Best organic farming deployment scenarios for pest control: a modeling approach

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Abstract

Organic Farming (OF) has been expanding recently around the world in response to growing consumer demand and as a response to environmental concerns. Its share of agricultural landscapes is expected to increase in the future. The effect of OF expansion on pest abundance and Conservation Biological Control (CBC) in organic and conventional fields is difficult to predict. Given the inherent complexity of CBC and the lack of CBC data across situations of OF expansion, and the probable interactions with landscape context, modeling is a useful tool to understand and forecast how pests and their control may vary during OF expansion. Here, we used a neutral spatially explicit landscape model simulating pests and predators interacting on an agricultural landscape to investigate the impact of different organic deployment strategies on the CBC. We modeled three spatial strategies of conversion of conventional fields to organic fields (Random, Isolated fields first, and Grouped fields first) in landscapes contrasting in terms of semi-natural habitat areas fragmentation. We performed simulations considering organic farming deployment, different initializations of population dynamics and various combinations of pesticides effects on pests and predators depending on the land use.

Our results showed that the organic farming deployment affected more predator densities than pest densities for most combinations of landscape types and deployment strategies. Its impact was also generally stronger in organic than conventional fields and in landscapes with large amounts of fragmented seminatural habitats. Based on pest densities and the predator to pest ratio, our results suggest that a progressive organic conversion with a focus on isolated conventional fields could help promote CBC. Careful landscape planning of OF deployment appeared most necessary when OF pesticides had a low efficiency, and in landscapes with low quantities of semi-natural habitats.

Introduction

The intensification of agricultural systems in recent decades has relied on both an increase in field area and a larger dependency on chemical pesticides (Duru et al. 2015; Knapp et van der Heijden 2018). This process led to profound changes in landscapes with a reduction and fragmentation of seminatural habitats (Sirami et al. 2019; Tscharntke et al. 2016) and a reduced diversity of the crop mosaic (Tscharntke et al. 2016). This process had demonstrated negative impacts on biodiversity (Perez-Alvarez, Nault, et Poveda 2019; Sánchez-Bayo et Wyckhuys 2019) including on species of interest for agriculture such as pollinators (Goulson Dave et al. 2015; Muth et Leonard 2019) and pest natural enemies (Sánchez-Bayo et Wyckhuys 2019; Sirami et al. 2019; Tsutsui, Kobayashi, et Miyashita 2018). Further, the intensive use of chemical pesticides had negative impacts on human health, and biodiversity (Mózner, Tabi, et Csutora 2012; Pärn, Pinay, et Mander 2012; Sánchez-Bayo et Wyckhuys 2019). Hence, there is an urgent need to identify alternative cropping systems that reduce the negative impacts of intensive agriculture while maintaining yields as much as possible (Colbach et al. 2020; Smith et al. 2020). Organic Farming (OF) is one of these possible alternative systems. Its performances have received much attention recently, in terms of yield (Knapp et van der Heijden 2018; Le Gal et al. 2020), of its effects on biodiversity (Caprio et al. 2015; Lourenço et al. 2021; Smith et al. 2020) and of its nutritional value and therefore its impact on human health (Gomiero 2018; Salomé et al. 2021).

Pest management in OF relies on biological control methods, specific cultural practices and on a restricted list of authorized, non-synthetic pesticides that may vary depending on the organic certificate. Among biological control methods, conservation biological control, i.e. the enhancement of natural enemy abundance and activity to reduce pest populations (Heimpel et Mills 2017), is of particular interest for OF as it takes advantage of the greater diversity and abundance of natural enemies that are present in organic fields (Holland et al. 2016). A wealth of literature, however, demonstrates that the potential and efficiency of conservation biological control within a field do not depend only on local agricultural practices but also on the structure of the surrounding landscape (Begg et al. 2017; Muneret, Auriol, Thiéry, et al. 2019), including its amount of seminatural habitat (Le Gal et al. 2020; Zamberletti et al. 2021) and the characteristics of the crop mosaic (Hillaert et al. 2018, 2020; Le Gal et al. 2020; Smith et al. 2020).

OF has been expanding recently around the world in response to growing consumer demand and environmental concerns, and its share in agricultural landscapes is expected to increase in the future (Paull et Hennig 2016). The effect of OF expansion in landscapes can be approximated, in a “space for time” approach (Blois et al. 2013), by investigating the effect of the proportion of OF in the landscape. A majority of the literature on OF expansion points toward new organic farmers and fields clustering around existing ones (Gabriel et al. 2009; Marton et Storm 2021; Sánchez Herrera et Dimitri 2019; Zollet et Maharjan 2021). Clustering happens for socio-economic and agronomic reasons, because OF conversion happens primarily “in agriculturally less-favored areas where economic incentives for conversion to organic farming do not need to be high and the loss of production due to conversion will be comparatively small” (Gabriel et al. 2009) such as isolated, hard to access, or less productive areas (Ilbery, Holloway, et Arber 1999), but also because OF is often driven by newcomers, who could settle down more easily in the proximity of existing clusters, in less-favored areas, and in places where a “prevalence of small-scale, part-time, and self-sufficiency-oriented farming” is observed (Zollet et Maharjan 2021).

Studies that investigated pest abundance in crops as a function of OF area in the landscape found that pests were either less (Gosme et al. 2012) or similarly (Muneret et al. 2018; Ricci et al. 2009) abundant when OF area increased. Moreover, predators were either more or similarly abundant (T. Diekötter et al. 2016; Tim Diekötter et al. 2010; Djoudi et al. 2018, 2019; Inclán et al. 2015; Lefebvre et al. 2016; Muneret, Auriol, Thiéry, et al. 2019; Puech et al. 2015), reviewed in (Petit et al. 2020), suggesting that earlier studies showing increases in damage associated with OF may have been influenced by the low amount of OF in the landscape in its early beginnings and that OF expansion strategies may be of utmost importance (Muneret, Auriol, Bonnard, et al. 2019).

The effect of OF expansion on pest abundance and conservation biological control in organic and conventional fields is difficult to predict. It will depend on the efficiency of pest control in organic crops, on the ability of predators to develop in these crops and on the interplay between pest and predator dispersal traits and landscape structure that conditions the ability of pests and predators to move among crops and between crops and seminatural habitats (Kremen et al. 2007; Le Gal et al. 2020). More complex landscapes, i.e. landscapes with more, and more fragmented, seminatural habitats and a more heterogeneous crop mosaic, may sustain more biodiversity (Batáry et al. 2011; Petit et al. 2020; Smith et al. 2020; Tscharntke et al. 2021; Tuck

et al. 2014) and spill-over of predators from seminatural habitats into crops is expected to be larger there (Concepción, Díaz, et Baquero 2008; Tscharntke et al. 2012). Such landscapes may also exhibit more movements of pests from seminatural habitats to crops if pests find resources in seminatural habitats at some point of their life cycle (Juhel et al. 2017). As a result, an increasing amount of seminatural habitat in the landscape generally increases the abundance and diversity of natural enemies as well as pest predation and parasitism but its effect on pest abundance or damage is case dependent (Chaplin-Kramer et al. 2011; Karp et al. 2018; Veres et al. 2013). Similarly, pest and predator movements between organic and conventional crops are expected to increase with the edge length between these two crop types, so organic expansion should affect more pest abundance in conventional crops when the two crop types are interspersed. The response of pest abundance to OF extension may moreover differ in organic and conventional fields: local management is expected to have large effects on biodiversity or ecological functions when landscapes are of intermediate intensity but to have little effect when landscapes are either very or very little intensive (the intermediate landscape hypothesis (Perez-Alvarez, Nault, et Poveda 2019; Tscharntke et al. 2005, 2012)) and, reciprocally, landscape effects are supposed to depend on local practice intensity (Petit et al. 2020). Such interactions have, however, seldom been observed in the field (Petit et al. 2020, but see e.g. (Perez-Alvarez, Nault, et Poveda 2019; Ricci et al. 2019)).

Given the inherent complexity of conservation biological control (Begg et al. 2017) and the lack of conservation biological control data along with situations of OF expansion, modeling appears as a useful tool to understand and forecast how pests and their control may vary during OF expansion in a diversity of landscape contexts. The only published modeling study to our knowledge considered a pest-parasitoid system in a landscape exclusively composed of conventional and organic fields (Bianchi, Ives, et Schellhorn 2013). This study interestingly showed that clustering organic and conventional fields decreased the proportion of OF necessary for maintaining the parasitoid population and decreased pest load. It also showed that intermediate levels of OF may lead to transitory peaks in pest load due to the delay of the parasitoid population response to pest abundance (Bianchi, Ives, et Schellhorn 2013). It is therefore interesting and necessary to study, through modeling approaches, how spatial strategies of organic farming deployment impact conservation biological control (Adl, Iron, et Kolokolnikov 2011; Bianchi, Ives, et Schellhorn 2013). As stated by Petit et al, (2020), such modeling approaches “can offer in silico tests of the consequences of much larger proportions

of agroecological practices in the landscape" and could be combined with empirical studies to "provide key insights about how natural enemies and pests will behave in future landscapes."

In the following, we pair a grid-based landscape model and a spatially explicit Lotka-Volterra type predator-prey model (Ciss et al. 2016; Roques 2015) to investigate how contrasted scenarios of OF expansion, defined by their spatial arrangements, impact pest abundance in organic and conventional crops. The scenarios are applied to a diversity of landscapes differing in their amount of seminatural habitat and its fragmentation. We further investigate to what extent conclusions would differ for contrasted types of OF differing in their pest control methods Intensity and specificity regarding predators.

