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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.

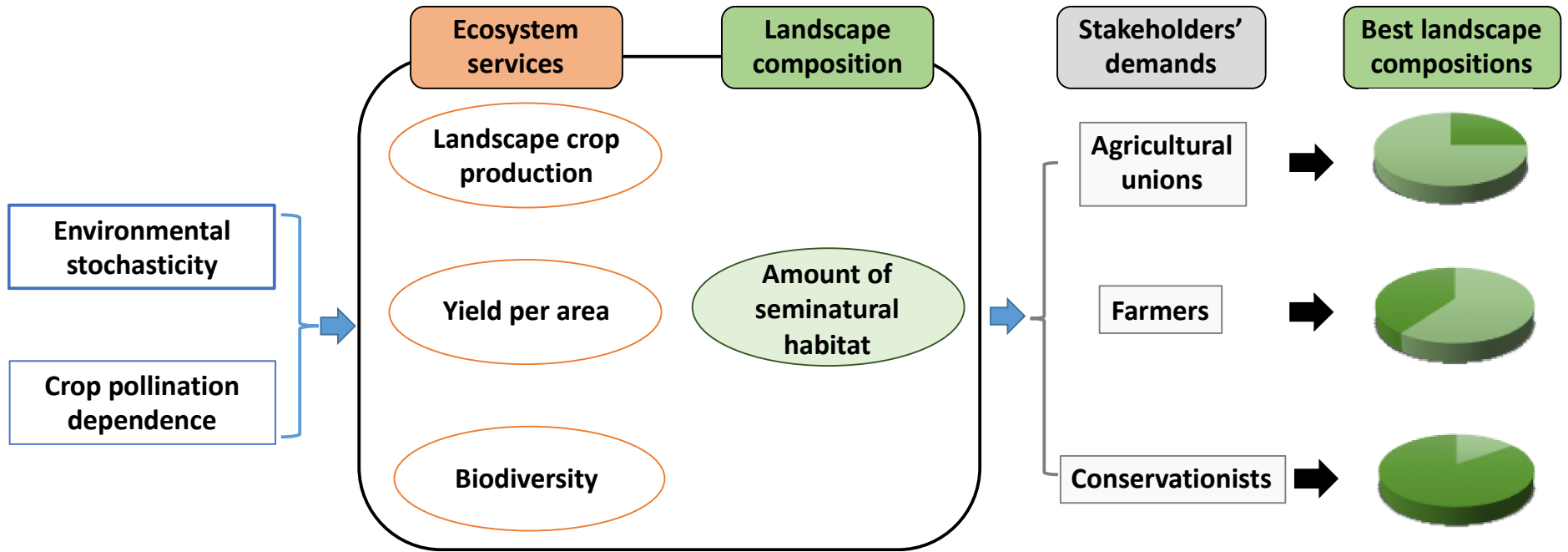
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130 Here, we use a model of biodiversity and crop production in intensively-managed
131 agricultural landscapes to derive landscape management solutions for different stakeholders'
132 demands. We analyze three main groups of stakeholders – individual 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.
153

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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.

