What land-use pattern emerges with landscape-scale management? An ecosystem-service perspective

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Paper prepared for presentation for the 142nd EAAE Seminar
Growing Success? Agriculture and rural development in an

enlarged EU

May 29-30, 2014
Corvinus University of Budapest

Budapest, Hungary

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Abstract

It is argued that landscape-scale management (LSM) of habitat is better than farm-scale management (FSM) when considering the externality of ecosystem services. Given this advantage, how to regulate individual farmers' land-use decisions to achieve the LSM solution is an issue of common concern both for farmers and policymakers. Specifically, it needs to be determined if there exists a dominant land-use pattern that characterizes the LSM solution compared to FSM solution. In addition to the area of habitat, we design a land-use pattern index (LPI) to characterize the configuration of habitat and project it onto the sharing-sparing continuum. We find that the LSM solution is characterized by less intensive farming, and configurations of habitat are closer to land sharing. However, as crop dependency on ecosystem-services declines, the land-use patterns with LSM and FSM converge and the configurations of habitat start to resemble to land sparing. In addition, when habitat quality improves the configurations of habitat on the border farms become important. Finally, the less mobile service-providers are, the more farmers should focus on land-use patterns on their own farms. Our indices of land-use patterns could be integrated into the cross-compliance of CAP (Common Agricultural Policy) to better manage ecosystem-service in the future.

Keywords

Agent-based model; landscape-scale management; ecosystem services; land sharing; land sparing; land-use pattern index; governance

1. Introduction

Landscape-scale management (LSM) implies that individual farmers' land-use decisions are coordinated from a holistic perspective to optimize aggregate output or achieve environmental targets at a larger scale than the field or farm. This can be seen in contrast to farm-scale management (FSM) where farmers are assumed to make their land-use decisions considering only their own benefits or environmental targets. LSM has shown its advantages in many respects compared with FSM including species conservation (Drechsler et al., 2010), pollution control (Haycock and Muscutt, 1995) and disaster prevention (Moreira et al., 2009). In a recent study considering the spatial interdependences among farmers' land-use decisions, Cong et al. (2014) constructed an agent-based model (ABM) to link farmers' income with on-farm habitat conservation via ecosystem services. They demonstrate that LSM of habitat is superior to FSM for both aggregate and individual farm profits when considering the externality of ecosystem services. They also show that farmers are trapped in a Prisoner's Dilemma that creates very strong incentives working against the LSM solution. This raises the issue of appropriate governance. Considering the high monitoring cost and the political reasons (e.g. in the market economy, farmers would like to have some flexibility to use their land), it is impossible to force farmers to mimic the landscape with LSM in reality. Therefore, both top-down governance and local governance could need manageable indicators to monitor and regulate farmers' land-use behaviors to better manage ecosystem services.

Given this background, the central aim of this paper is to study the land-use patterns of farmers with LSM systematically, and provide relevant indices that can be used to monitor and evaluate the land-use patterns deployed by individual farmers to promote efficient landscape governance in the future, i.e., achieving the LSM solution in practice.

The answer to this question could have important implications for the governance of ecosystem services. For example, European farmers are obligated to keep their land in good agricultural and environmental condition (cross-compliance) to obtain direct payments through the EU's Common Agricultural Policy (CAP), whose environmental benefits are although contested (Brady et al., 2009). In Switzerland farmers must manage 7% or more of their land as ecological compensation areas (ECAs). Similarly, in the ongoing CAP "Greening" reform it is proposed to make 30% of direct payments contingent on farmers reserving a fixed proportion (e.g., 3-7%) of their agricultural land as ecological focus areas, in particular, in order to safeguard and improve biodiversity (e.g., fallow, landscape features, terraces, buffer strips, afforested areas and agro-forestry areas, etc.) (EU, 2013). What relation an arbitrarily set habitat area has to ecological benefits and whether it should be implemented uniformly across all farms is still an open question (Davies and Hodge, 2006).

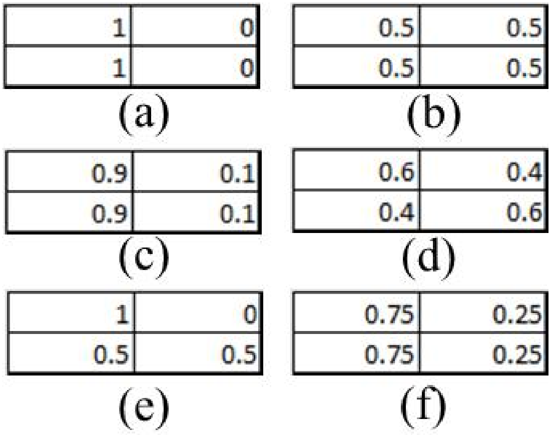
Further, not only the area but also the configuration of habitat affects the ecosystem service from a landscape (Kremen et al., 2007; Lonsdorf et al., 2009). However, in this respect most existing economic literature focuses on the conservation of biological assets per se, such as individual species (Drechsler et al., 2010), groups of species (Söderström et al., 2001) and ecosystems (Parkhurst and Shogren, 2007). From the perspective of conservation, the preferred land-use patterns with LSM should be connected habitats which are ecologically valuable for species populations and ecosystem-service providers (Steffan-Dewenter and Westphal, 2008).

By contrast, there is relatively less literature studying the synergies arise between habitat conservation and agricultural output via ecosystem services (Macfadyen et al., 2012). Ecosystem services provided by mobile organisms supported by source habitats, such as pollination (Klein et al., 2007) or biological control (Cardinale et al., 2003), are important for some crops' production and farmers' profits. However, farm-scale management of habitat may not generate the largest agricultural output for the entire landscape (Cong et al. 2014). From the perspective of ecosystem services, the preferred land-use patterns with LSM are to generate a landscape that can maximize agricultural output (e.g. crop yield). However, we lack the intuitive understanding of the configuration of this type of land-use patterns.