Material and Methods

1 - Model description

1.1 - Stochastic landscape model

We used a landscape model initially developed by Roques and Stoica (2007), improved by Roques (2015) and Martinet and Roques (2022). This landscape model generates dynamic stochastic landscapes with several types of land uses over a square grid ($n \times n$ matrix). The user controls the proportion of fields (=grid cells) allocated to each type of land use, the landscape fragmentation, and the temporal changes in land use (Ciss et al. 2016). Details on the model and its mathematical foundations can be found in (Roques 2015). Here, we consider landscapes composed of three land uses: (i) seminatural habitats (SNH), (ii) Organic Farming crops (OF), and (iii) conventional crops (CF).

The fragmentation of SNH is controlled by the *fr* parameter, which measures the landscape-level average proportion of neighbors among the 4 closest neighbors of each HSN cell that are not of the HSN type. *fr* is in the range [0,1], and increases with HSN fragmentation (see Table 1).

1.2 - Population dynamic model

1.2.1 - General description

The model describes the density of the predator population $P_t(x)$ and of the pest population

$N_t(x)$at each position $x=(i,j)$ over the grid and at each time step *t* by the following Lotka-Volterra equations:

$$\begin{cases} N_t'(x)=d_N D[N_t(x)]+f_N(t,x,N_t(x))-\rho n(t,x)N_t(x)-\alpha_1 N_t(x)P_t(x) \\ P_t'(x)=d_P D[P_t(x)]+f_P(t,x,P_t(x))-\rho p(t,x)P_t(x)+\alpha_2 N_t(x)P_t(x) \end{cases} (1)$$

where $D[.]$ defined as: $D[U(x)]=D[U_{ij}]=(U¿¿i+1j+U_{i-1j}+U_{ij+1}+U_{ij-1}-4U_{ij})/\delta_x^2$¿is the discrete Laplace operator modeling the movements of the individuals to adjacent cells, $\delta_x=1/n$ being the length of a unit cell in the landscape.

From each position $x=(i,j)$, and during a time interval $\delta_t \ll 1$, a proportion $\frac{4d_N\delta_t}{\delta_x^2}$ of the pest population (resp. $\frac{4d_P\delta_t}{\delta_x^2}$ of the predator population) moves to its 4 adjacent cells. Thus d_N and d_P directly control the mobility of the pest and predator populations. We assume periodic conditions at the boundaries of the lattice.

The terms $f_N(t,x,N_t(x))$ and $f_P(t,x,P_t(x))$ stand for the pest and predator growth functions while $\rho_N(t,x)N_t(x)$ and $\rho_P(t,x)P_t(x)$ account for the pest and predator death rates caused by the use of pesticides.

The interaction terms $-\alpha_1 N_t(x)P_t(x)$ and $\alpha_2 N(x)P_t(x)$ describe the effects of predation on the pest and predator growth rates, respectively.

The system is scaled so that the carrying capacities of P and N are both equal to 1 thus the population densities are expressed in units of their respective carrying capacities. We also assume that $\alpha_1=\alpha_2=\alpha$ (see Table 1)

1.2.2 - Timing of ecological processes

The year is divided into equal intervals $\delta_t$each corresponding to a dispersal event of pests and predators. The number of intra-annual time steps is thus calculated as 1+ (1/δ_t). Each year is

divided into two periods [0, ½[and [½, 1] during which ecological processes differ (Table 2). The first half of the year schematically represents the season where the crop is absent, pests do not reproduce and there are no pesticide treatments. During the second half of the year, pest populations grow only in the crops and crops are treated with pesticides. The predators, in contrast, reproduce all year long and only in semi-natural habitats. Like pests, they are submitted to pesticide treatments in crops during the second half of the year.

1.2.3 - Organic farming systems

We considered four types of organic farming (Table 3). In the most intensive OF types (1 and 2), pesticides are as efficient in organic fields as in conventional ones so that the mortality of pests due to crop protection practices is the same. These two OF types differ by the specificity of these control measures that either do not (type 1) or do (type 2) affect predators, but less than in conventional fields. In the less intensive OF types (3 and 4) pest management is less efficient in OF fields and pest mortality rates are half those in conventional fields. As before, types 3 and 4 differ by the specificity of their crop protection practices that either do (type 3) or do not (type 4) affect predators.

Table 1. List of model parameters.

Parameter	Description	Unit	Values
Dynamic landscape model:			
n	Size of the lattice		24
fr	Fragmentation index	dimensionless	{0.1,0.5,0.9}
T	Time horizon	year	50
Model of population dynamics:			
d_N	Pest dispersal coefficient	unit area.year^{-1}	$\frac{1}{n^2}\{0.1,0.5,1\}$
d_P	Predator dispersal coefficient	unit area.year^{-1}	$\frac{1}{n^2}\{0.1,0.5,1\}$
r_N	Pest intrinsic growth rate	year^{-1}	$2\{\ln(50), \ln(100)\}$
r_P	Predator intrinsic growth rate	year^{-1}	$\ln(2)$

γ	Predator life expectancy in crops	year	½
α	Predation index	indiv^{-1} year^{-1}	$\frac{1}{\gamma}\{4/3,4\}$
v	Pesticide effect	year^{-1}	$r_N/2=\{\ln(50),\ln(100)\}$

Table 2. Values of the growth functions $f_N(t,x,N_t(x))$ and $f_P(t,x,P_t(x))$. r_N is the pest intrinsic growth rate in the crops in the absence of pesticide, γ the natural enemy life expectancy in the absence of resources and r_P the natural enemy birth rate in seminatural habitats.

	$f_N(t,x,N)$		$f_P(t,x,P)$	
Time span	[0, ½[	[½, 1]	[0, ½[	[½, 1]
Land use: *CF*	0	$r_N N(1-N)$	$-P/\gamma$	$-P/\gamma$
Land use: *BIO*	0	$r_N N(1-N)$	$-P/\gamma$	$-P/\gamma$
Land use: *SNH*	0	0	$r_P P(1-P)$	$r_P P(1-P)$

Table 3. Effects of pesticides on the pest and the natural enemies in conventional and organic farming. Four organic farming systems were considered. OF1 and OF2 correspond to intensive crop protection (high pest mortality) while OF3 and OF4 are less intensive. In OF1 and OF4 pesticides do not affect natural enemies while OF2 and OF3 are less specific.

	$\rho(t,x)$ (second half of year)	
	$\rho_N(t,x)$	$\rho_P(t,x)$
CF	$2v$	$2v$
OF 1	$2v$	0
OF 2	$2v$	v
OF 3	v	$v/2$
OF 4	v	0

1.2.4 - Parameter values

Intrinsic growth rates: The pest reproduces only during the second half of the year. During one year, the population would increase by a factor of exp(rN)/2 in the absence of any limiting factor. We thus assumed that, under these conditions, the population would increase by a factor of 50 or 100 over the season. We assumed a lesser yearly increase for the predator of exp(rp)=2, i.e. a population doubling in the absence of pests or any limiting factor. To compensate for this increase, we assumed a life expectancy of the natural enemies on the crops of γ=1/2 year, in the absence of pests.

Mortality due to pesticides: We assumed that the mortality rate induced by the use of pesticides can reach levels comparable to the pest growth rates ($2\nu \in 2\{\ln 50, \ln 100\}$). The mortality due to pesticides reaches this maximum value for both pests and predators in the conventional fields and for pests only in the intensive OF systems (types 1 and 2). In these situations, mortality compensates for the pest population's local increase and drastically reduces predator populations. Mortality caused by pesticides is reduced by half or set to 0 for pests or predators depending on the OF systems (Table 3).

Dispersal: The values for dN and dP were chosen so that approximately between 0.1% (dN or dP=$0.1/n^2$) and 1% (dN or dP=$1/n^2$) of individuals in a given cell move to neighboring cells every day.

2 - Initial Conditions

2.1 - Landscapes

Simulations were run on 9 landscape types differing in their proportion of semi-natural habitats SNH (either 10, 25, or 50% of total area) and in the fragmentation of these habitats (*fr* values: 0.1, 0.5 and 0.9). Initially, 10% of crops were OF and 90% CF based on the current national proportions in France (ORAB PACA 2020) and on the proportion of worldwide cropped and pasture land that is practicing some forms of OF (Pretty et al, 2018). Based on that, we generated three types of initial landscapes corresponding to three proportions of each land-use, named respectively Qin1 (10% SNH; 9% OF; 81% CF), Qin2 (25% SNH; 7.5% OF; 67.5% CF),

and Qin3 (50% SNH; 5% OF; 45% CF). In the remainder of this paper, we refer to these three initial landscapes in terms of SNH proportions (SNH 10%, 25% and 50%).

Initial OF crops were allocated randomly among crop cells. Each simulation of the model was run on a different initial landscape. Each landscape type was thus represented by 11664 landscapes, each corresponding to a unique combination of population dynamics parameters (Table 1) and spatial strategy for organic farming deployment (see below).

2.2 - Population dynamics

At t=1 predators are introduced in all seminatural habitats with initial density P1(SNH). The predators are allowed to reproduce and disperse until t=3. At t=3 pests are introduced in the crops with initial density N1(crop) = P1(SNH). To assess the impact of initial conditions on our conclusions, we set three extreme values for P1(SNH): 0.1, 0.5 and 1. We then performed simulations during a 15-years burn-in period in order to allow the stabilization of pest and predator dynamics before organic farming deployment.

3 - Spatial strategies of organic farming deployment

From each initial landscape, we simulated OF expansion from t=15 to t= 50 years in order to sequentially convert 50% of the initial conventional crop area to OF. For each simulation, OF expansion was progressive, i.e. approximately 6.25% of the initial conventional crop area was converted to OF every 5 years. The total number of conventional fields to be converted depended on the initial cultivated area and the target proportion of OF. The final compositions of landscapes corresponding to the three initial amounts of seminatural habitats were respectively Qen1(10% SNH; 49.5% OF; 40.5% CF), Qen2(25% SNH; 41.25% OF; 33.75% CF), Qen3(50% SNH; 27.5.5% OF; 22.5% CF).

