

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

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		For Ecological N	Modelling: Research paper
Reconciling farmers' dem	biodiversity cons and in agricultura	ervation, food l landscapes	production and
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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 of pollination dependence of crops, the strength of environmental and demographic 38 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.

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

Agricultural landscapes involve a great variety of ecosystem services and stakeholders, and they globally represent about 40% of the total terrestrial surface of our planet (Foley et al. 2011). As such, agricultural landscapes are among the most interesting systems to analyze the balance between the supply and demand of various ecosystem services. The particularity of most modern agricultural landscapes is that the provision of a single service, i.e. crop production, is intensified by means of land conversion, mechanical work and the use of 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.

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).

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

129

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 demographic152 stochasticity scenarios.



Figure 1. Conceptual diagram of our modelling framework. We use a model of biodiversity and crop production in intensive farming systems 161 162 (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 most – agricultural unions (landscape crop production), individual farmers (yield per area) and conservationists (biodiversity), and derive the best 165 landscape compositions for each stakeholders' demands. Therefore, the model investigates how changes in environmental stochasticity (expected 166 167 under global change) and the degree of pollination dependence of crops may affect the provision and demand of ecosystem services in 168 agricultural landscapes.

# 2. MATERIALS and METHODS

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# 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 includes it through the consideration of environmental and demographic stochasticity 176 177 (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 hence the fragments of semi-natural habitat that host them, are distributed in such a way that pollinators have access to the whole landscape (or that pollinators are not spatially restricted in their foraging patterns). Therefore, the spatial extent can vary from roughly 5-10 ha (typical arable field in Europe) to any larger scale provided pollinators are not aggregated in 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**

We use our model to investigate how different stakeholders' demands determine the best landscape compositions in agricultural landscapes. Beneficiaries or stakeholders for 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 to design landscapes that are beneficial for a range of functions' (Shellhorn et al. 2008). 232

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 demanded ecosystem service; thus, considering function thresholds is useful for identifying 241 242 potential trade-offs and for balancing various demands for services.

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

Next, we address the effects of each stakeholder's demand on the other ecosystem services. For each stakeholder (scenarios 1-3), we set the function threshold of the ecosystem service they demand to 95%, i.e. agricultural unions demand  $\geq$ 95% of landscape production. The demand established by the function threshold is satisfied within a certain range of semi269 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.

279

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 fractions of semi-natural habitat within agricultural landscapes yielded only one result, the 282 283 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).

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Figure 2. Analytical protocol. We followed a 4-step procedure to estimate the best landscape compositions for each stakeholder's demand and 292 293 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 of landscape production as a function of semi-natural habitat is obtained (1b). This approach enables to explore the full probability distribution of 296 ecosystem service values as well as the possibility of setting thresholds values for services (Carnus et al. 2014). Absolute thresholds for 297 298 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 pollination dependence (1c). The vertical dashed line represents 50% of pollination dependence of crops (b). The % in (c) correspond to the 303 304 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.

### **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 habitat. For intermediate levels of crop pollination dependence and median values of 316 317 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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1.00

% Function threshold

T =

Pollination dependence = 0%

Ι





1.00

Ι

Α

# 354

### 355



Biodiversity (Conservationists) Multifunctionality (Social average) Social

average

with crop pollination dependence. Landscape production and biodiversity conservation are highly incompatible when agricultural unions' demands are prioritized. Agricultural unions and individual farmer's demands can be reconciled when the degree of pollination dependence of 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.

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

The best landscape compositions, and the trade-offs and synergies between stakeholders' demands, strongly depend on three factors: crop pollination dependence, the strength of environmental and demographic stochasticity, and the function threshold of ecosystem 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 fractions of semi-natural habitat for individual farmers and agricultural unions (Fig. 5, 377 378 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. Only at low levels of crop pollination dependence can agricultural unions and individual 385 386 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





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

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 environmental (compared to demographic) stochasticity of crops and wild pollinators in 415 416 determining changes in the best landscape compositions (Appendix C, Fig. C.1).

417

#### 418 *3.2.3. Function threshold*

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

426

# 427 **4. DISCUSSION**

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-Agundez et al. 2015; Yahdjian et al. 2015; Burkhard et al. 2012), and highlights the 441 442 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 pollination453 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

Crop type, defined here as the degree to which a crop depends on animal pollination, is a 467 468 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 fractions of semi-natural habitat, which results in better biodiversity conservation combined 480 481 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; Montova 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 importance of wild pollinators inhabiting non-crop areas for crop production – pollination of 523 524 crop plants – might be underestimated.

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 al. 2011b; Mitchell et al. 2015), and this may affect the best landscape compositions of 575

organisms with narrow foraging ranges. We plan to include more realistic patterns of 576 577 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

# **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 different stakeholders. Management for for social average. or

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

608	DM, ML and SG conceived the original idea and designed the research. DM, ML and CdM
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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	
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614	
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616	The datasets generated during and/or analyzed during the current study are available from
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618	
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Author's contributions:

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