**Optimizing intermediate ecosystem services in agriculture
using rules based on landscape composition and configuration
indices**

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4 Abstract

5 Important intermediate ecosystem services (ES) such as crop pollination and biological
6 control of pests, which underpin the final ES agricultural yields, are mediated by mobile
7 organisms that depend on availability of habitat and its arrangement in the landscape. It
8 has been suggested that landscape-scale management (LSM) of habitat in a multi-farm
9 setting results in higher provisioning of such ES compared to farm-scale management
0 (FSM). However, to achieve the LSM solution, farmers' land-use decisions need to be
1 coordinated. To this end, we develop rules based on novel landscape composition and
2 configuration indices. We model farmers' interdependencies through ES in an agent-
3 based model (ABM) and optimize land use at both the farm and landscape scales for
4 comparison. Our analysis is based on a simple artificial landscape with homogeneous soil
5 quality and uses crop pollination as an illustrative ES. We consider habitat configuration
6 at the field scale. Our rules demonstrate that the coordinated solution is characterized by
7 a higher degree of habitat availability and a configuration of habitat that is dispersed
8 rather than agglomerated. We tested these rules over a range of assumptions about
9 ecological parameter values and suggest that such rules could be used to improve
0 governance of ES in agricultural landscapes.

Keywords

Agent-based model; Agglomeration; Dispersion; Governance; Pollination; Agri-environmental policy

1. Introduction

Intermediate ecosystem services (ES) such as pollination and biological pest control benefit agriculture, by improving the final ecosystem service agricultural yields and/or saving on costly inputs (Bianchi et al., 2006; Bommarco et al., 2013; Cong et al., 2014a; Cong et al., 2015; Fisher et al., 2009; Klein et al., 2007; Power, 2010; Tilman et al., 2002). Consequently, farmers can boost productivity by maintaining or creating (semi-natural) habitat for organisms providing such ES, but usually at some opportunity cost because less land can be used in production. Furthermore, since ES such as pollination and biological pest control are mediated by mobile organisms, farmers need also to consider the potential externalities of their habitat conservation decisions. This is because one farmer's decisions will likely affect neighboring farmers' yields via changes in flows of ES (Fisher et al., 2009; Sutherland et al., 2012). These interdependencies imply that farmers acting independently are not likely to maximize the overall potential benefits from habitat conservation, resulting in the Tragedy of Ecosystem Services (Lant et al., 2008). Rather, optimizing management of ES requires coordinating habitat conservation among farmers (Cong et al., 2014b).

Some existing governance systems claim to support the conservation of habitat for ES providers. For example, in the US the Conservation Reserve Program (CRP) offers payments to farmers who cover environmentally sensitive crop land with permanent vegetation (Kirwan et al., 2005). The payments are, however, based on soil productivity

or land rental prices and the total area entered into the scheme (Plantinga et al., 2001). In Europe, Swiss farmers are required to manage at least 7% of their land as Ecological Compensation Areas to qualify for area-related subsidies (Herzog et al., 2005). Similarly, as a consequence of the recent CAP “Greening” reform, some 30% of annual direct payments are now contingent on farmers reserving at least 5% of their arable area as Ecological Focus Areas, with the intention to benefit biodiversity (EU, 2013). Nevertheless, none of these costly schemes consider habitat quality, other than on a rudimentary basis (e.g. 5% of the farm area should be classified as non-crop), or how habitat should be arranged across the landscape (i.e. habitat configuration); aspects which are likely to impact their effectiveness for promoting ES (Brady et al., 2009; Dicks et al., 2013; Hart et al., 2014).

In the existing Economics’ literature, the focus is mostly on how to increase habitat connectivity for the benefit of biological conservation, with the underlying assumption being that agglomerated habitat is ecologically more valuable than dispersed habitat (Drechsler et al., 2010; Fahrig et al., 2011; Parkhurst and Shogren, 2007; Söderström et al., 2001). Similarly, arguments used in the ecological literature also emphasize the need for agglomerating habitat, in particular by spatially separating food production and biodiversity conservation (so-called land-sparing) rather than making land used in production more conducive to biodiversity conservation (land-sharing) (Brussaard et al., 2010; Green et al., 2005; Law et al., 2015; Phalan et al., 2011). Accordingly, the current literature has a strong conservation perspective, i.e. how to conserve as many species as possible given an agricultural production target (von Wehrden et al., 2014), while ignoring potential synergies between habitat conservation and agricultural production via

ES (Ekroos et al., 2014; Holland et al., 2014; Rey Benayas and Bullock, 2012); which is also an argument for promoting land-sharing in the ecological literature (Fischer et al., 2008; Kremen, 2015).

