

# **Best organic farming expansion scenarios for pest control: a modeling approach**

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1 **Abstract**

2 Organic Farming (OF) has been expanding recently in response to growing consumer demand and as a  
3 response to environmental concerns. The area under OF is expected to further increase in the future. The  
4 effect of OF expansion on pest densities in organic and conventional crops remains difficult to predict  
5 because OF expansion impacts Conservation Biological Control (CBC), which depends on the surrounding  
6 landscape (i.e. both the crop mosaic and semi-natural habitats). In order to understand and forecast how  
7 pests and their biological control may vary during OF expansion, we modeled the effect of spatial changes  
8 in farming practices on population dynamics of a pest and its natural enemy. We investigated the impact  
9 on pest density and on predator to pest ratio of three contrasted scenarios aiming at 50% organic fields  
10 through the progressive conversion of conventional fields. Scenarios were 1) conversion of Isolated  
11 conventional fields first (IP), 2) conversion of conventional fields within Groups of conventional fields first  
12 (GP), and 3) Random conversion of conventional field (RD). We coupled a neutral spatially explicit  
13 landscape model to a predator-prey model to simulate pest dynamics in interaction with natural enemy  
14 predators. The three OF expansion scenarios were applied to nine landscape contexts differing in their  
15 proportion and fragmentation of semi-natural habitat. We further investigated if the ranking of scenarios  
16 was robust to pest control methods in OF fields and pest and predator dispersal abilities.

17 We found that organic farming expansion affected more predator densities than pest densities for most  
18 combinations of landscape contexts and OF expansion scenarios. The impact of OF expansion on final pest  
19 and predator densities was also stronger in organic than conventional fields and in landscapes with large  
20 proportions of highly fragmented semi-natural habitats. Based on pest densities and the predator to pest  
21 ratio, our results suggest that a progressive organic conversion with a focus on isolated conventional fields  
22 (scenario IP) could help promote CBC. Careful landscape planning of OF expansion appeared most  
23 necessary when pest management was substantially less efficient in organic than in conventional crops,  
24 and in landscapes with low proportion of semi-natural habitats.

25

26 **Keywords:** agricultural landscape; conservation biological control; pest-predator; spatial model.

27

## 28 Introduction

29 The intensification of agricultural systems in recent decades has relied on both an increase in field area  
30 and a larger dependency on chemical pesticides (Duru et al., 2015; Knapp & van der Heijden, 2018). This  
31 process led to profound changes in landscapes with a reduction and fragmentation of semi-natural  
32 habitats (Sirami et al., 2019; Tschardt et al., 2016) and a reduced diversity of the crop mosaic  
33 (Tschardt et al., 2016). This process had demonstrated negative impacts on biodiversity (Perez-Alvarez  
34 et al., 2019; Sánchez-Bayo & Wyckhuys, 2019) including on species of interest for agriculture such as  
35 pollinators (Goulson Dave et al., 2015; Muth & Leonard, 2019) and pest natural enemies (Sánchez-Bayo &  
36 Wyckhuys, 2019; Sirami et al., 2019; Tsutsui et al., 2018). Further, the intensive use of chemical pesticides  
37 had negative impacts on human health, and biodiversity (Móznér et al., 2012; Pärn et al., 2012; Sánchez-  
38 Bayo & Wyckhuys, 2019). Hence, there is an urgent need to identify alternative farming systems that  
39 reduce the negative impacts of intensive agriculture while maintaining yields as much as possible (Colbach  
40 et al., 2020; Smith et al., 2020). Organic Farming (OF) is one of these possible alternative systems. The  
41 multi- performance of OF recently received much attention, in terms of yield (Knapp & van der Heijden,  
42 2018), of effects on biodiversity (Caprio et al., 2015; Lourenço et al., 2021; Smith et al., 2020), of nutritional  
43 value and of global positive impact on human health (Gomiero, 2018; Salomé et al., 2021).

44 Pest management in OF relies on specific cultural practices and a restricted number of non-synthetic  
45 pesticides. Conservation Biological Control (CBC) methods that enhance natural enemy abundance and  
46 activity to reduce pest populations (Heimpel & Mills, 2017; Holland et al., 2016) are of particular interest  
47 for OF. A wealth of literature, however, demonstrates that the potential and efficiency of CBC within a  
48 field do not only depend on local agricultural practices but also on the structure of the surrounding  
49 landscape (Begg et al., 2017; Muneret, Auriol, Thiéry, et al., 2019), including its amount of semi-natural  
50 habitat (Le Gal et al., 2020; Zamberletti et al., 2021) and the characteristics of the crop mosaic (Hillaert  
51 et al., 2018, 2020; Le Gal et al., 2020; Smith et al., 2020).

52

53 Organic farming has been expanding recently around the world in response to growing consumer  
54 demand and environmental concerns, and the area under OF is expected to increase in the future (Paull  
55 & Hennig, 2016). A majority of the literature on OF expansion points toward new organic farmers and  
56 fields clustering around existing ones (Gabriel et al., 2009; Marton & Storm, 2021; Sánchez Herrera &  
57 Dimitri, 2019; Zollet & Maharjan, 2021). Clustering happens for socio-economic and agronomic reasons,  
58 because OF conversion happens primarily “in agriculturally less-favored areas where economic incentives

59 for conversion to organic farming do not need to be high and the loss of production due to conversion will  
60 be comparatively small” (Gabriel et al. 2009) such as isolated, hard to access, or less productive areas  
61 (Ilbery et al., 1999), but also because OF is often driven by newcomers, who could settle down more easily  
62 in the proximity of existing clusters, in less-favored areas, and in places where a “prevalence of small-  
63 scale, part-time, and self-sufficiency-oriented farming” is observed (Zollet & Maharjan, 2021).

64 The effect of OF expansion on pests and their natural enemies can be approximated, in a space for  
65 time approach (Blois et al 2013), by investigating how pests and natural enemies are affected by the  
66 proportion of OF in the landscape. Studies that investigated pest abundance in crops as a function of OF  
67 area in the landscape found that pests were either less (Gosme et al., 2012) or similarly (Muneret et al.,  
68 2018; Ricci et al., 2009) abundant when OF area increased. Moreover, predators of pests were either more  
69 or similarly abundant (Diekötter et al., 2010, 2016; Djoudi et al., 2018, 2019; Inclán et al., 2015; Lefebvre  
70 et al., 2016; Muneret, Auriol, Thiéry, et al., 2019; Puech et al., 2015), reviewed in (Petit et al., 2020),  
71 suggesting that earlier studies showing increases in crop damage associated with OF may have been  
72 influenced by the low amount of OF in the landscape in its early beginnings and that OF expansion  
73 scenarios may be of maximum importance (Muneret, Auriol, Bonnard, et al., 2019).

74 The effect of OF expansion on pest abundance and CBC in organic and conventional fields is difficult to  
75 predict. It will depend on the abilities of the pests and predators to develop in organic and conventional  
76 fields, on the interplay between pest and predator and landscape structure that conditions the ability of  
77 pests and predators to move among crops and semi-natural habitats (Kremen et al., 2007; Le Gal et al.,  
78 2020). More complex landscapes, i.e. landscapes with more, and more fragmented, semi-natural habitats  
79 and a more heterogeneous crop mosaic, may sustain more biodiversity (Batáry et al., 2011; Petit et al.,  
80 2020; Smith et al., 2020; Tscharrntke et al., 2021; Tuck et al., 2014) and may support higher spill-over of  
81 predators from semi-natural habitats into crops (Concepción et al., 2008; Tscharrntke et al., 2012). Such  
82 landscapes may also exhibit more movements of pests from semi-natural habitats to crops if pests find  
83 resources in semi-natural habitats at some point of their life cycle (Juhel et al., 2017). As a result, an  
84 increasing amount of semi-natural habitat in the landscape generally increases the abundance and  
85 diversity of natural enemies as well as pest predation and parasitism but its effect on pest abundance or  
86 damage is case dependent (Chaplin-Kramer et al., 2011; Karp et al., 2018; Veres et al., 2013). Similarly,  
87 pest and predator movements between organic and conventional crops are expected to increase with the  
88 edge length between these two crop types. Organic expansion should thus affect more pest abundance  
89 in conventional crops when the two crop types are interspersed. The response of pest abundance to OF

90 expansion may moreover differ in organic and conventional fields: local management is expected to have  
91 large effects on biodiversity or ecological functions when landscapes are of intermediate intensity but to  
92 have little effect when landscapes are either very or very little intensive (the intermediate landscape  
93 hypothesis (Perez-Alvarez et al., 2019; Tscharrntke et al., 2005, 2012)) and, reciprocally, landscape effects  
94 are supposed to depend on local practice intensity (Petit et al., 2020). Such interactions have, however,  
95 seldom been observed in the field (Petit et al. 2020, but see e.g. Perez-Alvarez, Nault, et Poveda 2019;  
96 Ricci et al. 2019).

97

98       Given the inherent complexity of conservation biological control (Begg et al., 2017) and the lack of CBC  
99 data in the context of OF expansion, modeling appears as a useful tool to understand and forecast how  
100 pests and their control may vary during OF expansion in a diversity of landscape contexts. The only  
101 published modeling study to our knowledge considered a pest-parasitoid system in a landscape  
102 exclusively composed of conventional and organic fields (Bianchi et al., 2013). This study interestingly  
103 showed that clustering organic and conventional fields decreased the proportion of OF necessary for  
104 maintaining the parasitoid population and decreased pest load. It also showed that intermediate levels of  
105 OF may lead to transitory peaks in pest load due to the delay of the parasitoid population response to  
106 pest abundance (Bianchi et al., 2013). It is therefore interesting and necessary to study, through modeling  
107 approaches, how spatial scenarios of organic farming expansion impact conservation biological control  
108 (Adl et al., 2011; Bianchi et al., 2013). As stated by Petit et al, (2020), such modeling approaches “can offer  
109 in silico tests of the consequences of much larger proportions of agroecological practices in the landscape”  
110 and could be combined with empirical studies to “provide key insights about how natural enemies and  
111 pests will behave in future landscapes.”