Therefore, we clarify the term of "land-use pattern" in our paper includes two aspects: (1) the area of habitat; (2) the configuration of habitat. Accordingly, we need a system of indices that can describe the land-use patterns chosen by individual farmers. To analyze the configuration of habitat we use the familiar land-sharing and land-sparing dichotomy as a conceptual construct (Fischer et al., 2008; Green et al., 2005). Land sharing integrates habitat conservation and agricultural production on the same land-unit. In contrast, land sparing implies separating land for habitat conservation from land for agricultural production. This simple categorization of configurations of habitat is however too simple for our purposes (e.g. the configuration of habitat in reality may be in between these two distinct configurations) and seemingly for studying the conservation issue (REF to critical paper, e.g., Johan et al??) which motivate our search for more accurate indicators and our study on the land-use patterns with LSM from the ecosystem-service perspective.

2. Indices Theory: indices of land-use patterns

Framing habitat conservation as having an either-or solution, such as land sharing or sparing debate, is very limiting because solutions in reality are likely to be more subtle (Lusiana et al., 2012) with important implications for economic efficiency: extremes are seldom optimal in economic decision-making. To illustrate the problem, consider the six hypothetical landscapes in the pedagogic example depicted in Fig. 1.



1	0
1	0

(a)

0.5	0.5
0.5	0.5

(b)

0.9	0.1
0.9	0.1

(c)

0.6	0.4
0.4	0.6

(d)

1	0
0.5	0.5

(e)

0.75	0.25
0.75	0.25

(f)

Fig. 1. Six landscapes with the same farming area

Each landscape (a) to (f) in Fig. 1 comprises four fields of identical size. The proportion of land farmed in each field is represented by a value and is interpreted as an index of farming intensity, I, where I=1 corresponds to farming on the total field and I=0 to no farming. The remaining area, 1-I, is assumed to function as habitat (but we make no assumption about how the habitat is distributed within the field). Following the definitions in Green et al. (2005), *perfect* land sparing at the farm-scale implies that the farmer chooses the maximum intensity on some fields, I=1 and spares other fields purely as habitat, I=0. Following this, we define *perfect* land sharing as the situation where intensity on a field is divided uniformly between conservation and farming, e.g., I= 0.5. According to these definitions landscape (a) is characterized by *perfect* land sparing and (b) by *perfect* land sharing.

To illustrate how the land sparing and sharing dichotomy effectively becomes a continuum, we make a small change in intensity to landscapes (a) and (b) to generate landscapes (c) and (d). We can now define landscape (c) to be closer to perfect land sparing and landscape (d) closer to perfect land sharing. However, some landscapes will be difficult to classify as being closer to perfect sparing or sharing, which we illustrate with landscapes (e) and (f). These are created from different combinations of landscapes (a) and (b). Landscape (e) mirrors the top-half of landscape (a) and the bottom-half of landscape (b); and landscape (f) is a linear combination of (a) and (b) such that each field in (f) = .5(a) + .5(b). For practical reasons, an index is clearly needed to locate any observed land-use pattern along the continuum from land sharing to sparing. We subsequently reviewed the literature on landscape pattern analysis and found that the main indices available are inadequate for our purposes.

To bridge this gap we propose three indices that can be used collectively to evaluate the land-use pattern generated at the farm and landscape scales: (i) Average farming intensity (AFI); (ii) Variance of farming intensity (VFI); and (iii) Land-use pattern index (LPI).

2.1 Average Farming Intensity index (AFI)

The first index we propose to describe the land-use pattern characterizing a particular landscape is the average farming intensity across all fields. A plethora of farming-intensity proxies have been used in the literature, typically output per ha (yield) or nitrogen input per ha, but also pesticide use, etc. Several of these proxies have been combined to indices to describe local management intensity (Herzog et al., 2006). Here we use the proportion of farmed area in a field as an index of farming intensity (Roschewitz et al., 2005). The area of habitat can be calculated using the product of total area and average farming intensity. It can be expected that a moderate increase in farming intensity will boost yield (Cassman, 1999). However, beyond a critical value any further increase in intensity will reduce the area of habitat consequently necessary ecosystem service provisioning.

2.2 Variance of Farming Intensity index (VFI)

The second index we propose to describe land-use pattern is the variance of farming intensity across fields. It is motivated because two landscapes with the same AFI can still have quite different configurations of habitat. Hence this index measures the variability of farming intensities across fields. The lower bound for VFI is zero, indicating uniform land use across fields (*perfect* land sharing). The upper bound of VFI should correspond to the largest possible difference (variation) in land use across the fields (*perfect* land sparing, recall landscape (a) in Fig. 1). Using VFI of *perfect* land sharing (zero) as the one endpoint and VFI of *perfect* land sparing as the other endpoint, we can map any landscape on the continuum of land sharing and sparing.

2.3 Land-Use Pattern index (LPI)

VFI is an absolute measure whose value is affected by the number of fields and AFI. To be comparable between landscapes, we need a relative measure. We define this relative measure as the land-use pattern index, LPI, calculated as the ratio of VFI of a real landscape to VFI in a perfect land-sparing landscape with the same amount of fields and AFI. Defining LPI in this way allows us to convert the continuum of land sharing and sparing ranging between 0 and 1, where LPI=0 stands for perfect land sharing and LPI=1 denotes perfect land sparing. VFI serves therefore as an intermediate variable and is not used directly in the ensuing analysis.

We now illustrate the utility of our three indices by calculating each indicator in Table 1 for the six hypothetical landscapes in Fig. 1. Based on these indices, we can see that landscape (f) (LPI=0.25) is closer to perfect land sharing (LPI=0) than landscape (e) (LPI=0.5). In summary, using the three indices above we can evaluate the land-use patterns within any landscape (e.g., on individual farms) and to compare different landscapes.