Only conventional fields were converted to organic. The area of seminatural habitat remained constant.

Three spatial conversion strategies were simulated based on the 4-neighborhood of conventional fields:

- the RD strategy in which we performed a random choice of conventional fields to be converted,

- the IP strategy, in which isolated conventional fields, i.e. fields with as few as possible conventional 4-neighbors, were converted first,
- the GP strategy in which, in contrast to IP, conventional fields with as many as possible conventional 4-neighbors were converted first.

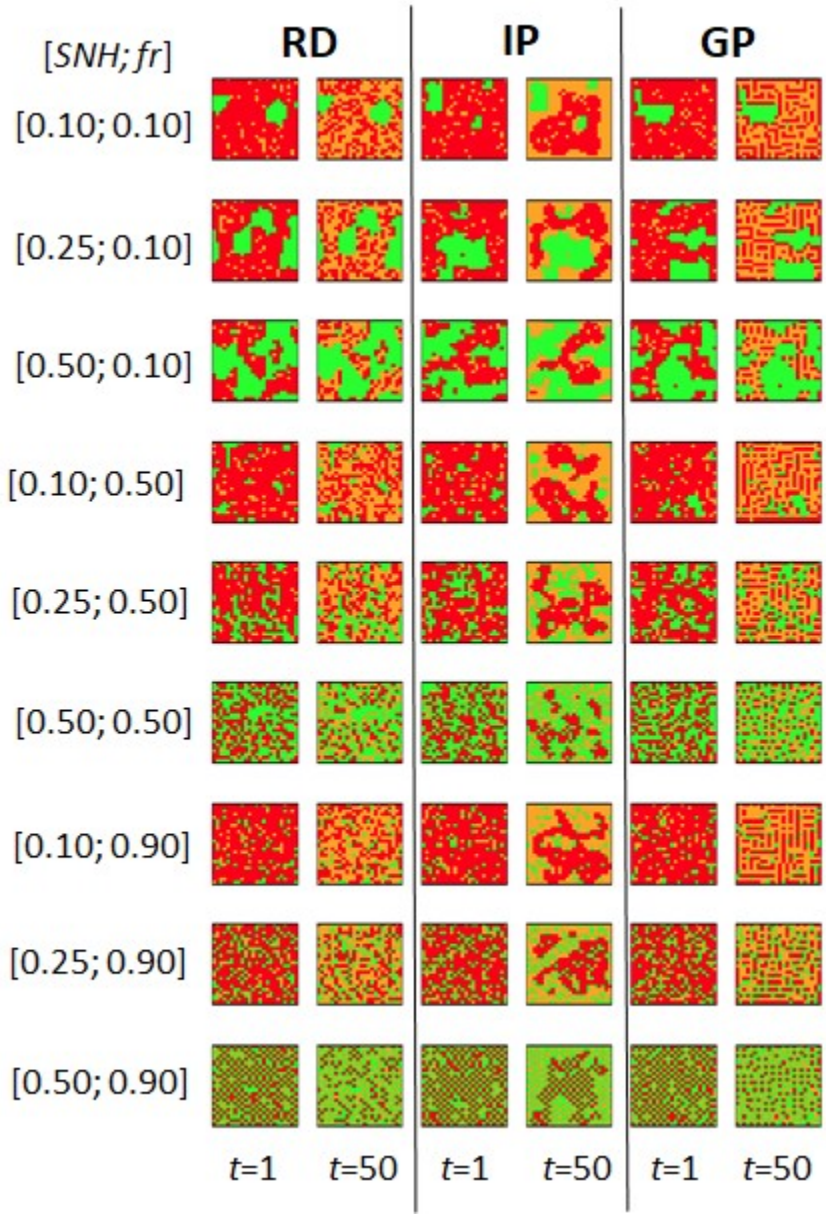


Figure 1. Examples of landscape structures at the beginning and the end of organic expansion. The figure provides one example landscape for each combination of landscape and OF expansion strategies. SNH= proportion of seminatural habitat; Fr: fragmentation of seminatural habitat; RD, IP and GP refer to the three strategies of selection of CF fields to convert to OF: selection of random, isolated or grouped fields; Red: conventional (CF), orange: organic (OF), green: seminatural habitat (SNH). The changes are largest for landscapes with lower SNH proportions.

4 - Simulation outputs

At each time step of each simulation, we recorded indicators of the landscape structure and of pest and predator densities in the three types of land use.

4.1 - Landscape structure

Landscapes can be described in terms of composition, i.e. proportion of the land uses, and configuration, i.e. the spatial arrangement of these land uses (Fahrig et Paloheimo 1988). Landscape composition was controlled during the simulation. We monitored landscape configuration using two landscape metrics for each land use: the mean patch area and the number of patches (R package *landscape metrics*, Hesselbarth et al, 2019). For a given land use, patches were made of fields of that given land use that were 4-neighbors to at least one field of the same land use. Together, these two metrics indicate whether, for a given proportion of landscape area, one land use is represented by a few large patches or many small patches.

4.2 - Pest and predator densities

For each simulation, the densities of pests and predators were monitored at the end of each year and averaged over each land use (SNH, OF and CF). From these, a median predator to pest ratio was calculated per land use as a proxy of the intensity of pest control by predators.

5 - Simulation study

Simulations for the three spatial conversion strategies mentioned above were performed for each of the nine types of landscapes (3 proportions of HSN x 3 levels of *fr*) aiming at 50% OF fields for each of the four types of OF (Table 3). These simulations were performed for all combinations of the values of the 7 parameters (pest and predator dispersal coefficients, pest and predator intrinsic growth rates, predator life expectancy in crops, predation index, and pesticides effect) governing pest and predator population dynamics (Table 1) and the three initial densities of pests and predators. This resulted in a total of 34992 Simulations.

Comparisons of pest and predator densities and predator to pest ratios among conversion strategies were performed at the end of the simulations (t=50) for each landscape type. As pest density was the main variable of concern regarding OF expansion, we further checked whether the ranking of strategies was robust with regards to the intensity of OF and the dispersal rate of the pest.

All simulations were performed with (MATLAB 2018a) and all statistical analyses were performed with R software (R Software 2017).

Results

1 - Effects of OF deployment strategies on the number and area of organic and conventional patches

As expected, changes in the areas and numbers of organic and conventional patches along organic farming deployment depended on the landscape characteristics (amount of seminatural habitat and its fragmentation) and on the organic farming deployment strategy. Organic and conventional patches were overall larger and less numerous in landscapes where the amount of seminatural habitat was small and little fragmented (upper left Fig. 2) indicating in particular that the level of seminatural habitat fragmentation translated to overall landscape fragmentation.

Overall the dynamics of the patch area were driven by two processes. Indeed, the conversion of individual fields from conventional to organic may lead to progressive changes in conventional patch area, either increasing it when converted fields were isolated and/or

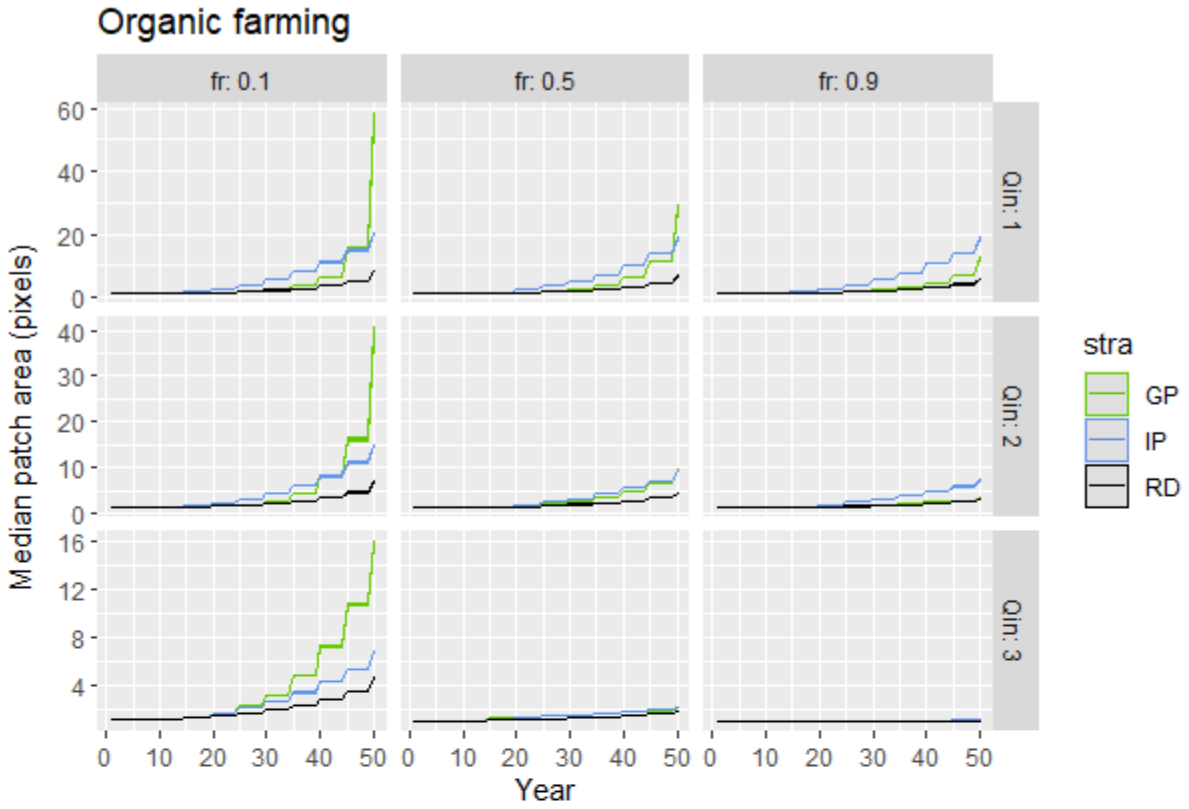
decreasing it when converted fields were part of a larger patch. In this second situation, the conversion of a single conventional field may occasionally lead to the splitting of a large conventional patch. Such splitting led to large drops in the mean conventional patch area (eg. Fig.2, at 35 years for the GP strategy with fr=0.1 and SNH=10%). The symmetrical process of merging organic patches following the conversion of individual fields may create a sudden large increase in mean organic patch area. This last process occurred when the organic share was high enough over the landscape.