112

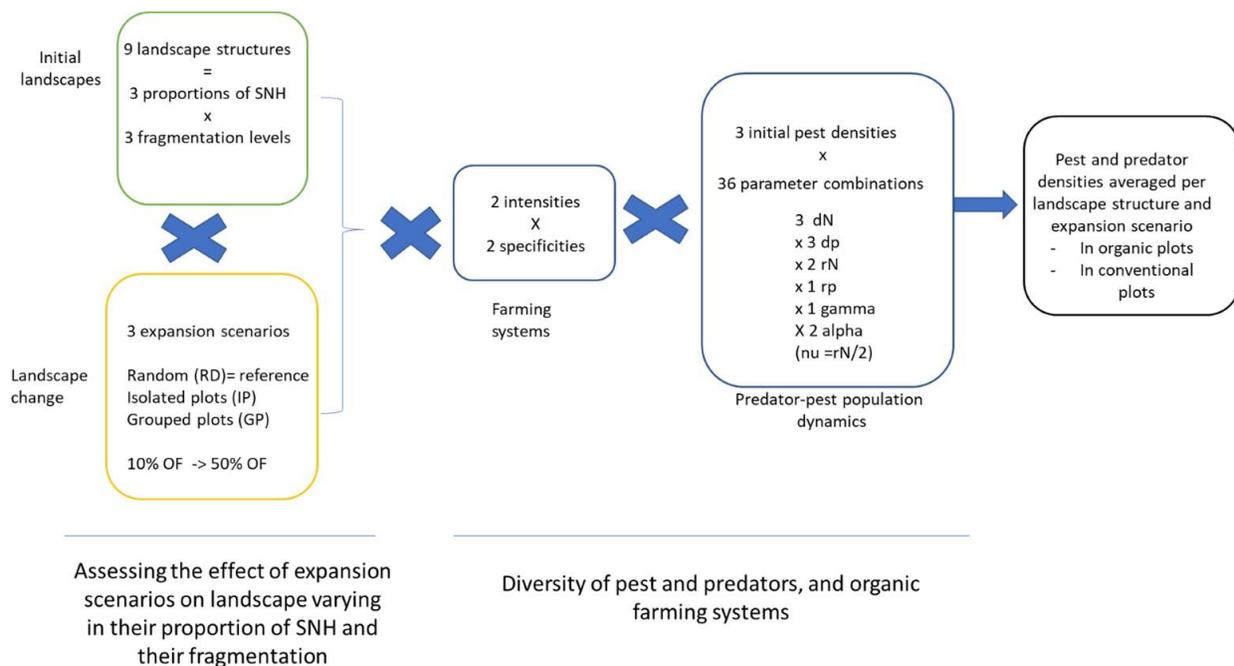
113       In the following, we pair a grid-based landscape model and a spatially explicit Lotka-Volterra type  
114 predator-prey model (Ciss et al., 2016; Roques, 2015) to investigate how contrasted scenarios of OF  
115 expansion, defined by their spatial arrangements, impact pest abundance in organic and conventional  
116 crops. The scenarios are applied to a diversity of landscapes differing in their amount of semi-natural  
117 habitat and its fragmentation. [We further investigate if the ranking of scenarios is robust to pest control  
118 methods in OF fields and pest and predator dispersal abilities.](#)

119

## 120 Material and Methods

### 121 1. Overview

122 The modeling procedure comprises three main elements. The first is a stochastic landscape model to  
123 initiate the structure of the landscape, i.e. the total area and fragmentation of semi-natural habitat and  
124 the initial area of organic and conventional crops. The second is a population dynamics model to represent  
125 the dynamics of interacting pests and their predators on the changing landscapes. The third is a set of  
126 spatial scenarios of OF expansion that govern landscape change over time (Figure 1).



127

128

129 **Figure 1.** The simulation design combines three spatial scenarios of organic farming expansion (Random  
130 versus IP or GP) in nine **landscape contexts** (3 proportions of seminatural habitats (SNH) x 3 fragmentation  
131 levels) for various predator-pest population dynamics (36 pest biology parameter combinations and 4 pest  
132 management types in the organic farming system). The green box corresponds to the landscape model,  
133 the blue box to the population dynamic model and the orange box to the land change scenarios.

134

## 135 2. Landscape and population dynamics models

### 136 2.1. Stochastic landscape model to set the initial landscape context

137 To set the landscape context in which to initiate the joint simulation of OF expansion and pest and  
138 predator population dynamics, we used a landscape model initially developed by Roques and Stoica  
139 (2007), then improved by Roques (2015). This landscape model generates stochastic landscapes with  
140 several types of land uses over a square grid ( $n \times n$  matrix). Land use allocations were parametrized by  
141 the proportion of each type of land use and the fragmentation level of one target land use (Roques 2015;  
142 Ciss et al. 2016). This fragmentation is controlled by the  $fr$  parameter, which is an index of fragmentation  
143 *per se* (Fahrig, 2003).  $fr$  measures the landscape-level average proportion of neighbors among the 4  
144 closest neighbors of each cell of that land use that are not of the same land use type.  $fr$  is in the range  
145 [0,1], and increases with fragmentation. To reach the desired fragmentation level, grid cells are first  
146 randomly allocated to one of the land uses, controlling for the proportion of cells associated to each land  
147 use. Then a Metropolis-Hastings algorithm is run to optimize the spatial distribution of the cells associated  
148 with the target land use. The algorithm stops when the distance between the observed and the desired  
149 fragmentation index is below a tolerance threshold.

150 Here, we set up initial landscapes composed of three land uses: (i) semi-natural habitats (SNH), (ii)  
151 Organic Farming crops (OF), and (iii) Conventional Farming crops (CF). We controlled the proportions of  
152 these land uses and the fragmentation level  $fr$  of SNH. (Table 1).  $fr$  is thus an index of fragmentation *per*  
153 *se*. High values of  $fr$  resulted in landscapes with more numerous and smaller SNH patches and increased  
154 edge length between SNH and crop patches (Fig. 1, S1.1, S1.2, S1.3).

### 155 2.2. Population dynamic model

#### 156 2.2.1 - General description

157 We modeled the spatio-temporal dynamics of a pest and a generalist predator species interacting over  
158 the lattice generated by the landscape model according to (Martinet & Roques, 2022). The model  
159 describes the density of the predator population  $P_t(x)$  and of the pest population  $N_t(x)$  at each position  
160  $x = (i, j)$  over the grid and at each time step  $t$  (equations 1). The variation over time (indicated with sign  
161 ') of pest ( $N'_t(x)$ ) and predator ( $P'_t(x)$ ) densities at each position depends on their dispersal in and out  
162 of this position, their intrinsic growth (i.e. population growth in absence of pesticides and of interactions  
163 between pests and predators), mortality due to pesticides, and mortality (for the pest) or growth (for the  
164 predator) due to predation.

$$\begin{cases} N_t'(x) = \underbrace{d_N D[N_t(x)]}_{\text{Dispersal}} + \underbrace{f_N(t, x, N_t(x))}_{\text{Growth}} - \underbrace{\rho n(t, x) N_t(x)}_{\text{Mortality}} - \underbrace{\alpha_1 N_t(x) P_t(x)}_{\text{Predation}} \\ P_t'(x) = \underbrace{d_P D[P_t(x)]}_{\text{Dispersal}} + \underbrace{f_P(t, x, P_t(x))}_{\text{Growth}} - \underbrace{\rho p(t, x) P_t(x)}_{\text{Mortality}} + \underbrace{\alpha_2 N_t(x) P_t(x)}_{\text{Predation}} \end{cases} \quad (1)$$

165

166 Dispersal:  $D[.]$  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  
 167 discrete Laplace operator modeling the movements of the individuals to adjacent cells,  $\delta_x = 1/n$  being  
 168 the length of a unit cell in the landscape. From each position  $x = (i, j)$ , and during a time interval  $\delta_t \ll 1$ ,  
 169 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  
 170 cells. Thus  $d_N$  and  $d_P$  directly control the mobility of the pest and predator populations. We assume  
 171 periodic conditions at the boundaries of the lattice.

172 Growth: The terms  $f_N(t, x, N_t(x))$  and  $f_P(t, x, P_t(x))$  stand for the pest and predator [intrinsic](#) growth  
 173 functions. They are controlled by parameters  $r_N$  and  $r_P$  respectively (Table 1). [The predator being a](#)  
 174 [generalist, it can grow in absence of pests.](#)

175 Mortality:  $\rho_N(t, x)N_t(x)$  and  $\rho_P(t, x)P_t(x)$  account for the pest and predator death rates caused by pest  
 176 management. Mortality is controlled by parameter  $v$  (Table 1).

177 Predation: 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  
 178 the pest and predator growth rates, respectively. [We assume standard Lotka–Volterra interactions](#)  
 179 [between the pest population and its predator, which means that the pest death rate increases linearly](#)  
 180 [with the density of the predator, and conversely the growth rate of the predator increases linearly with](#)  
 181 [the pest population density. We also assume that  \$\alpha\_1 = \alpha\_2 = \alpha\$  \(Table 1\)](#)

182 The system is scaled so that the carrying capacities of  $P$  and  $N$  are both equal to 1 thus the population  
 183 densities are expressed in units of their respective carrying capacities.

184

185 **Table 1.** List of model parameters.

Parameter	Description	Unit	Values
<b>Landscape model:</b>			
$n$	Size of the lattice		24
$fr$	Fragmentation index	dimensionless	{0.1,0.5,0.9}
$pSNH$	Percentage semi-natural habitat	%	{10, 25, 50}
T	Time horizon	year	50
<b>Model of population dynamics:</b>			
$d_N$	Pest dispersal coefficient	unit area.year <sup>-1</sup>	$\frac{1}{n^2}\{0.1,0.5,1\}$
$d_P$	Predator dispersal coefficient	unit area.year <sup>-1</sup>	$\frac{1}{n^2}\{0.1,0.5,1\}$
$r_N$	Pest intrinsic growth rate	year <sup>-1</sup>	$2\{\ln(50), \ln(100)\}$
$r_P$	Predator intrinsic growth rate	year <sup>-1</sup>	$\ln(2)$
$\gamma$	Predator life expectancy in crops	year	1/2
$\alpha$	Predation index	indiv <sup>-1</sup> year <sup>-1</sup>	$\frac{1}{\gamma}\{4/3, 4\}$
$v$	Pest management effect	year <sup>-1</sup>	$r_N/2=\{\ln(50), \ln(100)\}$

186

187

### 2.2.2 - Timing of ecological processes

188 The year is divided into equal intervals  $\delta_t$  each corresponding to a dispersal event of pests and predators.

