of the farm production (Waterfield and Zilberman, 2012; Osteen and Fernandez-Cornejo, 2013). This association is however also in line with ecological expectations, i.e. large crop patches facilitate movement and establishment of crop pests, leading to higher pest pressure and thus to a higher use of insecticides. There are indeed a few large-scale demonstrations of the relationships between crop cover or patch size, pest pressure and insecticides use (but see Meehan et al., 2011; Gagic et al., 2021). Ecological theory also predicts that significant cover of semi-natural habitats boosts populations of natural enemies and therefore limit pest populations (Tscharntke et al., 2012) and possibly lead to a lower use of pesticides. Here, to our knowledge, the link between semi-natural habitats, pest abundance and insecticide use has not been established based on data at large scale (but see Paredes et al., 2021 on vineyards). Simple landscapes do not either consistently exacerbate insect pest problems (Rosenheim et al., 2022) or reduce pest control services (Karp et al., 2018; Petit et al., 2020). The current state of knowledge is thus insufficient to assess to what extent the landscape context of arable fields could be a lever to help farmers reduce their pesticide use.

In this paper, we develop a nationwide analysis of the links between landscape, pests and insecticide use, taking advantage of two unique national datasets, the DEPHY farm network, with pluri-annual agricultural practices currently recorded c.a. 3000 farms and the EPIPHYT database which centralises data from the French pest monitoring service. Analyses of 2009–2011 data from ca. 950 arable farms from the DEPHY farm network revealed a high variability of insecticide use among farmers adopting similar cropping systems, suggesting that other factors may drive their use (Lechenet et al., 2017). Here, based on data collected between 2014 and 2019, we specifically explore to what extent the landscape context of farms affected insecticide use in a subset of 557 DEPHY farms. These farms were selected because they adopted a comparable cropping strategy, allowing us to really evaluate the effect of the landscape context on insecticide use. In this subset of farms, we expected insecticide use to be lower in farms located in complex landscapes, characterised by small-sized crop patches and higher cover of semi-natural habitats (forests and permanent grasslands) and hedgerows, than those located in simple landscapes. We also examined the effect of landscape characteristics on insect pest pressure.

2. Material and methods

2.1. Selection of DEPHY farms

We first selected farms describing at least three fields during three consecutive years between 2014 and 2019 from the DEPHY farm network (Lechenet et al., 2016). We then selected a subset of farms conducting comparable cropping systems. This step was crucial to control that the use of insecticide was not due to farmers' cropping strategy, to ensure that our analyses focused on farms that were not too different in terms of crop sequences and to avoid potential confounding effects between cropping system and landscape context. The subset was identified by conducting a clustering analysis to type farms based on agronomic variables such as the nature of crops grown, tillage regime and fertilization (Supp Mat. 6). We kept the dominant type; it gathered 557 farms that grew at least one winter wheat over the 3-year crop sequence, used tillage and ploughing and applied intermediate amounts of nitrogen. The 557 farms were located across 252 municipalities and covered 93 different French Small Agricultural Areas (hereafter SAA), defined as homogeneous production basins (Fig. 1). The main crop types that were grown alongside wheat in the rotations were barley (58 % of the farms), oilseed rape (54 %), maize (36 %), beet (14 %), sunflower (12 %), mustard (10 %) and spring pea (8 %).

2.2. Insecticide use

Our objective was to analyse the effect of the landscape context of the 557 farms on their overall pesticide use, across crops and years. The response variable was thus the average insecticide use over the three-year crop sequences at the farm level. The applied doses of commercial products were reported by farmers for each field and year in the AGROSYST database (Ancelet et al., 2015). Insecticide use was estimated by the Treatment Frequence Index 'TFI', an indicator widely used in Europe to assess the reliance of cropping systems on pesticides (Lechenet et al., 2017; Guinet et al., 2023). TFI is the number of reference doses applied per hectare and per crop season (OECD, 2001). All reference doses were extracted from the *E*-phy online database provided by the French Ministry of Agriculture (ANSES, 2023). Seed coating with chemical pesticides was included in the TFI computation (1.0 additional TFI point for each crop sown with coated seeds). Non-chemical pesticides were excluded from TFI computation (according to the 'biocontrol' list of the French Ministry of Agriculture, MASA, 2023) We compiled yearly data to obtain an average TFI value per field for the 3 year-long crop sequence and then averaged these values at the farm level.

$$TFI = \sum_{j=1}^{k} \left(\sum_{i=1}^{n} \frac{D_{ij}.S_{ij}}{Dh_{ij}.S_t} \right) .\omega_j$$

where D_{ij}, Dh_{ij}, and S_{ij}, $i = 1, \ldots, n$, $j = 1, \ldots, k$ are, respectively, the applied dose, the reference dose (registered dose of the applied insecticide), and the treated surface area for each spraying operation i on each crop j; S_t is the total field area; and ω_j are the proportions of each crop j in the crop sequence.

