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Nonlinearities in biodiversity incentive schemes: A study using an integrated agent-based and metacommunity model☆

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A B S T R A C T

We report results from over 20,000 runs of a coupled agent-based model of land use change and species metacommunity model. We explored the effect of increasing government incentive to improve biodiversity, in the context of other influences on land manager decision-making: aspirations, input costs, and price variability. The experiments test the four kinds of policy varying along two dimensions: activity-versus-outcome-based incentive, and individual-versus-collective incentive. The results from the experiments using boundedly rational agents, and comparison with profit-maximisation reveal thresholds in incentive schemes, where a sharp increase in environmental benefit occurs for a small increase in incentive. Further, the context affects the level of incentive at which turning points occur, and the degree of effect. Variability in outcome can also change with incentive and context, and some evidence suggests that environmental benefits are not always monotone increasing functions of incentives. Intuitively, if the incentive signal is large enough, land managers will farm the subsidy; and if the subsidy does not exactly match desired landscape outcomes, deterioration in environmental benefits may occur for higher incentives. Our results, whilst they suggest that outcome-based incentives may be more robust than activity-based, also highlight the importance of context in determining the success of agri-environmental incentive schemes. As such, they lend theoretical support to schemes, such as the Scottish Rural Development Programme, that include a localised component.

"the matter promises to be even more complex and mysterious than was originally supposed"

(Sir Arthur Conan-Doyle, *The Sign of the Four*)

1. Introduction

The Convention on Biological Diversity (Article 11) requires the subscribing countries to "adopt economically and socially sound measures that act as incentives for the conservation and sustainable use of components of biological diversity". Intensive agriculture is a major source of biodiversity loss, due to habitat destruction and loss of heterogeneity (Meehan et al., 2010; Kwaiser and Hendrix, 2008; Benton et al., 2003; Hald, 1999), and therefore an excellent candidate for policy intervention. Besides its important intrinsic value, biodiversity matters in agro-ecosystems because it can influence the long term sustainable productivity (Carvalheiro et al., 2011; Tilman et al., 2002; Naeem et al., 1995; Tilman and Downing, 1994), and hence system resilience, especially in view of increasingly costly inputs ultimately derived from oil. The Scottish Government adopted the biodiversity 2010 agenda of reducing biodiversity loss from agriculture.

In designing interventions, many governments favour a mix of market-based approaches and regulatory policy measures. Market-based approaches, according to economic theory, are more cost-effective, allow a flexible response to price signals, and avoid biodiversity being seen as a liability rather than an opportunity. Under this ideology, conservation incentives to land managers may be offered as voluntary measures aimed at correcting market failures causing the loss of species and ecosystem services. The removal of perverse (from the perspective of biodiversity conservation) incentives leading to over-intensification, has also been advocated as a policy measure (see, for example, Polasky et al., 1997). However, price volatility has the potential to compound the impact of intensification on biodiversity. Such volatility is a feature of liberalised agricultural markets with important effects on farmers' income, and as a consequence, on biodiversity levels (as we will show). Careful design of incentives based on an understanding of the underlying biological system is therefore crucial for policy success in agricultural socio-ecosystems.

☆ Thematic Issue on Spatial Agent-Based Models for Socio-Ecological Systems.

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Cost-effectiveness is an important metric of policy evaluation. This can be interpreted in two ways with different consequences for evaluation. Firstly, a set of policy measures can be considered more cost-effective than others, if the total cost needed to achieve a policy goal is lower than for other measures. This interpretation is useful when there is a specific conservation objective, such as the survival of an endangered species. The second interpretation is concerned with overall conservation output. In this case a set of policy measures is more cost-effective than others if it results in higher overall biodiversity for a given cost. This point of view is useful when policy makers want to maximise the conservation output for a given available budget. In this study our focus is on overall biodiversity, measured by species richness at the landscape scale.