Table 1. Values of land-use pattern indices for landscapes in Fig. 1

Landscape	Index	Value	Landscape	Index	Value
(a)	AFI	0.5	(d)	AFI	0.5
	VFI	0.33		VFI	0.013
	LPI	1		LPI	0.04
(b)	AFI	0.5	(e)	AFI	0.5
	VFI	0		VFI	0.167
	LPI	0		LPI	0.5
(c)	AFI	0.5	(f)	AFI	0.5
	VFI	0.213		VFI	0.083
	LPI	0.64		LPI	0.25

3. Method: Agent-based and global optimization models

In this section, we first present an Agent-Based Model (ABM) to describe the FSM as a benchmark. Second, a global optimization model is employed to describe the LSM.

3.1 Farm-scale management

The ABM is developed and described in Cong et al. (2014) to simulate individual farmers' behavior without landscape-wide coordination (FSM). In the ABM the total landscape is represented as a $N \times N$ grid. Each farm is represented by $n \times n$ fields, where $n < N$, and indexed by its ID (i) and coordinate (v, w). Individual fields constitute the minimum decision unit for the farmers. The spatial configuration of habitat within a field is not considered, i.e. the land use within a field is homogeneous.

Fig. 2 illustrates a hypothetical landscape for this paper by setting $N = 33$ and $n = 5$. The shaded fields are private land that can be used by farmers while the white fields are public land.

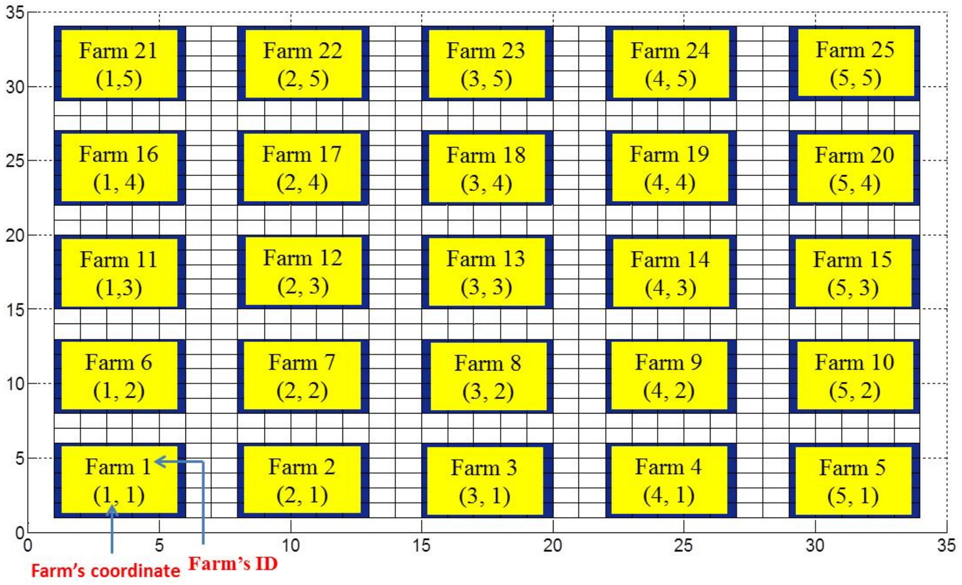


Fig. 2. Hypothetical landscape in the model and identification of farms

The ABM proceeds in annual time steps. In each year, first the ecosystem services across all the fields are calculated based on the current landscape, after which each farm-agent (farmer) calculates the profits from agricultural production on all of its fields, which is dependent on the ecosystem services. Finally each farm-agent optimizes the land use on each field (by allocating a proportion of farmed area on a field, while the remaining part can function as habitat for organisms providing ecosystem services), assuming that other farm-agents will keep their landscapes constant in the next year. Changes in habitat located on a particular farm could affect the level of ecosystem services benefiting its neighbors and hence their land-use decisions in the next year.

3.2 Landscape-scale management

We employed a global optimization model to determine the landscape-scale management solution. It is identical to the solution for a single owner of the landscape. The single owner optimizes the land use on all the fields of the landscape and maximizes the total profit which is affected by the spatial configuration of habitat via ecosystem services.

4. Results analysis

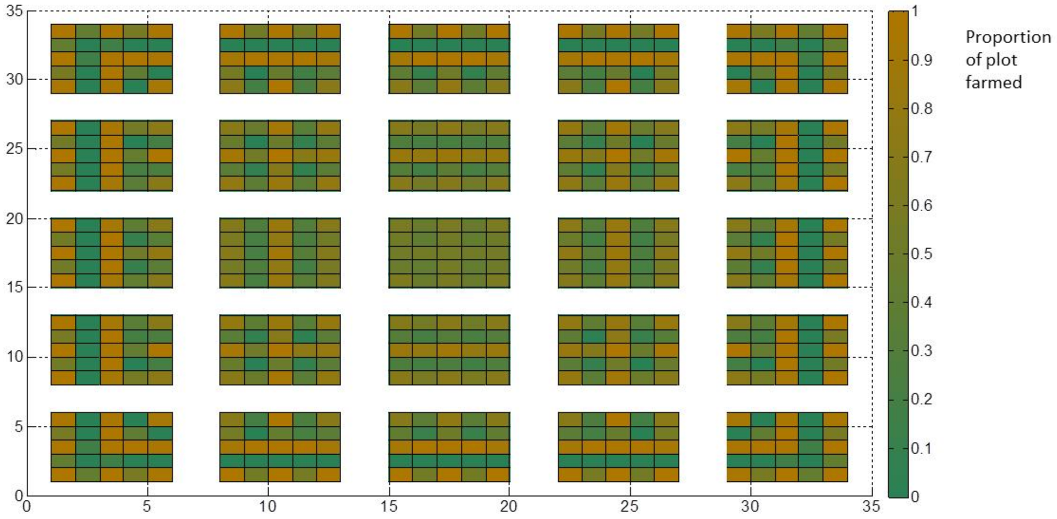
In this section, we first simulate and compare the land-use patterns emerging at the landscape and farm scales respectively in the baseline scenario (i.e., using plausible, or non-extreme, values of the main parameters of the model; see Table 1 in Cong et al. (2014)). We then explore the effects of three main uncertainties (the initial landscape, crop type and pollinator type) on the emergent land-use patterns.