2.3. Regional Pest pressure

To assess the level of insect pest pressure on each of the 557 farms, we mobilised data from the French national epidemiological monitoring network EPIPHYT, which reports the proportion of crop plants affected by pest types on a set of monitored fields in each region. In EPIPHYT, aphid damages were those that were the most widely monitored in cropping systems that include wheat and barley, which are the two dominant crops in our subset of 557 farms. Although we recognise that there are damages caused by insects other than aphids on our farms, we considered the nationwide aphid observational data as the best possible proxy to account for variations in insect pest pressure across the 557 farms. As observational protocols varied between SAAs, we could not use directly this quantitative data and each local record was converted into presence/absence data at the field scale. The pressure was then calculated at the spatial scale of the SAAs as the proportion of surveyed fields where the presence of aphids was recorded. Insect pest pressure per SAA was estimated in each SAA that included at least one of the 557 farms and for each year of the crop sequence of farms, yielding 398 values that varied between 0 and 0.72 across the 93 SAAs and six years. To estimate the contribution of pest pressure to variations in insecticide TFI, each of the 557 farms were attributed the average SAA level aphid pressure value over the three years of the crop sequence (Sup. Fig. 1e). There was some interannual variability in aphid pressure (Sup. Fig. 2.), reflecting differences in climatic conditions between years (Courson et al., 2022). The 398 annual SAA pest pressure values were used to test for an effect of landscape complexity.

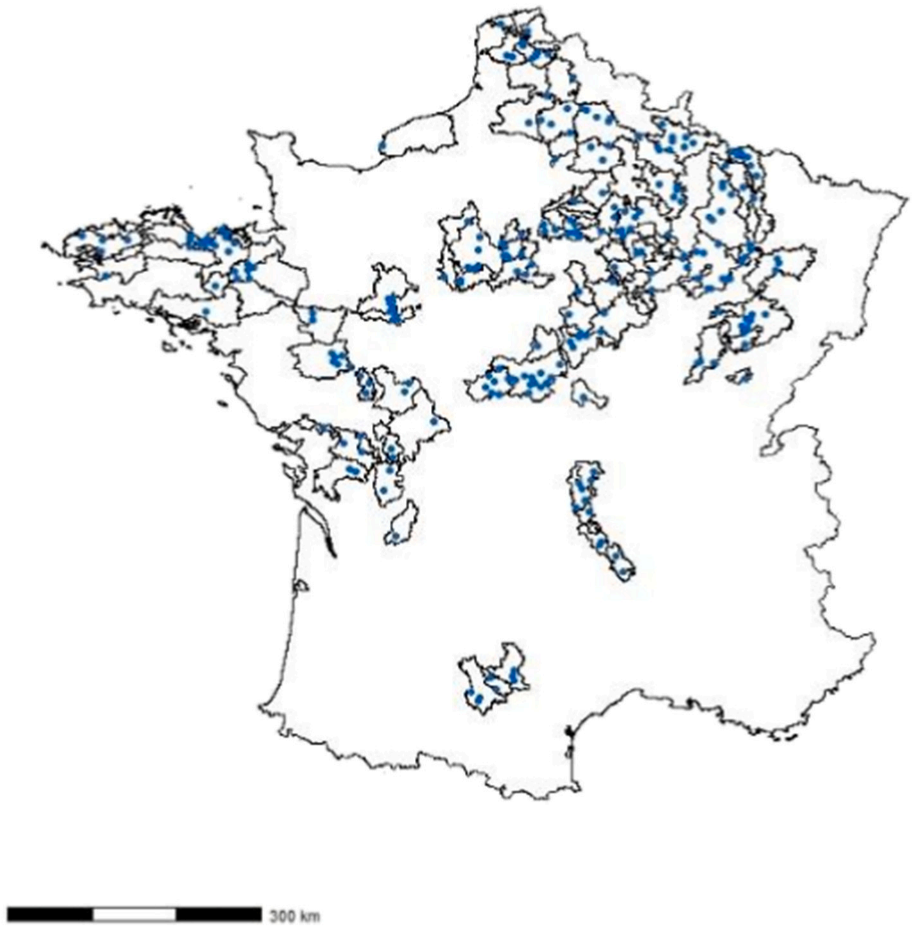

Fig. 1. Location of the 557 farms. Black borders line the small agricultural areas (SAAs).

