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Daniel Montoya, Sabrina Gaba, Claire de Mazancourt, Vincent V. Bretagnolle, Michel Loreau. Reconciling biodiversity conservation, food production and farmers' demand in agricultural landscapes. *Ecological Modelling*, 2020, 416, 10.1016/j.ecolmodel.2019.108889 . hal-02378282

**HAL Id: hal-02378282**

**<https://hal.science/hal-02378282>**

Submitted on 21 Jul 2022

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*For Ecological Modelling: Research paper*

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## **Reconciling biodiversity conservation, food production and farmers' demand in agricultural landscapes**

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25 ***Abstract***

26

27 Efficient management of agricultural management should consider multiple services and  
28 stakeholders. Yet, it remains unclear how to guarantee ecosystem services for multiple  
29 stakeholders' demands, especially considering the observed biodiversity decline following  
30 reductions in semi-natural habitat (SNH), and global change. Here, we use an ecosystem  
31 service model of intensively-managed agricultural landscapes to derive the best landscape  
32 compositions for different stakeholders' demands, and how they vary with stochasticity and  
33 the degree of pollination dependence of crops. We analyse three groups of stakeholders  
34 assumed to value different ecosystem services most – individual farmers (crop yield per  
35 area), agricultural unions (landscape production) and conservationists (biodiversity).  
36 Additionally, we consider a social average scenario that aims at maximizing  
37 multifunctionality. Trade-offs among stakeholders' demands strongly depend on the degree  
38 of pollination dependence of crops, the strength of environmental and demographic  
39 stochasticity, and the relative amount of an ecosystem service demanded by each  
40 stakeholder. Intermediate amounts of SNH deliver relatively high levels of the three services  
41 (social average). Our analysis further suggests that the current levels of SNH protection lie  
42 below these intermediate amounts of SNH in intensively-managed agricultural landscapes.  
43 Given the worldwide trends in agriculture and global change, current policies should start to  
44 consider factors such as crop type and stochasticity, as they can strongly influence best  
45 landscape compositions for different stakeholders. Our results suggest ways of managing  
46 landscapes to reconcile several actors' demands and ensure for biodiversity conservation and  
47 food production.

48

49 **Key words:** *landscape composition, crop pollination, biodiversity, trade-offs, stakeholder*  
50 *demands, agroecology*

## 51 1. INTRODUCTION

52

53 Natural ecosystems provide a wide range of benefits to mankind. The concept of ecosystem  
54 services (Ehrlich and Ehrlich, 1981) was originally proposed to draw attention to these  
55 benefits and raise awareness about the importance of biodiversity and its conservation.  
56 Ecosystem services are products of the functioning of ecosystems that are of value to  
57 humans, such as pollination, pest control, food production, and water catchment services  
58 (Montoya et al. 2012). More recently, the ecosystem service metaphor has incorporated two  
59 additional elements. First, ecosystems provide multiple services simultaneously to humans  
60 (provisioning, supporting, regulating and cultural), a situation called multifunctionality  
61 (Winston 2007; Lovell and Johnston 2009; Manning et al. 2018). This has led to a growing  
62 consensus that landscape design and management should target a range of functions (Wilson  
63 2007; Shellhorn et al. 2008; Birkhofer et al. 2015; Landis 2017). Second, the ecosystem  
64 service concept is a complex construct that comprises both supply (ecosystems) and demand  
65 (stakeholders) components (Burkhard et al. 2012; Palacios-Agundez et al. 2015; Yahdjian et  
66 al. 2015). Human use of ecosystem services thus depends on the capacity of ecosystems to  
67 supply these services as well as on the social demand for them.

68

69 Agricultural landscapes involve a great variety of ecosystem services and stakeholders, and  
70 they globally represent about 40% of the total terrestrial surface of our planet (Foley et al.  
71 2011). As such, agricultural landscapes are among the most interesting systems to analyze  
72 the balance between the supply and demand of various ecosystem services. The particularity  
73 of most modern agricultural landscapes is that the provision of a single service, i.e. crop  
74 production, is intensified by means of land conversion, mechanical work and the use of  
75 agrochemicals (pesticides, fertilizers). But this generates negative indirect effects, as land

76 use favors crop production at the cost of other services that in turn influence crop production  
77 (Nelson et al. 2009; Allan et al. 2015; Sutter and Albrecht 2016). The need to incorporate  
78 various ecosystem services into management decisions is thus essential, especially  
79 considering that agricultural intensification and increased pesticide levels are no longer  
80 enhancing the yields of many major crops worldwide (Ray et al. 2012; Gaba et al. 2016;  
81 Lechenet et al. 2017). This has been acknowledged by the 2017 UN Sustainable  
82 Development Goals, which assert that the future of intensive farming systems requires  
83 management strategies that achieve food security and sustainable agriculture.

84  
85 The supply and demand components of ecosystem services in agricultural systems are  
86 multifaceted because of the multiple ecological processes involved on the supply side and  
87 the multiple stakeholders that benefit from them on the demand side. On the supply side,  
88 trade-offs between ecosystem services seem to be common (Bennett et al. 2009; Raudsepp-  
89 Hearne et al. 2010; Allan et al. 2015). Intensive agricultural management, for example, may  
90 lead to high crop yields, but intensively managed fields often have simplified communities  
91 and hence low levels of other ecosystem services such as biological control by natural  
92 enemies and pollination (Médiène et al. 2011; Dainese et al. 2019). Such trade-offs depend  
93 on various factors, including landscape composition (crop land vs semi-natural land) and the  
94 degree of pollination dependence of crops (Aizen et al. 2009; Garibaldi et al. 2014, 2011a, b;  
95 Deguines et al. 2014; Montoya et al. 2019). Together, landscape composition, crop type and  
96 their associated service trade-offs lead to scenarios where either different ecosystem services  
97 can be reconciled or, conversely, the provision of several ecosystem services is  
98 incompatible. Evaluating landscape performance when multiple interacting factors act  
99 simultaneously is thus a challenge, especially considering questions such as which  
100 combination of drivers is able to reconcile crop production and biodiversity conservation.

101

102 Human demand is the other side of the ecosystem-service equation, and comprises different  
103 agents or stakeholders. These stakeholders vary in both their demand for and valuation of  
104 different ecosystems services, and have specific perspectives about how to efficiently  
105 manage agricultural landscapes. For example, agricultural unions or cooperatives often aim  
106 at maximizing crop production at the regional level, i.e. landscape production, for food  
107 security purposes. Farmers, on the other hand, may have different perceptions of ecosystem  
108 services (Teixeira et al. 2018); yet, they are mainly interested in maximizing crop yield per  
109 area of their cultivated land as this is mostly related to their profitability. Conservationists  
110 (NGO's, wildlife-friendly organizations) defend that the preservation of the remaining  
111 biodiversity within the agricultural landscape should be one main goal of agricultural  
112 policies. The existence of ecosystem service trade-offs on the supply side implies that any  
113 stakeholder's demand does not necessarily maximize multifunctionality of agricultural  
114 landscapes, because each stakeholder may prioritize one ecosystem service or set of services  
115 over others. Considering various stakeholders is thus required to identify potential trade-offs  
116 and balance multiple, often conflicting, demands for ecosystems services (Baro et al. 2017;  
117 Turkelboom et al. 2018).

118

119 To complicate things further, recent studies show that global change factors can act  
120 interactively with land use modifications and influence both ecosystem service supply and  
121 demand components (Shoyama and Yamagata 2014; Ding et al. 2016; Martinez-Harms et al.  
122 2017). In this context, it is increasingly important for ecologists to be able to generate  
123 predictions of the effects of global change on the long-term provision of crop production in  
124 agricultural landscapes. However, food stability is considered to be one of the major  
125 challenges of food security that is missing in ecosystem service research (Cruz-Garcia et al.

126 2016). Therefore, there is an urgent need for studies that explicit consider both the mean and  
127 the variability of crop production and other ecosystem services provided by agricultural  
128 landscapes, and that investigate their expected changes following global change predictions.