4.1 Comparison of land-use patterns with LSM and FSM

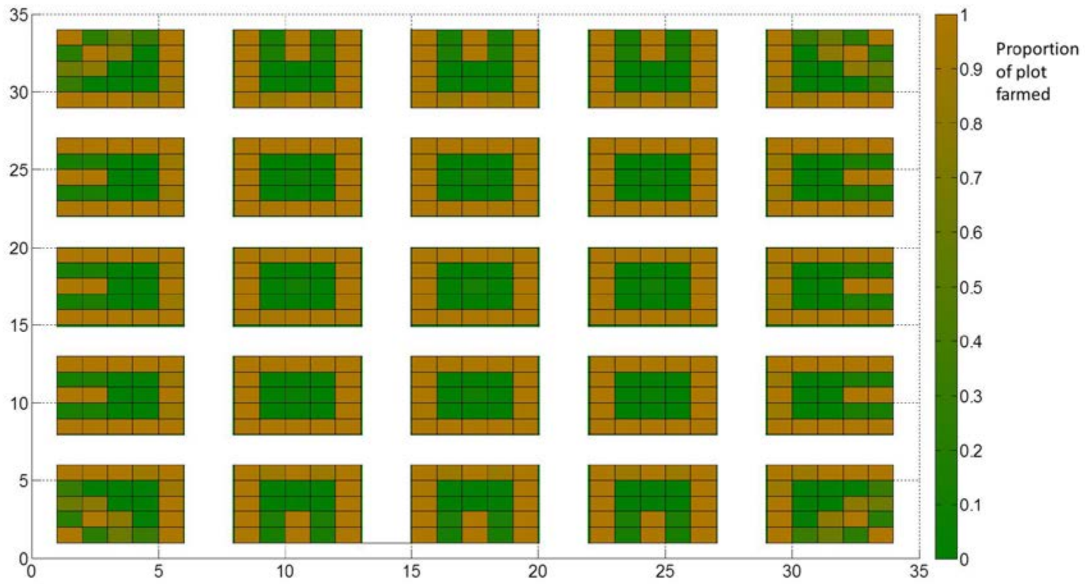
First we examine the emergent land-use patterns at the landscape scale subsequently the land-use patterns emerging on individual farms at different spatial locations.

4.1.1 Landscape-scale results

Under the baseline scenario, we found a large difference between land-use patterns emerging on individual farms with LSM compared to FSM (Fig. 3), which can be quantified with our indicators. Specifically, AFI with LSM (0.537) is smaller than it is with FSM (0.619).



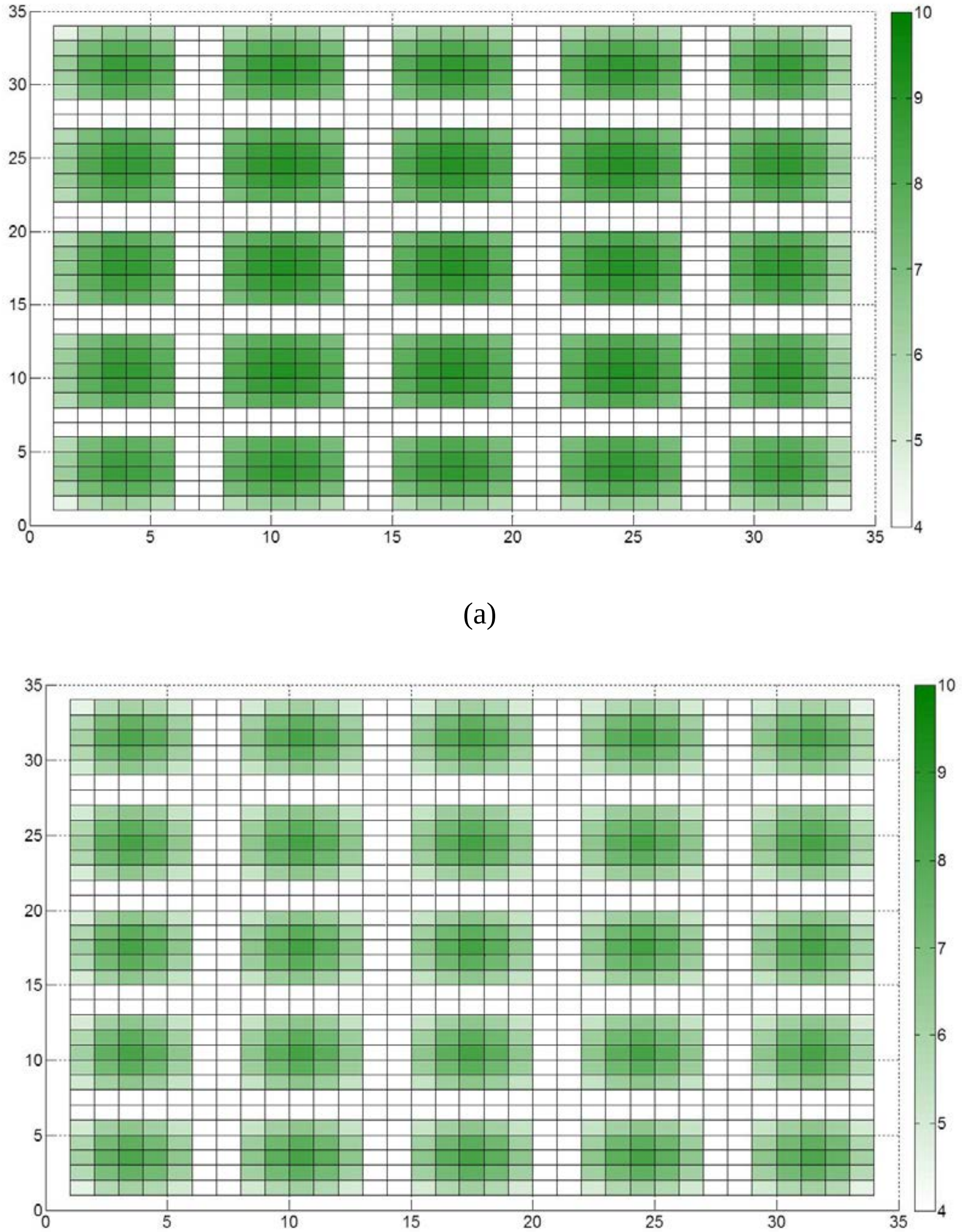
(a)