189 The number of intra-annual time steps is thus calculated as  $1 + (1/\delta_t)$ . Each year is divided into two periods

190  $[0, \frac{1}{2}[$  and  $[\frac{1}{2}, 1]$  during which ecological processes differ (Table 2). [Pests are specialized on the crop and](#)

191 [their phenology matches that of the crop. The first half of the year schematically represents the season](#)

192 [where the crop is absent, pests do not reproduce and there are no pest management practices. Pest](#)

193 [densities only depend on their dispersal and predation by predators. During the second half of the year,](#)

194 [when the crop is present, pests furthermore reproduce and are affected by pest management practices](#)

195 [in the crop. The predators, in contrast, reproduce all year long in semi-natural habitats \(loosely mimicking](#)

196 [taxa that include both spring and autumn reproduction\) and suffer from intrinsic mortality in crops. Their](#)

197 density increases further in both semi-natural habitats and crops when the pest is present. Predators thus  
 198 behave as generalist predators that feed on the pest prey, and on alternative prey in semi-natural habitats.  
 199 Like pests, they are affected by pest management practices in crops during the second half of the year.

200

201 **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  
 202 growth rate in the crops in the absence of pest management,  $\gamma$  the natural enemy life expectancy in the  
 203 absence of resources and  $r_P$  the natural enemy birth rate in semi-natural habitats.

Time span	$f_N(t, x, N)$		$f_P(t, x, P)$	
	$[0, \frac{1}{2}[$	$[\frac{1}{2}, 1]$	$[0, \frac{1}{2}[$	$[\frac{1}{2}, 1]$
<b>Land use</b>				
Conventional	0	$r_N N(1 - N)$	$-P/\gamma$	$-P/\gamma$
Organic	0	$r_N N(1 - N)$	$-P/\gamma$	$-P/\gamma$
Semi-natural habitats	0	0	$r_P P(1 - P)$	$r_P P(1 - P)$

204

### 205 2.2.3 - Organic farming systems

206 There exists a diversity of organic farming systems with more or less intensive pest management strategies  
 207 (Marliac et al., 2015). To represent this diversity, we considered four theoretical types of organic farming  
 208 (Table 3). In the most intensive OF systems (*Int-Gen* and *Int-Spe*), pest management is as efficient in  
 209 organic fields as in conventional ones so that the mortality of pests due to pest management practices is  
 210 the same. These two OF systems differ by the specificity of these control measures that either do not (*Int-*  
 211 *Spe*) or do (*Int-Gen*) affect predators, but less than in conventional fields. Examples of efficient and specific  
 212 pesticides are microorganisms targeting pests such as viruses (Graillot et al., 2016) or other  
 213 microorganisms (Deshayes et al., 2017). Other pest management measures such as pesticides (*e.g.*  
 214 spinosad) or nets are efficient on pests but also affect some predators (Dib et al., 2010). In the extensive  
 215 OF systems (*Ext-Gen* and *Ext-Spe*) pest management is less efficient in OF fields and pest mortality rates  
 216 are half those in conventional fields. As before, these two OF systems differ by the specificity of their pest  
 217 management practices that either do (*Ext-Gen*) or do not (*Ext-Spe*) affect predators (Table 3).

218

219 **Table 3.** Effects of [pest management practices](#) on the pest and the natural enemies in conventional (CF)  
 220 and organic farming. Four organic farming systems were considered. [Int-Spe and Int-Gen](#) correspond to  
 221 intensive pest management (high pest mortality) while [Ext-Spe and Ext-Gen](#) are less intensive. In [Int-Spe](#)  
 222 [and Ext-Spe](#) systems, [pest management practices are specific to the pest and](#) do not affect predators  
 223 while in [Int-Gen and Ext-Gen](#) systems, [management is less specific.](#)

	$\rho_N(t, x)$	$\rho_P(t, x)$
<b>CF</b>	$2\nu$	$2\nu$
<b>Int-Spe</b>	$2\nu$	0
<b>Int-Gen</b>	$2\nu$	$\nu$
<b>Ext-Gen</b>	$\nu$	$\nu/2$
<b>Ext-Spe</b>	$\nu$	0

224

225 2.2.4 - Parameter values

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

232 *Mortality due to [pest management practices](#):* We assumed that the mortality rate induced by [pest](#)  
 233 [management practices](#) is comparable to pest growth rates ( $2 \nu \in 2\{\ln 50, \ln 100\}$ ). The mortality due to  
 234 pest management practices reaches its maximum value for both pests and predators in the conventional  
 235 fields and for pests only in the most intensive OF systems ([Int-Spe and Int-Gen](#)). In these situations,  
 236 mortality compensates for the pest population's local increase and drastically reduces predator  
 237 populations. Mortality caused by [pest management practices](#) is reduced by half or set to 0 for predators  
 238 depending on the OF systems (Table 3).

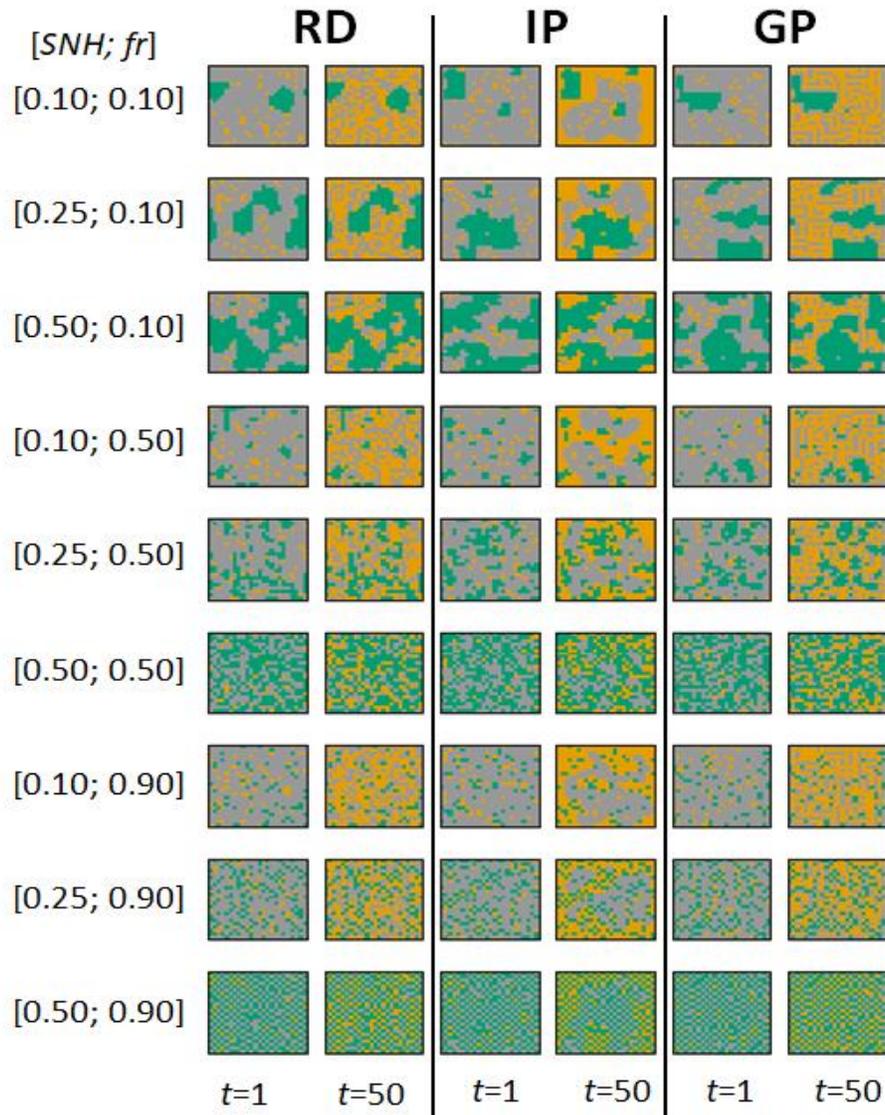
239 *Dispersal:* The values for  $d_N$  and  $d_P$  were chosen so that approximately between 0.1% ( $d_N$  or  $d_P=0.1/n^2$ ) and  
 240 1% ( $d_N$  or  $d_P=1/n^2$ ) of individuals in a given cell move to neighboring cells every day.

241

### 242 3. Initial Conditions

#### 243 3.1. Landscapes

244 Simulations were run on 9 landscape contexts differing in their proportion of semi-natural habitats (SNH)  
245 (either 10, 25, or 50% of total area) and in the fragmentation of these habitats (*fr* values: 0.1, 0.5 and 0.9).  
246 Initially, 10% of crops were organic (OF) and 90% conventional (CF) based on the current national  
247 proportions in France (ORAB PACA, 2020) and on the proportion of worldwide cropped and pasture land  
248 that is practicing some forms of organic farming (Pretty et al, 2018). Based on that, we generated initial  
249 landscapes with three proportions of each land-use, named respectively Qin1 (10% SNH; 9% OF; 81% CF),  
250 Qin2 (25% SNH; 7.5% OF; 67.5% CF), and Qin3 (50% SNH; 5% OF; 45% CF). In the remainder of this paper,  
251 we refer to these three initial conditions in terms of their SNH proportions (SNH 10%, 25% and 50%). Initial  
252 OF crops were allocated randomly among crop cells. Each simulation of the model was run on a different  
253 initial landscape.



254

255 **Figure 2.** Examples of landscape structures at the beginning ( $t=1$ ) and the end ( $t=50$ ) of the organic  
 256 expansion. The figure provides one example landscape for each combination of **landscape context** and OF  
 257 expansion scenarios. SNH= proportion of semi-natural habitat;  $fr$ : fragmentation of semi-natural habitat;  
 258 RD, IP and GP refer to the three scenarios of selection of CF fields to convert to OF: selection of random,  
 259 isolated or grouped fields; Grey: conventional (CF), orange: organic (OF), green: semi-natural habitat  
 260 (SNH).

261 **3.2. Population dynamics**

262 At  $t=1$  predators are introduced in all semi-natural habitats with initial density  $P1_{SNH}$ . The predators are  
 263 allowed to reproduce and disperse until  $t=3$ . At  $t=3$  pests are introduced in the crops with initial density

264  $N_{1_{crop}} = P_{1_{SNH}}$ . To assess the impact of initial conditions on our conclusions, we set three extreme values  
265 for  $P_{1_{SNH}}$ : 0.1, 0.5 and 1. We then performed simulations during a 15-years burn-in period in order to allow  
266 the stabilization of pest and predator dynamics before organic farming expansion.

267

#### 268 **4. Spatial scenarios of organic farming expansion**

269 From each initial landscape, we simulated OF expansion from  $t=15$  to  $t= 50$  years in order to sequentially  
270 convert 50% of the initial conventional crop area to OF. For each simulation, OF expansion was  
271 progressive, i.e. approximately 6.25% of the initial conventional crop area was converted to OF every 5  
272 years. The total number of conventional fields to be converted depended on the initial cultivated area and  
273 the target proportion of OF. The final compositions of landscapes corresponding to the three initial  
274 proportion of semi-natural habitats were respectively Qen1(10% SNH; 49.5% OF; 40.5% CF), Qen2(25%  
275 SNH; 41.25% OF; 33.75% CF), Qen3(50% SNH; 27.5.5% OF; 22.5% CF). Only conventional fields were  
276 converted to organic. The area of semi-natural habitat remained constant.