Managing ES efficiently may, in contrast to biodiversity conservation where agglomerating habitat is more desirable, require greater dispersion of habitat across a landscape (Ekroos et al., 2014; Mitchell et al., 2015; Smith et al., 2010). Although ES providers may be affected positively by habitat agglomeration, their capacity to provide ES across a landscape declines with increasing distance. Consequently, dependence on the landscape-wide configuration of habitat arises for agricultural crops (Garibaldi et al., 2011; Ricketts et al., 2008; Rusch et al., 2010; Tschardt et al., 2005).

In principal, there are two spatial scales relevant to the evaluation of the efficiency of farmers' management of ES: landscape-scale management (LSM) and farm-scale management (FSM). LSM implies that individual farmers' land-use decisions are coordinated from a holistic perspective to optimize aggregate output at a larger scale than the field or farm, the landscape. In contrast, FSM implies that farmers make their decisions considering only their own benefits. LSM has been found superior to FSM for solving many environmental problems, including species conservation (Drechsler et al., 2010; Hale et al., 2001), pollution control (Haycock and Muscutt, 1995) and disaster prevention (Moreira et al., 2009).

LSM might also benefit crop production of individual farmers. Based on agent-based modelling (ABM), Cong et al. (2014b) show that LSM of intermediate ES produced by mobile organisms is superior to FSM for maximizing individual farm profits. However, they also demonstrate that strong incentives work against the LSM solution because of

the externalities of ES, giving rise to a classical Prisoner's Dilemma. Another potential barrier to LSM arises because of transaction costs, e.g. the monitoring and enforcement costs for implementing LSM in reality. The prisoner's dilemma and transaction costs raise the issue of finding appropriate decision support tools to achieve efficient management of ES in agricultural landscapes (Lant et al., 2008; Stallman, 2011).

A first step towards designing such decision support tools, and an ancillary aim of this paper, is to describe or quantify landscape configuration emerging under LSM, FSM or any real settings using two indices: habitat availability index (HAI) and habitat configuration index (HCI). The overriding aim of this paper, however, is to examine the composition and configuration of habitat emerging under different ecological assumptions and contrast the LSM and FSM solutions. We use pollination to exemplify the provision of ES by mobile organisms (Kremen et al. 2007), but a similar approach could equally well be applied on biological pest control (Jonsson et al., 2014).

2. A conceptual example

Since habitat configurations in reality are likely to be more subtle than strict agglomeration or dispersion (Lusiana et al., 2012), quantifying the degree of agglomeration or dispersion has important implications for economic analysis. To illustrate the problem, consider a simple example of six hypothetical farms (a-f) with four equal-sized fields each (Fig. 1).

[Insert Fig. 1 here]

Each field can be used for farming and/or providing habitat for ES providers. The number, I , indicates the proportion of each field used for farming. No assumption is made about

configuration within the field. Let us examine farms (a) and (b). *Perfect* agglomeration at the farm-scale implies that the farm-agent, in this case farm (a), uses some fields purely for farming ($I=1$) and reserves other fields purely for habitat ($I=0$). In contrast, *perfect* dispersion, as illustrated by farm (b), implies that habitat for ES providers is distributed uniformly among fields, i.e. I is identical for all fields. Clearly, an index is needed to locate any observed landscape configuration (e.g. farms (c-f)) along the agglomeration-dispersion continuum. In this paper we use the terms "agglomerated" and "dispersed" habitat to describe habitat configuration relevant for ES considering the synergy between conservation and production, instead of the terms "land sharing or sparing" which are generally used in the debate about trade-offs between conservation and production.

3. Method: Indices and Agent-based models

We first introduce the two landscape indices: HAI and HCI, after which we present an ABM, where individual farmers are represented by agents, to describe the FSM solution as a benchmark, i.e. without any coordination of their decisions. Third, we employ the same ABM (as used for the FSM solution) but with a single agent to describe the LSM solution. Finally, we present the uncertainties for the main model parameters.