2.4. Landscape context of farms

The landscape context of each farm was characterised by compiling two spatial national datasets, the Registre Parcellaire Graphique which describes agricultural land cover and the BD TOPO® (IGN, 2021) which maps forests, permanent grasslands and hedgerows. Here, we computed three landscape metrics which cover different aspects of landscape complexity, namely (i) pHedgerow, the proportional cover of hedgerows, (ii) pSNH, the proportional cover of patches of semi-natural habitats, i.e. forest as well as permanent and rotational grasslands, and (iii) MeanFieldSize, the mean field size of arable crops in the landscape. Landscape metrics were computed using the landscapemetrics package (v1.5.4 Hesselbarth et al., 2019) at a 1 m resolution and the alm package (v1.1; Allart et al., 2020) on the R software (R v. 4.0.4, R Core Team, 2022).

These three landscape metrics were used in two different models. They were first used as explanatory variables of the variations of on-farm insecticide use TFI. To this end, metrics were calculated at the municipality level, i.e. the most accurate data of each farm location in the AGROSYST database. They were calculated on the median year of the three year-long crop sequence given the high interannual correlation between the values for each landscape metrics (r values ranging from 0.998 to 0.999). Our dataset covered a wide range of landscape contexts (Sup. Fig. 1b, c, d). MeanFieldSize was negatively correlated to pHedgerow (rho = −0.5) and to pSNH (rho = −0.23) (Sup. Fig. 3.). The three landscape metrics were also used in a second model developed to test the expectation that pest pressure is lower in more complex landscapes. As pest pressure was expressed as aphid pressure per SAA, the metrics included in this second model were calculated at this same regional spatial grain, and for each year.

2.5. Other potential drivers of insecticide use

Since the amount of insecticides used is primarily crop-dependent (Urruty et al., 2016), we accounted for the nature of the crops in the crop sequences of the 557 farms. We identified several crop types that are highly dependent on insecticide use in France, namely oilseed rape, mustard, potatoes, peas and faba beans (Agreste, 2019). We thus created a covariable "Crop_sequence" that represented the cover of insecticide demanding crops (ha) relative to the total area of crops within the 3-year crop sequence (ha). Crop_sequence varied from 0 to ca. 0.5 (Sup. Fig. 1a.).

In addition, to ensure that potential associations between insecticide use and landscape metrics were not resulting from their independent responses to agricultural intensification, we checked the relationship of these variables with the potential crop productivity of farms. Crop productivity goals are often determined according to the yield potential that is substantially due to soil texture and associated available water. We used as a proxy of this potential the soil water holding capacity of farms which depends on soil depth, soil texture and soil organic matter content and describes the vulnerability of farms to water deficit, an issue of increasing concern for wheat production across France, and more widely across Europe (Wilcox and Makowski, 2014; Williams et al., 2016). We extracted for each of the 557 farms the soil water holding capacity (hereafter SWHC) from the french soil database (Gis SOL, 2011). SWHC data was available in five classes, ranging from <50 mm to >200 and its spatial distribution was consistent with the distribution of the average wheat crop yield per administrative unit across France

(Agreste, 2022).

2.6. Statistical analysis

First, to explain variations in insecticide TFI, we used a linear mixed model with a gaussian distribution. Fixed effects were the insect pest pressure, the three landscape metrics and the two covariables, Crop_sequence and SWHC. We also included interactions between the insect pest pressure and each landscape metrics. The identity of the farm was used as a random factor. We detected no correlation higher than 0.6 between any couple of explanatory continuous variables (Sup. Fig. 3.) and found no relationship between the SWHC class of each farm and the landscape metrics (Sup. Fig. 4.). To avoid any issues of collinearity, we performed a VIF score for all the predictors (vif function, car package v3.0.12 in R, Table 1). We detected no spatial autocorrelation of model residuals (see variogram in Sup. Fig. 5). Second, to test the expectation that pest pressure is lower in complex landscapes, we explored the relationship between annual SAA insect pest pressure and landscape metrics at the SAA level through a linear mixed model with a gaussian distribution, with the year as a random factor. We detected no spatial autocorrelation of model residuals (see variogram in Sup. Fig. 5).

To deal with issues of overdispersion and normality of residuals, the response variable of each model was normalized, squared transformed, and normalized again. All the explanatory variables were normalized. To assess the performance of models, we report both the marginal R^2 (R^2_m, associated to fixed effects only) and the total R^2 (R^2_{tot}, associated to the whole model therefore conditioning on the random effects; Nakagawa and Schielzeth, 2013). All analyses were performed with R software v4.0.4. (R Core Team, 2022).

We performed additional analyses following the same statistical procedure but focusing on specific crop types, namely soft wheat crops and oilseed rape crops. A first model was developed to explain variations in yearly insecticide TFI in the crop type with year as a random factor. and a second model was developed to examine the relationship between insect pest pressure and landscape metrics at the SAA level. Insect pest pressure was derived from observational data in the specific crop type, namely aphids observed in winter wheat and insect pests observed in oilseed rape.