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

- 278 - the RD scenario in which we performed a random choice of conventional fields to be converted,
- 279 - the IP scenario, in which isolated conventional fields, i.e. fields with as few as possible  
280 conventional 4-neighbors, were converted first,
- 281 - the GP scenario in which, in contrast to IP, conventional fields with as many as possible  
282 conventional 4-neighbors were converted first.

283 [The IP and GP scenarios are two possibly planned scenarios that we compared to the baseline RD scenario](#)  
284 [in terms of resulting pest densities and predator to pest ratio.](#)

285

#### 286 **5. Simulation outputs**

287 At each time step of each simulation, we recorded indicators of the landscape structure and of pest and  
288 predator densities in each land use (CF, OF and SNH).

##### 289 **5.1. Landscape structure**

290 Landscapes can be described in terms of composition, i.e. proportion of the land uses, and configuration,  
291 i.e. the spatial arrangement of these land uses (Fahrig & Paloheimo, 1988). Landscape composition was

292 controlled during the simulation. We monitored landscape configuration using three landscape metrics  
293 for each land use: the mean patch area, the number of patches, and the edge length (R package *landscape*  
294 *metrics*, Hesselbarth et al, 2019). For a given land use, patches were made of fields of that given land use  
295 that were 4-neighbors to at least one field of the same land use. Together, these three metrics indicate  
296 whether, for a given proportion of landscape area, one land use is represented by a few large patches or  
297 many small patches.

## 298 **5.2. Pest and predator densities**

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

302

## 303 **6. Simulation study**

304 Simulations for the three spatial organic farming expansion scenarios mentioned above were performed  
305 for each of the nine types of landscapes (3 proportions of SNH x 3 levels of *fr*) aiming at 50% OF fields for  
306 each of the four types of OF (Table 3). These simulations were performed for all combinations of the  
307 values of the 6 parameters (pest and predator dispersal coefficients, pest and predator intrinsic growth  
308 rates, predator life expectancy in crops, interaction term,) and the four farming systems governing pest  
309 and predator population dynamics (Table 1, Fig. 1) and the three initial densities of pests and predators.  
310 This resulted in a total of 11664 Simulations, each run on a different landscape. We performed 11664  
311 more simulations without any action on the landscapes. These simulations are referred to as Reference  
312 (REF).

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

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

319

## 320 **Results**

### 321 **1. Pest and predator dynamics**

#### 322 **1.1 Pest and predator dynamics in absence of organic farming expansion**

323 The model behavior was first studied in the absence of organic farming expansion, *i.e. at the initial*  
324 *proportions of organic farming*. This step first shows that in the absence of organic farming expansion, the  
325 *average landscape scale* densities of pest and predator *remained stable over time* after approximately 15  
326 years (Figure 3, scenario: REF). These equilibrium densities were independent of the initial pest density  
327 (not shown). Consistent with parameter values, both pest and predator densities were higher in organic  
328 fields than conventional fields. Moreover, the density of pests was always larger than that of predators,  
329 in both conventional and organic fields (Fig. 3, scenario: REF).

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

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

#### 342 **1.2 - Pest and predator dynamics during organic farming expansion**

343 The cultivated landscape changed during organic farming expansion. Compared to their initial area, at the  
344 end of organic farming expansion, conventional patches were generally smaller and organic patches  
345 larger. Constraints were furthermore imposed by the spatial distribution of semi-natural areas so that  
346 patch area varied more in little fragmented landscapes or when there was little semi-natural area. Because  
347 they set different priorities regarding field conversion, the different scenarios led to different cultivated  
348 patch area dynamics, with some dramatic changes due to conventional patch splitting. The IP scenario

349 notably always resulted in conventional patches that were larger than the other scenarios while the GP  
350 scenario generally resulted in larger organic patches (Supplementary material S1.3).

351 The organic farming expansion affected more predator densities than pest densities for most  
352 combinations of landscape contexts and expansion scenarios (Fig. 3). Its impact was also generally  
353 stronger in organic than conventional fields and in landscapes with large proportions of fragmented semi-  
354 natural habitats. As expected, predator densities in organic fields generally increased. Changes in pest and  
355 predator densities and their dynamics, however, depended on expansion scenarios and landscape  
356 contexts.

### 357 1.2.1 Pest dynamics

358 Pest densities in organic fields showed similar changes for the three expansion scenarios (Fig. 3). They  
359 tended to slightly increase or remain stable over time in landscapes with little or intermediate proportions  
360 of semi-natural habitat and to decrease in landscapes with large proportions of semi-natural habitat. In  
361 conventional fields, pest densities showed this same pattern with the RD and GP scenarios but not with  
362 the IP scenario. With the IP scenario, pest densities in conventional fields tended to decrease slightly over  
363 time whatever the [landscape context](#). As a result, at  $t=50$ , pest densities were generally smaller with the  
364 IP than with the RD and the GP scenario in conventional fields and similar for the three expansion  
365 scenarios in organic fields.

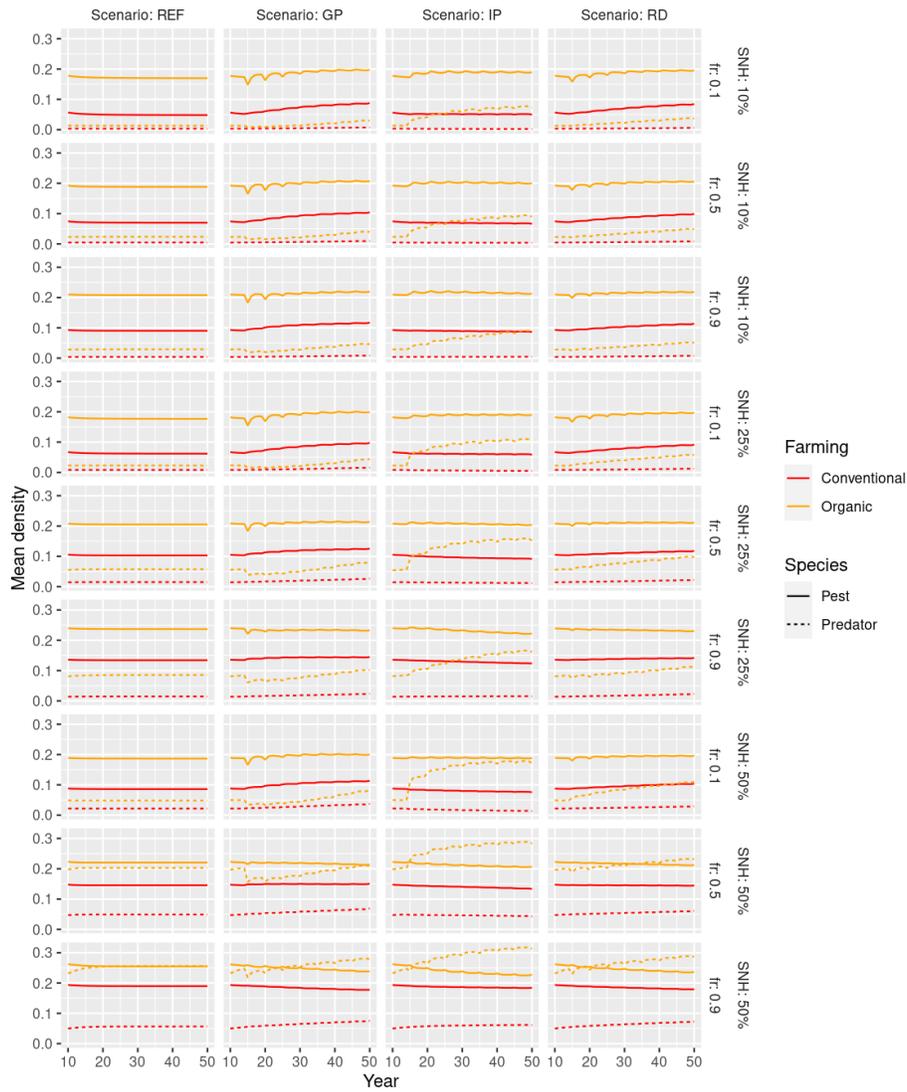
### 366 1.2.2 Predator dynamics

367 In organic fields, the effect of organic farming expansion on predator densities was very large compared  
368 to its effect on pest densities (Fig. 3). Predator densities increased for the three expansion scenarios. The  
369 increase was larger for the IP scenario than for other scenarios, particularly in little fragmented landscapes  
370 with intermediate or large proportion of semi-natural habitats. For example, when  $SNH=25\%$  and  $fr=0.1$ ,  
371 with the IP scenario the predator density at  $t=50$  was 5.38 times larger than the initial density and was  
372 2.44 times higher than the predator density at  $t=50$  with the GP scenario. In contrast, the three scenarios  
373 performed similarly in landscapes with the highest proportion and fragmentation of semi-natural habitat  
374 ( $SNH=50\%$ ,  $fr=0.9$ ). In these landscapes, the predator density increased by a factor of 1.34 between  $t=0$   
375 and  $t=50$  with the IP scenario and was only 1.20 times higher than with the GP scenario at  $t=50$ . The  
376 increase in predator density was moderate for the RD and GP scenarios and reached similar values at  $t=50$ .  
377 Their dynamics were, however, qualitatively different. While predator densities increased steadily for the

378 RD scenario, for the GP scenario, most predator densities showed a transient decrease in the first years  
379 following the beginning of organic farming expansion.

380 Note that in landscapes with 50% SNH predator densities were sometimes larger than pest densities in  
381 organic fields (Fig. 3). This was most prominent when fragmentation was high, an indication that it  
382 resulted from spillover of predators from semi-natural habitats.

383 The pattern was very different in conventional fields. Predator densities remained stable at very low  
384 values for most landscapes and expansion scenarios. They only increased in the GP scenario in landscapes  
385 with high proportion of semi-natural habitats but still remained at low values.