3.1 HAI and HCI

After reviewing the landscape ecology literature on indices, we found no single index immediately suitable for our purposes (e.g. Rutledge (2003), Dale (1999), Ripple et al. (1991), Scheldeman and van Zonneveld (2010)). Inspired by the analysis of habitat amount and habitat fragmentation (Fahrig, 2002), we use instead two indices to jointly evaluate the composition and configuration of habitat at the farm and landscape scales: (i)

Habitat Availability Index (HAI) to measure the composition of habitat; and (ii) Habitat Configuration Index (HCI) to measure the configuration of habitat.

We use HAI, to describe the proportion of farmland area left as semi-natural habitat and hence not used for farming (Fahrig, 2002; Kirwan et al., 2005). Here, HAI simply reflects the average amount of habitat available in a particular field (plot or landscape), with the remainder assumed to be used for growing crops. It can be expected that a moderate increase in habitat availability will boost yield (Cassman, 1999) because of greater provisioning of ES. However, beyond a critical threshold any further increase in habitat availability in a field will depress yield due to the overriding loss of area for growing crops on the field (Ekroos et al., 2014). This index is also the inverse of the proportion of arable land which is commonly used to describe agricultural landscapes (Roschewitz et al., 2005).

To measure habitat configuration we propose a habitat configuration index (HCI) that varies between perfectly agglomerated to perfectly dispersed habitat. Inspired by the landscape shape index and classic indices of dispersion (Plantinga et al., 2001), we make HCI independent of HAI and the number of fields, by defining it as the ratio of the variance of habitat availability (VHA)¹ among fields of a real landscape to VHA in a perfectly agglomerated landscape with the same number of fields and habitat availability. The lower bound for HCI is zero, indicating uniform farming intensity across all fields (*perfect* dispersion). The upper bound of HCI is one and corresponds to the largest possible variability of farming intensities across the fields (*perfect* agglomeration, recall

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¹ If there are n fields in the landscape, $VHA = Var(HAI) = \frac{1}{n} \sum_{i=1}^n (HAI_i - \mu)^2$; $\mu = \frac{1}{n} \sum_{i=1}^n HAI_i$. HAI_i is the habitat availability of field i .

farm (a) in Figure 1). Using HCI of *perfect* dispersion (zero) as one endpoint and HCI of *perfect* agglomeration (one) as the other endpoint, we can map any habitat configuration on the dispersion-agglomeration continuum, i.e. $HCI \in [0,1]$.

In Table 1, we illustrate the utility of the two indices by calculating these for the six hypothetical farms depicted in Fig. 1. Based on these indices, it can be seen that farm (f) has a habitat configuration ($HCI=0.25$) that is closer to perfect dispersion ($HCI=0$) than farm (e) ($HCI=0.5$). Using both indices, we can measure and compare the landscape compositions and configurations emerging within farms and for the landscape.

[Insert Table 1 here]

3.2 ABM at farm and landscape scales

ABM at farm scale

The ABM, described in Cong et al. (2014b), is developed to simulate interdependent farmers' behavior without landscape-wide coordination (i.e. FSM). In the ABM the total landscape is represented as a $N \times N$ grid (see Fig. 2). Each farm is represented by $n \times n$ fields, where $n < N$, and indexed by its ID (i) and coordinate (v, w). Individual fields (i.e. grid plots) constitute the minimum decision unit for each farm. The spatial configuration of habitat within a field is not considered, i.e. the land use within a field is assumed to be homogeneous. With FSM, each farm aims to maximize its own profit independently of other farms.

[Insert Fig. 2 here]

The basis of ABM is that, since ES are important for yields of some crops, farmers need to weigh the benefits of conserving habitat (where providers of ES can survive) against the costs (losing the opportunity of farming the land). The main assumptions of the ABM

are that (i) crop production is (at least partly) dependent on the ES whose level is determined by the landscape (Garibaldi et al., 2011; Kennedy et al., 2013; Ricketts et al., 2008); (ii) the ES declines exponentially with the distance from the source habitat (Ricketts et al., 2008); and (iii) the ES emanating from habitat parcels are additive, i.e. potential interactions among ES providers from different habitats are not considered (Lonsdorf et al., 2009). Based on these assumptions, the key parameters are the degree of yield dependence on the ES (b/a , which thereby differentiates the crop types), pollinator mobility (β , which describes the typical foraging distance of ES providers) and habitat suitability (α , which reflects the suitability of different types of habitat for ES providers and hence their abundances).