Because they set different priorities regarding field conversion, the different strategies led to different mean patch area dynamics. Constraints were furthermore imposed by the spatial distribution of seminatural areas. The IP strategy always resulted in conventional patches that were larger than the other strategies. This is because, when available, conventional fields in the smallest conventional patches were converted to organic which resulted in an initial disappearance of small conventional patches and thus an increase in average conventional patch area. When these small patches were all converted, larger ones started being partially converted to organic, leading to a secondary decrease in conventional patch area (Fig1, after ca. 25 years). These two trends (increase then decrease) were observed in landscapes with both small and large conventional patches initially, i.e. moderately fragmented landscapes with a small to moderate proportion of seminatural habitat. In little fragmented landscapes with few seminatural habitats (upper left panel, Fig.2) all conventional patches were large initially so that patch size decreased slowly from the beginning of organic farming deployment. In contrast, in highly fragmented landscapes with a high proportion of seminatural habitat (lower right panel, Fig.2), there were mostly isolated conventional fields initially so that patch size remained almost constant. The GP strategy, by eroding small parts of large conventional patches at first, slowly and moderately reduced the average conventional patch area. This decrease accelerated in a second step when the erosion incidentally led to the splitting of the still rather large conventional patches into smaller ones. This process was strongest in landscapes with large conventional patches initially, i.e. little fragmented or with a small proportion of seminatural habitats (left column and upper row panels, Fig. 2). Lastly, the RD strategy led to a progressive reduction of conventional patch area by both converting fields located in small patches and reducing the area of large conventional patches.

The effect of organic deployment on the area and number of organic patches was consistent with the above changes to conventional patches. Whatever the deployment strategy, when the

landscape was very fragmented and with a large proportion of seminatural habitat, conversion of conventional fields increased the number of organic fields but not their average area, conventional patches being mostly composed of single fields (lower right panel, Fig.2). Mean organic patch area increased in all other situations.

Mean organic patch area increased most at first with the IP strategy, particularly when the landscape was a little fragmented (left column, Fig. 2) because conventional fields that were converted tended to be neighboring already organic fields. In contrast, with the GP strategy, organic fields first tended to be isolated from other organic fields so that the average patch area increased slowly. However, when the landscape was little fragmented (left column, Fig. 2), these small organic patches merged when the proportion of organic farming increased and the average organic patch area increased sharply while the number of patches decreased.


Organic farming
fr: 0.1
fr: 0.5
fr: 0.9
Qin: 1
Qin: 2
Qin: 3
Median patch area (pixels)
Year
stra
GP
IP
RD

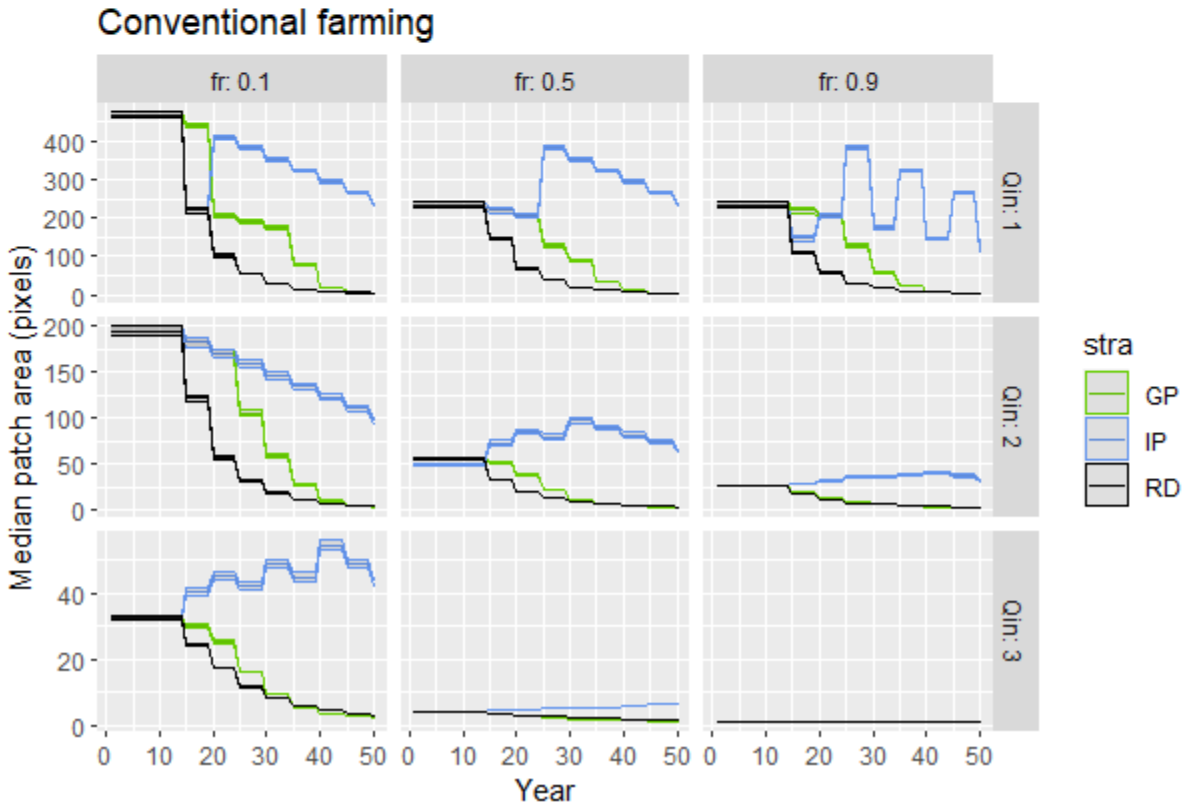

Conventional farming
fr: 0.1
fr: 0.5
fr: 0.9
Qin: 1
Qin: 2
Qin: 3
Median patch area (pixels)
Year
stra
GP
IP
RD

Figure 2. Effects of OF deployment strategies on the area of organic and conventional patches. Landscape change (median patch area in pixels) during the simulations. The envelope around each curve represents the standard error.

2 - Pest and predator dynamics in absence of organic farming deployment

The model behavior was first studied in the absence of organic farming deployment. This step first shows that in the absence of organic farming deployment, the densities of pests and predators stabilized after approximately 15 years. The equilibrium densities were independent of the initial pest density (not shown). Consistent with our parameter values, both pest and predator densities were higher in organic fields than conventional fields. Moreover, the density of pests was always larger than that of predators, in both conventional and organic fields (Fig.2 ref column).

Pest and predator densities did not show a clear response to the increase of proportion of seminatural habitat and increased with its fragmentation, probably because cultivated fields were more likely to be close to a seminatural habitat, increasing spill-over of individuals into cultivated fields. These effects were stronger on predators than pests in organic fields, consistent with the higher dependency of predator reproduction and survival on seminatural habitats. The predator density, in contrast, remained very low in conventional fields due to pesticides.

These differential effects of landscape characteristics on pests and predators had two consequences. First, pest densities were 2.6 times larger in organic fields than in conventional fields in landscapes with little seminatural habitat and little fragmentation (SNH=10%, fr=0.1) while they were only 1.3 times larger in landscapes with large amounts of fragmented seminatural habitats (SNH=50%, fr=0.9). Second, the predator to pest ratio increased in organic fields but decreased in conventional fields when seminatural habitat amount and fragmentation increased.

3 - Effects of spatial strategies of organic deployment on pest and predator dynamics

The organic farming deployment affected more predator densities than pest densities for most combinations of landscape types and deployment strategy (Fig. 3). Its impact was also generally stronger in organic than conventional fields and in landscapes with large amounts of fragmented

seminatural habitats. As expected, predator densities in organic fields generally increased. Changes in pest and predators densities and their dynamics, however, depended on deployment strategies and landscape characteristics.

Pest dynamics

Pest densities in organic fields showed similar changes for the three deployment strategies (Fig. 3). They tended to slightly increase or remain stable over time in landscapes with little or intermediate proportions of seminatural habitat and to decrease in landscapes with large proportions of seminatural habitat. In conventional fields, pest densities showed this same pattern with the RD and GB strategies but not with the PI strategy. With the PI strategy, pest densities in conventional fields tended to decrease slightly over time whatever the landscape type. As a result, at t=50, pest densities were generally smaller with the PI than with the RD and the GP strategy in conventional fields and similar for the three deployment strategies in organic fields.

Predator dynamics

In organic fields, the effect of organic farming deployment on predator densities was very large compared to its effect on pests densities (Fig.3). Predator densities increased for the three deployment strategies. The increase was larger for the IP strategy than for other strategies, particularly in little fragmented landscapes with intermediate or large amounts of seminatural habitats. For example, when SNH=25% and fr=0.1, with the IP strategy the predator density at t=50 was 5.38 times larger than the initial density and was 2.44 times higher than at t=50 with the GP strategy. In contrast, the three strategies performed similarly in landscapes with large amounts of fragmented seminatural habitat (SNH=50%, fr=0.9). In these landscapes, the predator density increased by a factor of 1.34 between t=0 and t=50 with the IP strategy and was only 1.20 times higher than with the GP strategy at t=50. The increase in predator density was moderate for the RD and GP strategies and reached similar values at t=50. Their dynamics were, however, qualitatively different. While predator densities increased steadily for the RD strategy, for the GP strategy, most predator densities showed a transient decrease in the first years following the beginning of organic farming deployment.