387

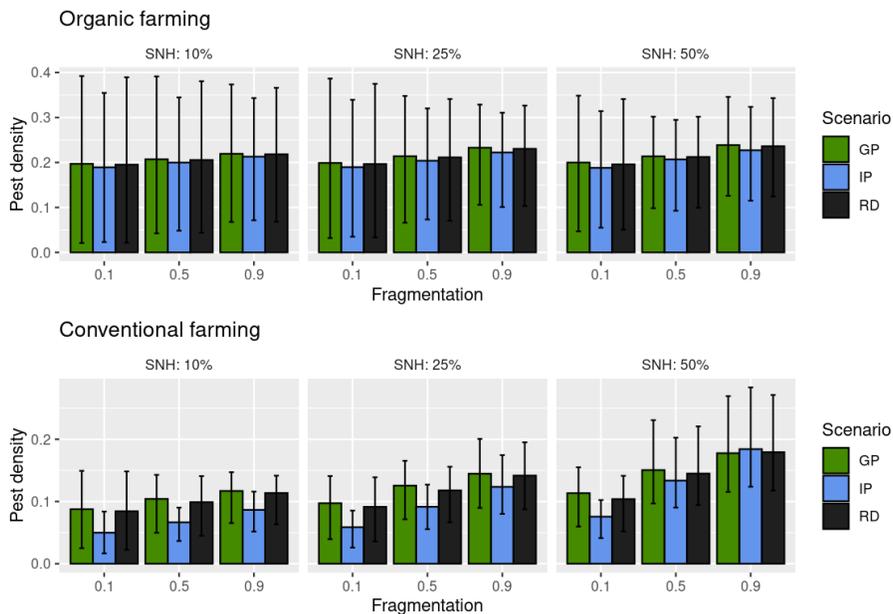
388 **Figure 3.** Effect of organic expansion scenarios on the temporal evolution of the mean density of pests  
 389 and predators in organic (OF) and conventional farming (CF), as a function of fragmentation (*fr*) and  
 390 initial proportion of semi-natural habitat (SNH). Reference (REF) represents the absence of organic  
 391 expansion.

392

393 **2 - Effect of spatial scenarios of organic farming expansion and landscape contexts on resulting**  
394 **pest densities and conservation biological control**

395 **2.1 Pest densities**

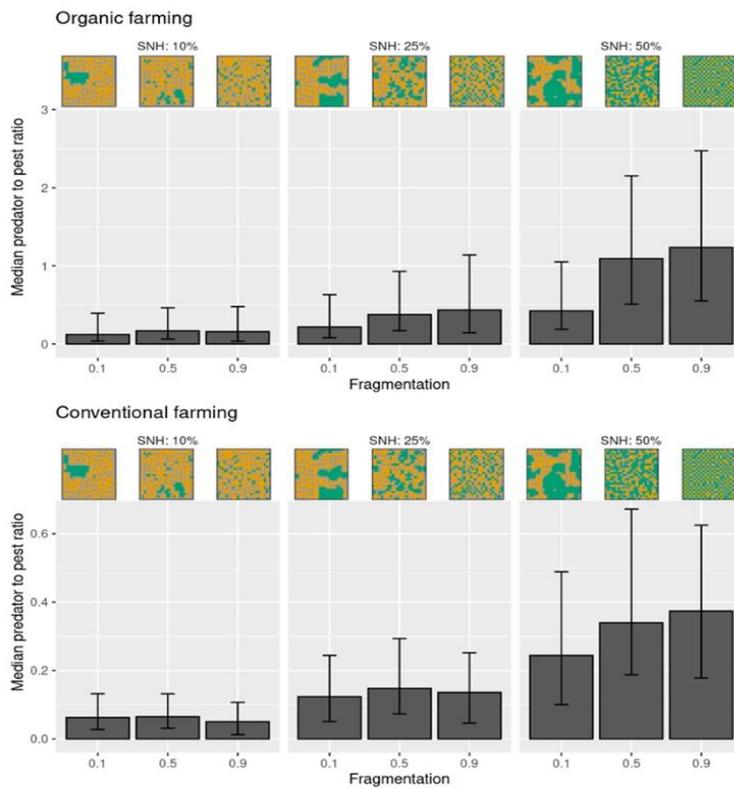
396 In organic fields, differences in final pest density were limited among expansion scenarios. Pest density in  
397 organic fields responded overall little to landscape characteristics and, in particular, less to the different  
398 scenarios of OF expansion, despite differences in organic or conventional patch areas (Fig. S1.3), than to  
399 the fragmentation of semi-natural habitats (Fig. 4, upper panel). The highest levels of pest densities were  
400 obtained for the highest fragmentation levels. For a given level of fragmentation, pest densities in organic  
401 fields tended to be lower for the IP scenario but the amplitude of effect was smaller than for  
402 fragmentation. In contrast, final pest density in conventional fields (Fig. 4, lower panel) responded both  
403 to the OF expansion scenario and to fragmentation, indicating a dependence on conventional and organic  
404 patch area (Fig S1.3). As in organic fields, pest density increased with the level of semi-natural habitat  
405 fragmentation. In conventional fields, low levels of pest densities could thus be attained for different  
406 fragmentation levels given that conventional patch areas were large, a situation provided by the IP  
407 scenario in landscapes with small proportion of semi-natural habitats (SNH=10%). Furthermore, the range  
408 of variation of pest densities was larger in conventional than organic fields.



409  
410 **Figure 4.** Mean final (t=50) density of pests in organic (upper panel) and conventional (lower panel) fields  
411 as a function of the landscape context (fragmentation and percentage of semi-natural habitat). Results  
412 are presented for each OF spatial expansion scenario: GP (grouped plots), IP (isolated plots), RD (random).

413 **2.2 Conservation biological control**

414 The predator to pest ratio is an indicator of the potential for conservation biological control: a higher ratio  
415 indicates that pests are more likely to come across a predator. As a result of the pest and predator  
416 dynamics described above, the predator to pest ratio at the end of the simulation was three to four times  
417 larger in organic fields than in conventional fields (Fig. 5). It increased with the proportion of semi-natural  
418 habitat, in similar relative proportions in organic and conventional fields, from an average of approx 0.2  
419 to 1.25 in organic fields and 0.05 to 0.35 in conventional fields, when the proportion of SNH increased  
420 from 10% to 50%. It also increased, but to a much lesser extent with SNH fragmentation. The only  
421 significant increase with fragmentation was for landscapes with large proportion of SNH (Fig. 5).



422 **Figure 5.** Median Predator to pest ratio at t=50 for the nine types of initial landscapes, in organic  
423 fields (upper) and conventional fields (lower). Error bars represent the first and third quartiles over  
424 all scenarios and parameter values. Examples of landscape contexts (combinations of  
425 fragmentation and percentage of SNH) are provided for illustration. Note that y-axes are on  
426 different scales.  
427

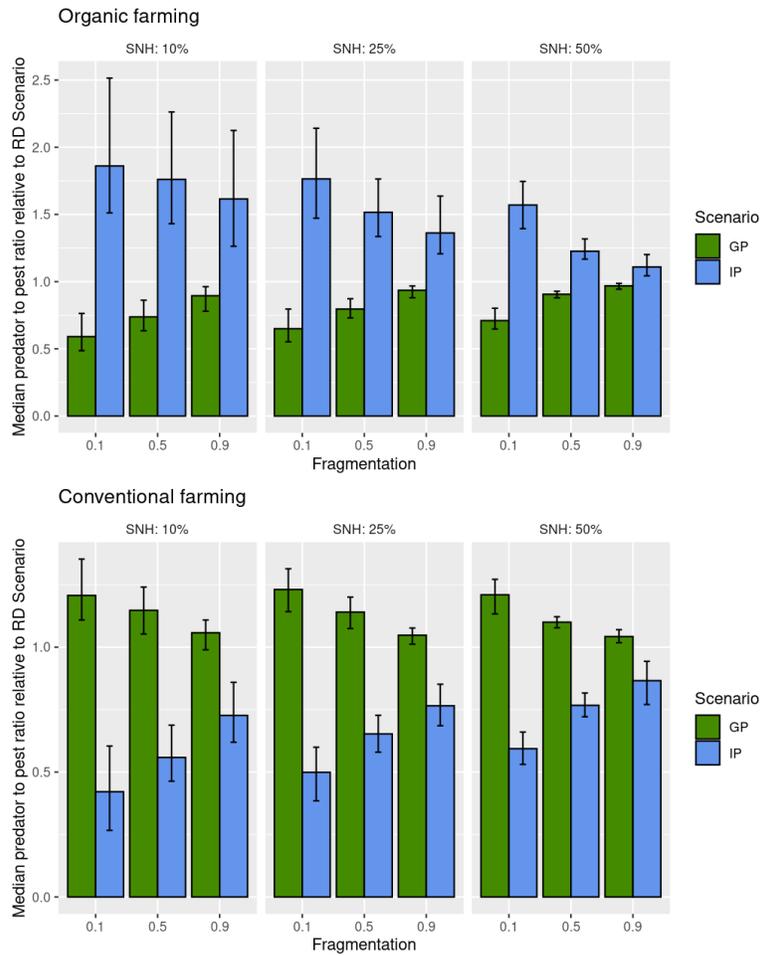
428

429 More interestingly, we observed a clear ranking of spatial expansion scenarios with IP>RD>GP for the  
430 predator to pest ratio in organic fields (Fig. 6). This ranking might be due to the larger increase of predator  
431 densities during OF expansion with the IP scenario and the somewhat larger pest densities with the GP  
432 scenario (Fig. 3). Relatively to the RD scenario, the predator to pest ratio was from 1.83 times higher  
433 (SNH=10%, fr=0.1) to 1.1 (SNH=50%, fr=0.9) times higher for the IP scenario. In contrast, these ratios for  
434 the GP scenario ranged from 0.55 (SNH=10%, fr=0.1) to ~1(SNH=50%, fr=0.9) times those for the RD  
435 scenario.

436 In conventional fields, predator to pest ratios showed the opposite GP>RD>IP ranking. The difference here  
437 was mainly between the IP and the two other scenarios. Ratios were a little larger for the GP scenario  
438 than for the RD scenario whatever the landscape context, with values ranging from 1.2 (SNH=10%, fr=0.1)  
439 to ~1 (SNH=50%, fr=0.9) times those for the RD scenario. They were the smallest for the IP scenario,  
440 particularly in fragmented landscapes with low proportions of semi-natural habitats (from 0.55  
441 (SNH=10%, fr=0.1) to 0.8 (SNH=50%, fr=0.9) times higher than with the RD scenario, Fig. 6). Consistent  
442 with the larger differences in crop patch area in landscapes with few and little fragmented semi-natural  
443 habitat, differences between the GP and IP scenarios were largest in such landscapes and very small in  
444 landscapes with a large proportion of highly fragmented semi-natural habitats.

445

446



447

448 **Figure 6.** Median predator to pest ratio at t=50 in organic and conventional crops for the IP and GP  
 449 scenarios relative to the ratio obtained for the RD scenario with the same parameter values. Error  
 450 bars represent first and third quartiles over all combinations of population dynamic parameters.