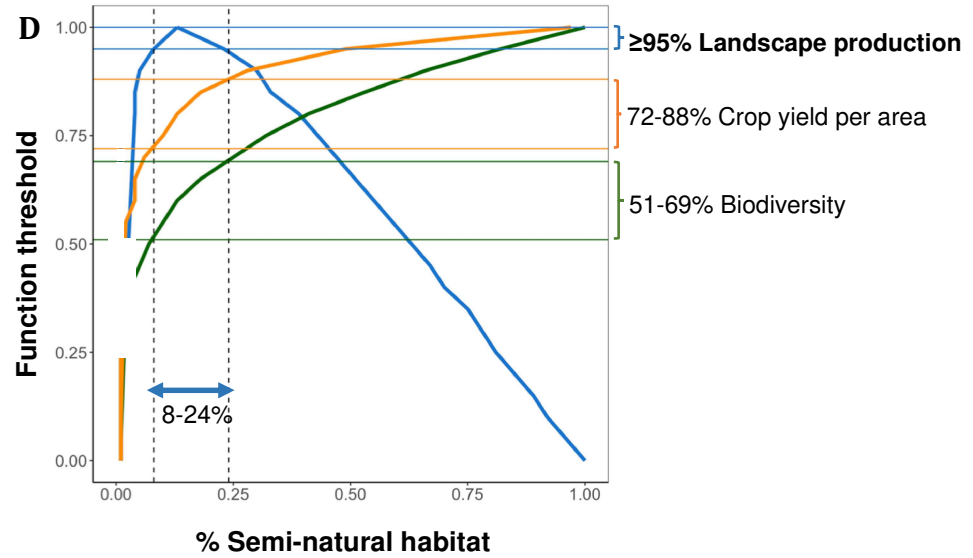
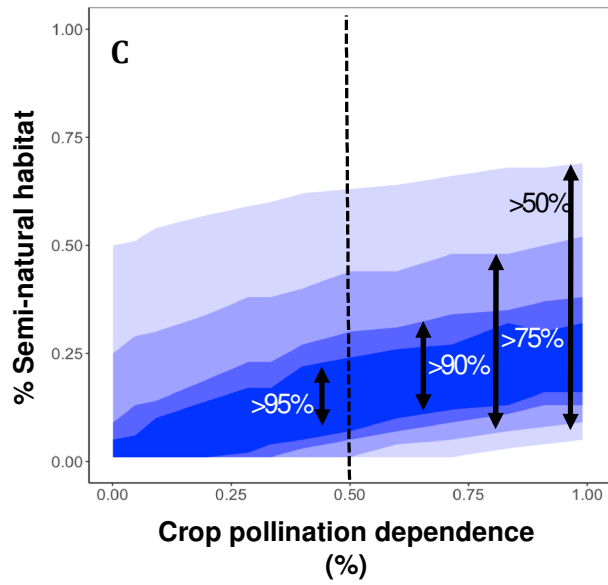
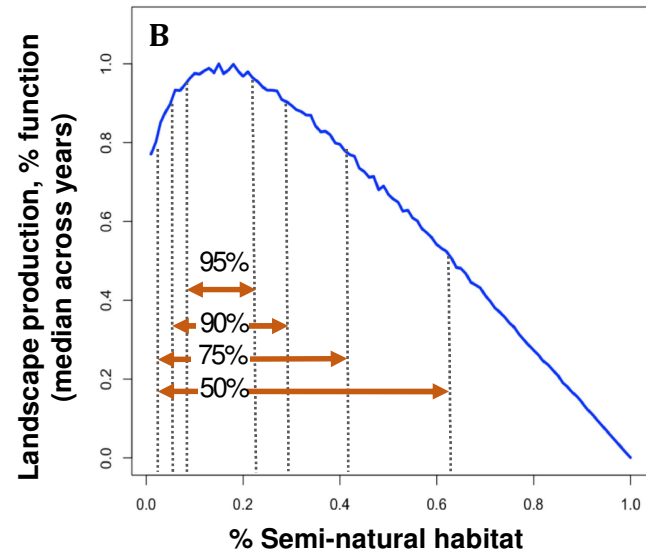
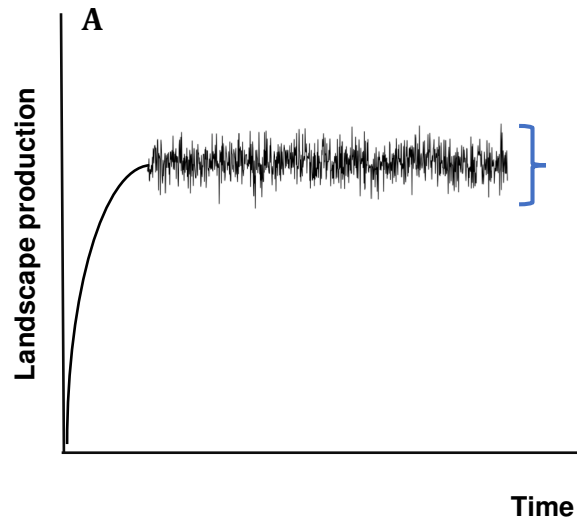
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280 Finally, we compare the best landscape compositions obtained by our model with current
281 management of agricultural landscapes. Our search for actual policies targeting specific
282 fractions of semi-natural habitat within agricultural landscapes 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