The pattern was very different in conventional fields. Predator densities remained stable at very low values for most landscapes and deployment strategies. They only increased in the GP strategy in landscapes with high amounts of seminatural habitats but still remained at low values.

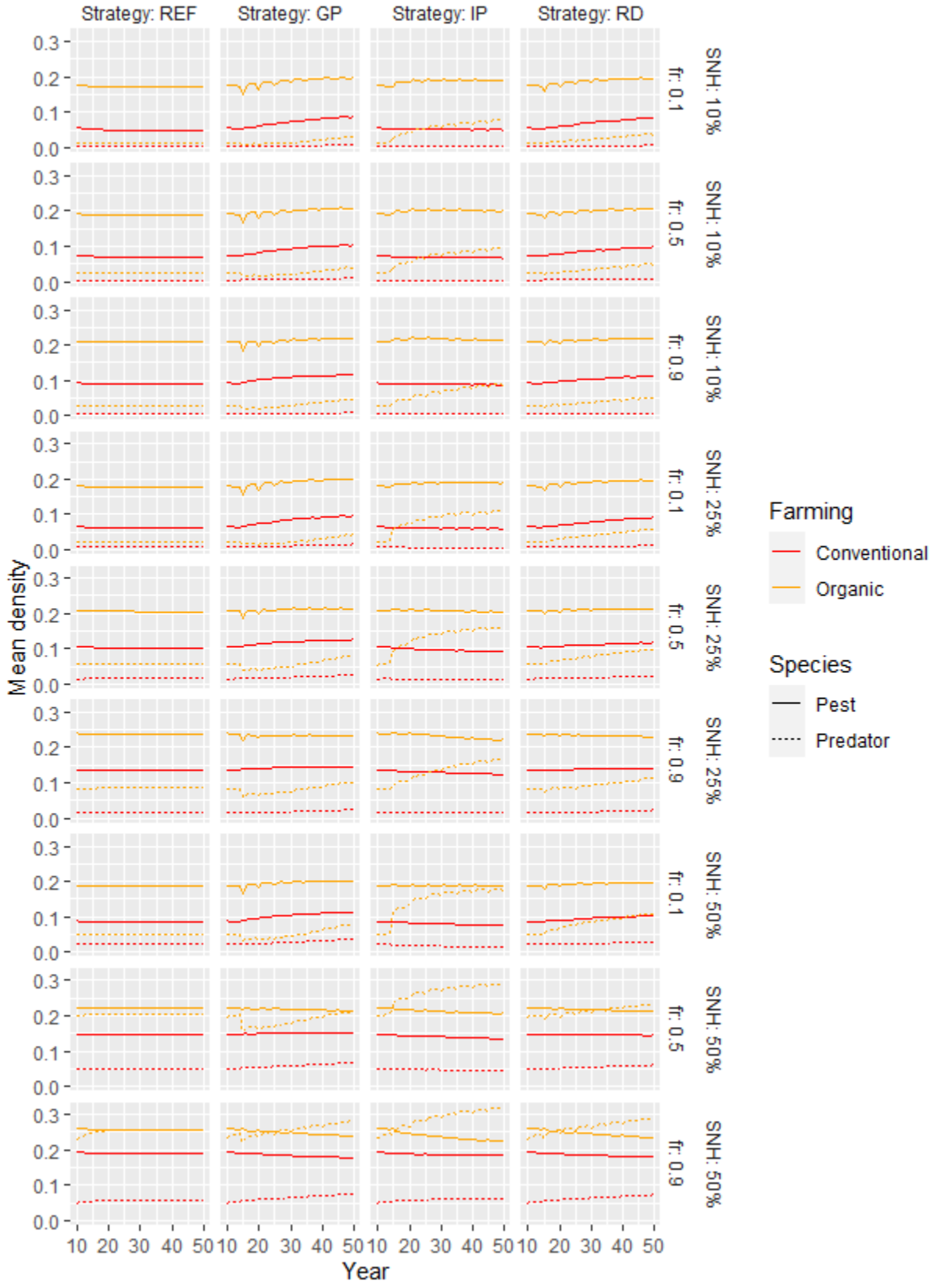

Strategy: REF
Strategy: GP
Strategy: IP
Strategy: RD
SNH: 10%
SNH: 25%
SNH: 50%
fr: 0.1
fr: 0.5
fr: 0.9
Mean density
Year
Farming
Conventional
Organic
Species
Pest
Predator

Figure 3. Effect of organic deployment strategies on the temporal evolution of the mean density of pests and predators in organic (OF) and conventional farming (CF), as a function of fragmentation (fr) and initial habitat amount (SNH). Reference (REF) represents the absence of organic deployment.

Resulting pest densities at t=50

Differences in final pest density in organic fields were limited among deployment strategies. This is because pest density in organic fields responded much less to organic or conventional patch areas than to the fragmentation of seminatural habitats (Fig. 4, left panels). Indeed, the highest levels of pest densities were obtained for the highest fragmentation levels. For a given level of fragmentation, pest densities in organic fields also tended to decrease with increasing mean conventional or organic patch area but the amplitude of effect was much smaller. In contrast, final pest density in conventional fields (Fig. 4, right panels) largely decreased with increasing conventional and organic patch area and was less responsive to the level of seminatural habitat fragmentation. Low levels of pest densities could thus be attained for different fragmentation levels given that conventional patch areas were large, a situation provided by the PI deployment strategy in landscapes with small amounts of seminatural habitats. Note furthermore that the range of variation of pest densities was larger in conventional than organic fields.

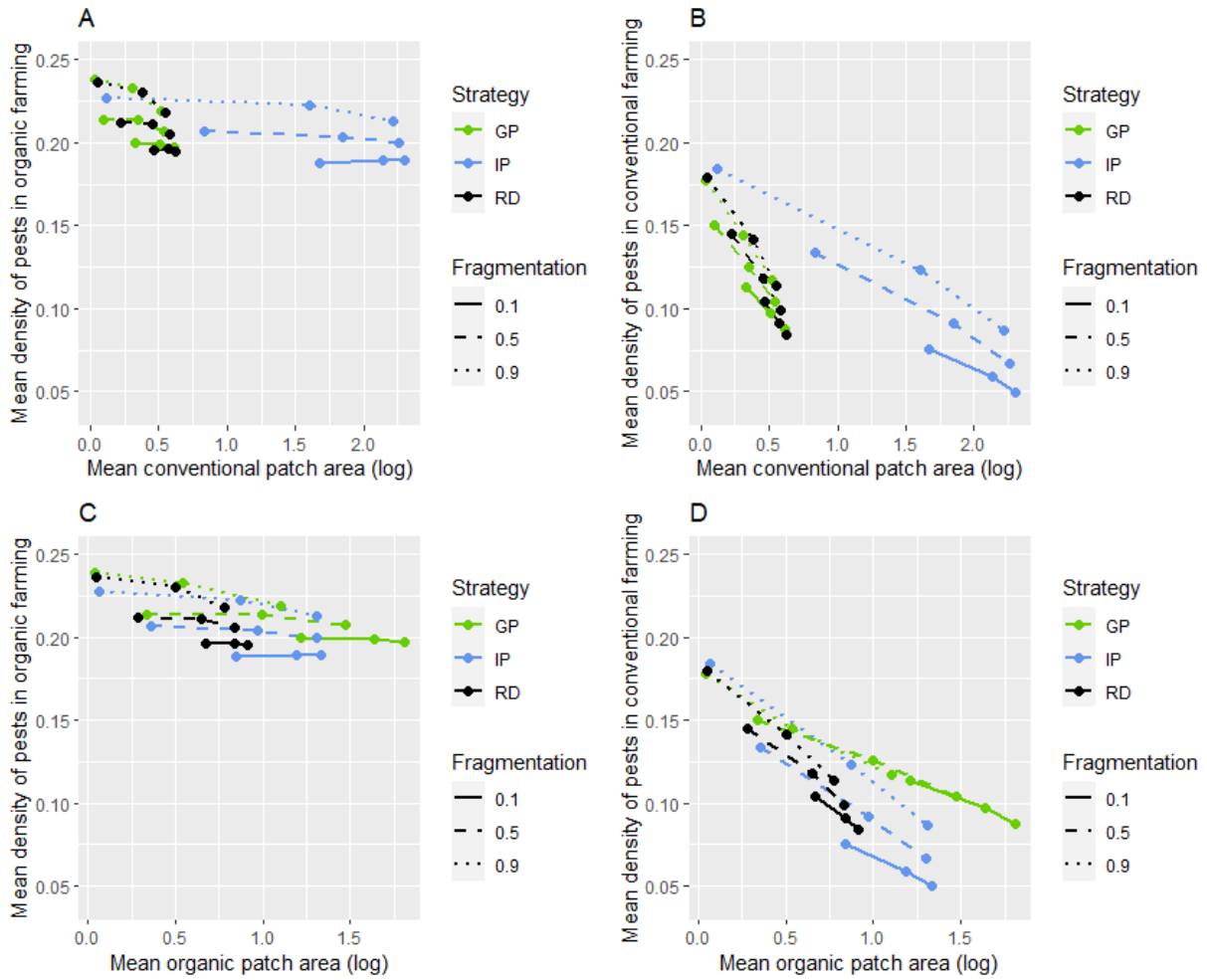


Figure 4. Mean density of pests in organic (A, C) and conventional (B, D) fields as a function of the mean area of conventional (A, B) or organic (C, D) patches at t=50. For a given strategy and level of fragmentation, the mean organic or conventional patch area increases with decreasing % of SNH.