3. Results

The insecticide TFI varied from 0 to 3.1 across the 557 farms. As expected, insecticide use was higher in farms that included a higher proportion of insecticide demanding crops in their rotation (Table 1, Fig. 2a, $R^2_m = 0.27$, $R^2_{tot} = 0.89$). Conversely, SWHC was not related to insecticide use (Chi2 = 3.4832, df = 5, p value = 0.778). Insecticide use increased with regional pest pressure, although the effect was limited here (Table 1, Fig. 2b).

We found that insecticide use was lower in landscapes with high cover of hedgerows (Table 1 and Fig. 2c). Analyses performed on yearly data for specific crop types confirmed this negative relationship, see Supp Mat. S7 for winter soft wheat and Supp Mat. S8 for oilseed rape.

At the SAA level, insect pest pressure decreased when hedgerow cover increased (Table 2, Fig. 3, R^2m = 0.05, R^2tot = 0.12). This relationship was also found for insect pests specifically observed in soft wheat (Supp Mat. S7) and for insect pests specifically observed in oilseed rape (Supp Mat. S8).

4. Discussion

Detecting consistent pest and pesticide responses to landscape characteristics requires to mobilise datasets of much larger size than those used in classical landscape ecological studies. Using an insecticide use dataset from 557 farms growing winter-wheat across France, and accounting for differences in cropping strategies, crop sequences and potential crop productivity among farms, we show that farmers used less insecticides in more complex landscapes, i.e. landscapes that contain a higher cover of hedgerows. We also show that the association between landscape simplification and insecticide use is very likely led by ecological processes, i.e. decreasing cover of hedgerows increased pest pressure, and increased pest pressure resulted in increased insecticide use per unit of arable land. To our knowledge, this is the first national-scale study providing empirical evidence of the beneficial role of the landscape-scale cover of hedgerows on pest levels and on sustainable crop production issues.

The strength of our approach is that the patterns observed are generic, as the relationship was tested over a large range of pedoclimatic conditions across France. Such approach can however only be correlative, which means that it requires to carefully consider the relationship with other possible covariables explaining the observed patterns. Accounting for the presence in the crop rotation of crops highly reliant on insecticides proved relevant, as could be expected (see Meehan et al., 2011). These crops were mostly Brassicaceae (oilseed rape and mustard), present in almost 60 % of our farms. We also explored the potential effect of the farm crop yield potential, which could positively influence insecticide use and landscape simplification. We detected no such effect on insecticide use, and this is in line with the lack of correlation between crop productivity and insecticide use on most arable farms of the DEPHY network (Lechenet et al., 2017) but as also shown elsewhere (Gagic et al., 2021). Potential crop yield did not affect landscape metrics either, suggesting that the degree of landscape simplification across our farms was driven by other factors. Among those, the history of farmers' individual decisions to enlarge his fields, remove or plant hedgerows is probably key (Barbottin et al., 2018) although the

Table 1
Model estimates for insecticide TFI in each farm ($N = 557$ farms) in response to SWHC (Soil Water Holding Capacity, a proxy of the potential crop productivity of farms), Crop_sequence (the proportion of insecticide-demanding crops in the crop sequence), Pest pressure (the regional aphid pressure) and three landscape metrics, i.e. pHedgerow the proportional cover of hedgerow, pSNH the proportion of semi-natural habitats, and MeanFieldSize the mean size of arable fields in the landscape surrounding farms.

	Estimate	Std. Error	df	t value	Pr(>|t|)		VIF
SWHC <50 mm	0.180	0.20	265.37	0.921	0.36	ns	
SWHC 50-100 mm	0.096	0.094	269.51	1.028	0.30	ns	
SWHC 100-150 mm	−0.022	0.13	272.15	−0.175	0.86	ns	1.46
SWHC 150-200 mm	0.082	0.14	266.97	0.592	0.55	ns	
SWHC >200 mm	−0.05	0.13	275.72	−0.421	0.67	ns	
Crop_sequence	0.31	0.045	543.46	6.910	**0.0001**	***	1.16
Pest Pressure	0.069	0.035	537.35	1.956	**0.049**	*	1.10
pSNH	0.030	0.052	392.99	0.577	0.564	ns	1.25
pHedgerow	−0.230	0.060	338.37	−3.842	**0.0001**	***	1.48
MeanFieldSize	0.101	0.059	537.04	1.702	0.089	.	1.72
Pest Pressure:pSNH	0.053	0.039	523.51	1.356	0.176	ns	1.10
Pest Pressure:pHedgerow	0.004	0.039	543.99	0.116	0.907	ns	1.47
Pest Pressure:MeanFieldSize	−0.056	0.041	464.40	−1.366	0.173	ns	1.63