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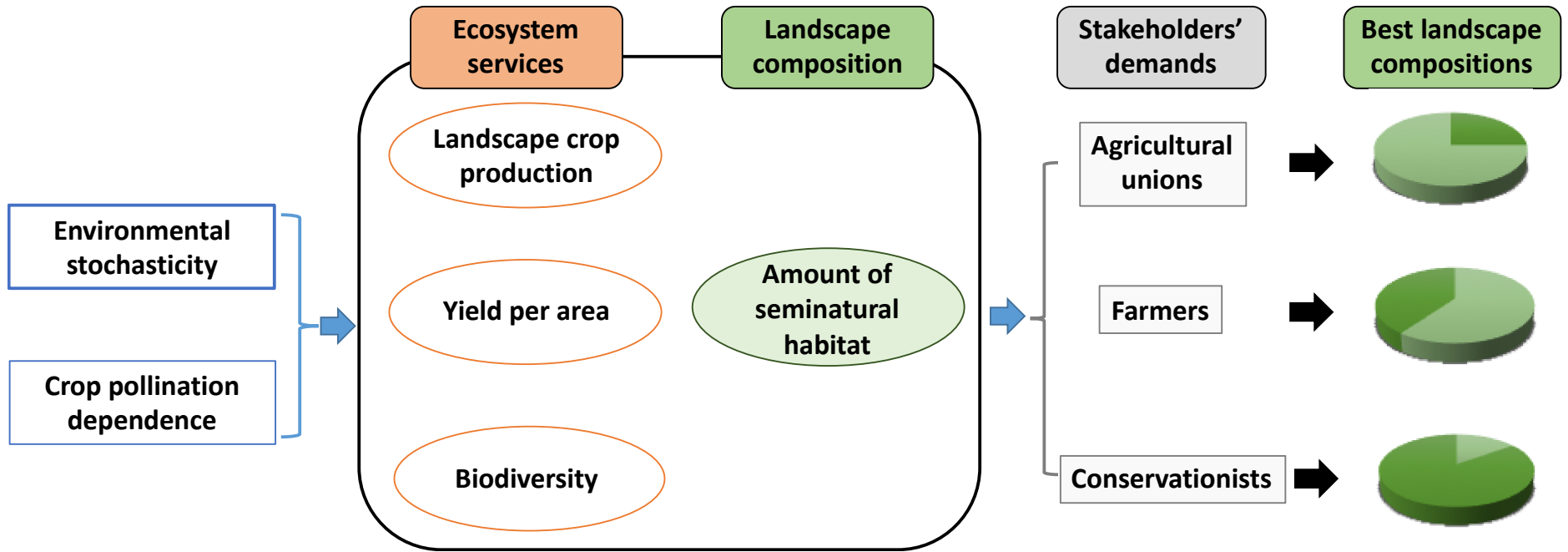
130 Here, we use a model of biodiversity and crop production in intensively-managed  
131 agricultural landscapes to derive landscape management solutions for different stakeholders'  
132 demands. We analyze three main groups of stakeholders – individual farmers, agricultural  
133 unions and conservationists – and identify three ecosystem services they value most – crop  
134 yield per unit of agricultural area, crop production at the landscape scale, and biodiversity,  
135 respectively. Using information given by ecosystem service trade-offs, we determine the  
136 best landscape composition, defined as the fraction of semi-natural habitat within the  
137 agricultural landscape, that corresponds to each stakeholder's demand, and how this affects  
138 the provision of the other ecosystem services. We define conditions under which stakeholder  
139 demands are compatible or not, e.g. when food production and biodiversity conservation are  
140 positively correlated. We also investigate how changes in stochasticity (expected under  
141 global change predictions) and the degree of pollination dependence of crops may affect the  
142 best landscape composition for each stakeholder (Fig. 1). Specifically, our work has three  
143 objectives: (i) to determine the best landscape compositions that correspond to different  
144 stakeholders' demands, (ii) to investigate the effects of a given stakeholder's demand on  
145 other ecosystem services, and (iii) to establish the best landscape composition for ecosystem  
146 multifunctionality, i.e. a social average scenario that targets the highest provision of the  
147 three ecosystem services beyond any single stakeholder's demand. Finally, we confront the  
148 model outputs with current policies and discuss their efficiency to promote multifunctional  
149 agricultural landscapes. Our approach is unique in its attempt to achieve some balance  
150 and/or maximize the provision of ecosystem services and stakeholder demands for different



151 crop types (pollination dependence of crops) and environmental and demographic  
152 stochasticity scenarios.  
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161 **Figure 1. Conceptual diagram of our modelling framework.** We use a model of biodiversity and crop production in intensive farming systems  
162 (Montoya et al. 2019). We analyse the impacts of environmental stochasticity and crop pollination dependence on three ecosystem services –  
163 landscape crop production, crop yield per area and biodiversity conservation –, and the effects of landscape composition (amount of seminatural  
164 habitat) associated with the provisioning of those services. We then study three groups of stakeholders assumed to value each ecosystem service  
165 most – agricultural unions (landscape crop production), individual farmers (yield per area) and conservationists (biodiversity), and derive the best  
166 landscape compositions for each stakeholders' demands. Therefore, the model investigates how changes in environmental stochasticity (expected  
167 under global change) and the degree of pollination dependence of crops may affect the provision and demand of ecosystem services in  
168 agricultural landscapes.

## 169 **2. MATERIALS and METHODS**

170

### 171 **2.1. Model description**

172 We extend a model of biodiversity and crop production in a spatially heterogeneous  
173 agricultural landscape that incorporates environmental and demographic stochasticity  
174 (Montoya et al. 2019). Food stability is one of the major challenges of food security that is  
175 missing in ecosystem service research (Cruz-Garcia et al. 2016), and our model explicitly  
176 includes it through the consideration of environmental and demographic stochasticity  
177 (Appendix A). The model represents intensively-managed agricultural landscapes, where  
178 crop land does not harbour significant levels of biodiversity. Note that, although some levels  
179 of biodiversity can be observed in crop land areas (e.g. Pascher et al. 2011 for vascular  
180 plants, grasshoppers and butterflies), we focus on wild central-place pollinators (i.e. all types  
181 of wild bees, including bumble bees and solitary bees) whose presence and abundance  
182 directly depend on the amount of seminatural habitat, which provides shelter and habitat for  
183 these insects. Spatial heterogeneity is defined by two types of patches: (i) crop land, which is  
184 used to grow annual crops with varying degrees of dependence on animal pollination, and  
185 (ii) semi-natural habitat, which shelters biodiversity, including wild plants and pollinators.  
186 Topography and soil conditions are considered to be homogeneous. Crop land and semi-  
187 natural habitat are linked by pollinators' foraging movement, and pollinators are assumed to  
188 be generalist central-place foragers that feed on both 'wild' plants and crops (Kleijn et al.  
189 2015). The model focuses on wild pollinators as they directly depend on semi-natural habitat  
190 for nesting, foraging, and refuge. Space is implicitly considered, so that pollinators can  
191 potentially feed on all crops and wild plants present in the agricultural landscape,  
192 irrespective of the spatial configuration of the landscape, i.e. fragmentation effects are not  
193 considered. The model can apply to any spatial extent provided that the pollinators, and

194 hence the fragments of semi-natural habitat that host them, are distributed in such a way that  
195 pollinators have access to the whole landscape (or that pollinators are not spatially restricted  
196 in their foraging patterns). Therefore, the spatial extent can vary from roughly 5-10 ha  
197 (typical arable field in Europe) to any larger scale provided pollinators are not aggregated in  
198 a small part of the landscape.