451

## 452 Discussion

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

460 (Isolated Plots converted first) scenario would provide the most benefits for conservation biological  
461 control (i.e. predator to pest ratio) in organic fields with little impact on pest densities in conventional  
462 fields.

463

#### 464 **1 - Landscape context and OF expansion affect pest and predator densities.**

465 Populations responded to organic farming expansion in the landscape with up to a 437% increase and a  
466 46% decrease in pest and predator densities, indicating that organic farming expansion could indeed lead  
467 to significant changes in biological control of pests in both organic and conventional fields depending on  
468 the landscape context. Predator densities generally increased or remained stable while pest densities  
469 either increased or decreased along OF expansion. When both pest and predator densities increased,  
470 predator densities increased more strongly than pest densities. The predator to pest ratio was about three  
471 to four times larger in organic than in conventional fields. Changes in pest and predator densities and their  
472 dynamics strongly depended on expansion scenarios in interaction with landscape contexts, i.e. the  
473 amount and fragmentation of SNH. Although most scenarios led to overall improvements in predator to  
474 pest ratios (seen here as a proxy of conservation biological control, CBC), some led to increases in pest  
475 densities, particularly in conventional fields which indicates that in some specific landscapes, carefully  
476 planning the spatial expansion of organic farming would be useful to avoid undesirable side effects.

477 From an ecological point of view, the predator to pest ratio dynamics observed in this study appeared  
478 driven by the dynamics of predators which was mostly dependent on the amount of semi-natural habitat  
479 (SNH). It was striking that only in landscapes with large proportion of SNH (SNH=50%), did predator  
480 densities increase very largely in organic fields and even increase slightly in conventional fields, leading to  
481 a decrease of pests in both types of fields. CBC also increased with landscape fragmentation in both OF  
482 and CF fields but mostly when the proportion of SNH was high. Since SNH fragmentation increased its  
483 edge length with cultivated habitats, this synergy between SNH amount and fragmentation on the level  
484 of CBC indicates the importance of predators' spillover from semi-natural habitats on biological control.  
485 This interaction is also in line with the frequent observation that complex landscapes with more and more  
486 fragmented semi-natural habitats sustain more biodiversity within fields (Muneret, Auriol, Bonnard, et al.,  
487 2019; Smith et al., 2020; Tscharntke et al., 2021) and that reduced distance between SNH and crops favor  
488 spillover of predators (Holland et al., 2016; Jonsson et al., 2014; Lavandero et al., 2006; Tylianakis et al.,  
489 2006). Incidentally, it may indicate that landscape structures favoring the movement of predators into

490 conventional fields may act as an ecological trap also luring non-target species to fields where mortality  
491 is high and long-term persistence impossible (Robertson & Hutto, 2006; Shelton & Badenes-Perez, 2006).  
492 Whatever the expansion scenario, we observed smooth changes in pest and predator densities. This was  
493 unexpected given the dramatic changes in the size of patches of OF and CF fields that underwent peculiar  
494 processes of progressive percolation/agglomeration (for OF) and its opposite disintegration (for CF)  
495 through the conversion of single central fields, leading to non-linear changes and even dramatic  
496 thresholds of mean OF and CF patch areas (especially in the IP scenario). This may indicate that the spatial  
497 smoothness of a conversion scenario over time is not necessary to maintain generally stable dynamics of  
498 biological control at landscape scale, neither in organic nor in conventional farms. This result is an  
499 indication that carefully curated temporal plans for OF expansion may not be not necessary, and that  
500 mean pest infestation risks may remain low for CF farms at the landscape scale. It contrasts with findings  
501 on the consequences of OF expansion in a pest - parasitoid model that indicated peaks of pest density for  
502 intermediate proportions of OF in the landscape (Bianchi et al. 2013). One main difference is that  
503 generalist predators, such as modeled here, may increase in density even in the absence of pests, thus  
504 limiting pest population peaks (Symondson et al., 2002).

## 505 **2 - One better scenario of organic farming expansion for CBC?**

### 506 **2.1 - A general pattern**

507 The similar pest densities with all spatial expansion scenarios indicates that the choice of one scenario  
508 over another bears low risks, while potential benefits were more obvious with noticeable effects on  
509 predators. Both the level of conservation biological control (CBC) and pest densities have been used to  
510 evaluate the efficiency of pest control in spatial pest-predator models (Bianchi et al., 2013; Zamberletti et  
511 al., 2021). Yield or income have also been used (e.g. Le Gal et al., 2020; Milne et al., 2016). Here, because  
512 conventional fields relied on pesticides for pest control, and pest densities varied little in organic fields,  
513 CBC was a target mostly in organic fields while the main target for conventional fields was the density of  
514 pests.

515 Using these criteria, the IP scenario performed better, by improving CBC in organic fields and doing so at  
516 the expense of lower CBC, but not higher pest densities, in conventional fields. Regarding CBC, the IP  
517 scenario performed overall better for organic fields because of its clear positive effect on the predator to  
518 pest ratio. Patterns were more nuanced for conventional fields. While some scenario x landscape context  
519 combinations caused a small improvement in CBC, others caused strong decreases. Interestingly, the

520 effect of expansion scenarios was weaker when they caused increases in CBC than when they caused  
521 decreases in CBC. Additionally, the ranking of scenarios was opposite in conventional vs organic fields  
522 (IP>RD>GP in organic fields vs GP>RD>IP in conventional fields). From the conventional farming point of  
523 view, the absence of planning (RD scenario) may thus constitute a reasonable scenario. However, pest  
524 densities in conventional fields were lower with IP than with the other scenarios. [The best ranking of the](#)  
525 [IP scenario with](#) higher CBC in organic fields and lower pest densities in conventional fields was observed  
526 in all landscape configurations, while some landscapes limited the decrease of CBC in conventional fields  
527 without canceling it.

528

529 The best performance of the IP scenario resulted from two distinct mechanisms: a predator spillover  
530 improving CBC in organic fields, and a combination of ‘chemical umbrella’ and lesser pest spillover in  
531 conventional fields. The IP scenario prioritized the conversion of fields neighboring organic fields or semi-  
532 natural areas. This meant that new organic fields benefitted from the spillover of predators from SNH,  
533 albeit with weak effects on pest density. Indeed, [the predator to pest ratio improved](#) mainly by an increase  
534 in predator numbers. Such trophic network top-heaviness can be caused by exogenous pathways that  
535 transfer energy into communities from across spatial and temporal boundaries: here, transfers from SNH  
536 (McCauley et al., 2018). With the IP scenario, CBC in organic fields may also have benefitted from a greater  
537 distance to conventional fields and from clustering of organic fields and SNH, as chemical pesticide use in  
538 conventional fields was modeled to kill most of the pests with strong side-effect on predators, drying both  
539 pest and predator populations in their surroundings through a sink effect. Clusters of conventional fields  
540 were more preserved from pests by the IP scenario, meaning that conventional fields benefitted from the  
541 protection of pesticides used in neighbor fields (the “chemical umbrella” effect) and that organic fields, a  
542 potential source of pests, were farther away from the conventional fields. A similar benefit of aggregating  
543 fields was found by Edwards et al. (2018) who simulated pest and predator dynamics in annual crops.  
544 Grouping annual crops could limit the abundance of dispersal limited pests because pests had to move  
545 over longer distances to reach new crop patches and reach central fields and could not build-up  
546 populations in the central fields. [This best IP scenario is in accordance with the current trend of OF](#)  
547 [extension mostly happening in areas already rich in OF fields \(Gabriel et al., 2009; Marton & Storm, 2021;](#)  
548 [Sánchez Herrera & Dimitri, 2019; Zollet & Maharjan, 2021\).](#)

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## 2.2 - Effect of the landscape context on differences between scenarios

In our simulations, landscape configuration had a strong effect with differences in pest density up to two times for a given scenario. The proportion and fragmentation of SNH were generally of similar importance to the difference in the level of CBC between scenarios, although there was a clear decrease associated with the interaction between the two parameters, i.e. the difference between the IP and GP scenarios decreased with higher proportions and fragmentation of SNH. In conventional fields, this amounted mainly to the IP scenario that benefited slightly from SNH, while SNH did not affect pest density with the GP scenario. In organic fields, IP and GP converged at highest proportion and fragmentation levels, with pest densities of the GP scenario being favored while those of the IP scenario decreased. Interestingly, the IP scenario could bring higher benefits in organic fields in degraded landscapes, while both scenarios brought similar but lower benefits in preserved landscapes. This is consistent with the IP scenario breaking up large clusters of conventional fields, which were less present in landscapes with high proportions and fragmentation of SNH. Consequently, it may be less important to manage the OF expansion scenario in preserved landscapes, while the IP scenario should be favored in degraded landscapes.

## 2.3 Robustness of the ranking of expansion scenarios

The ranking of OF expansion scenarios appeared robust to both the intensity and specificity of OF systems and the dispersal ability of pests and predators (Supplementary material S2). Varying these parameters did not affect the ranking of spatial expansion scenarios, only their relative differences. For example, intensive OF systems corresponding to intensive pest management (high pest mortality) were characterized by strong control of pest densities, therefore they showed little differences between scenarios. The only clear interaction between OF pest management and expansion scenario was in conventional fields: under extensive OF farming systems, the tendency of the IP scenario towards lower pest densities in conventional fields was reinforced (Supplementary material S2). This is because pest densities were overall higher for extensive OF systems but this did not strongly affect conventional fields, because, by limiting the decrease in CF patch size, the IP scenario resulted in less pest spill-over from organic to conventional fields. Further, dispersal ability had a marginal effect on pest densities (Supplementary material S3). Increasing dispersal tended to increase pest density's response to landscape configuration (in particular to its fragmentation) in conventional fields, thus increasing differences in pest densities among expansion scenarios.

### 580 **3 - Limits and benefits of the modelling approach**

581 Most mechanistic models of pest control by natural enemies are specific to a biological system and few  
582 address landscape scale crop management (reviewed in Alexandridis et al. (2021)). Such models generally  
583 comprise numerous parameters and allow deriving conclusions for specific landscape arrangements.  
584 Vinatier et al. (2012) for example showed that longer crop rotations reduced the parasitism of oilseed  
585 rape pollen beetle by decreasing the spatial and temporal connectivity of the resource for the parasitoid.