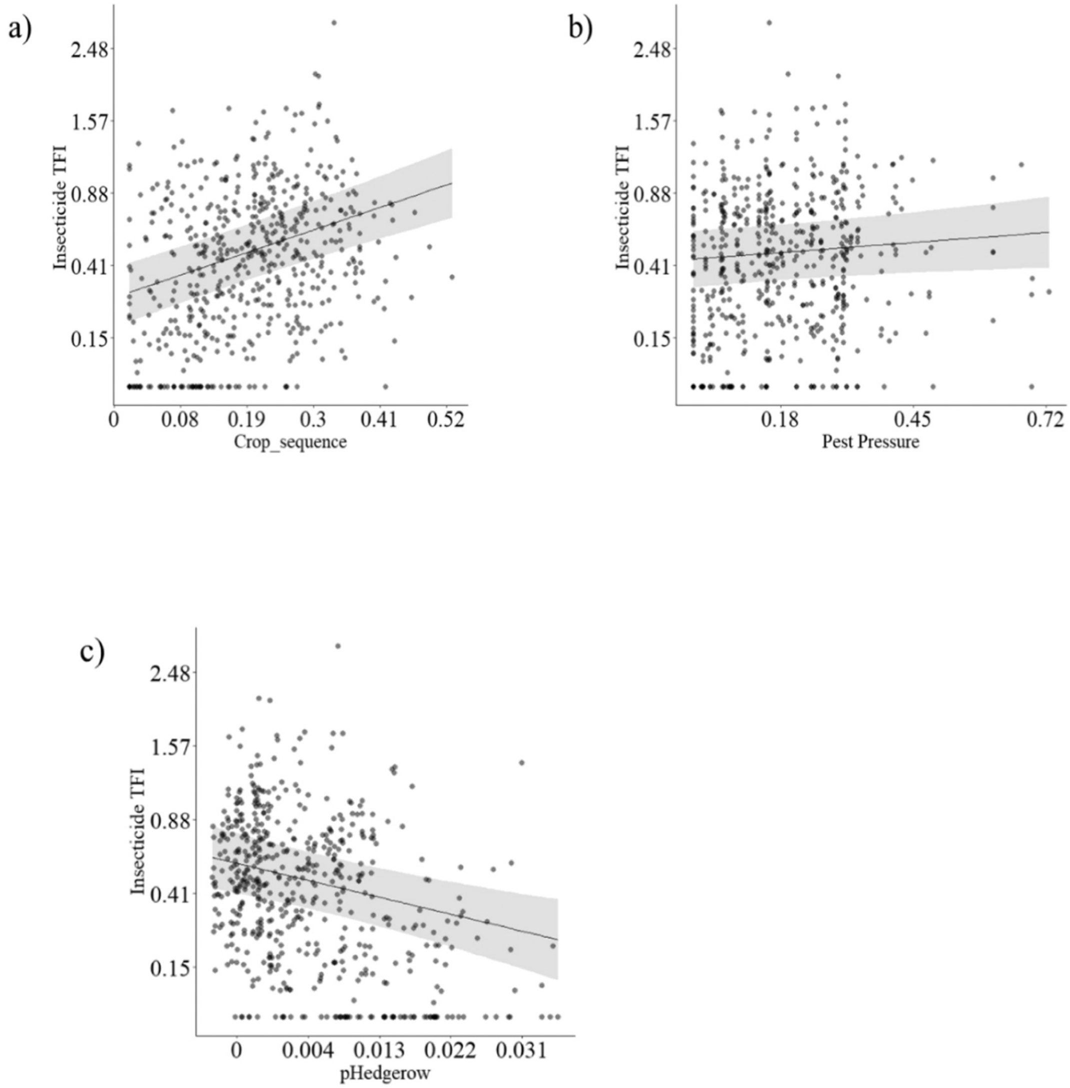

Fig. 2. Marginal effects of a) the proportion of crops highly dependent on insecticides in the crop sequence (Crop_sequence); b) the regional pest pressure; c) the proportion of hedgerows (pHedgerows) surrounding farms on the insecticide TFI.

Table 2
Model estimates for the insect pest pressure at the Small Agricultural Area level (SAA) in response to landscape metrics estimated at the SAA level ($N = 398$ SAA/year). the proportion of semi-natural habitats (pRegionalSNH), the proportional cover of hedgerow (pRegionalHedgerow) and the mean size of arable fields (RegionalMeanFieldSize).