199

200 The model studies three ecosystem services provided by agricultural landscapes – crop yield  
201 per unit of agricultural area, crop production at the landscape scale, and biodiversity, and  
202 describes mechanistically the trade-offs between these ecosystem services in intensive  
203 agricultural landscapes (Montoya et al. 2019). This model is a useful first approximation to  
204 studying the crop production in agroecosystems, as it successfully reproduces empirical  
205 observations on the stability of pollination-dependent crop yield (Garibaldi et al. 2011a;  
206 Deguines et al. 2014), and it provides rigorous theoretical foundations for previously  
207 hypothesized functional relationships between the magnitude of ecosystem services and  
208 landscape composition (Braat and ten Brink, 2008). Model dynamics are governed by two  
209 key parameters: the degree of pollination dependence of crops, which we vary to represent  
210 different crop types (see Appendix A), and environmental and demographic stochasticity.  
211 Here, we analyse the effects of these parameters on the best landscape composition  
212 associated with each stakeholder's demand. A complete description of the model, the model  
213 equations and the estimation of model parameters is provided in Appendix A.

214

## 215 **2.2. Stakeholders and management scenarios**

216 We use our model to investigate how different stakeholders' demands determine the best  
217 landscape compositions in agricultural landscapes. Beneficiaries or stakeholders for  
218 ecosystem services include individuals, cooperatives, corporations, non-governmental

219 organisations, and the public sector. To illustrate our approach, we analysed three main  
220 groups of stakeholders – individual farmers, agricultural unions and conservationists –, and  
221 identify three ecosystem services valued by those stakeholders most – crop yield per area of  
222 their cultivated land, crop production at the landscape scale (landscape production) and  
223 biodiversity (scenarios 1-3). We use this example as a case study to determine the best  
224 landscape compositions for each different stakeholder' demands and how they affect the  
225 magnitude of the various ecosystems services. Best landscape composition is defined as the  
226 range of fraction of semi-natural habitat within which the targeted level of a given  
227 ecosystem service is achieved. Additionally, we define a fourth scenario where no single  
228 ecosystem service is prioritized; this scenario targets the highest possible provision of the  
229 three ecosystem services described above, i.e. multifunctionality (scenario 4), and it can be  
230 viewed as a social average scenario beyond the specific demands of the individual  
231 stakeholders. The social average scenario follows the idea that a 'challenge for the future is  
232 to design landscapes that are beneficial for a range of functions' (Shellhorn et al. 2008).

233  
234 Stakeholders may demand a minimum amount of ecosystem service provision, e.g.  
235 protecting  $\geq 75\%$  of biodiversity or producing  $\geq 80\%$  of crop biomass. This is accounted for  
236 in our model by incorporating *function thresholds*. A function threshold is defined as the  
237 relative amount of an ecosystem service demanded by each stakeholder, i.e. how much of  
238 the maximum possible value of that ecosystem service (given by model simulations) a given  
239 stakeholder is willing to accept. The best landscape compositions within the agricultural  
240 landscape are likely to change if stakeholders assume higher or lower thresholds of their  
241 demanded ecosystem service; thus, considering function thresholds is useful for identifying  
242 potential trade-offs and for balancing various demands for services.

243

### 244 **2.3. Analytical protocol**

245 We follow a four-step process summarized in Fig. 2. First, for each fraction of semi-natural  
246 habitat, we run model simulations to obtain the frequency distribution for each ecosystem  
247 service after 1000 time steps (landscape production is used as an example, Fig. 2a). This is  
248 performed for the whole range of semi-natural habitat (0-100%) to obtain the frequency  
249 distribution of landscape production as a function of semi-natural habitat (Fig. 2b). The  
250 strength of this approach lies in its ability to explore the full probability distribution of  
251 ecosystem service values as well as the possibility of setting thresholds values for services  
252 (see Carnus et al. 2014, for the justification of this approach). Absolute thresholds for  
253 ecosystem services are generally lacking, so we look at the best landscape compositions that  
254 provide a given proportion of the maximum ecosystem service value along the range of  
255 semi-natural habitat (Appendix B provides an alternative application of the approach using  
256 absolute ecosystem service values). Using the median values of the frequency distributions,  
257 we calculate the best landscape composition where median landscape production is above a  
258 certain % of its maximum value, i.e. function threshold. This is performed for all levels of  
259 crop pollination dependence (i.e. for a wide range of crop types) to show the best landscape  
260 composition as a function of crop pollination dependence (Fig. 2c). We use median values  
261 because they are the most frequent values; besides, median values are robust to non-  
262 Gaussian distributions, which are increasingly typical when stochasticity is high. Using any  
263 other quantile yields qualitatively similar results (Appendix B).

264

265 Next, we address the effects of each stakeholder's demand on the other ecosystem services.  
266 For each stakeholder (scenarios 1-3), we set the function threshold of the ecosystem service  
267 they demand to 95%, i.e. agricultural unions demand  $\geq 95\%$  of landscape production. The  
268 demand established by the function threshold is satisfied within a certain range of semi-

269 natural habitat (Fig. 2d), which is used to determine the corresponding provision of the other  
270 ecosystem services (Fig. 2d). For the social average scenario (scenario 4), we apply a  
271 *maximin* approach, a common method of performing multi-objective optimization (Solteiro  
272 Pires et al. 2005; for general multi-criteria decision analysis, see also Huang et al. 2011,  
273 Mendoza and Martins 2006). This method selects the best landscape composition that  
274 maximises, within the set of three ecosystem services, the provision of the least provisioned  
275 one. In sum, this protocol produces the best landscape compositions for different  
276 stakeholders' demands (scenarios 1-4), crop types (degrees of pollination dependence of  
277 crops), and function thresholds, and explores the effects of such demands on other  
278 ecosystem services.