The ABM proceeds in annual time steps. At the start of each year, the flow of ES to each field is calculated based on the current landscape, after which each farm-agent (farmer) calculates the profits from agricultural production on all of their fields, which is dependent on ES as calculated above. Finally, each farm-agent determines its land use on each field for the coming year (i.e. the proportion of crops on each field, implying the remainder is managed as habitat), to maximize profits when assuming that all other farm-agents will keep their current landscapes. Consequently changes in habitat composition and configuration on a particular farm could affect the level of ES benefiting its neighbors and hence their land-use decisions in the following year.

ABM at landscape scale

We employ the agent-based model with a single agent to determine the landscape-scale management (LSM) solution. It is identical to the solution for a single owner of the

landscape. The single agent determines the land use on all fields in the landscape to maximize the total profit which is affected by the spatial configuration of habitat via ES.

3.3 Sensitivity analysis

Crop production function

We assume that crop yield can be divided into two components: (1) the yield, a , that is independent of ES (e); (2) the yield, b , that is dependent on the level of ES (see equation (4) in Cong et al. (2014b) for details). Accordingly, crop yield on plot (c,d) is calculated as follows:

$$y_{c,d} = a + b \times e_{c,d} \quad (1)$$

In the baseline model, 50% of maximum yield is assumed to be independent of ES (i.e. a is set to 5, and b is set to 5). In the sensitivity analysis (section 4.2.1), we consider the implication of crops having different degrees of dependency on ES. The two extreme situations are defined as yield being fully dependent on ES ($a=0$, $b=10$) and yield having least dependence on ES ($a=9$, $b=1$), after which we analyze several alternatives between these two extremes.

ES production function

Building on Lonsdorf et al. (2009), the unit ES to plot (c,d) generated from habitat on plot (f,g), $SES(f,g,c,d)$, is calculated as follows (see equation (2) of Cong et al. (2014b)):

$$SES(f, g, c, d) = \alpha \times \exp^{-\beta \times \sqrt{(f-c)^2 + (g-d)^2}} \quad (2)$$

Different types of habitat may vary in their suitability for service providing organisms and hence affect the abundances of different organisms (Roulston and Goodell, 2011).

Organisms characterized by variations in mobility are also likely to utilize the landscape at different spatial scales, resulting in different distance-decline functions (Gathmann and Tscharntke, 2002; Knight et al., 2005; Westphal et al., 2006). Interpreting both aspects in terms of our model, the unit ES flowing to any plot (i.e. SES) is dependent on the scale parameter α and the distance parameter β . In the reference scenario, $\alpha = 1, \beta = 0.1$. We tested the sensitivity of our results to a range of values for one parameter, while keeping the other parameter constant.

4. Results

We start by evaluating the compositions and configurations of habitat that emerged with FSM and LSM on individual farms and then for the entire landscape using the baseline parameters (i.e., using plausible, or non-extreme values of the main parameters of the model; see Table 1 in Cong et al. (2014b)). We then explore the effects of the two main uncertainties (crop and ES provider types) on the compositions and configurations of habitat at both scales.

4.1 Comparison of habitat compositions and configurations with LSM and FSM

4.1.1 Farm-scale results

In this section, we examine the emergent compositions and configurations of habitat on individual farms with different locations in the landscape. First, we compare the results for farms with many neighbors (i.e. central farms) to those with few neighbors (i.e. peripheral farms). Then, we compare farms with an intermediate number of neighbors depending on their locations in the landscape.

Farms with many neighbors (Central farm, e.g. Farm 13 (3, 3))

A distinct visual difference can be discerned in Fig. 3 between the composition and configuration (i.e. arrangement) of habitat that emerges with (a) FSM and (b) LSM, respectively, on farms with many neighbors (central farms) compared to those with few neighbors (peripheral farms). With FSM the resultant arrangement of habitat on farms with many neighbors is dominated by agglomerated land use, i.e. having either purely habitat (strong green shading) or purely crops (strong brown shading) on each field. The striking difference in the configuration of habitat on central farms compared to peripheral farms is due to the interdependencies created by ES. However, farms, regardless of location, generally concentrate their cropped fields along their borders with other farms, so as to take advantage of ES flowing from neighboring farms, and configure or place their own habitat so as to maximize ES to their own crops. Accordingly, central farms crop their outer fields and maintain habitat on their inside fields symmetrically, while peripheral farms tend to concentrate habitat on their neighborless fields which gives a less symmetric configuration, and implying an agglomerated configuration of habitat.