4 - Effect of spatial strategies of organic farming deployment on the level of CBC

The predator to pest ratio is an indicator of the potential for conservation biological control: a higher ratio indicates that pests are more likely to come across a predator. As a result of the pest and predator dynamics described above, the predator to pest ratio at the end of the

simulation was three to four times larger in organic fields than in conventional fields (Fig. 5). It increased with the initial proportion of seminatural habitat, in similar relative proportions in organic and conventional fields, from an average of approx 0.2 to 1.25 in organic fields and 0.05 to 0.35 in conventional fields, when the proportion of SNH increased from 10% to 50%. It also increased, but to a much lesser extent with SNH fragmentation. The only significant increase was for landscapes with large amounts of SNH (Fig. 5)

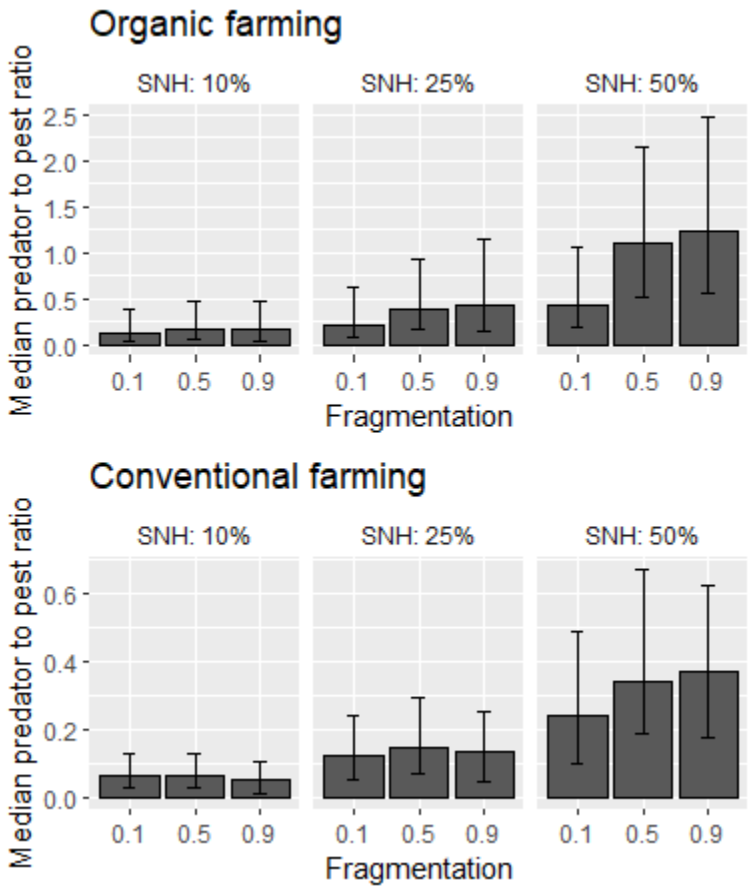


Figure 5. Median Predator to pest ratio at t=50 for the nine types of initial landscapes, in organic and conventional farming. Error bars represent quartiles over all strategies and parameter values. Note that y-axes are on different scales.

More interestingly, regarding spatial deployment strategies, in organic fields, the larger increase of predator densities with the IP strategy (Fig. 2) and the somewhat larger pest densities in the GP strategy lead to a clear ranking of strategies with IP>RD>GP for the predator to pest ratio (Fig. 6). Relatively to the RD strategy, the predator to pest ratio was from 1.83 times higher (SNH=10%, fr=0.1) to 1.1 (SNH=50%, fr=0.9) times higher for the IP strategy. In contrast, these ratios for the GP strategy ranged from 0.55 (SNH=10%, fr=0.1) to ~1(SNH=50%, fr=0.9) times those for the RD strategy. As a consequence, differences between the GP and IP strategies were largest in landscapes with few and little fragmented seminatural habitat and very small in landscapes with a large proportion of highly fragmented seminatural habitats.

In conventional fields, predator to pest ratios showed the opposite GP>RD>IP ranking. The difference here was mainly between the IP and the two other strategies. Ratios were a little larger for the GP strategy than for the RD strategy whatever the initial landscape, with values ranging from 1.2 (SNH=10%, fr=0.1) to ~1 (SNH=50%, fr=0.9) times those for the RD strategy. They were the smallest for the IP strategy, particularly in fragmented landscapes with low proportions of seminatural habitats (from 0.55 (SNH=10%, fr=0.1) to 0.8 (SNH=50%, fr=0.9) times higher than with the RD strategy, Fig. 6).

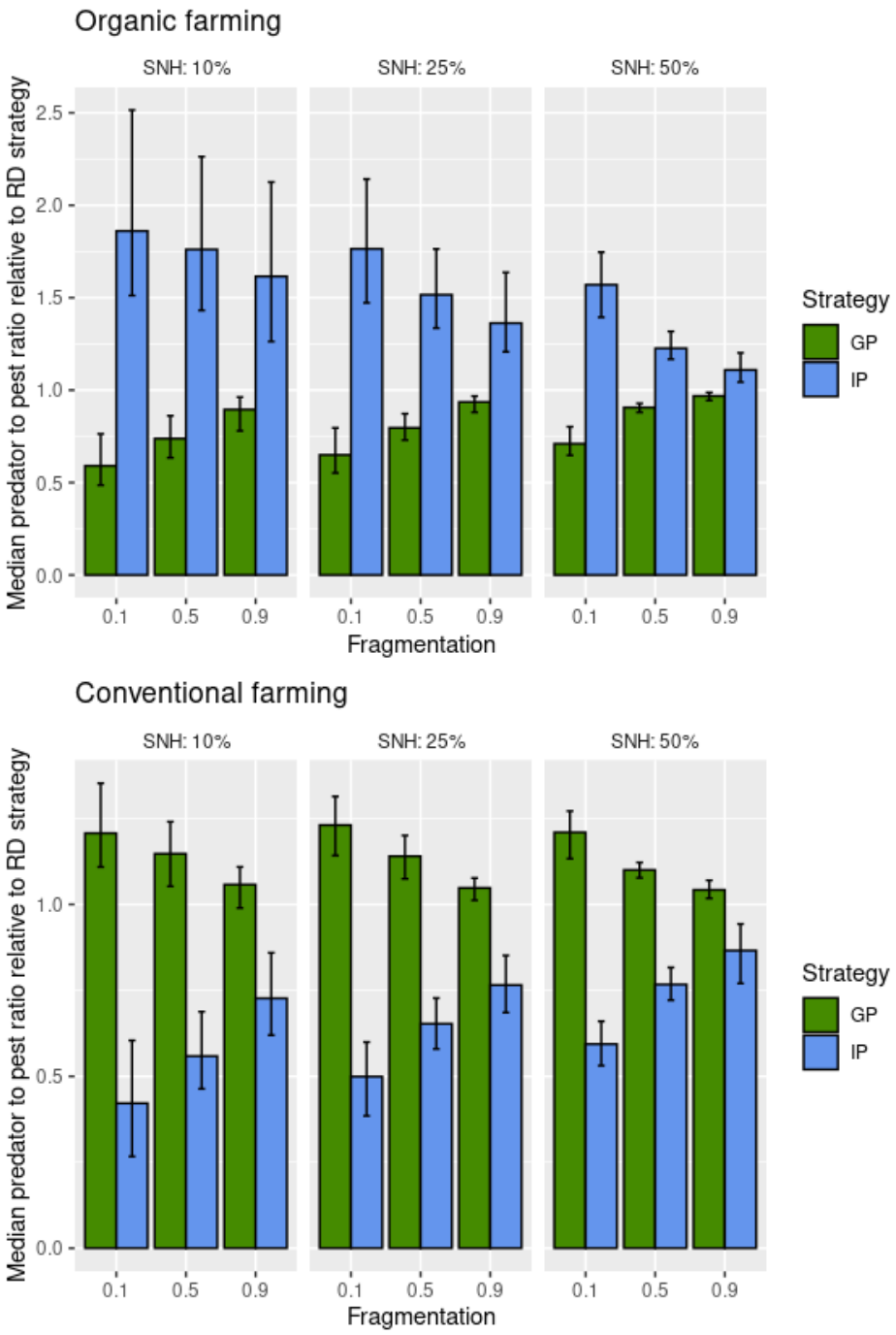


Figure 6. Median predator to pest ratio at t=50 in organic and conventional farming for the IP and GP strategies relative to the ratio obtained for the RD strategy with the same parameter values. Error bars represent quartiles over all combinations of population dynamic parameters.