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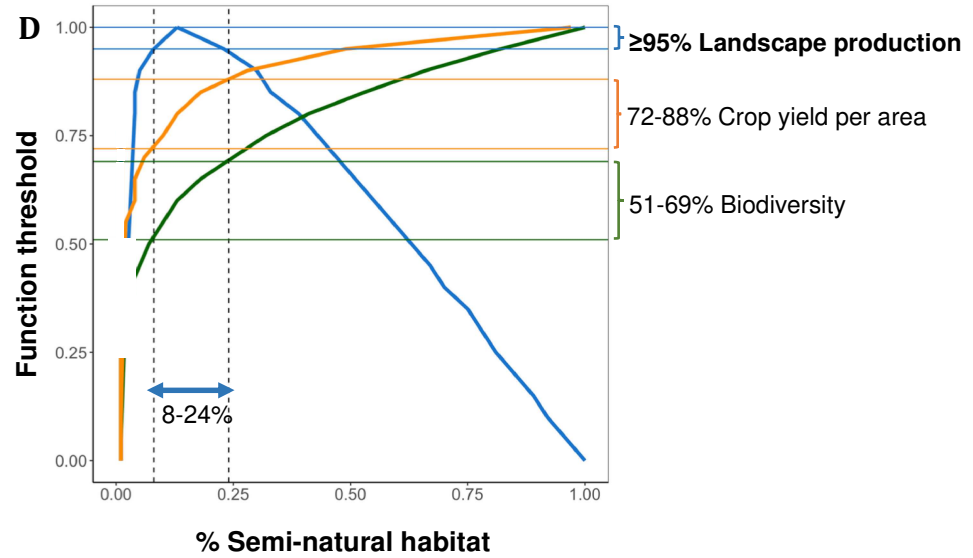
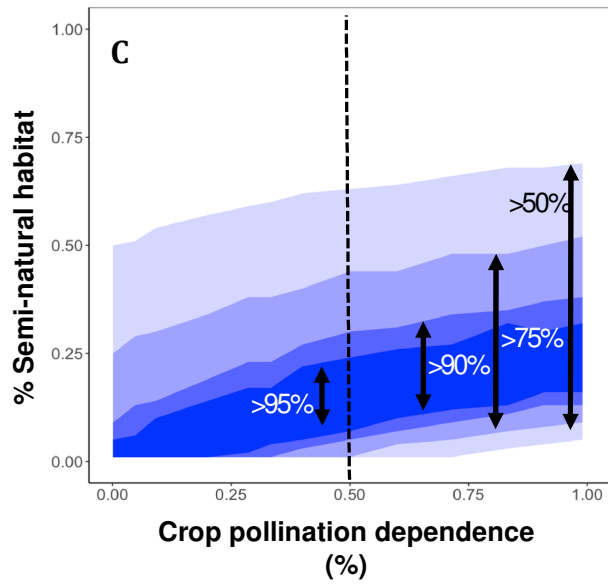
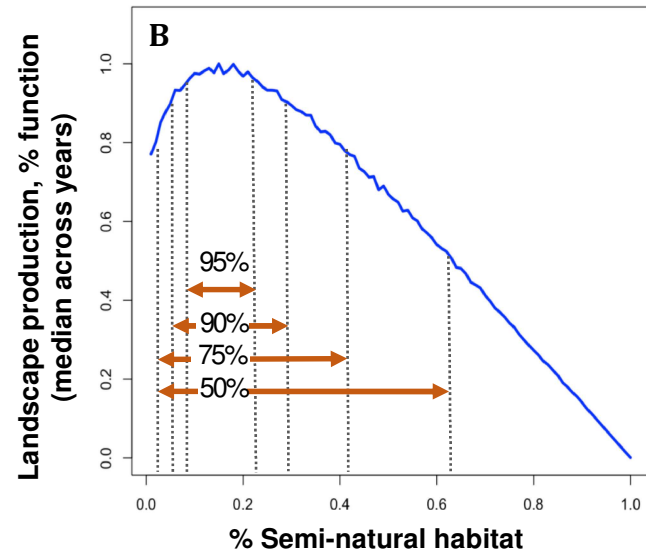
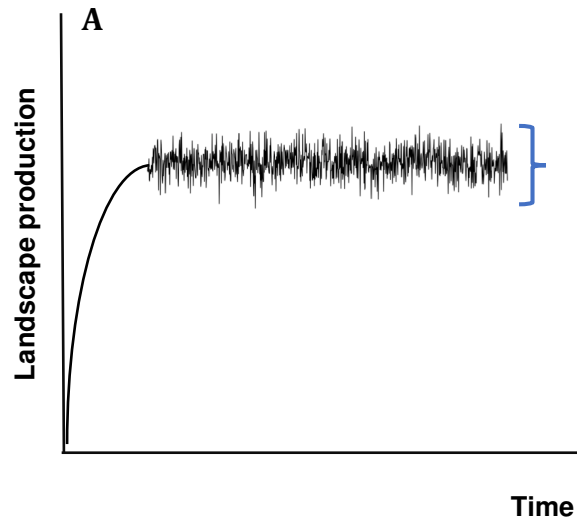
280 Finally, we compare the best landscape compositions obtained by our model with current  
281 management of agricultural landscapes. Our search for actual policies targeting specific  
282 fractions of semi-natural habitat within agricultural landscapes yielded only one result, the  
283 European Union Green Policy, which aims at preserving 5% of semi-natural elements at the  
284 farm level (Pe'er et al. 2014). Additionally, we assessed two conservation policies focused  
285 on terrestrial ecosystems: the 2020 Aichi Biodiversity Targets (ABT; Global Biodiversity  
286 Outlook 2014) and the Brazilian Forest Code (BFC; Soares-Filho et al. 2014). Analyses  
287 were performed in R software (R version 3.6.0; R Core Team 2017).

288

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290





292 **Figure 2. Analytical protocol.** We followed a 4-step procedure to estimate the best landscape compositions for each stakeholder's demand and  
293 its consequences on the provision of other ecosystem services. For illustrative purposes, we assume the agricultural unions' perspective  
294 (prioritizes total landscape production). For each fraction of semi-natural habitat, we run model simulations for 1000 time steps (1a), which are  
295 used to obtain the frequency distribution of landscape production. Once performed for the whole gradient of semi-natural habitat, the distribution  
296 of landscape production as a function of semi-natural habitat is obtained (1b). This approach enables to explore the full probability distribution of  
297 ecosystem service values as well as the possibility of setting thresholds values for services (Carnus et al. 2014). Absolute thresholds for  
298 ecosystem services are generally lacking, so we investigate the best landscape compositions that provide  $\geq 95\%$  of landscape production along the  
299 range of semi-natural habitat (see Appendix B for an alternative application based on absolute values of ecosystem services). Using the median  
300 values of landscape production (blue line), we calculate the best landscape composition (range of % of semi-natural habitat) where median crop  
301 yield is above a certain % of its maximum value, i.e. function threshold (here, 95%, 90%, 75% and 50% function thresholds are shown). We  
302 complete model simulations for all levels of crop pollination dependence to show the best landscape composition as a function of crop  
303 pollination dependence (1c). The vertical dashed line represents 50% of pollination dependence of crops (b). The % in (c) correspond to the  
304 functional thresholds, and the Y axis shows the range of semi-natural habitat at which the functional thresholds are achieved. More flexible  
305 demands (lower function thresholds) imply a wider range of semi-natural habitat values. Finally, (1d) shows the range of semi-natural habitat  
306 (delimited by dashed vertical lines) that achieves  $\geq 95\%$  of landscape production (agricultural unions' goal, highlighted in bold). The shadow area

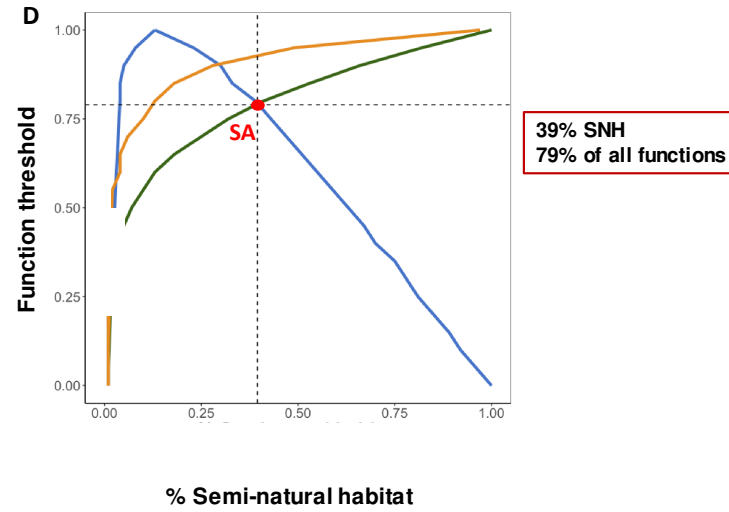
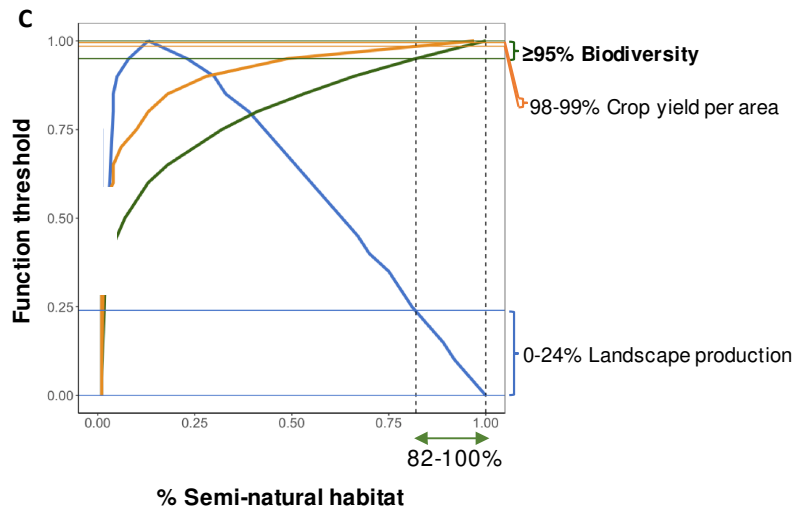
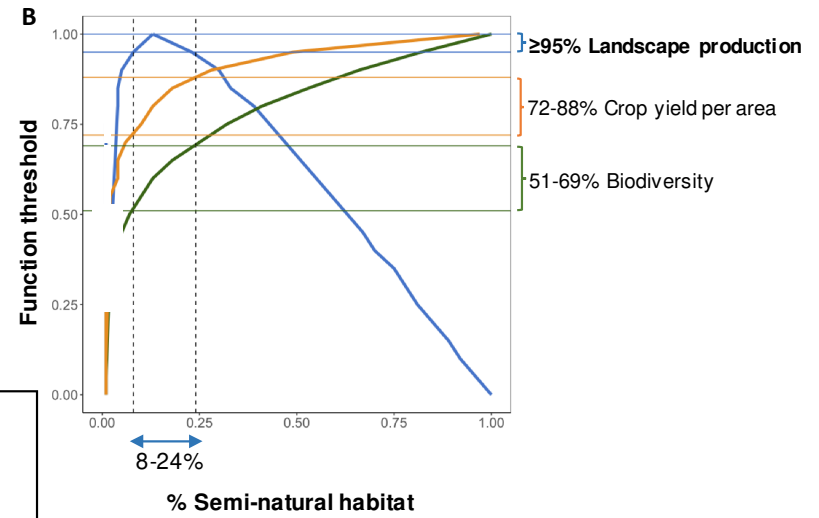
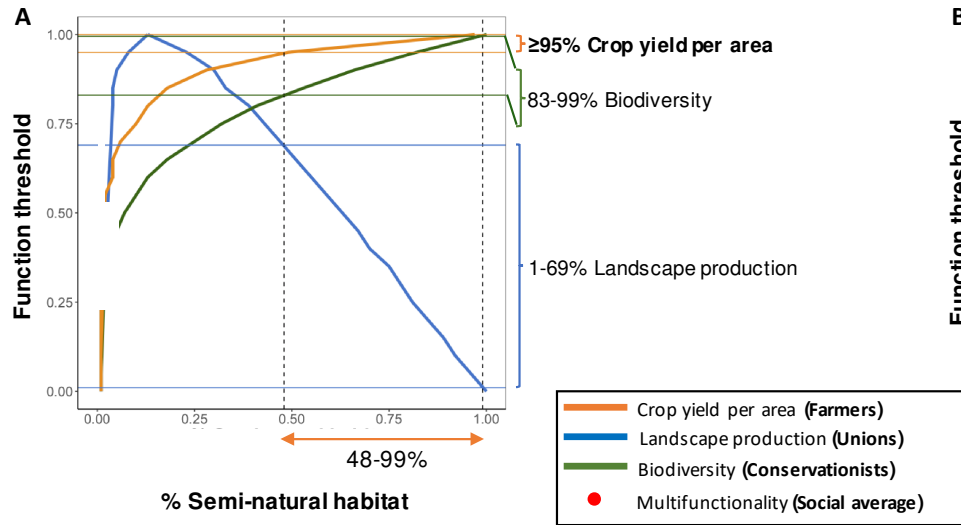
307 represents the % of provision of the other two ecosystem services that corresponds to that range of semi-natural habitat. Figs B, D are calculated  
308 for 50% of crop pollination dependence, and median values of environmental and demographic stochasticity.