289

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

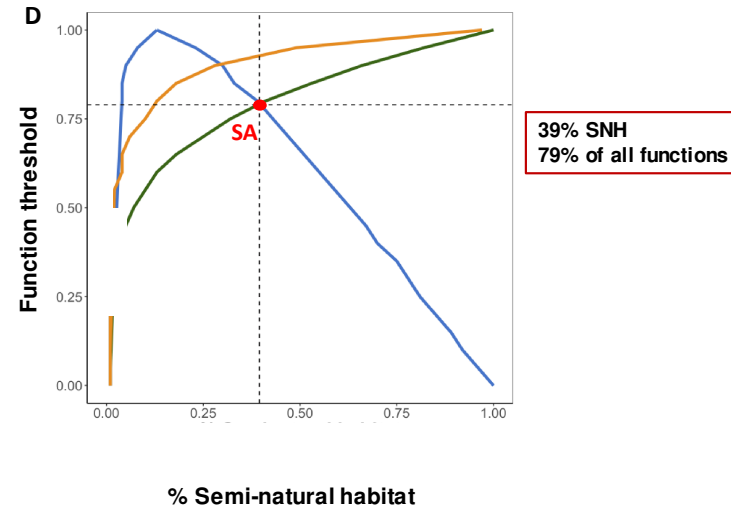
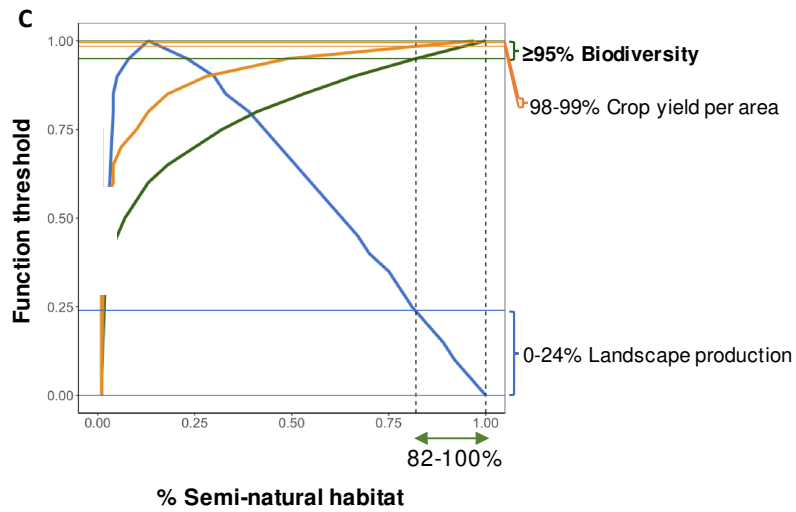
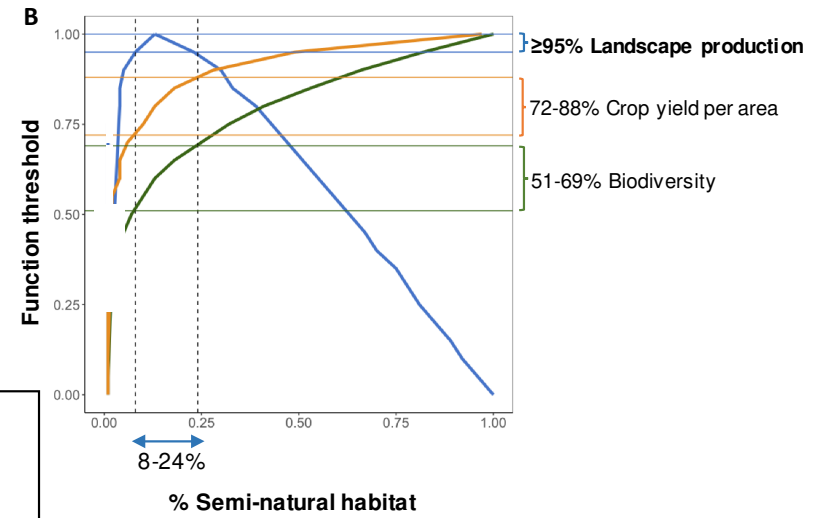
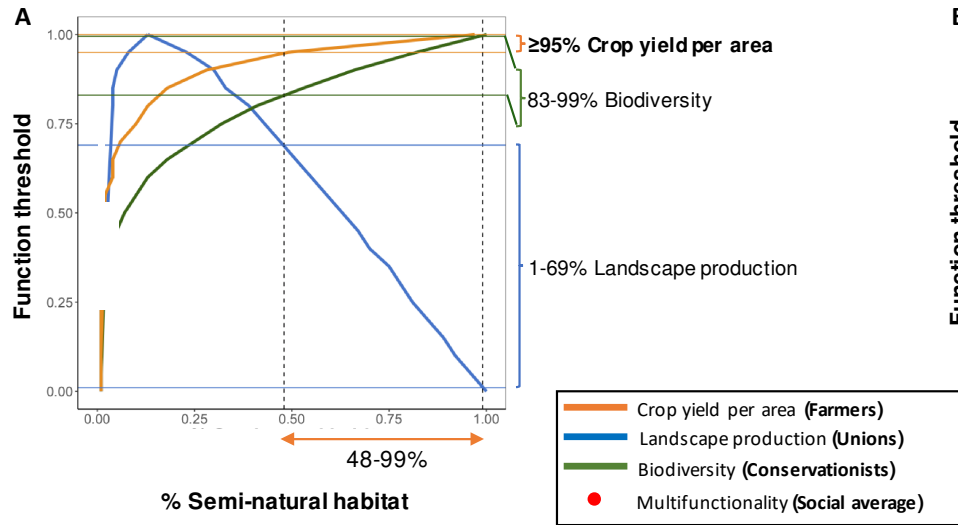
307 represents the % of provision of the other two ecosystem services that corresponds to that range of semi-natural habitat. Figs B, D are calculated
308 for 50% of crop pollination dependence, and median values of environmental and demographic stochasticity.