5 - Effect of the type of organic farming on pest densities

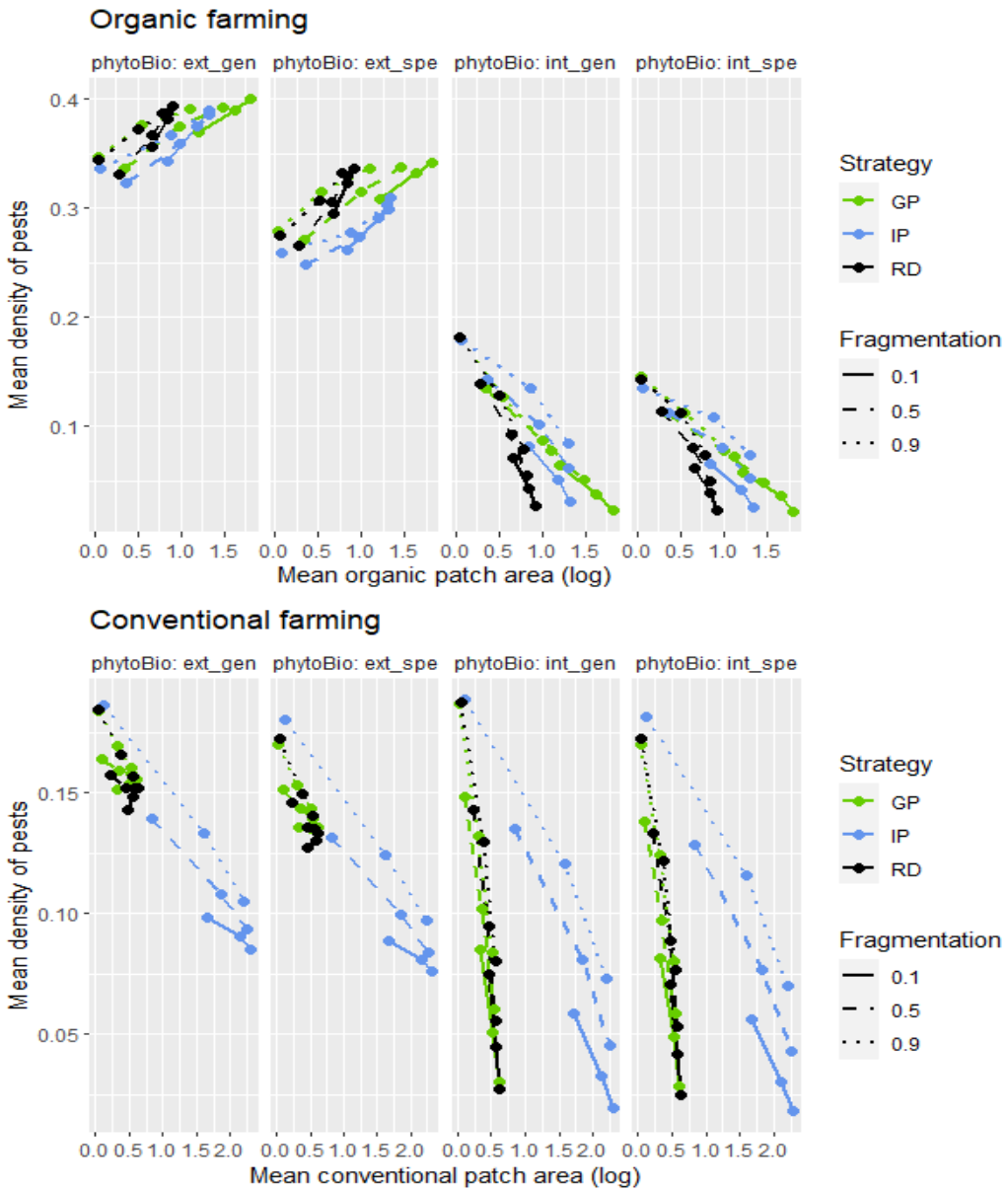


Figure 7. Effects of organic farming deployment strategy, crop protection intensity, crop protection specificity, and landscape structure on the density of pests in organic and conventional farming. “ext” and “int”: low vs high pesticide intensity, respectively. “spe” vs “gen”: specific vs generalist pesticide, respectively. For a given strategy and level of fragmentation, the mean organic or conventional patch area increases with decreasing % of SNH.

Pests were on average more abundant in both types of fields when organic farming was less intensive, i.e. pesticides affected pest population growth less (Table 3) and, to a lesser extent, when it was less specific, i.e. there was a small differential in pesticide-induced mortality between predators and pests (Table 3). In organic fields, the intensity of organic farming affected pest abundance far more than specificity, regardless of the amount of seminatural habitat and its level of fragmentation. In conventional fields, the effect of organic farming intensity and specificity was much less pronounced. The effect of specificity was very weak. The effect of intensity was observable mainly in landscapes that were characterized by either little semi-natural habitat or a low fragmentation.

6 - Effect of pests dispersal and HSN fragmentation on pest densities

Pest levels in organic and conventional fields were overall higher when pest dispersal was high with some variation in response depending on fragmentation and strategy. Indeed the effect of landscape structure, and thus strategy, increased with pest dispersal.

In both types of fields, the positive effect of dispersal increased with the level of fragmentation of seminatural habitats. This effect was more pronounced in organic fields. For the RD strategy and a landscape characterized by SNH=10% for example, mean pest density increased from a value of 0.18 for low dispersal to 0.20 for high dispersal with fr=0.1, whereas these values were 0.20 and 0.23 when fr=0.9 (Fig. 8). There were two exceptions to this trend with a decrease in pest density with dispersal. They were observed with the IP strategy in organic fields in the particular case of little fragmented landscapes (fr=0.1 or 0.5) with a large amount of seminatural habitat (HSN=50%) (Fig. 8).

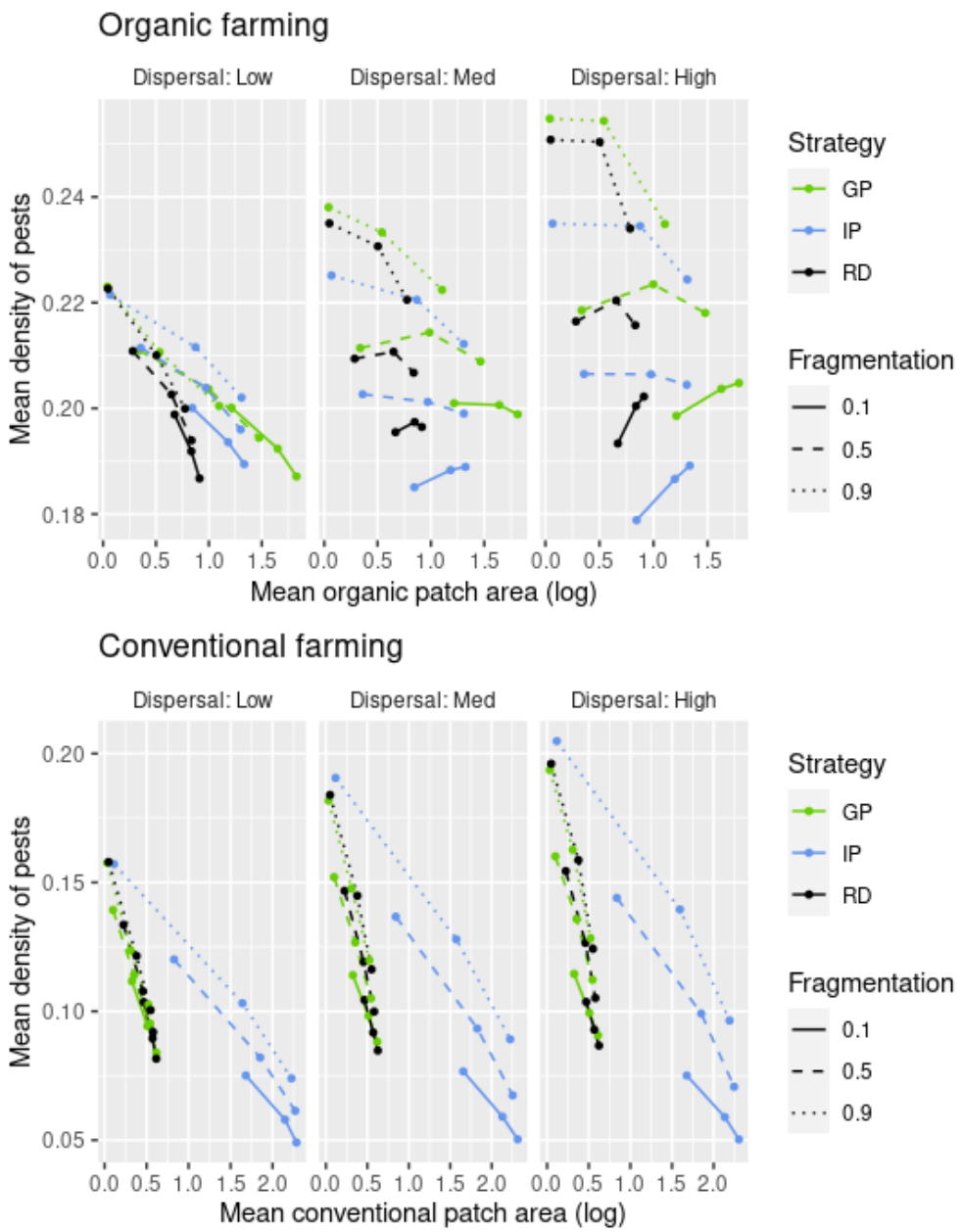


Figure 8. Mean density of pests as a function of pest dispersal, organic farming deployment strategy, habitat fragmentation, and conventional patch area. For a given strategy and level of fragmentation, the mean organic or conventional patch area increases with decreasing % of SNH.

Discussion

Existing evidence of the positive impacts of OF on agrobiodiversity and pest control (eg. Muneret et al. 2019) and its growing adoption by customers and farmers (Paull et Hennig 2016) highlight the importance of considering how OF expansion may impact the dynamics of agricultural pests (e.g. Petit et al., 2020). Modeling approaches are useful tools to understand and forecast how pest densities and pest control may vary according to crop management and semi-natural habitats at the landscape scale (Begg et al. 2017). In this study, we modeled pest abundance for contrasted scenarios of OF expansion in different landscapes.

Our results showed that changes in the areas and numbers of organic and conventional patches along organic farming deployment depended on the landscape characteristics (amount of seminatural habitat and its fragmentation) and on the organic farming deployment strategy. They indicate that the IP strategy would provide the most benefits for biological control at the landscape scale. This is in accordance with the literature regarding OF extension that suggests accompanying the current trend and promoting OF in areas already rich in OF fields. Indeed, this literature points toward new organic farmers and fields clustering around existing ones (Gabriel et al. 2009; Marton et Storm 2021; Sánchez Herrera et Dimitri 2019; Zollet et Maharjan 2021), in a process similar to our IP strategy in this study.

1 - Landscape complexity and OF expansion strategies affect pest and predator densities.

Generally speaking, populations responded to OF expansion in the landscape with up to a 437% increase and a 46% decrease in densities, indicating that OF expansion could indeed lead to significant changes in biological control of pests in both OF and CF fields depending on the landscape SNH context (Fig. 2). Predator densities generally increased or remained stable while pest densities either increased or decreased along OF expansion. When both pest and predator densities increased, predator densities increased more strongly than pest densities. The predator to pest ratio was about three to four times larger in organic than in conventional

fields.