### 309 3. RESULTS

310

#### 311 3.1. Best landscape compositions for each stakeholder

312 The best landscape composition depends on stakeholders' demands, and thus on which  
313 ecosystem service is prioritized. In general, the best landscape compositions for individual  
314 farmers and conservationists were associated with higher fractions of semi-natural habitat,  
315 whereas agricultural unions' demands were achieved at lower fractions of semi-natural  
316 habitat. For intermediate levels of crop pollination dependence and median values of  
317 stochasticity, prioritizing individual farmers' demands yields intermediate-to-high fractions  
318 of semi-natural habitat (Fig. 3a). While this favors biodiversity conservation, landscape  
319 production is highly variable (1-69%; Figs 3a, 4b). Whereas total production at landscape  
320 scale depends on both yields (i.e. related to semi-natural habitat) and crop land, the trade-off  
321 between crop yields per area and total production at the landscape scale is explained because  
322 yields per unit area increase with more pollinator supply, which in turn increases with semi-  
323 natural land. Agricultural unions' goal to maximize landscape production occurs at low-  
324 intermediate fractions of semi-natural habitat (Fig. 3b). This leads to relatively high levels of  
325 individual farmers' demands, but conservationists' goals may not be fulfilled as biodiversity  
326 would remain at intermediate levels (Figs. 3b, 4b). More biodiversity remains at higher  
327 fractions of semi-natural habitat (Fig. 3c), and it is positively correlated with high levels of  
328 crop yield per area, reconciling conservationists' demands and farmers' profitability (Figs.  
329 3c, 4b). Conversely, landscape production would be low (0-24%), revealing a trade-off  
330 between conservationists' and agricultural unions' demands. Finally, the social average  
331 scenario corresponds



335 **Figure 3. Example of the methodological approach.** (A, B, C) show the range of semi-natural habitat (delimited by dashed vertical lines) that  
336 achieves  $\geq 95\%$  of the stakeholder or ecosystem service prioritized (highlighted in bold in the right-hand side of each plot). The shadow area in  
337 (A-C) represent the % of provision of the other two ecosystem services that corresponds to that range of semi-natural habitat. (D) The social  
338 average scenario is calculated using the *maximin* approach, a common method for multi-objective optimization. This method selects the best  
339 landscape composition that maximizes, within the set of three ecosystem services, the provision of the least provisioned one. In this example,  
340 the social average scenario (SA) achieves a 79% of all ecosystem services at 39% of semi-natural habitat (red dot). Figs A-D are calculated for  
341 50% of crop pollination dependence and median values of environmental and demographic stochasticity.

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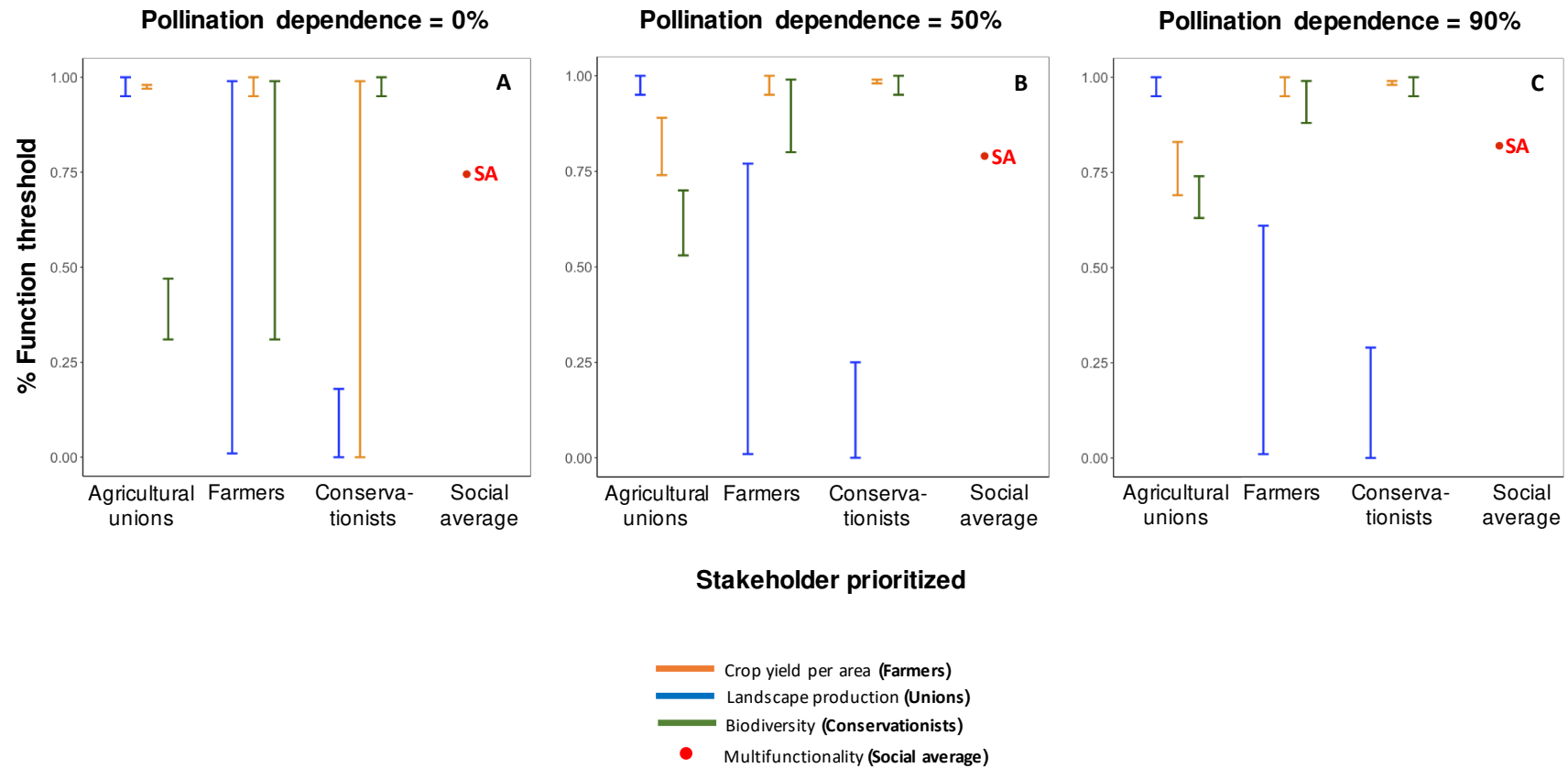
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356 **Figure 4. Effects of stakeholders' demands on the provision of other ecosystem services.** In each plot, the stakeholder prioritized is on the  
 357 X axis (function threshold of its most valued ecosystem service is set to  $\geq 95\%$ ), and its effects on the amount of the other two ecosystem  
 358 services is analyzed. Pollination dependence of crops increases from left to right (a-c). High levels of crop yield per area and biodiversity  
 359 conservation are compatible, suggesting that individual farmers and conservationists' demands can be reconciled; this compatibility increases