In contrast, LSM results in all the fields on farms with many neighbors becoming, basically, a mixture of crops and habitat (yellow-green shading), implying a dispersed configuration of habitat. Specifically, LSM results in a habitat configuration that is almost perfectly dispersed ($HCI=0.017$ or close to 0), while with FSM it is almost perfectly agglomerated ($HCI=0.958$ or close to 1) (Table 2).

[Insert Fig. 3 here]

Since ES providing organisms have the least average distance to travel to any location in the landscape from the central farm (that with most effective neighbors), this farm has the

largest ES coverage (i.e., not only in respect to the level of ES the farm can provide, but also the farm area that can be affected by ES). Consequently, the dispersion of habitat on this farm with LSM provides more ES, and hence contribution to aggregate (or landscape-scale) profits, than the agglomerated configuration resulting from FSM. That is, with FSM the central farm places its habitat completely inside the farm to maximally benefit its own crops. On the other hand, the self-interest of peripheral farms results in some dispersion of habitat with FSM, because it benefits their own production. The extent of dispersion will depend, however, on the non-linear relationship between the yield gain and the characteristics of the ES providers. For example, under parameters $\alpha=5$, $\beta=0.1$ (Section 4.2.2) we found that farmers with many neighbors should also keep some habitat on the borders of their farms.

Furthermore, in addition to LSM resulting in greater dispersal of habitat on the central farm, its habitat composition is also higher ($HAI=0.473$) than with FSM (0.364), which means that farms with relatively many neighbors should provide relatively more habitat and disperse it across the farm to achieve the LSM solution than implied by farm-scale optimality (FSM).

Farms with few neighbors (the corner farms, e.g. Farm 1 (1, 1))

For farms with the least neighbors (the corner farms), their habitat configuration resulting from both LSM and FSM is closer to perfect agglomeration than dispersion ($HCI=0.754$ and $HCI=0.725$, respectively), but the location of the fields devoted to habitat within the farms varies considerably due to ES interdependencies (Fig. 3). However, habitat composition with LSM ($HAI= 0.458$) is still higher than with FSM ($HAI=0.408$).

Farms with intermediate numbers of neighbors (Farm (1, 2), (2, 2), (1, 3), (2, 3))

We sort farms with an intermediate number of neighbors in Table 2 according to their distance from the center farm, Farm 13. To summarize, habitat availability resulting from LSM is generally higher than for FSM. Additionally, the configuration of habitat with LSM is generally closer to perfect dispersion than with FSM; and the degree of dispersion increases the closer a farm is to the center farm (since the spatial interdependency increases). Further, while their HAIs are quite similar, their HCIs show large differences, implying that HAI is a necessary but not sufficient index for improving landscape management. Rather HCI is needed to complement HAI to inform landscape management.

[Insert Table 2 here]

4.1.2 Landscape-scale results

The two management strategies, LSM or FSM, result in distinct differences in habitat compositions and configurations when evaluating the emergent landscapes as a whole, similar to the farm-scale results. With FSM, agglomerated land uses emerge in two ways from the landscape-scale perspective. On the one hand, crops or habitat are agglomerated on each field, which is similar to farm-scale management. On the other hand, fields of identical land use tend to be arranged contiguously within farms and between farms (e.g. habitat areas are placed beside each other without intervening fields of purely crops, Fig. 3 (a)). With LSM fields with mixtures of crops and habitat dominate farms, and hence the landscape (Fig. 3 (b)). In addition to these visual differences, our landscape indices show that to achieve the LSM solution, farmers should maintain more habitat (higher HAI) with greater dispersal (lower HCI) compared to individual optimality (FSM).