(b)

Fig. 3. Total landscapes (a. LSM, b. FSM)

The pattern that emerges for the landscape under the baseline scenario with LSM is close to perfect land sharing (LPI=0.498), while the landscape pattern with FSM is closer to perfect land sparing (LPI=0.88) because with FSM farmers maximize intensity without considering spatial interdependencies via coordination. However, with LSM the average ecosystem service level per field (7.68) and total profit (14407) is larger than for FSM (6.60, 13821) (Fig. 4) (The calculation method can be found in Cong et al. (2014)). In summary, with LSM farmers should choose less intensive farming and their associated configurations of habitat being closer to perfect land sharing compared to FSM.



(a)

(b)

Fig. 4. Levels of the ecosystem service on each field in the landscape (a) LSM and (b) FSM)

4.1.2 Farm-scale results

In this section, we evaluate the land-use patterns emerging on individual farms at different locations within the landscape. First, we study the central farm's and the corner farms' land-use patterns as two extremes. Then, we compare farms at other locations in the landscape.

Central farm (Farm (3, 3))

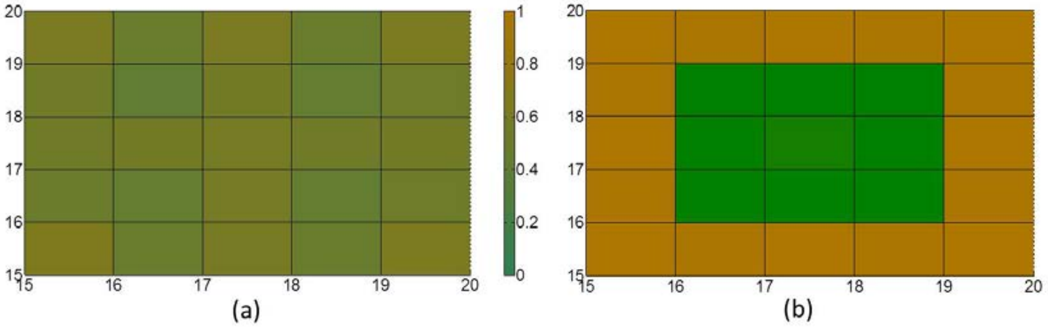


Fig. 5. Land-use patterns of central farms: (a) LSM and (b) FSM

From Fig. 5 a large visual difference can be seen between land-use patterns of central farms that emerge from LSM and FSM. With LSM the landscape of central farms is close to perfect land sharing (LPI=0.017 or close to 0) while with FSM it is close to perfect land sparing (LPI=0.958 or close to 1) (Table 2). Since service providing organisms have the least average distance to travel to any location in the landscape from the central farm this farm can be said to have the largest ecosystem service coverage. As a consequence, for this farm the land-sharing pattern could provide more ecosystem services to the collective profit than the land-sparing pattern. On the contrary, with FSM the central farm-agent only places the habitat inside the farm to maximize its own profit. In addition, for the central farm AFI with LSM (0.527) is still lower than it with FSM (0.636).

Corner farms (Farm (1, 1))

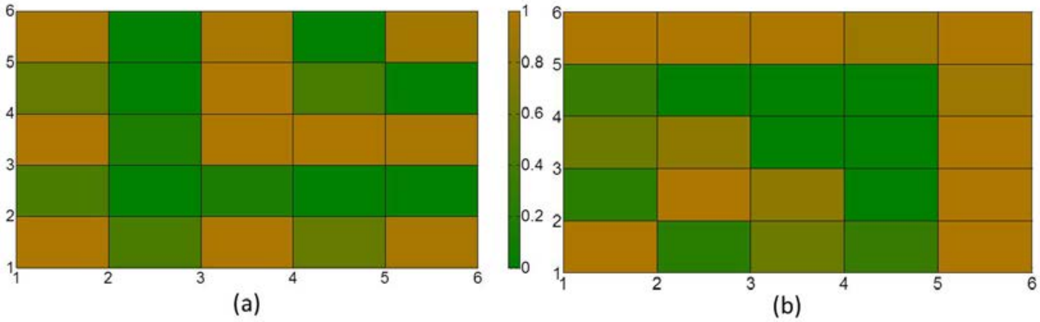


Fig. 6. Land-use patterns of corner farm: (a) LSM; (b) FSM

For the corner farm, it seems that the landscapes are closer to perfect land sparing both with LSM (LPI=0.754) and FSM (LPI=0.725) (Fig. 6). However, AFI with LSM (AFI= 0.542) is still lower than with FSM (AFI=0.592). This result is logical since a corner farm has the smallest ecosystem coverage (i.e., service providing organisms have the largest average distance to travel to any location in the landscape from the corner farm). The land-use decision is mainly self-contained, and independent of the LSM or FSM solution.

Other farms (Farm (1, 2), (2, 2), (1, 3), (2, 3))

For farms at other locations than the center or corners, we sort farms according to their distances from the center farm (Table 2). To summarize, AFIs with landscape-scale management are usually lower than with farm-scale management, implying that farming intensity should be lower generally when considering spatial interdependencies and land-use pattern closer to perfect land sharing compared to FSM. The difference between LPIs with LSM and FSM increases when the farm is closer to the center farm (the spatial interdependency increases, i.e., the positive effects flowing to other farms of creating habitat). In addition, while AFIs are quite similar the LPIs show large differences, which implies that AFI could be a poor index alone. Rather it is needed to complement LPI to improve landscape management (since the calculation of LPI needs to keep landscapes with the same AFI; see section 2.3).