586 In the present study, we chose a mechanistic theoretical model that was based on few ecological  
587 processes and a very simplified representation of crop protection practices. Our focus was on comparing  
588 spatial scenarios and understanding how these interacted with the landscape patterns. It is recognized  
589 that the complexity of processes underlying conservation biological control in landscapes limits the ability  
590 of models to represent actual situations. For example, in reality many organisms show complex movement  
591 behavior (Gurarie et al., 2016) and interact within complex trophic networks, even in agricultural fields  
592 (Macfadyen et al., 2009). Further, while we assumed similar dispersal abilities for the pest and the  
593 predator, real species may have different dispersal abilities and thus perceive the landscape at a different  
594 grain (Jackson & Fahrig, 2012). Differences among scenarios would, for example, obviously be reduced for  
595 long-distance dispersers that would be less affected by landscape structure. We also made strong  
596 assumptions about the role of semi-natural habitats for pests and predators, assuming a generalist  
597 predator and a crop specialist pest that may survive in semi-natural habitats. Differences among spatial  
598 expansion scenarios would, for example, probably have been less if the pest had been able to reproduce  
599 in semi-natural habitats and would thus have been less sensitive to the spatial distribution of organic or  
600 conventional fields. Interestingly, despite these limitations, our conclusions about the best spatial  
601 scenario are consistent with those of the only pest-natural enemy spatially explicit model that, to our  
602 knowledge, addressed OF expansion (Bianchi, Ives and Schellhorn, 2013). Using a spatially explicit pest-  
603 parasitoid model these authors found that the spatial clustering of organic fields allowed a higher level of  
604 biocontrol in organic fields by protecting parasitoids from the detrimental effects of insecticides sprayed  
605 in conventional fields. In contrast to our results, however, they reported peaks of pests along OF  
606 expansion, possibly because, contrary to our assumptions, the parasitoid was specialized on the pest.

607 A last limitation of our approach is that results were averaged for organic and conventional fields at the  
608 landscape level. This simplification was driven by the large number of simulations to analyze. Aggregating  
609 outputs over space, however, may have masked local patterns and possible local peaks in pest densities.  
610 In a recent modelling study of a specialist pest and a generalist predator interacting in an heterogeneous

611 agricultural landscape, Zamberletti et al. (2021, 2022) showed for example that semi-natural habitats  
612 increased the average landscape scale pest density (by reducing the number of necessary pesticide  
613 treatments) but locally reduced peaks of pest populations (Zamberletti et al., 2021, 2022). Further  
614 analyses of pest density dynamics at the field level would, thus, be necessary to confirm the better ranking  
615 of the IP scenario regarding local CBC and pest densities.

616 Despite these limitations, our approach set in light processes such as increased spill-over of predators in  
617 isolated fields, increased pest management efficiency in large patches of conventional fields and the  
618 importance of distance between organic and conventional fields, that help understand consequences of  
619 diverse organic farming expansion scenarios. They further highlight that landscape planning appeared  
620 most necessary when organic pest management had a low efficiency on pests and in landscapes with low  
621 quantities of semi-natural habitats.

622

## 623 **Conclusion**

624 The scenario that consisted in setting the priority on isolated conventional fields for conversion to organic  
625 (IP) appeared as the most promising scenario to limit pest densities in conventional crops and improve  
626 CBC in organic crops, without increasing pest densities there. By examining a large number of landscape  
627 contexts and population parameters, we found that this result was robust but that landscape planning  
628 appeared most necessary when organic pesticides had a low efficiency on pests. Furthermore, landscape  
629 contexts with large proportions and fragmentation of semi-natural habitats supported the highest level  
630 of CBC. The modeling of agricultural landscapes is still a research objective (Poggi et al., 2018) and  
631 improving both the consideration of agricultural practices and the calibration of models using observed  
632 data regarding the life history traits of pests and predators will hopefully help design agroecological  
633 landscapes.

634

## 635 **Acknowledgements**

636 The work was partially supported by the PEERLESS project (ANR-12-AGRO-0006). The authors thank  
637 Lionel Roques and Mamadou Ciss for valuable discussions at the genesis of the work.

638

639 **Data and code availability**

640 The model used in this study is based on a model developed by Martinet and Roques (2022) that is  
641 available on the following public repository: <https://doi.org/10.17605/OSF.IO/Z2QCX>

642 The model outputs of the present study, as well as the R scripts used to build graphs and analyse data  
643 are available on the Zenodo public repository: <https://doi.org/10.5281/zenodo.6597282>

644

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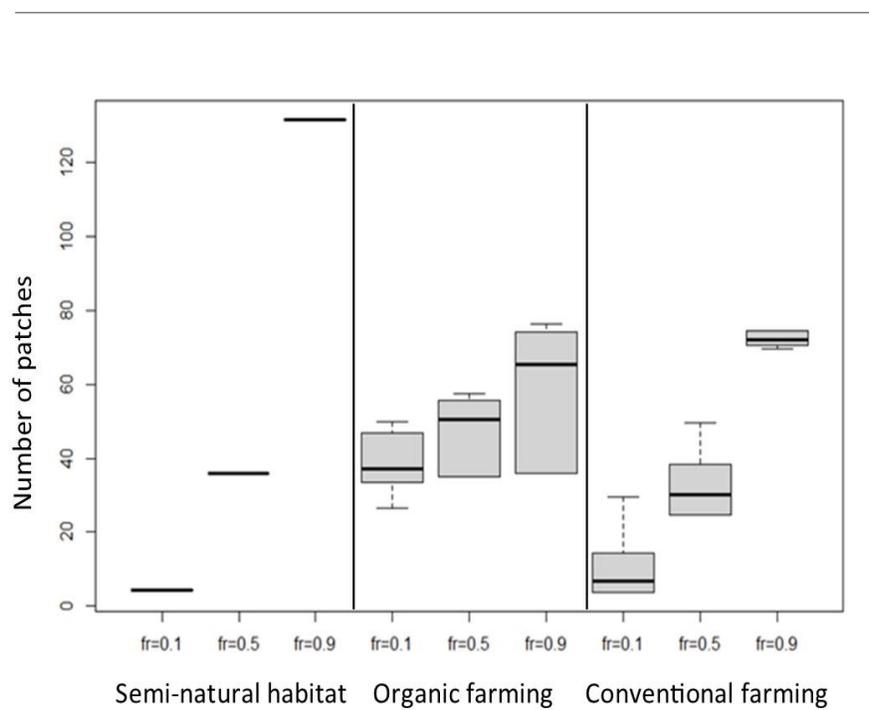
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## Supplementary materials

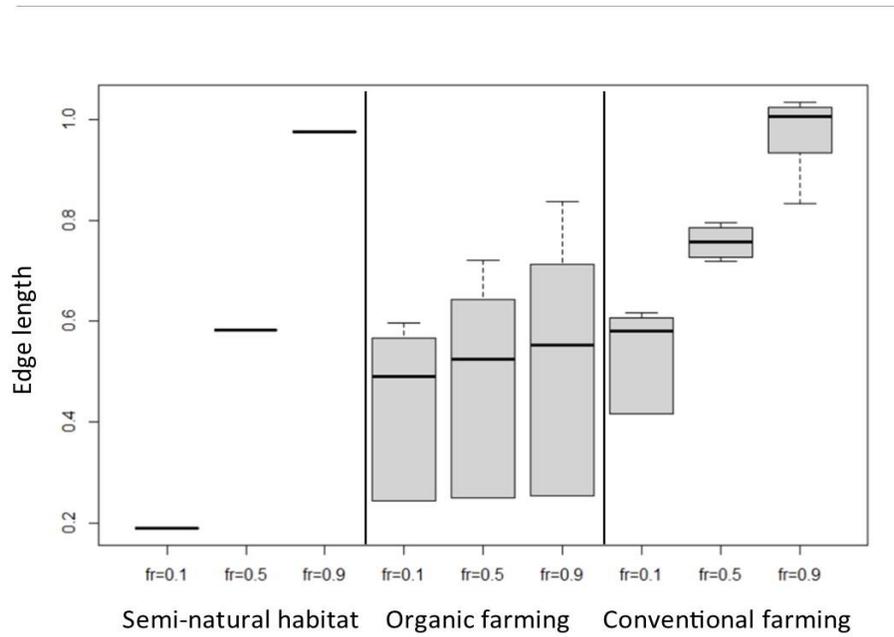
### SM1 - Effects of semi-natural habitat fragmentation and OF expansion scenarios on landscape structure

#### Landscape structure

Increasing semi-natural habitat (SNH) fragmentation (parameter  $fr$ ) resulted in an increase in the number of patches of each habitat type (SNH but also organic farming (OF) and conventional farming (CF)) (Figure S1.1) as well as an increase in edge length among habitat type (Figure S1.2). Patch area and edge length were calculated with R package `landscapemetrics` (Hesselbarth et al. 2019, *Ecography* 42:1648-1657)



**Figure S1.1:** Number of patches per landscape and habitat type for the three levels of semi-natural habitat fragmentation  $fr$ . The graph presents box plots of all values pooled over the 11664 landscapes at the end of simulations of OF expansion ( $t=50$ ). The dark line is the median, whiskers represent the first and third quartiles.



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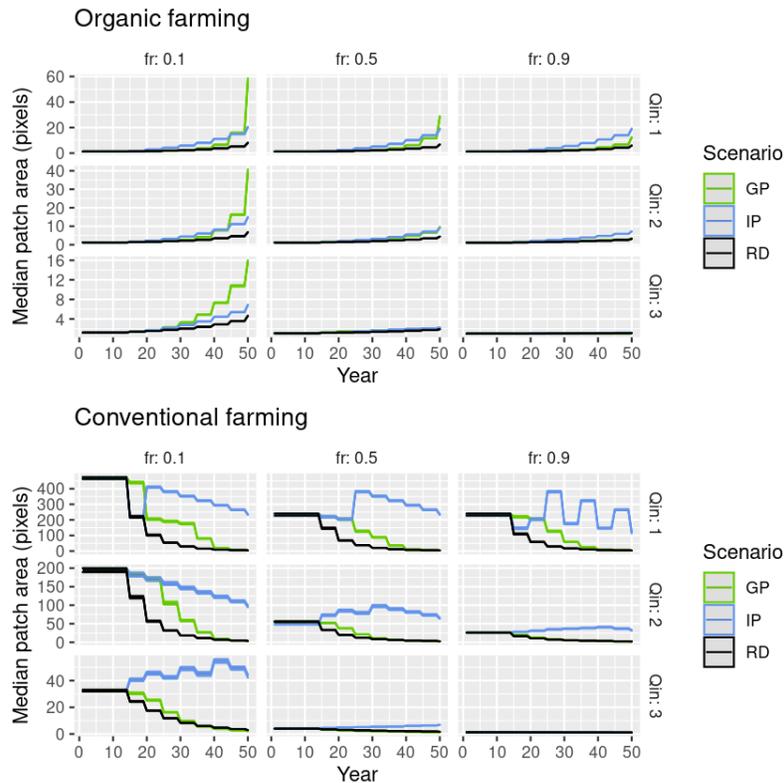
**Figure S1.2:** Edge length (in pixel side length per pixel) per landscape by habitat type for the three levels of semi-natural habitat fragmentation  $fr$ . The graph presents box plots of all values pooled over the 11664 landscapes at the end of simulations of OF expansion ( $t=50$ ). The dark line is the median, whiskers represent the first and third quartiles.