360 with crop pollination dependence. Landscape production and biodiversity conservation are highly incompatible when agricultural unions'  
361 demands are prioritized. Agricultural unions and individual farmer's demands can be reconciled when the degree of pollination dependence of  
362 crops is low. The social average scenario (SA) yields high provision levels for all three ecosystem services (73-82.5%). Figs A-C are calculated  
363 for median values of environmental and demographic stochasticity.



364 to intermediate fractions of semi-natural habitat (39%; Fig. 3d), yielding 79% of the function  
365 threshold for all three ecosystem services, which can be considered as indicative of a highly  
366 multifunctional agricultural landscape.

367

### 368 **3.2. Effects of crop type, stochasticity and function thresholds on landscape** 369 **composition**

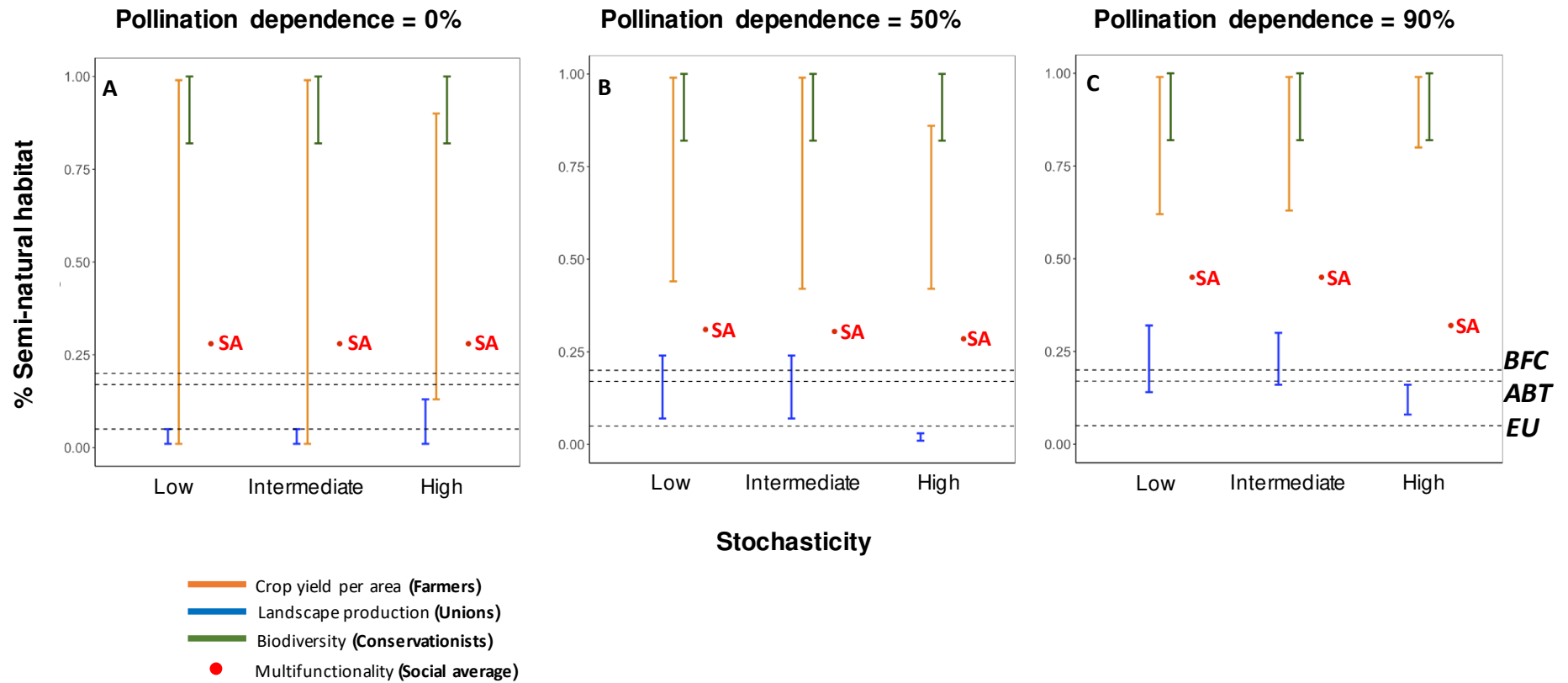
370 The best landscape compositions, and the trade-offs and synergies between stakeholders'  
371 demands, strongly depend on three factors: crop pollination dependence, the strength of  
372 environmental and demographic stochasticity, and the function threshold of ecosystem  
373 services, i.e. the relative amount of an ecosystem service demanded by each stakeholder.

374

#### 375 *3.2.1. Crop pollination dependence*

376 Higher pollination dependence of crops shifts the best landscape compositions to higher  
377 fractions of semi-natural habitat for individual farmers and agricultural unions (Fig. 5,  
378 intermediate stochasticity). For increasing levels of pollination dependence, crop yield per  
379 area and total landscape production require more pollinators, and hence semi-natural habitat;  
380 thus, compatibility between conservationists' and individual farmers' demands increases  
381 with the level of pollination dependence of crops. Compatibility of union and  
382 conservationist demands improves as well given their ranges move closer, yet they do not  
383 overlap. Conservationists and agricultural unions' goals cannot however be reconciled for  
384 any type of crop if both stakeholders target  $\geq 95\%$  of their most valued ecosystem service.  
385 Only at low levels of crop pollination dependence can agricultural unions and individual  
386 farmers coincide in their best landscape composition, but this leads to low biodiversity  
387 levels (Fig. 4a). For the social average scenario, the fraction of semi-natural habitat increases

388 with crop pollination dependence, this mainly driven by the dependency of landscape  
389 production and crop yield per area on wild pollination.



390

391

392 **Figure 5. Effects of crop pollination dependence and stochasticity on landscape composition.** Function threshold for individual  
 393 stakeholder's demand are set to  $\geq 95\%$ . (a-c) Fraction of semi-natural habitat as a function of stochasticity (minimum, median and maximum  
 394 values for all parameters, both demographic and environmental, are plotted). The effects of stochasticity are more pronounced for high values of  
 395 stochasticity. Maximum stochasticity shifts the best landscape composition to higher values of semi-natural habitat for landscape production and

396 multifunctionality, and reduces the range width of semi-natural habitat for crop yield per area. The social average scenario (SA) is achieved at  
397 higher fractions of semi-natural habitat when the degree of pollination dependence of crops is intermediate and high. The dashed horizontal lines  
398 represent the fraction of semi-natural habitat targeted by the EU Green Policy (*EU*), the Aichi Biodiversity Targets (*ABT*) and the Brazilian  
399 Forest Code (*BFC*).