Table 2. Summary of farm-agents' land-use patterns at different locations

Farm location	Index	Landscape-scale management	Farm-scale management	Difference
Central	AFI	0.527	0.636	0.109
	VFI	0.004	0.228	0.224
	LPI	0.017	0.958	0.941
Farm (2, 3)	AFI	0.532	0.638	0.106
	VFI	0.053	0.231	0.178
	LPI	0.211	0.967	0.756
Farm (2, 2)	AFI	0.537	0.639	0.102
	VFI	0.09	0.234	0.144
	LPI	0.361	0.978	0.617
Farm (1, 3)	AFI	0.537	0.613	0.076
	VFI	0.152	0.216	0.064
	LPI	0.609	0.907	0.298
Farm (1, 2)	AFI	0.538	0.613	0.075
	VFI	0.163	0.217	0.054
	LPI	0.657	0.911	0.254
Corner	AFI	0.542	0.592	0.05
	VFI	0.187	0.178	-0.009
	LPI	0.754	0.725	-0.029

Landscape	AFI	0.573	0.619	0.046
	VFI	0.124	0.208	0.084
	LPI	0.494	0.873	0.379

4.2 Implications of initial landscape, crop and ecosystem service characteristics

In this section, we examine the effects of three main uncertainties (initial landscape, crop and ecosystem service characteristics) on the modeled land-use patterns and evaluate how the emergent land-use patterns respond to changes in the parameters of the model.

4.2.1 Initial landscape

The baseline landscapes depicted in section 3.1 and discussed in section 4.1 are initialized randomly. In Table 3 we present the initial landscape settings from six uniformly distributed landscapes, which we compare with the baseline results. These landscapes are represented by scenarios 1.1-1.6, where scenario 1.1 initializes landscape entirely consisting of habitat, scenario 1.2 with the proportion of habitat on each field being 0.8 initially, and so on until the initial proportion of habitat becomes 0 in scenario 1.6). We found that the initial landscape setting had no effects on the final land-use patterns emerging with either LSM or FSM; hence no path-dependence exists. This is reasonable because we assume that the farm-agents have full flexibility to change their land use over time (e.g., potential costs of reserving habitat, other than reduced crop yield, are not considered in the model).

Table 3. Alternative landscape settings

Scenario	Ref	1.1	1.2	1.3	1.4	1.5	1.6
Initial landscape setting (Proportion of field farmed)	U(0,1)	0	0.2	0.4	0.6	0.8	1

4.2.2 Crop characteristic

A crop must have some dependence on ecosystem services to be relevant: the implications of land-use decisions based on zero dependence are trivial. In the baseline model 50% of maximum yield is assumed to be independent of pollination (i.e. in the yield function, $y = a + b \times e$, *a* is set to 5 to represent the yield which is independent of ecosystem services, and *b* is set to 5 to represent the yield which is dependent on ecosystem services; see equation (4) in Cong et al. (2014) for details). In the following we consider the implication of crops having different degrees of dependency on ecosystem services. The two extreme situations are defined as yield being fully dependent on pollination (a=0, b=10) and yield having minimal dependence on pollination (a=9, b=1), after which we analyze several linear combinations of these extremes (Table 4).

Table 4. Crop dependence on ecosystem services as represented by different combinations of the parameters *a* and *b*

Scenario		Ref	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
Combination	a	5	0	1	2	3	4	6	7	8	9
	b	5	10	9	8	7	6	4	3	2	1

We find that for all relevant crop-type parameterizations, the AFIs and LPIs with LSM are always lower than those with FSM (Fig. 7), which supports our conclusion that the farm-agents with LSM should choose less intensive farming and the land-use pattern closer to perfect land sharing compared with those for FSM. However, we find that as yield dependence on pollination falls from fully dependent (Scenario 2.1) to minimally dependent (Scenario 2.9), the difference between LPIs with LSM and FSM become smaller (e.g., for the landscape it decreases from 0.76 to 0.03). Thus the crop type mainly affects LPIs while the effects on AFIs are relatively small. Overall the crop-type parameters do not affect our general results.

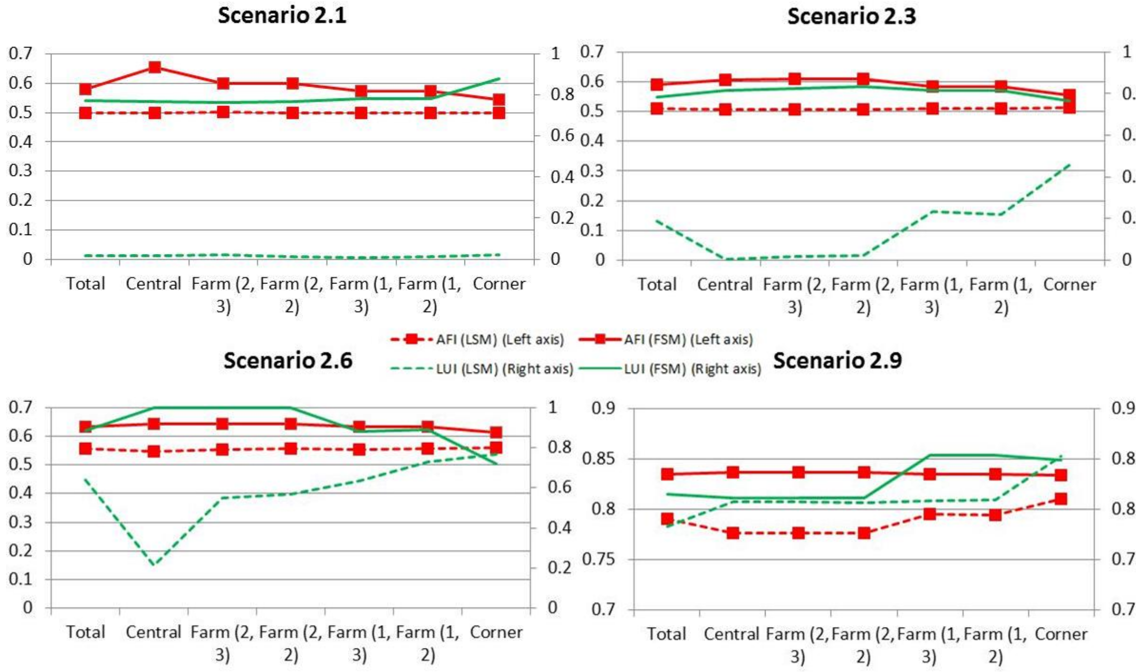


Fig. 7. The effects of crop type on land-use patterns of total landscape and farmers with different locations. Due to the limited space, we only present the results for four scenarios. However, the diagrams for in-between scenarios show consistent trends.