### Dynamics of 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 expansion depended on the landscape characteristics (amount of semi-natural habitat and its fragmentation) and on the organic farming expansion scenario. Organic and conventional patches were overall larger and less numerous in landscapes where the amount of semi-natural habitat was small and little fragmented (upper left Fig. S1.3) indicating in particular that the level of semi-natural 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.S1.3, at 35 years for the GP scenario 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.



**Figure S1.3.** Effects of OF expansion scenarios 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.

Because they set different priorities regarding field conversion, the different scenarios led to different mean patch area dynamics. Constraints were furthermore imposed by the spatial distribution of semi-natural areas. The IP scenario always resulted in conventional patches that were larger than the other scenarios. 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 (Fig S1.3, 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 semi-natural habitat. In little fragmented landscapes with few semi-natural

habitats (upper left panel, Fig. S1.3) all conventional patches were large initially so that patch size decreased slowly from the beginning of organic farming expansion. In contrast, in highly fragmented landscapes with a high proportion of semi-natural habitat (lower right panel, Fig. S1.3), there were mostly isolated conventional fields initially so that patch size remained almost constant. The GP scenario, 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 semi-natural habitats (left column and upper row panels, Fig. S1.3). Lastly, the RD scenario 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 expansion on the area and number of organic patches was consistent with the above changes to conventional patches. Whatever the expansion scenario, when the landscape was very fragmented and with a large proportion of semi-natural 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.S1.3). Mean organic patch area increased in all other situations.

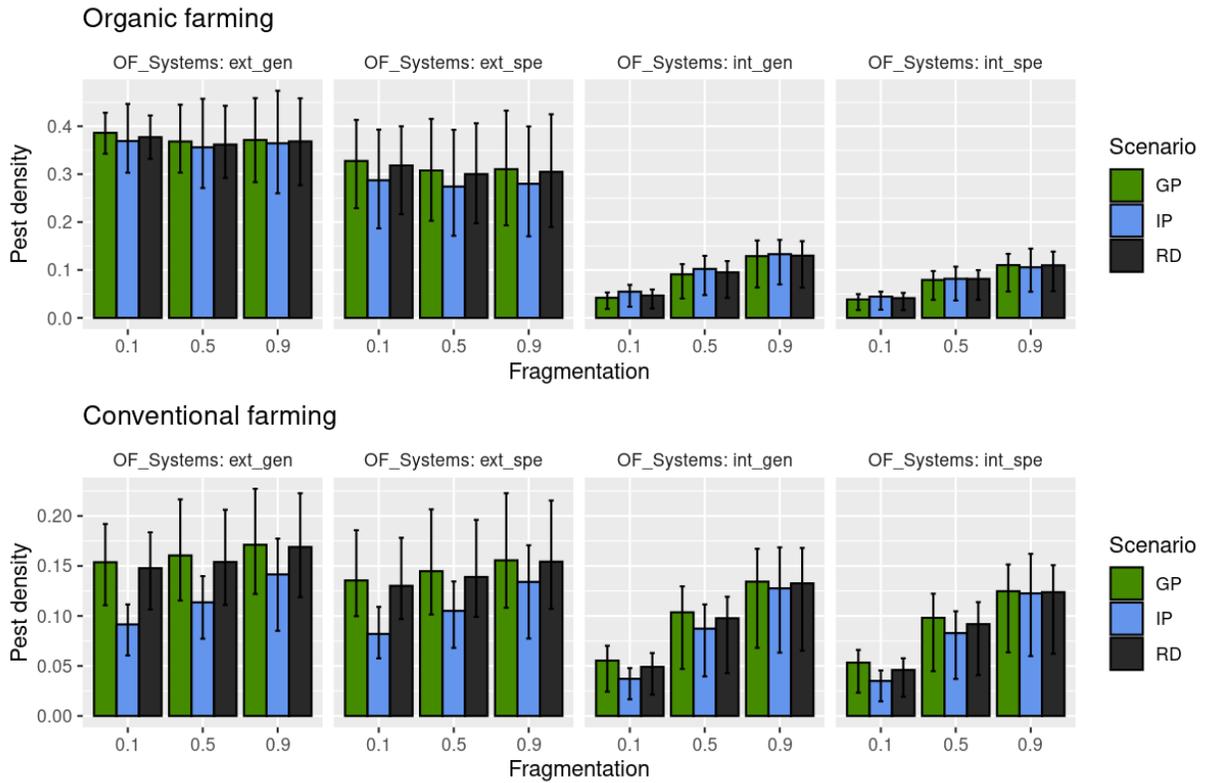
Mean organic patch area increased most at first with the IP scenario, particularly when the landscape was a little fragmented (left column, Fig. S1.3) because conventional fields that were converted tended to be neighboring already organic fields. In contrast, with the GP scenario, organic fields first 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. S1.3), 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.

## SM2 - Effect of the type of organic farming on pest densities and interaction with expansion scenario

Pests were on average more abundant in both types of fields when organic farming was less intensive, i.e. pest management 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 pest management-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 semi-natural habitat and its level of fragmentation.

As expected, the effect of organic farming intensity and specificity was much less pronounced in conventional fields. The effect of specificity was very weak. The effect of OF intensity was observable mainly in landscapes that were characterized by a low fragmentation (figure S2) Interestingly, the response of pest density to expansion scenario showed the same pattern whatever the OF type. It was very similar whatever the expansion scenario in organic fields and pest densities were generally lower for the IP scenario in conventional fields.

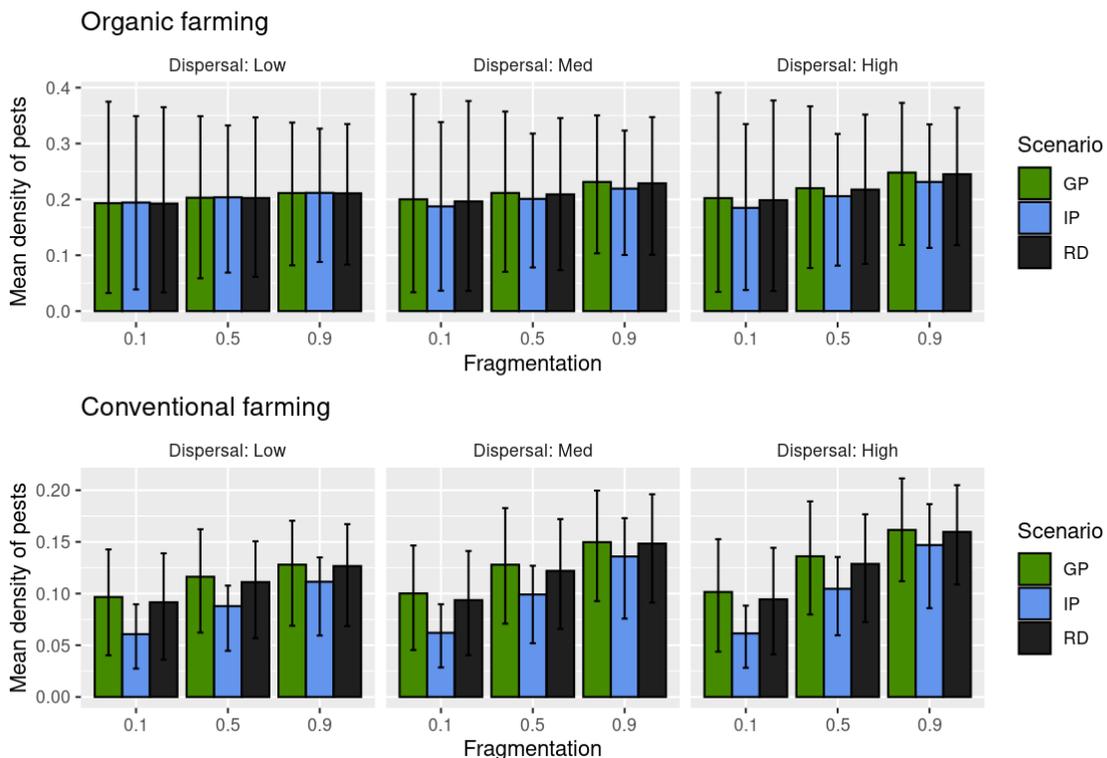
The fact that pest management specificity generally had little effect except for the extensive OF systems, confirmed the low effect of predators on pest densities in conventional fields, and the high impact of pest management compared to CBC in our simulations. For extensive organic systems, organic fields were possibly a source of pests for surrounding fields. Indeed, we observed more pests in conventional fields when organic farming systems were extensive, possibly indicating pest spillover from OF fields with higher pest populations. The latter is supported by the fact that the effect of OF farming system on pest density in CF was reduced in some landscape configurations. Specifically, conventional fields in landscapes with high proportion of SNH were less sensitive to OF farming system intensity, possibly because of lesser proximity to OF sources, and because of higher predator's spillover from SNH.



**Figure S2.** Effects of organic farming expansion scenario, organic farming type and landscape structure on the density of pests in organic and conventional fields. “ext” and “int”: low vs high pest management intensity, respectively. “spe” vs “gen”: specific vs generalist pest management practices, respectively (see Table. 3). Error bars represent standard deviations over landscapes.

### SM3 - Effect of pests dispersal and SNH fragmentation on pest densities and interaction with OF expansion scenario

Pest dispersal had a lower effect than the other parameters with a maximum delta of  $\pm 0.05$  in pest densities (Fig.S3). Pest densities in organic and conventional fields were overall higher when pest dispersal was high but this effect was weak, and mainly observable in conventional fields. In both types of fields, the positive effect of dispersal increased with the level of fragmentation of semi-natural habitats (for example, in conventional fields, for the GP scenario, pest density increased by 0.01 when  $fr=0.1$ , and by 0.04 when  $fr=0.9$  – Fig. S3). There was one exception to this trend with a small decrease in pest density with dispersal. It was observed with the IP scenario in organic fields (from 0.19 to 0.18 for  $fr=0.1$ , Fig. S3). The 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. Globally speaking, dispersal ability amplified the effect of every landscape parameter (fragmentation, expansion scenario).



**Figure S3.** Mean density of pests as a function of pest dispersal, semi-natural habitat fragmentation and organic farming expansion scenario