400

401

402

### 403 3.2.2. *Stochasticity*

404 A higher stochasticity increases the fraction of semi-natural habitat that meets individual  
405 farmers' demands, but it decreases the best fraction of semi-natural habitat for agricultural  
406 unions, especially for animal-pollinated crops (Figs. 5b-c), revealing a trade-off between the  
407 two stakeholders. In general, a high stochasticity only slightly reduces the compatibility  
408 between farmers and conservationists, but it completely decouples demands of individual  
409 farmers and agricultural unions. The latter is due to a large reduction in the fraction of semi-  
410 natural habitat to meet agricultural unions' demands when stochasticity is high together with  
411 an increment of the fraction of semi-natural habitat for farmers' goals. The social average  
412 scenario is met at intermediate fractions of semi-natural habitat (30.5, 39 and 45%, for  
413 different crop types), but high stochasticity reduces that fraction to lower values (28.5, 29.5  
414 and 31%) because of changes in agricultural unions' demands. We found a greater effect of  
415 environmental (compared to demographic) stochasticity of crops and wild pollinators in  
416 determining changes in the best landscape compositions (Appendix C, Fig. C.1).

417

### 418 3.2.3. *Function threshold*

419 Compatibility among stakeholders' demands increases with diminishing function thresholds,  
420 i.e. the relative amount of an ecosystem service demanded by each stakeholder (Fig. E1).  
421 Lower function thresholds expand the range of semi-natural habitat associated with the best  
422 landscape composition of each stakeholder. This increases the overlap in the best landscape  
423 composition of different stakeholders. Compatibility of stakeholders' demands with varying  
424 function thresholds is higher for intermediate and high levels of crop pollination  
425 dependence.

426

## 427 **4. DISCUSSION**

428

429 An efficient, sustainable design of agricultural systems is a major challenge of our time, and  
430 the integration of various services and stakeholders is crucial to meet that challenge. Our  
431 model is a useful first approximation to studying the crop production in agroecosystems, as  
432 it has been shown to successfully reproduce empirical observations on the stability of  
433 pollination-dependent crop yield (Garibaldi et al. 2011a; Deguines et al. 2014), and it  
434 provides rigorous theoretical foundations for previously hypothesized functional  
435 relationships between the magnitude of ecosystem services and landscape composition  
436 (Braat and ten Brink, 2008). This study adds to the large body of literature on how to make  
437 management decisions involving multiple objectives, including multi-criteria decision  
438 analyses based on multiple valued outcomes (e.g. see reviews by Huang et al. 2011;  
439 Mendoza and Martins 2006), and studies addressing the role of ecosystem trade-offs and the  
440 role of demand of multiple stakeholders (Landis 2017; Cavender-Bares et al. 2015; Palacios-  
441 Agundez et al. 2015; Yahdjian et al. 2015; Burkhard et al. 2012), and highlights the  
442 importance of considering the multifaceted nature in the supply of and demand for  
443 ecosystem services. Further, our model assesses the potential effects of global change on  
444 ecosystem services, thus explicitly including food stability in ecosystem service research  
445 (Cruz-Garcia et al. 2016). Our simple case-study model of three ecosystem services and  
446 three groups of stakeholders contributes to develop a general understanding of the balance of  
447 biodiversity and crop production, and of the various stakeholders, in intensively-managed  
448 agricultural systems based on landscape composition. Our results reveal trade-offs and  
449 compatibilities between stakeholders' demands that mirror those observed in the supply  
450 side, indicating that prioritization of individual stakeholders' demands has consequences on  
451 the other services, and on ecosystem multifunctionality. Such trade-offs strongly depend on

452 factors seldom considered by management policies, including the degree of pollination  
453 dependence of crops and the strength of environmental and demographic stochasticity.

454

455 The best landscape compositions, measured as the fraction of semi-natural habitat within the  
456 agricultural landscape, differ among stakeholders. In general, individual farmers' and  
457 conservationists' demands are associated with higher fractions of semi-natural habitat,  
458 whereas agricultural unions' demands are achieved at lower fractions of semi-natural  
459 habitat. This trade-off in the ecosystem service demand between agricultural unions, on one  
460 hand, and individual farmers and conservationists, on the other hand, implies that  
461 management focusing on single stakeholders will invariably reduce multifunctionality in  
462 agricultural systems, at least for the three services considered in this study. But the best  
463 landscape composition is not a static figure; rather, it depends on the same factors that  
464 determine trade-offs in the provision of ecosystem services in agricultural landscapes  
465 (Montoya et al. 2019).

466

467 Crop type, defined here as the degree to which a crop depends on animal pollination, is a  
468 main driver of the best landscape composition for both individual farmers and agricultural  
469 unions. Although the three major crops in terms of biomass are independent of animal  
470 pollination (wheat, rice, corn), the cultivated area of pollination-dependent crops is  
471 expanding faster than the area of pollinator-independent crops (Aizen and Harder 2009,  
472 Breeze et al. 2014). A higher pollination dependence of crops (e.g., most fruit crops such as  
473 *Prunus* spp., *Malus* spp., watermelon, *Cucurbita* spp.) generally shifts the best landscape  
474 composition to larger fractions of semi-natural habitat, irrespective of the stakeholder  
475 considered. Yet, to our knowledge this shift is not taken into account by actual policies. For  
476 low levels of pollination dependence of crops and crops independent of animal pollination,

477 prioritizing agricultural unions' demands increases landscape production, but reduces  
478 farmers' benefits and harms biodiversity significantly. However, with increasing  
479 dependence of crops on animal pollination the best landscape composition involves larger  
480 fractions of semi-natural habitat, which results in better biodiversity conservation combined  
481 with farmers' profitability, but does not satisfy agricultural unions' demands. Because  
482 agriculture worldwide is becoming more pollinator-dependent over time (Breeze et al. 2014;  
483 Aizen et al. 2009), changes in the best landscape compositions driven by crop pollination  
484 dependence are highly relevant in the global context.

485

486 Current global change enhances the inter-annual variance of several climate variables, i.e.  
487 environmental stochasticity (Giorgi et al. 2001; Li and Xian 2003; Saltz et al. 2006), as  
488 shown by the increasing frequency of extreme climatic events such as floods, heat waves  
489 and droughts (Fischer et al. 2016; Woodward et al. 2016; Craven et al. 2016). These events  
490 may in turn increase environmental stochasticity of crops and wild pollinators, and there is  
491 evidence that climate trends are partly responsible for observed increases in yield variability  
492 (Iizumi and Ramankutti 2016; Osborne and Wheeler 2016), and influence the delivery of  
493 ecosystem services (Shoyama and Yamagata 2014; Ding et al. 2016; Martinez-Harms et al.  
494 2017). Our results suggest that increasing stochasticity has contrasting effects on the best  
495 landscape composition for different stakeholders. Individual farmers' demands are generally  
496 met at higher fractions of semi-natural habitat when stochasticity is high, whereas the  
497 opposite holds true for agricultural unions. Such differences are driven by the different  
498 effects of stochasticity on the provision of ecosystem services. More specifically, high  
499 stochasticity changes the relationship between ecosystem services and semi-natural habitat:  
500 on one hand, the unimodal relationship of landscape production reported elsewhere (Braat  
501 and ten Brink 2008; Montoya et al. 2019) becomes monotonically decreasing for high



502 stochasticity (Appendix C, Fig. C.1), and this shifts maximum landscape production to  
503 lower fractions of semi-natural habitat; on the other hand, the saturating relationship of crop  
504 yield per area becomes flat when stochasticity is high (Appendix C, Fig. C.2), thus  
505 constraining the range of semi-natural habitat that maximizes farmers' profitability.  
506 Agricultural management should thus consider global change predictions, as changes in  
507 stochasticity directly influence the best landscape compositions that maximize stakeholders'  
508 demands.