4.2.3 Ecosystem characteristic

In this section, we examine the effects of the scale and distance parameters of the ecosystem service production function (See equation (2) of Cong et al.) on the modeled land-use patterns. 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). Different mobile organisms will also likely 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). Translating these two aspects to our model, the service provided by the organism is dependent on the scale parameter α, and the distance parameter β. The sensitivity of the results to the parameters of the ecosystem service production function is tested and the range of parameter values tested is shown in Table 5. Note when we test the influence of one parameter on outcomes, we keep the other parameter constant.

Table 5. Alternative combinations of α and β

Scenario	Ref	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
α	1	2	3	4	5	1	1	1	1
β	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.5

We find that for the entire range of tested scenarios for α and β, the AFIs and LPIs with LSM are always lower than those with FSM (Fig. 8), which supports our conclusion, that LSM implies that farm-agents should use less intensive farming than emerges with FSM and a land-use pattern that is closer to perfect land sharing. As α increases from 2 to 5, the gap between LPIs with LSM and FSM for farmers on the boundary (corner farms (1, 2) and (2, 3)) becomes larger. Therefore, when habitat becomes more suitable for the service providing organisms, even farmers on the boundary should pay more attention to the land-use pattern on their farms (i.e. to choose land sharing).

However, as β increases from 0.2 to 0.5 the differences between both AFIs and LPIs with LSM and FSM become smaller, which means when the organisms are very sensitive to the forage distance (i.e., have limited mobility) the land-use decisions of farmers with LSM and FSM converge. This is because the interdependence among farmers becomes weaker. Consequently farmers should use more intensive farming and the land-use pattern which is roughly the midpoint of the continuum of land sharing and sparing (i.e. LPI=0.5). Overall the characteristic of service-providing organisms does not affect our general results.

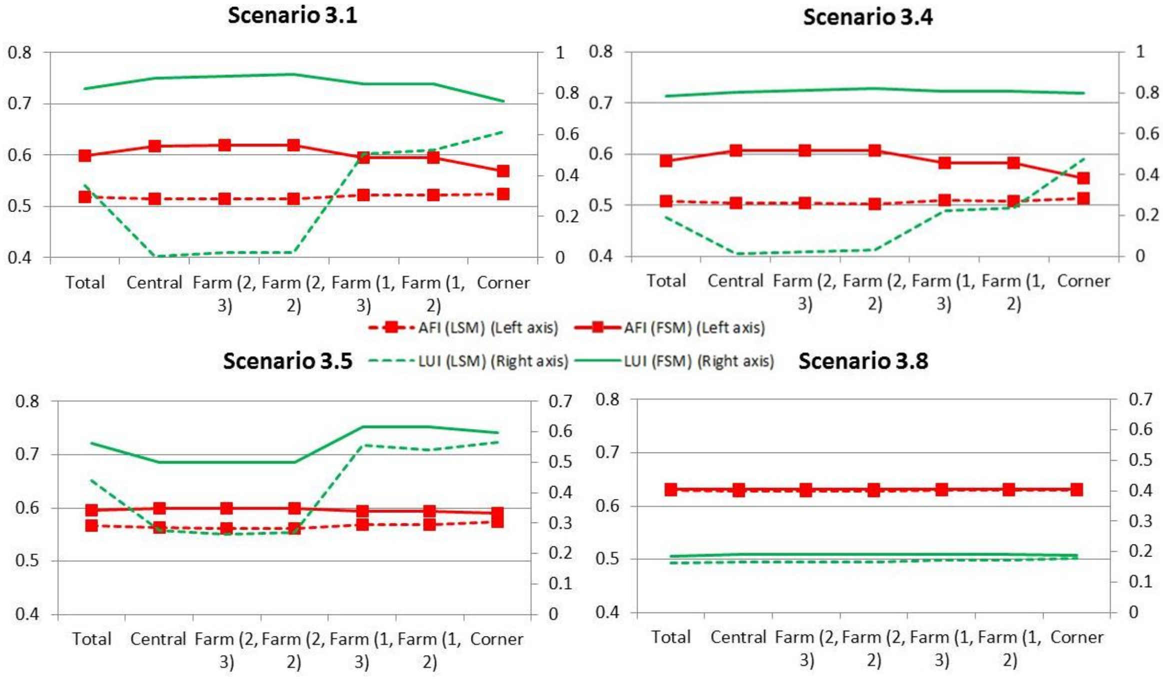


Fig. 8. The effects of the service providing organism's type on land-use pattern on the landscape and farm at different locations. Due to the limited space, we only present

results for four scenarios. However, the diagrams for the in-between scenarios show consistent trends.

5. Conclusions and discussion

The land-use behavior of farmers may be one of the most complicated economic behaviors to understand and model when considering ecosystem services: not only because it is multi-dimensional (farmers use their land to produce multiple outputs and in parallel can choose different combinations of manufactured and natural inputs to produce these), but also because of potential spatial interdependencies: each farmer's outcome will depend on the land-use decisions made by other farmers. Previously, landscape-scale management (LSM) has been shown to be superior to farm-scale management (FSM) (Cong et al. 2014) for optimizing ecosystem services of benefit to agriculture. The key question we answer here is "If the LSM solution is better, how can we regulate individual farmers to achieve it?" Considering the high monitoring cost and social acceptance in reality, forcing the farmers to mimic the landscape with LSM is impractical. Instead, we want to jump from the complex landscape to investigate the core law of land-use patterns with LSM. The core law should be manageable and informative.