	Estimate	Std. Error	df	t value	Pr(>|t|)		VIF
(Intercept)	−0.007	0.112	6.34	−0.065	0.952		
pRegionalHedgerow	−0.170	0.050	400.83	−3.394	**0.001**	**	1,13
pRegionalSNH	0.065	0.053	358.15	1.239	0.216		1,04
RegionalMeanFieldSize	0.105	0.057	218.65	1.823	0.069	.	1,11

past municipality-wide land consolidation programmes have had very significant effects on mean field size and hedgerow density in many French landscapes (Burel and Baudry, 1990).

Once these covariates were accounted for, we detected a strong signal of a negative association between the proportional cover of hedgerows in the landscape and on-farm insecticide use. The cover of hedgerows around most farms was c.a. 1 %, which is the average cover of hedgerows at the national level (Pointereau, 2002). Our model suggests that when landscape-scale hedgerow cover reaches 3 %, insecticide use is halved. We also provide evidence that increased cover of hedgerows around farms is significantly associated with lower occurrence of aphids, every year. This pattern is most likely explained by the beneficial effects of hedgerows on ground-dwelling and flying aphid natural enemies (Alignier et al., 2014) that can altogether reduce aphid abundance up to 60 % in wheat crops (Rusch et al., 2013). Increasing landscape-scale hedgerow cover from 1 % to 5 % was shown to boost aphid parasitism by 30 % (Dainese et al., 2017) and to increase aphid predation by ladybeetles by up to 50 % (Bianchi and van der Werf, 2003). We additionally demonstrated that a higher regional aphid pressure led to increased use of pesticides across our farms and this pattern matches the standard economic assumption that farmers aim at maximizing their economic income, and hence use insecticide when insect pest levels are likely to cause crop damage. The association, though significant, was maybe not as strong as could be expected. This may be related to our

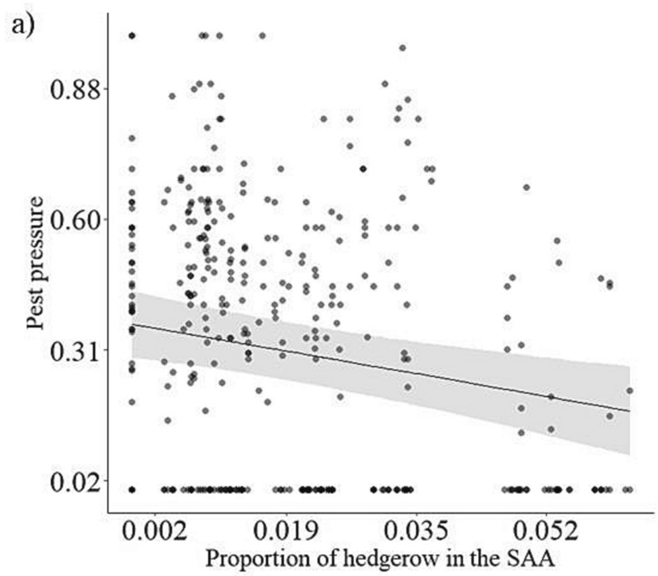

Fig. 3. Marginal effects of the regional proportional cover of hedgerow (PRegionalHedgerow) on the regional insect pest pressure (data ranging from 2014 to 2019).

pest data resolution, which represented a proportion of fields where the pest was observed rather than real pest abundances. It could as well be due to variations in the behaviour of farmers when it comes to spray insecticides which can stem from many factors, such as the differences in knowledge and skills or in the perception of risk (Wu et al., 2018; Bakker et al., 2021).

Reducing the reliance of agriculture on pesticides is a primary goal and will benefit biodiversity as well as farmers and consumers (Dudley et al., 2017; Jacquet et al., 2022). Our research shows that pathways towards reduced pesticide use operate at multiple spatial scales and should account for the landscape context of farms. Specifically, our nationwide analysis demonstrates that maintaining hedgerows in the landscape means lower aphid pressure and less insecticide use in French wheat-based crop rotations. Hedgerows are important elements of many landscapes around the world (Baudry et al., 2000) and their contribution to multiple services widely acknowledged (Montgomery et al., 2020). We show here that hedgerow restoration in simple landscapes could be part of a strategy towards reduced insecticide use in arable cropping systems that are dominant in many countries.

CRediT authorship contribution statement

Emeric Courson: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Benoit Ricci:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Lucile Muneret:** Writing – review & editing. **Sandrine Petit:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships

that could have appeared to influence the work reported in this paper.