509

510 The demands of individual farmers and conservationists generally align at higher fractions  
511 of semi-natural habitat. Therefore, the farmers' best interest is that, despite how much  
512 farmed is their land, the landscape around their cultivated land is not farmed. This is  
513 consistent with empirical research in grassland ecosystems showing that higher levels of  
514 biodiversity are beneficial for landowners (Binder et al. 2018), but contrasts with recent  
515 trends in modern agriculture, where individual farmers tend to increase crop land at the  
516 expense of semi-natural habitat, and thus biodiversity. We identify various reasons to  
517 explain the discrepancy between the individual farmers' demand defined in our study and  
518 their 'actual' demand. First, crops whose production does not depend on wild pollination do  
519 not require semi-natural habitat; in this case, farmers tend to expand crop area. Second, wild  
520 pollinators might suffer from the tragedy of the commons, where wild pollinators are the  
521 commons and farmers deplete semi-natural habitat through their collective action. Also,  
522 farmers actions may reflect a 'Not In My Back Yard' (NIMBY) phenomenon. Finally, the  
523 importance of wild pollinators inhabiting non-crop areas for crop production – pollination of  
524 crop plants – might be underestimated.

525

526 Our results suggest that a reduction in the amount of an ecosystem service that stakeholders  
527 are willing to accept (i.e. function thresholds) is a necessary condition to reconcile various  
528 stakeholders' demands (Fig. 3d, Fig. E1). This is because lower function thresholds expand  
529 the range of semi-natural habitat, increasing the overlap in the best landscape composition  
530 for different stakeholders. Indeed, this idea underpins the social average scenario, which  
531 suggests that overall performance of agricultural landscapes can be improved by combining  
532 multiple demands for ecosystem services, as opposed to a traditional focus constrained by  
533 provisioning services, mainly total landscape production (Lovell and Johnston 2009; Jordan  
534 and Warner 2010). Our results suggest that prioritizing multifunctional landscapes achieves  
535 relatively high levels of the three ecosystem services analysed and satisfies stakeholders'  
536 demands for intermediate amounts of semi-natural habitat. Further, the social average  
537 scenario is more robust to changes in crop type and stochasticity (Figs. 4, 5, and Appendix  
538 C, Fig. C.1). Therefore, management of agricultural systems for multifunctionality may  
539 better align with the increasing consensus supporting the need for agricultural landscapes to  
540 simultaneously provide ecosystem services that guarantee food security, livelihood  
541 opportunities, and biodiversity conservation (i.e. ecosystem service multifunctionality,  
542 Manning et al. 2018).

543

544 Our findings suggest that, unless the amount of an ecosystem service that stakeholders are  
545 willing to accept is reduced, the proportion of semi-natural habitat that conservation policies  
546 aim to protect lies below the best landscape composition in intensively-managed agricultural  
547 systems, especially for high levels of crop pollination dependence. The EU Green Policy  
548 succeeds in achieving high levels of landscape production (agricultural unions' demand) of  
549 crops that do not depend much on animal pollination, although this leads to low biodiversity  
550 levels (Figs. 5, Figs. D1, E1). Similar conclusions can be drawn for the Aichi Biodiversity

551 Targets (now implemented in the EU Biodiversity Strategy) and the Brazilian Forest Code,  
552 although they target higher fractions of semi-natural habitat (17% and 20%, respectively).  
553 Therefore, the regional and global-scale policies analyzed here satisfy agricultural unions'  
554 demands in one scenario only, that is, when crops depend little (or not at all) on animal  
555 pollination, although it leads to low biodiversity levels. By and large, preserving 5-20% of  
556 semi-natural habitat lies below the best landscape composition for biodiversity and crop  
557 production in intensively-managed agricultural systems for any other combination of  
558 stakeholders' demands considered here, crop type, or stochasticity. Such policies also fail to  
559 meet the social average scenario. Under the current trends of increasing pollinator-  
560 dependence of agriculture and global change, such targets seem too low to either meet  
561 stakeholders' demands or achieve adequate, sustainable levels of multifunctionality in  
562 agricultural systems (social average scenario). Designing more sustainable ways of food  
563 production is thus a challenge for the future of intensive farming systems in the context of  
564 global change.

565

#### 566 **4.1. Future research**

567 Our model is a useful starting point for future research. A future extension of our model  
568 would be to analyze other farming types, e.g. organic and wildlife-friendly farming, where  
569 pollinator diversity may thrive to some extent within crop land and the best landscape  
570 compositions may not be necessarily similar to those of intensively-managed agricultural  
571 systems (Clough et al. 2011). Also, metrics other than landscape composition could be used  
572 complementarily (e.g. agrochemical inputs) to compare management scenarios in  
573 agricultural systems. Besides, the spatial configuration of seminatural habitat is expected to  
574 determine ecosystem service flows between crop land and seminatural habitat (Garibaldi et  
575 al. 2011b; Mitchell et al. 2015), and this may affect the best landscape compositions of

576 organisms with narrow foraging ranges. We plan to include more realistic patterns of  
577 landscape fragmentation to assess the generality of the results presented here. Additionally,  
578 we have illustrated our approach using three ecosystem services and three groups of  
579 stakeholders as a case study; however, agricultural landscapes include a greater variety of  
580 ecosystem services (water quality, pest control, soil conditions, nutrient cycling, flood  
581 mitigation, as well as recreational and aesthetic services) and stakeholders whose demands  
582 may partially overlap (e.g. farmers may not only favor crop yield per area, but also a  
583 minimum amount of crop land). A wider consideration of ecosystem services will likely  
584 reveal additional trade-offs and synergies among services, such as between different  
585 provisioning services (timber vs crop yield; Rapidel et al. 2015), and between provisioning  
586 and regulating services (crop yield vs water quality, crop yield vs development of fungal  
587 diseases, long-term soil fertility vs immediate crop production; Stosch et al. 2017, Rapidel et  
588 al. 2015, see Klapwijk et al. 2014 and references therein). Such additional trade-offs may  
589 affect the best landscape compositions. Future work will thus benefit from assessing a  
590 greater representation of ecosystem services determining the overall performance of  
591 agricultural landscapes, and of stakeholders.

592

## 593 **4.2. Conclusions**

594 The future of intensive farming systems in the context of global change is a key component  
595 of the 2017 UN Sustainable Development Goals. Our analysis of three ecosystem services  
596 related to biodiversity and crop production, and three groups of stakeholders, shows that the  
597 best landscape composition differs among stakeholders, and that current policies should start  
598 to consider factors such as crop type, stochasticity, and the amount of an ecosystem service  
599 that stakeholders are willing to accept, as they can strongly influence these best landscape  
600 compositions for different stakeholders. Management for social average, or

601 multifunctionality scenario, may be a better option for food security, livelihood  
602 opportunities, and biodiversity conservation, thus meeting various stakeholders' demands.  
603 These results are relevant given the worldwide trends in agriculture (more pollinator-  
604 dependent over time) and global change (associated with the strength of environmental and  
605 demographic stochasticity).  
606

607 **Author's contributions:**

608 DM, ML and SG conceived the original idea and designed the research. DM, ML and CdM  
609 designed the analytical protocol. DM performed the analysis. All authors contributed to  
610 interpretation of results. DM wrote the first draft of the manuscript. All authors critically  
611 reviewed drafts and have approved the final version.

612

613 **Declarations of interest:** none

614

615 **Data accessibility:**

616 The datasets generated during and/or analyzed during the current study are available from  
617 the corresponding author on reasonable request.

618

619 **Acknowledgements:**

620 DM was funded by the EU and INRA in the framework of the Marie-Curie FP7 COFUND  
621 People Program, through the award of an AgreeSkills/AgreeSkills+ fellowship. This work  
622 was supported by the TULIP Laboratory of Excellence (grant number ANR-10-LABX-41),  
623 ANR AGROBIOSE (grant number ANR-13-AGRO-0001), ERANET ECODEAL, and  
624 BIOSTASES Advanced Grant, funded by the European Research Council under the  
625 European Union's Horizon 2020 research and innovation program (grant agreement No  
626 666971). We thank Bart Haegeman and the Centre for Biodiversity Theory and Modelling  
627 members for helpful discussions, and two anonymous referees for their insightful comments.

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