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Analysis

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

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ABSTRACT

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

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, 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

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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; Tscharntke 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).

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" habitats 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.

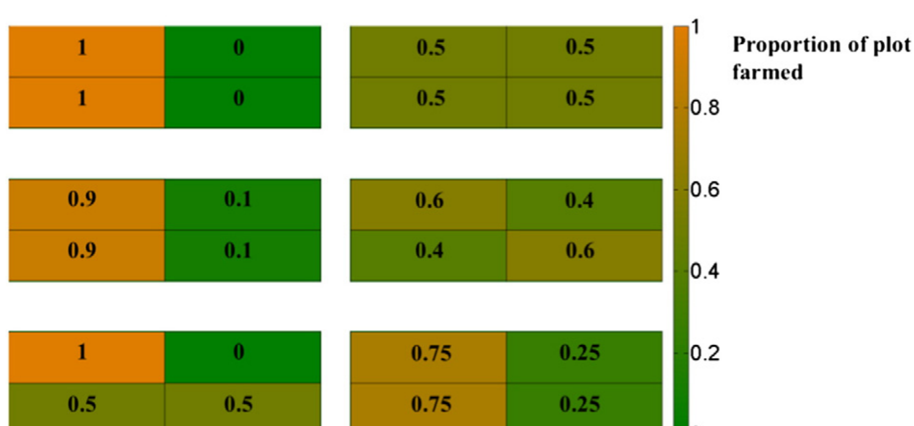

Fig. 1. Six farms with the same composition (availability) of habitat but with varying configurations (arrangement) of habitat and crops. Note: Metrics indicate the proportion of the field (plot) area used for cropping with the remainder comprising habitat