Data availability

The data is available at https://doi.org/10.57745/MLZFRO (Courson et al., 2023)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170182

References

Agreste, 2019. Agreste chiffres et données. Pratiques culturales en grandes cultures 2017. IFT et nombre de traitements. Juin n° 2019-3.
Agreste, 2022. Agreste conjoncture Grandes Cultures. Aout n° 2022-94.
Alignier, A., Raymond, L., Deconchat, M., Menozzi, P., Monteil, C., Sarthou, J.-P., Vialatte, A., Ouin, A., 2014. The effect of semi-natural habitats on aphids and their natural enemies across spatial and temporal scales. Biol. Control 77, 76–82.
Allart, R., Ricci, B., Poggi, S., 2020. R Package Alm: Automated Landscape Mapping. https://doi.org/10.15454/AKQW7Y.
Ancelet, E., Munier-Jolain, N., Jolys, O. 2015. Agrosyst, le système d'information au coeur du Plan Ecophyto de réduction d'usage des pesticides. Colloque" Données, Agriculture, Environnement… Innovation", Agreenium-IAVFF.
ANSES. 2023 E-Phy: Le catalogue des produits phytopharmaceutiques et de leurs usages, des matières fertilisantes et des supports de culture autorisés en France https://ephy.anses.fr/.
Bakker, L., Sok, J., van der Werf, W., Bianchi, F.J.J.A., 2021. Kicking the habit: what makes and breaks Farmers' intentions to reduce pesticide use? Ecol. Econ. 180, 106868.
Barbottin, A., Bouty, C., Martin, P., 2018. Using the French LPIS database to highlight farm area dynamics: the case study of the Niort plain. Land Use Policy 73, 281–289.
Baudry, J., Bunce, R.G.H., Burel, F., 2000. Hedgerows: an international perspective on their origin, function and management. J. Environ. Manag. 60, 7–22.
Bianchi, F.J.J.A., van der Werf, W., 2003. The effect of the area and configuration of hibernation sites on the control of aphids by Coccinella septempunctata (Coleoptera: Coccinellidae) in agricultural landscapes. Environ. Entomol. 32, 1290–1304.
Burel, F., Baudry, J., 1990. Structural dynamic of a hedgerow network landscape in Brittany. France. Land. Ecol. 4, 197–210.
Courson, E., Petit, S., Poggi, S., Ricci, B., 2022. Weather and landscape drivers of the regional level of pest occurrence in arable agriculture: a multi-pest analysis at the French national scale. Agric. Ecosyst. Environ. 338, 108105.
Courson, E., Ricci, B., Muneret, L., Petit, S., 2023. Reducing pest pressure and insecticide use by increasing hedgerows in the landscape – dataset. Recherche Data Gouv.
Dainese, M., Montecchiari, S., Sitzia, T., Sigura, M., Marini, L., 2017. High cover of hedgerows in the landscape supports multiple ecosystem services in Mediterranean cereal fields. J. Appl. Ecol. 54, 380–388.
Dudley, N., Attwood, S.J., Goulson, D., Jarvis, D., Pretty, J., 2017. How should conservationists respond to pesticides as a driver of biodiversity loss in agroecosystems? Biol. Conserv. 209, 449–453.
Gagic, V., Holding, M., Venables, W.N., Hulthen, A.D., Schellhorn, N.A., 2021. Better outcomes for pest pressure, insecticide use, and yield in less intensive agricultural landscapes. Proc. Natl. Acad. Sci. U. S. A. 118 (12).
Geiger, F., Bengtsson, J., et al., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97–105.
Guinet, M., Adeux, G., Cordeau, S., Courson, E., Nandillon, R., Zhang, Y., Munier-Jolain, N. 2023 Fostering temporal crop diversification to reduce pesticide use. Nat Commun. 2023 Nov 16;14(1):7416. doi: 10.1038/s41467-023-43234-x.
Gis SOL, 2011. L'état des sols de France. Groupement d'intérêt scientifique sur les sols.
Hesselbarth, M.H.K., Sciaini, M., With, K.A., Wiegand, K., Nowosad, J., 2019. Landscapemetrics: an open-source R tool to calculate landscape metrics. Ecography 42, 1648–1657 (v0.0).
IGN, 2021. BDtopo V3. https://geoservices.ign.fr/bdtopo.
Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022. Pesticide-free agriculture as a new paradigm for research. Agron. Sustain. Dev. 42, 8. https://doi.org/10.1007/s13593-021-00742-8.
Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., et al., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proc. Natl. Acad. Sci. U. S. A. 115, E7863–E7870.