Specifically, HAI with LSM (0.463) is larger than it is with FSM (0.381), implying that a generally greater availability of habitat across the landscape (or average habitat per field) is required to achieve LSM compared to FSM. The habitat configuration that emerges for the landscape under the baseline scenario with LSM is close to neutral (neither agglomeration nor dispersion) ($HCI=0.498$), while that for FSM is closer to perfect agglomeration ($HCI=0.88$), implying that FSM results in farmers maximizing intensity on cropped fields without considering spatial interdependencies with their neighbors via ES. In contrast, with LSM the average level of ES per field (7.68) and total profit (14407) are larger than for FSM (6.60, 13821), implying that the landscape composition and configuration resulting from FSM certainly result in different levels of ES across the landscape compared to LSM (Fig. 4, the calculation method can be found in Cong et al. (2014b)).

[Insert Fig. 4 here]

4.2 Implications of crop and ES provider characteristics

In this section, we examine the effects of two main uncertainties (crop and ES provider characteristics) on the modeled landscapes and evaluate how the emerging habitat compositions and configurations respond to changes in these model parameters.

4.2.1 Crop characteristics

We find that for all relevant crop-type parameterizations, the HAIs (HCIs) with LSM are always higher (lower) than those with FSM (Fig. 5), which supports our conclusion that the farm-agents with LSM should maintain more habitat and disperse it compared to FSM. However, we find that as yield dependence on pollination falls from fully dependent ($a=0$, $b=10$) to least dependent ($a=9$, $b=1$), the difference between HCIs with

LSM and FSM decline faster than HAIs (e.g., for the landscape it decreases from 0.76 to 0.03). Thus, the crop type primarily affects habitat configuration while the effects on habitat availability are relatively small. Overall, the crop-type parameters do not affect our general results qualitatively.

[Insert Fig. 5 here]

4.2.2 Characteristics of ES providers

We find that for the entire range of tested parameter scenarios for α and β , the HAIs (HCIs) for LSM are always higher (lower) than those for FSM (Fig. 6), thereby supporting our conclusion that farm-agents should maintain a greater area or composition of habitat under LSM, and keep it dispersed compared to FSM. As α increases from 2 to 5, the gap between HCIs resulting from LSM compared to FSM for peripheral farms (corner farms: farm (1, 2) and farm (2, 3)) becomes larger (See Fig. 6 (b)). Therefore, when habitat becomes more suitable for the service-providing organisms, even farms with few neighbors (e.g. those on the periphery) should disperse the habitat on their farms.

However, as β increases from 0.2 to 0.5 the differences between the resultant HAIs and HCIs with LSM and FSM diminish respectively (See Fig. 6 (c) and (d)); if the organisms are very sensitive to the distance parameter (i.e., have limited mobility for foraging), the landscape compositions and configurations of farms resulting from LSM and FSM converge. This is because the interdependencies among farmers become weaker as a consequence of lower mobility of the service-providing organisms. Consequently farmers should conserve less habitat and configure the habitat at roughly the midpoint of the continuum of agglomeration and dispersion (i.e. HCI=0.5). Overall, the characteristics of ES providers do not affect our general results qualitatively.

[Insert Fig. 6 here]

5. Discussion and conclusions

Farmers' land-use decisions are complex to understand and model even under the best of circumstances. This complexity increases manifold when the potential spatial interdependencies created by intermediate ecosystem services (ES) from mobile organisms are taken into account. This is because each farmer's optimal outcome is dependent on the land-use (habitat conservation) decisions of other farmers. Previously, holistic or landscape-scale management (LSM) has been shown to be superior to individual or farm-scale management (FSM) for managing such ES of benefit to agriculture (Cong et al., 2014b). The key contribution of this study is to investigate the composition and configuration of habitat at the farm and landscape scales that result from LSM compared to FSM, and to test the sensitivity of the results to different ecological assumptions as they might change in reality compared to modelled solutions.

To achieve this aim we provide measures or indices that make it possible to monitor landscapes over time and hence provide, in a first step, necessary information to improve the governance of agricultural landscapes. Inspired by the habitat agglomeration and dispersion dichotomy in the literature, we propose using the habitat availability index (HAI) and habitat configuration index (HCI) to construct rules that jointly describe any particular landscape in terms of the composition and configuration of habitat. This approach can be used to coordinate habitat management decisions among individual farmers.