The first difficulty in this respect and a contribution of this paper, is how to measure the pattern of land-use behavior with LSM. Considering the spatial complexity, we did not expect to find a perfect index but rather suggest a practical set of indices that can be used to evaluate, at least partly, land-use patterns observed in reality. These indices would make it possible to monitor land-use patterns over time and hence provide, in a first step, the information necessary to improve governance of agricultural landscapes. Inspired by the land sharing and land sparing dichotomy, we designed the land-use pattern index (LPI) to map any landscape along the continuum of land-use patterns existing between the extremes of perfect land sharing and land sparing. Although the LPI cannot capture all the information characterizing the spatial configuration of habitat, it still reflects the spatial complexity to a large extent, and makes it possible to distinguish between and rank emergent patterns.

Our main conclusion is that for a landscape with homogeneous soil quality and its crop production is influenced by ecosystem services, farmers should, generally, choose less intensive farming and a land-use pattern that is closer to perfect land sharing than sparing to achieve the LSM solution. This land-use pattern is especially important for central farms which have the most neighbors, i.e. the greater the spatial interdependencies of a farm with other farms, the more the land-use pattern emerging from FSM will diverge from the desirable pattern of LSM. This conclusion holds for a range of model parameters that characterize plausible crop and organism characteristics. As the crop becomes less dependent on the ecosystem service, the interdependencies among farmers' land-use decisions become weaker and as the dependence approaches zero the land-use patterns emerging from FSM and LSM converge, as would be expected. Under such conditions, farmers could choose a relatively high farming intensity and the land-use pattern closer to perfect land sparing.

As the mobility of the service-providing organisms declines, the spatial interdependencies among farmers, naturally, weakens. Consequently, it is sufficient for farmers to focus on the land-use pattern on their own land (i.e., FSM), as this will also generate LSM. To maximize profits in this case, farmers should then choose the land-use pattern which is roughly at the midpoint of the continuum of land sharing and sparing (i.e. LPI=0.5).

Finally as the habitat becomes more suitable for supporting greater abundances of service providing organisms , even the configuration of habitat on boarder (i.e., more isolated) farms becomes important, i.e., farmers on the boundary should also choose the land-use pattern that is closer to perfect land sharing.

In the conceptual, homogeneous landscape we study, we find that in general the land-use pattern emerging with LSM is closer to perfect land sharing compared to FSM, which contradicts recommendations based on trade-off analyses between yields and biodiversity (Fischer et al., 2008; Gabriel et al., 2013; Hodgson et al., 2010). Our conclusion that with landscape-scale management of ecosystem services the land-use patterns should be closer to land sharing is partly supported by Brosi et al. (2008)'s study. Our contributions could be (1) we designed the indices of land-use patterns; and (2) we compare land-use patterns of LSM and FSM while they compare the land-use patterns from the perspectives of conservation and provision of ecosystem services.

The minimum decision unit of our analysis is the field, and each farm consists of 25 contiguous fields. There are two reasons for choosing this scale (i.e. field) as the minimum decision unit. First, if we divide the landscape into infinitesimally small fields (e.g., 1 square centimeter), it would be very difficult if not infeasible to find a solution given our computing capacity; and second, in practice farmers need to weigh the costs of management at finer scales against the potential benefits and convenience, therefore they will usually apply similar farming practices within predefined management units of land (i.e., a field). In reality how to decide the suitable size of a field is a problem that farmers must resolve. On the one hand, if the size is too small it will increase the costs of farming and the complexity of decision-making; on the other hand, if the size is too large the spatial configuration of habitat within one field will matter. In our illustrative case of pollination, the typical size of a field is 3 ha, which is certainly a relevant size for arable farming.

Consequently, the spatial planning of land use by farmers can be thought of in terms of three steps: (1) decide the total area to be farmed; (2) divide the farmed area into parts according to the number of fields; and (3) allocate to the fields in space. Our land-use indices match steps (1) and (2). Furthermore, if the parts to be farmed are identical, step (3) makes no sense (i.e., it doesn't matter where you place them). If we recall the landscapes generated with LSM and FSM respectively (Fig. 3), we can discern a clear difference between the central farmers' land-use patterns (e.g. the central field with LSM is almost homogeneous with a farming intensity of 0.53). For an infinitely large landscape, the central farmers in our landscape can be conceived as characterizing the vast majority of farms as internal farms rather than boarder farms. Our aim is to urge farmers to act according to the optimal land-use pattern defined by LSM. For most farmers (central farmers), it means using a uniform farming intensity across their fields. Therefore, we argue that although our indices cannot capture the full spatial information of land-use pattern they can still serve our research aim well.

Although our model links habitat conservation with economic output via ecosystem services, there are also some limitations in the model per se, particularly in regard to the ecology of service providing organisms (see discussion in Cong et al. (2014)), which should be improved in the future utilizing advances in ecological research. The direct application of this paper is to add the subsidy to the profit calculation - equation (6) in Cong et al. (2014) - with the condition that the land-use pattern meets the conclusion we obtain in this paper to examine whether these could be implemented as general environmental regulations to achieve efficient landscape-scale management. If it works, it would be a strong evidence for the effectiveness of our indices and conclusions (i.e. generally land-sharing patterns are preferable to management of ecosystem service at the landscape scale) of this paper.

Currently predominating agricultural governances may be too simple for managing real landscapes when considering ecosystem services. In this paper we hope that we identify a possible approach for improving management at the landscape scale. We suggest, that based on the method and our indices introduced in this paper, government agencies could have a better way to regulate land-use patterns in practice.

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