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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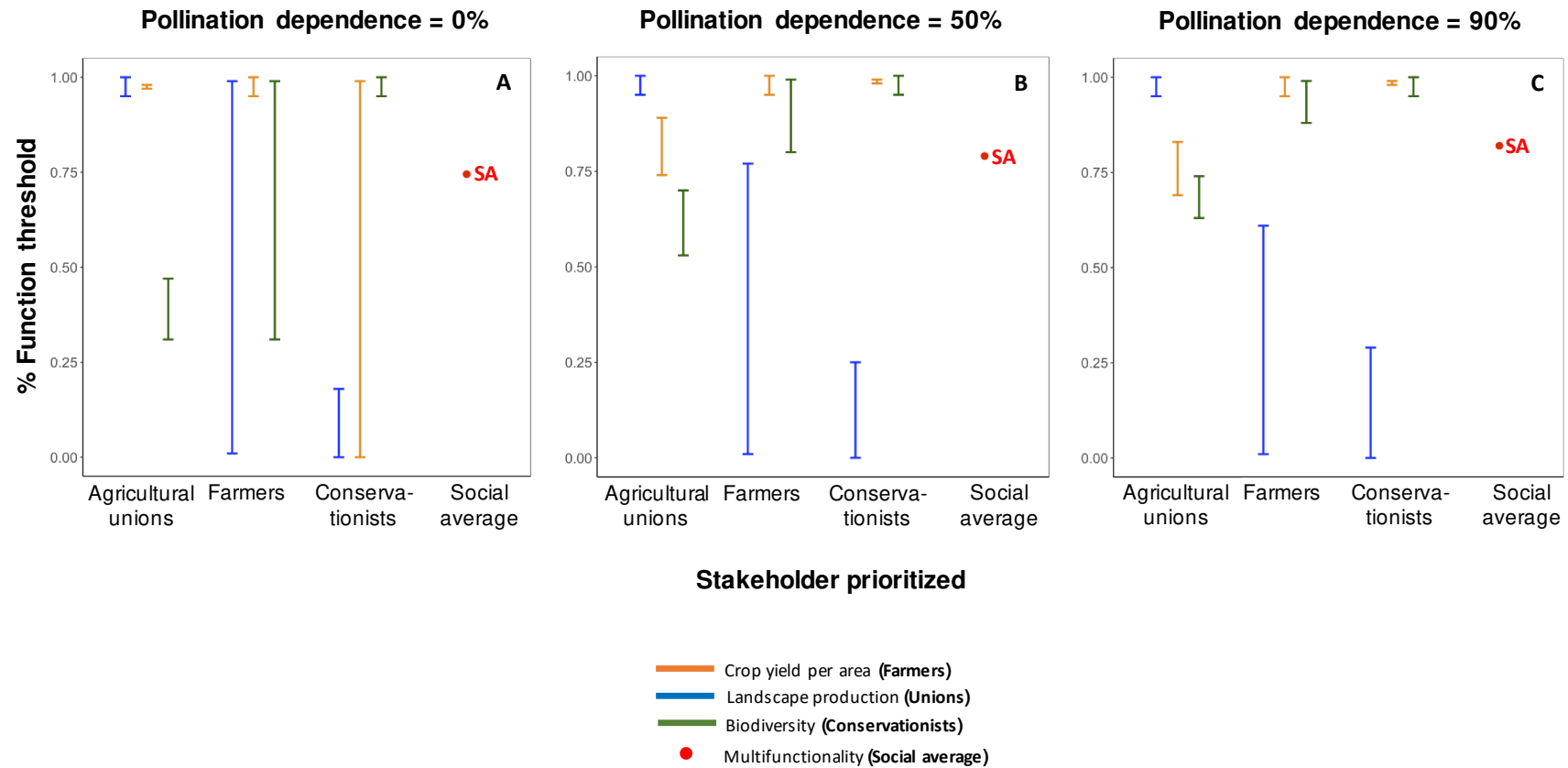
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356 **Figure 4. Effects of stakeholders' demands on the provision of other ecosystem services.** In each plot, the stakeholder prioritized is on the
 357 X axis (function threshold of its most valued ecosystem service is set to $\geq 95\%$), and its 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**