Kim, K.H., Kabir, E., Jahan, S.A., 2017. Exposure to pesticides and the associated human health effects. Sci. Total Environ. 575, 525–535.
Lechenet, M., Makowski, D., Py, G., Munier-Jolain, N., 2016. Profiling farming management strategies with contrasting pesticide use in France. Agric. Syst. 149, 40–53. https://doi.org/10.1016/j.agsy.2016.08.005.
Lechenet, M., Dessaint, F., Py, G., Makowski, D., Munier-Jolain, N., 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nat. Plants 3, 1–6. https://doi.org/10.1038/nplants.2017.8.
Malaj, E., Morrissey, C.A., 2022. Increased reliance on insecticide applications in Canada linked to simplified agricultural landscapes. Ecol. Appl. 32 (3), e2533.
MASA. 2023. Memorandum DGAL/SDSPV/2022-949 of the 22/12/2022 : List of biocontrol plant protection products under Articles L.253-5 and L.253-7 of the Rural and Maritime Fishing Code https://agriculture.gouv.fr/quels-sont-les-produits-de-biocontrole.
Meehan, T.D., Gratton, C., 2015. A consistent positive association between landscape simplification and insecticide use across the Midwestern US from 1997 through 2012. Environ. Res. Lett. 10, 114001.
Meehan, T.D., Werling, B.P., Landis, D.A., Gratton, C., 2011. Agricultural landscape simplification and insecticide use in the Midwestern United States. Proc. Natl. Acad. Sci. U. S. A. 108, 11500–11505. https://doi.org/10.1073/pnas.1100751108.
Montgomery, I., Caruso, T., Reid, N., 2020. Hedgerows ad ecosystems: service delivery, management and restoration. Annu. Rev. Ecol. Evol. Syst. 51, 81–102.
Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. https://doi.org/10.1111/j.2041-210x.2012.00261.x.
Nicholson, C.C., Williams, N.M., 2021. Cropland heterogeneity drives frequency and intensity of pesticide use. Environ. Res. Lett. 16 (7), 074008 https://doi.org/10.1088/1748-9326/ac0a12.
OECD 2001. Environmental Indicators for Agriculture, Volume 3: Methods and Results (http://www.oecd.org/tad/sustainable-agriculture/40680869.pdf.
Osteen, C.D., Fernandez-Cornejo, J., 2013. Economic and policy issues of U.S. agricultural pesticide use trends. Pest Manag. Sci. 69, 1001–1025.
Paredes, D., Rosenheim, J.A., Chaplin-Kramer, R., Winter, S., Karp, D.S., 2021. Landscape simplification increases vineyard pest outbreaks and insecticide use. Ecol. Lett. 24, 73–83. https://doi.org/10.1111/ele.13622.
Petit, S., Muneret, L., Carbonne, B., Hannachi, M., Ricci, B., Rusch, A., Lavigne, C., 2020. Landscape-scale expansion of agroecology to enhance natural pest control: a systematic review. Adv. Ecol. Res. 63 https://doi.org/10.1016/bs.aecr.2020.09.001.
Pointereau, P., 2002. Les haies: évolution du linéaire en France depuis 40 ans. Courrier de l'environnement de l'INRA 46.
Popp, J., Pető, K., Nagy, J., 2013. Pesticide productivity and food security. A review. Agron. Sustain. Dev. 33, 243–255. https://doi.org/10.1007/s13593-012-0105-x.
R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.
Rosenheim, J.A., Cluff, E., Lippey, M.K., Cass, B.N., Paredes, D., Parsa, S., Karp, D.S., Chaplin-Kramer, R., 2022. Increasing crop field size does not consistently exacerbate insect pest problems. Proc. Natl. Acad. Sci. U. S. A. 119 (37), e2208813119.
Rusch, A., Bommarco, R., Jonsson, M., Smith, H.G., Ekbom, B., 2013. Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. J. Appl. Ecol. 50, 345–354. https://doi.org/10.1111/1365-2664.12055.
Sánchez-Bayo, F., Wyckhuys, K.A.G., 2019. Worldwide decline of the entomofauna: a review of its drivers. Biol. Conserv. 232, 8–27. https://doi.org/10.1016/j.biocon.2019.01.020.
Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., et al., 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. Biol. Rev. 87, 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x.
Urruty, N., Deveaud, T., Guyomard, H., Boiffin, J., 2016. Impacts of agricultural land use changes on pesticide use in French agriculture. Eur. J. Agron. 80, 113–123.
Van der Werf, W., Bianchi, F.J., 2022. Options for diversifying agricultural systems to reduce pesticide use: can we learn from nature? Outlook on Agriculture. 51 (1), 105–113. https://doi.org/10.1177/00307270221077442.
Waterfield, G., Zilberman, D., 2012. Pest management in food systems: an economic perspective. Annu. Rev. Environ. Resour. 37, 223–245.
Wilcox, J., Makowski, D., 2014. A meta-analysis of the predicted effects of climate change on wheat yields using simulation studies. Field Crop Res. 156, 180–190.
Williams A, Hunter MC, Kammerer M. et. al. 2016. Soil water Holding capacity mitigates downside risk and volatility in US Rainfed maize: time to invest in soil organic matter? PLoS One 11(8): e0160974.
Wu, Y., et al., 2018. Policy distortions, farm size and the overuse of agricultural chemicals in China. Proc. Natl. Acad. Sci. U. S. A. 115, 7010–7015.