5.1 Differences between farm-scale and landscape-scale management of ES

Our main conclusion is that, for a landscape with homogeneous soil quality where ES mediated by mobile organisms influence crop production, farmers should generally conserve a greater area of habitat (composition) and disperse it more evenly across their fields to achieve the LSM solution compared to the FSM. Such rules emerging from LSM are especially important to follow for farms with more neighbors because they need to provide higher levels of ES compared to the FSM solution. Regarding farms with few neighbors, the habitat configurations are closer to perfect agglomeration under both LSM and FSM. This result is logical since a farm with few neighbors has a small ES coverage (i.e., ES providers have the largest average distance to travel to any location in the landscape from peripheral farms). Therefore, their land-use decisions are more self-contained and independent of the LSM or FSM solution.

5.2 Uncertainties and limitations

Our conclusion holds for the range of model parameters that characterize plausible crop and organism characteristics. Naturally, as the crop becomes less dependent on ecosystem services, the interdependencies among farmers' land-use decisions become weaker, and in the extreme where the dependence approaches zero, the landscapes emerging from FSM and LSM will converge.

Similarly, as the mobility of the ES providers declines, the spatial interdependencies among farmers weaken. Consequently, it is sufficient for farmers to focus on their own land (i.e., FSM), as this will also generate efficient LSM. To maximize profits in this case, farmers should choose the habitat configuration that is roughly at the midpoint of the continuum of agglomeration and dispersion (i.e. HCI=0.5).

400 Finally, as habitat becomes more suitable for supporting greater abundances of ES
401 providers, even the configuration of habitat on farms with fewer neighbors becomes
402 important, i.e., they should also disperse their habitat rather than agglomerating it.

403 Our conclusion following from the LSM solution that habitat should be more dispersed
404 is similar to Brosi et al. (2008), although they do not consider the ES interdependencies
405 among farms. Our conclusion contrasts, however, with some prevailing views in the
406 conservation literature. In particular, most studies on the topical land sharing/sparing
407 debate suggest that the highest biodiversity benefits are achieved by agglomerating
408 habitat, i.e. land sparing (Balmford et al., 2012; Drechsler et al., 2010). Although this
409 configuration may benefit organisms of particular conservation concern, it might not be
410 optimal to enhance organisms providing ES that benefit agricultural yields (Mitchell et al.,
411 2015). Our research, focusing on synergies between yields and biodiversity in terms of
412 ES providing organisms, suggests that greater dispersion of habitat at small scales will
413 therefore benefit crop production via flows of ES (Mastrangelo et al., 2014; Mitchell et
414 al., 2015).

415 The minimum decision unit (scale) of our analysis is the field, which is appropriate for
416 farm management. However, it is straightforward to adapt our model to other choices of
417 scale. Considering the potential complexity of emerging landscapes, we did not expect to
418 find a perfect index reflecting the spatial configuration of habitat but rather suggest a
419 practical and intuitive set of indices that can capture central features of habitat
420 arrangement in reality. Although HCI (combined with HAI) cannot capture all the spatial
421 information characterizing the landscape (i.e., where to allocate habitat in space), they

still serve our research aim well by approximating the necessary spatial allocation of habitat to optimize ES in agriculture.

In addition, we acknowledge that our model is largely conceptual and that better specifications of the crop production function and the bio-physical processes for ecosystem services (see discussion in Cong et al. (2014b)) can be improved in future research utilizing advances in ecological research. However, the basic relationships based on distance decay of ecosystem service providers from semi-natural habitat will most likely hold, making our conclusions qualitatively robust. Finally, including additional objectives, such as integrating both ecosystem service and conservation perspectives to optimize landscape composition from a societal perspective may result in diverging regional solutions, because biodiversity conservation may demand solutions involving habitat agglomeration (or land sparing) and ES providers may instead demand habitat dispersion (small-scale land sharing) across production landscapes (Ekroos et al., 2014).

5.3 Implications with respect to real-world management

The landscape in our model is small and finite. In reality, the landscape in which individual farms are embedded could be large. Landscapes dominated by farmland (e.g., where non-agricultural land use is less than say 20%) can be viewed as farms with many neighbors in our model. In other landscapes where farms are embedded in a matrix of say forests and lakes (e.g. Persson et al. (2010)), the farms would more likely correspond to peripheral farms in our model because the interdependencies among farmers' land-use decisions are trivial.