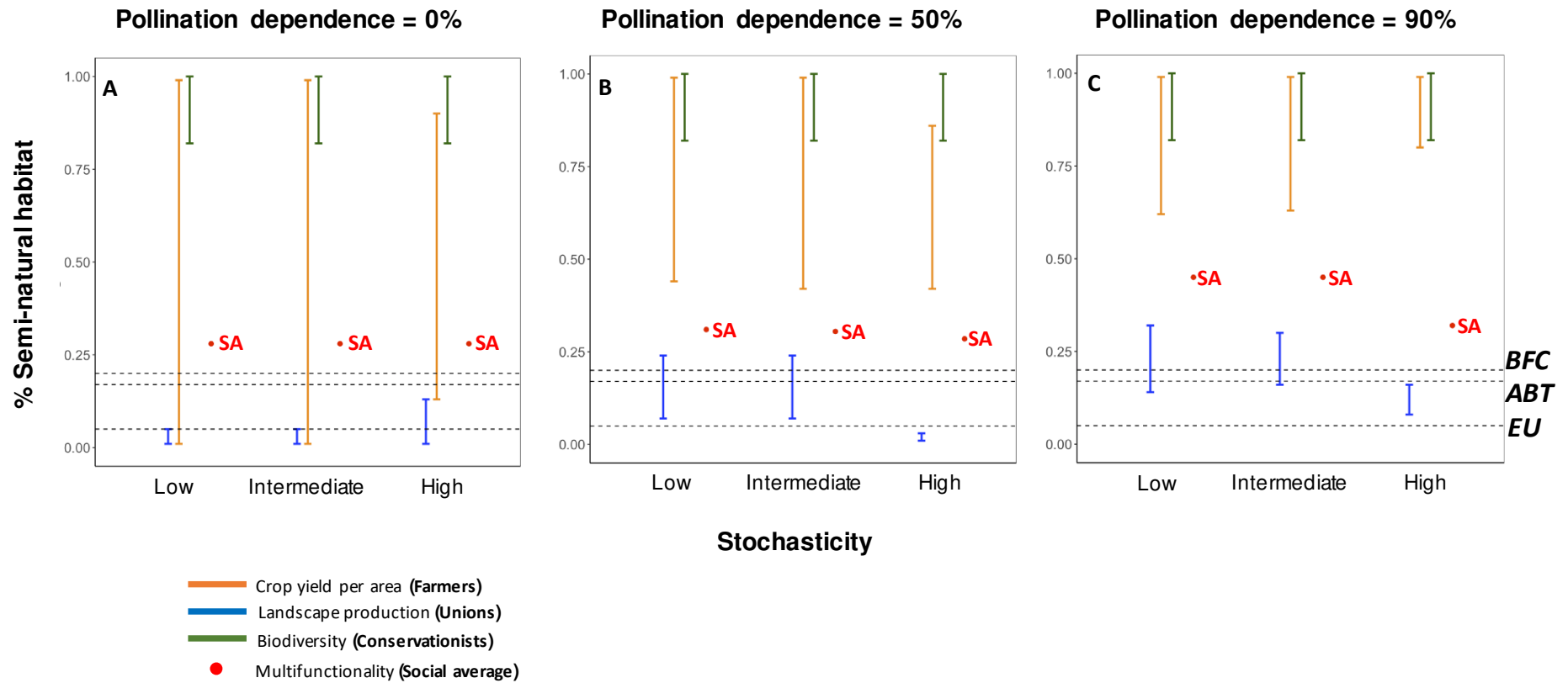
370 The best landscape compositions, and the trade-offs and synergies between stakeholders'
371 demands, strongly depend on three factors: crop pollination dependence, the strength of
372 environmental and demographic stochasticity, and the function threshold of ecosystem
373 services, i.e. the relative 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
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618

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