Changes in pest and predator densities and their dynamics strongly depended on deployment strategies in interaction with landscape characteristics, i.e. the amount and fragmentation of SNH. Although most scenarios led to overall improvements in predator pests ratios (seen here as a proxy of biological control, CBC), some led to increases in pest densities, particularly in CF fields (e.g. Fig.3) which indicates that in some specific landscapes, carefully planning the spatial deployment of OF would be useful to avoid undesirable side effects.

The random deployment of OF was used as a baseline reference and generally resulted in increased predator densities in OF and increased pest densities in CF (Fig. 2). Only in landscapes with large amounts of SNH (SNH=50%), did predator densities increase very largely in OF and even increased slightly in CF, leading to a decrease of pests in both types of fields. This may indicate that some of the predator/prey ratio dynamics observed in this study are driven by the dynamics of predators.

For the IP and GP strategies, both OF and CF underwent peculiar processes of progressive percolation/agglomeration (for OF) and its opposite disintegration (for CF). These processes may be good representations of how OF conversion occurs in the absence of stronger landscape planning because, within the constraints of the strategy, CF fields to be converted were chosen randomly. Indeed, conventional fields neighboring organic fields tend to be converted to organic first as in the GP strategy (Zollet et Maharjan 2021) but the current boom of organic farming may also result in patterns that resemble the IP strategy. Because these processes occurred randomly and at the field scale, agglomerates of OF and CF merged and split at random times through the conversion of single central fields, leading to non-linear changes and even dramatic thresholds of mean OF and CF field areas (especially in the IP strategy, see Fig. 2). Interestingly, however, we did not observe similarly dramatic dynamics of pest and predator populations. This may indicate that the spatial smoothness of a conversion strategy over time is not necessary to maintain generally stable dynamics of biological control neither in organic nor conventional farms. This should lead to good predictability of the outcomes of conversion strategies, a low need for carefully curated temporal plans, and lower mean risks for CF neighbor farms at the landscape scale.

The SNH area had a stronger effect on CBC than its fragmentation. Furthermore, CBC in OF fields increased more with fragmentation when the proportion of SNH was high (Fig. 5). The same was visible in CF fields, but mostly at higher SNH, suggesting that it was masked by the

effect of pesticide. This interaction indicates the importance of predators' spillover from semi-natural habitats on biological control and that the predator/pest ratio may be strongly driven by variations in predator densities due to their dispersal from these habitats. Incidentally, it may indicate that landscape structures favoring the movement of predators and other non-target species into CF fields may act as an ecological trap luring non-target species to fields where mortality is high and long-term persistence impossible (Robertson et Hutto 2006; Shelton et Badenes-Perez 2006). This interaction is also in line with the frequent observation that complex landscapes with more and more fragmented seminatural habitats sustain more biodiversity within fields (Muneret, Auriol, Thiéry, et al. 2019; Petit et al. 2020; Smith et al. 2020; Tscharntke et al. 2021) and favor spillover of predators (Bianchi, Ives, et Schellhorn 2013).

2 - One better strategy for CBC?

2.1 - A general pattern

The similar pest densities with all strategies (Fig. 2) indicated that the choice of one strategy over another bears low risks, while potential benefits were more obvious with noticeable effects on predators.Strategies may be ranked either on CBC or pest densities at the end of the deployment. Because CF fields rely on pesticides for pest control, it can be argued that CBC matters most in OF fields while the main target for CF fields is the amounts of pests.

Regarding CBC, the IP strategy performed overall better for organic fields because of its clear positive effect on the predator: prey ratio (1.1:1 to 1.7:1 predator: prey ratio with IP, vs 0.95:1 to 0.6:1 with GP, Fig. 6). Patterns were more nuanced for CF. While some scenarios caused a small improvement in CBC (GP strategy, up to 1.25:1 predator: prey ratio), others caused strong decreases (IP strategy, up to 0.4:1 predator: prey ratio, Fig. 6). Interestingly, the effect of deployment strategies was weaker when they caused increases in CBC than when they caused decreases in CBC. Additionally, the ranking of strategies was opposite in CF vs OF (IP>RD>GP in OF fields vs GP>RD>IP in CF fields). From the CF point of view, the absence of planning (RD strategy) may thus constitute a reasonable scenario. However, pest densities in CF were lower with IP than with the other strategies (Fig. 7 & 8). The IP strategy thus performed better, by improving CBC in OF and doing so at the expense of lower CBC, but not higher pest densities, in CF. That effect was visible in all landscape configurations, while some landscapes limited the decrease of CBC in CF without canceling it.

The IP strategy was the best in both OF and CF fields thanks to two distinct mechanisms: a predator spillover improving CBC in OF fields, and a combination of chemical umbrella and

predator spillover improving CBC in CF fields. The IP strategy prioritized the conversion of fields neighboring OF fields or semi-natural areas. This meant that new OF fields benefitted from the spillover of predators from SNH, albeit with weak effects on pest density. Indeed, the predator/pest ratio improved mainly by an increase in predator numbers (Fig.3, Fig. 4). Such trophic network top-heaviness can be caused by exogenous pathways that transfer energy into communities from across spatial and temporal boundaries: here, transfers from SNH (McCauley et al. 2018). OF fields may also have benefitted from distance to CF fields and clusters of OF fields, as chemical pesticide use in CF fields was modeled to kill most of the pests with strong side-effect on predators, drying both pest and predator populations in their surroundings through a sink effect. Clusters of CF fields were more preserved by the IP strategy, meaning that CF fields benefitted from the protection of pesticides used in neighbor fields (the “chemical umbrella” effect) and that OF fields, a potential source of pests, were farther away from the CF fields.

2.2 - Landscape complexity effect on differences between strategies

In our simulations, landscape configuration had a strong effect with differences in pest density up to 2 times for a given strategy (e.g. Fig. 4). The amount and fragmentation of SNH were generally of similar importance to the difference in the level of CBC between strategies, although there was a clear decrease associated with the interaction between the two parameters, i.e. the difference between IP and GP decreased with higher amounts and fragmentation of SNH (Fig.5). In CF, this amounted mainly to the IP strategy that benefited slightly from SNH, while it didn’t affect GP. In OF, IP and GP converged at higher amounts and fragmentation levels, with GP being favored while IP decreased. Interestingly, IP can bring higher benefits in OF fields in degraded landscapes, while both strategies bring similar but lower benefits in preserved landscapes. This is to be expected since the IP strategy mainly relies on breaking up big clusters of CF, which are less present in landscapes with high amounts and fragmentation of SNH. Consequently, it may be less important to manage the OF deployment strategy in preserved landscapes, while the IP strategy should be favored in degraded landscapes.

2.3 - Pesticide intensity and specificity in OF systems have a low effect on differences between strategies

As expected, intensive OF systems were characterized by strong control of pest densities, therefore they showed little differences between strategies (Fig. 7). The effect of the intensity of organic farming on the pests in organic fields was largely predominant over the effect of its specificity. Pests were globally more abundant in both CF and OF when OF was less intensive and, to a lesser extent, when it was less specific. Pesticide specificity generally had little effect except in less intensive OF, thereby confirming the low effect of predators on CF pest densities, and the high impact of pesticides compared to CBC in our simulations.

In extensive OF plots, pest densities increased with patch area, possibly because patch size protected pests from the ‘umbrella effect’ of CF pesticides. On the contrary, pest densities decreased with patch area in intensive OF plots, possibly because of higher local extinction rates and lower recolonisation rates from external sources.

Less intensive organic systems were possibly a source of pests for surrounding fields, including CF fields. Indeed, we observed more pests in OF because less intensive OF fields provided less direct control of pests, and more pests in CF possibly because of their spillover from OF fields with higher pest populations. The latter is supported by the fact that the effect of pesticide intensity in OF on pest density in CF was compensated by some landscape configurations. Specifically, CF fields in landscapes with high amounts of SNH (in Fig.7, lower patch sizes) were less sensitive to OF pesticide intensity, possibly because of lesser proximity to OF sources, and because predator's spillover from SNH suffered less from pesticides in CF patches.

The only clear interaction between OF pesticides and deployment strategy was visible in CF plots, where under extensive OF pesticides, IP allowed lower pest densities in CF than other strategies (Fig. 7) by limiting OF patch size and pest densities in OF, and colonization rates from OF to CF.

2.4 - Pest dispersal has a low effect on differences between strategies

Pest dispersal had a lower effect than the other parameters with a maximum delta of ±0.05 in pest densities (Fig.8). Pest and predator levels in organic and conventional fields were generally higher and more variable when dispersal was high, especially when conventional patches were small. There was also a positive interaction of dispersal with the fragmentation of seminatural

habitats. This increase in densities with dispersal, fragmentation and their interaction was probably due to a higher ability of pests to avoid CBC-heavy areas (near SNH, which are sources of predators) and to reach resource-rich areas. OF patch area reduced pest densities except when dispersal was high, which is possibly due to the interaction between OF pesticides and OF plot size described earlier (2.3) that dispersal helped mitigate. Globally speaking, dispersal ability amplified the effect of every landscape parameter (patch area, fragmentation, deployment strategy).

In the present study, the IP strategy thus appeared as the most promising strategy to limit pest densities in conventional crops and improve CBC in organic crops, without increasing pest densities there. By examining a large number of landscape situations and population parameters, we found that this result was robust but that landscape planning appeared most necessary when organic pesticides had a low efficiency on pests, in landscapes with low quantities of seminatural habitats and for pests with high dispersal abilities.

Acknowledgements

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Data and code availability

The model used in this study is based on a model developed by Martinet and Roques (2022) that is available on the following public repository: https://doi.org/10.17605/OSF.IO/Z2QCX The model outputs of the present study, as well as the R scripts used to build graphs and analyse data are available on the Zenodo public repository: https://doi.org/10.5281/zenodo.6597282

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