Currently, a dominating agricultural landscape governance scheme in Europe is the EU's Single Payment Scheme (SPS) under the Common Agricultural Policy (CAP)

(Cong et al., 2012). An important criterion for collecting full payments is the area of greening measures (ecological focus areas and permanent grasslands), i.e. habitat availability. If a goal of greening is to improve local biodiversity for the benefit of ecosystem services (Plieninger et al., 2012), then the spatial configuration of the greening measures will be important for achieving this goal. However, additional information would be required if the payment is to be related to habitat configuration, which would give rise to additional transaction costs and hence reduce the likelihood of success in reality.

In this paper we identify a possible approach for improving management at the landscape scale, by identifying the need to consider habitat configuration across the landscape and within individual farms, and how to measure it. We suggest that governance of ecosystem services in agricultural landscapes could instead be based on the habitat indices generated in this paper, which are more practical and hence less costly than alternatives. However, this requires both an increased understanding of how ecosystem service providers benefit from semi-natural habitat of different quality and at what spatial scale they impact crops.

Finally, any real-world implementation needs to consider the multiple ecosystem services provided by agricultural landscapes, which may be differently affected by habitat composition and configuration, making solutions more complex than implied by our approach (Galler et al., 2015).

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Figures:

Fig. 1. Six farms with the same composition (availability) of habitat but with varying configurations (arrangement) of habitat and crops

Note: Metrics indicate the proportion of the field (plot) area used for cropping with the remainder comprising habitat

Fig. 2. Hypothetical landscape as represented in the model and identification of farms

Note: The landscape is represented as a $N \times N$ grid while individual farms are represented by $n \times n$ plots ($n < N$). We set $N = 33$ and $n = 5$. The shaded plots are private land (or fields) that can be used by farmers while the white plots are non-agricultural land.

Fig. 3. Landscapes resulting from: (a) farm-scale management (FSM) and (b) landscape-scale management (LSM).

Note: Metrics indicate the Habitat Availability Index (HAI) for chosen farms. We only show HAIs for farms with specific locations because symmetrically located farms (e.g. farm 1 and farm 25) have identical HAI.

Fig. 4. Potential ecosystem-service levels for each field in the landscape resulting from:
(a) FSM and (b) LSM

Fig. 5. The effect of crop type on habitat composition (HAI) and configuration (HCI) on farms at different locations in the landscape.

Note: a and b are the parameters of the crop yield function: a is the yield that is independent of ecosystem services and b is the potential additional yield that is dependent on the level of ecosystem services.

Fig. 6. The effect of the service-providing organism's type on habitat composition (HAI) and configuration (HCI) on farms at different locations in the landscape: (a) the effect of the scale parameter α on HAI; (b) the effect of α on HCI; (c) the effect of the distance parameter β on HAI; and (d) the effect of β on HCI.

Note: We present only a subset of all scenarios because the diagrams for the in-between scenarios show consistent trends.

Tables:

Table 1. Values of the landscape-scale composition (HAI) and configuration (HCI) indices for the illustrative landscapes (a)-(f) depicted in Fig. 1

Landscape	Index	Value	Landscape	Index	Value
(a)	HAI	0.5	(b)	HAI	0.5
	HCI	1		HCI	0
(c)	HAI	0.5	(d)	HAI	0.5
	HCI	0.64		HCI	0.04
(e)	HAI	0.5	(f)	HAI	0.5
	HCI	0.5		HCI	0.25

719 Table 2. Summary of the farm-scale composition (HAI) and configuration (HCI) indices
 720 for farms at different locations in the landscape

Farm location	Index	Landscape-scale	Farm-scale	Difference
		management (LSM)	management (FSM)	
Central	HAI	0.473	0.364	-0.109
	HCI	0.017	0.958	0.941
Farm (2, 3)	HAI	0.468	0.362	-0.106
	HCI	0.211	0.967	0.756
Farm (2, 2)	HAI	0.463	0.361	-0.102
	HCI	0.361	0.978	0.617
Farm (1, 3)	HAI	0.463	0.387	-0.076
	HCI	0.609	0.907	0.298
Farm (1, 2)	HAI	0.462	0.387	-0.075
	HCI	0.657	0.911	0.254
Corner	HAI	0.458	0.408	-0.05
	HCI	0.754	0.725	-0.029
Landscape	HAI	0.427	0.381	-0.046
	HCI	0.494	0.873	0.379

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