We have developed FEARLUS–SPOMM (Gimona et al., 2011; Gimona and Polhill, 2011) to explore biodiversity incentive schemes, by coupling FEARLUS (Polhill et al., 2001; Gotts et al., 2003; more recent versions described in Polhill et al., 2008; Gotts and Polhill, 2009; Polhill et al., 2010b), an agent-based model of agricultural land use change, with an enhanced version of Moilanen's (1999, 2004) Stochastic Patch Occupancy Model. Moilanen's (1999, 2004) model is a metapopulation model, simulating the occupancy of a single species in a space of connected patches (Levins, 1968), We have enhanced this model to simulate multiple species and interactions among them, making SPOMM a metacommunity model (Gilpin and Hanski, 1991; the extra '*M*' in SPO*M*M stands for 'Metacommunity'). In previous work (Gimona and Polhill, 2011), we explored the robustness of biodiversity policy and agri-environmental incentives across several scenarios of land manager, government policy and environmental attributes using a small sample of values for the incentive amount. These results suggested that it might be interesting to explore the effect of more gradually increasing the incentive, with a view to examining the relationship between incentive amount and species richness in more detail. We therefore chose a subset of the scenarios in Gimona and Polhill (2011) with which to increase the sample size of the incentive amount in this paper. We show here some selected results from this exploration, which amounted to over 20,000 runs of the coupled models, with a view to revealing more about the potential relationships between incentives and species richness, highlighting some of the sensitivities of biodiversity to farmer agent attributes, incentive scheme design, and other drivers of farmer behaviour.

In agro-ecosystems biodiversity is influenced by local management and by the landscape structure, which is a product of the decisions of individual land managers. Agent-based modelling is a natural tool to model the human portion of such systems, and is particularly well suited to studying coupled human–natural systems (Hare and Deadman, 2004; Boulanger and Bréchet, 2005), because it allows an intuitive representation of the environment and the embedding of agents within it. However, such couplings are not necessarily straightforward. Matthews et al. (2005) summarise various challenges in coupling social and environmental models, noting the stress many authors, reflecting on experiences in the area, place on a consistent integrated ontology in the coupled whole. In FEARLUS–SPOMM, some of these issues have been addressed because FEARLUS and SPOMM operate at compatible levels of abstraction and spatio-temporal scales. SPOMM was also specifically designed to be coupled with FEARLUS, and the process involved the developer of the latter.

The style of modelling in FEARLUS has been described by Boero and Squazzoni (2005) as a 'typification': the model constitutes a theoretical construct "intended to investigate some properties that apply to a wide range of empirical phenomena that share some common features" (para 3.8). As such, it is contrasted with 'theoretical abstractions' (Boero and Squazzoni cite work on the prisoner's dilemma as an example (Axelrod, 1997; Axelrod et al., 2002)) and 'case-based models', designed to be fitted to a particular time and place and provide an explanation of some of the phenomena observed there. Dean et al.'s (2000) work on the Anasazi is one of the examples given. As another example of a typification, Boero and Squazzoni (2005) cite their own work on industrial districts (Squazzoni and Boero, 2002; Boero et al., 2004). Typifications tend to make use of qualitative information, theory and second-order data (e.g. stylised facts) in exploring a class of phenomena, as opposed to case-based models, which will require significant amounts of quantitative data to fit to a specific instance of such a class. The version of FEARLUS used here is based on qualitative research with farmers and key informants in northeast Scotland, key assumptions in the model being checked with interviewees (Polhill et al., 2010b). Similar arguments would apply to the SPOMM, which may also be deemed a typification in the domain of ecology, and hence to FEARLUS–SPOMM. Typifications are useful for exploring questions 'in principle' about the relationships among phenomena in a class of systems.

One of the earliest agent-based models of a coupled human–natural system is Lansing and Kremer's (1994) work on Balinese water temples. This model was validated on empirical data, and was successfully used to persuade policy-makers of the merits of the water temple system for managing pests and irrigation. More recent work includes Guzy et al. (2008), who use a spatially-explicit agent-based model to assess the impact of urban expansion into farmlands and forests under various land use policy scenarios, and Brady et al.'s (2012) empirical model of the effects on ecosystem services of reforms of the European Union's Common Agricultural Policy on marginal agricultural regions in Sweden. Scenario analysis is a popular way to use agent-based models of coupled human–natural systems; Lempert (2002) recommend the use of ensembles of scenarios to model possible futures to explore robustness, resilience and stability of alternative policies. Participatory modelling techniques are often used in the study of such systems to capture local knowledge and engage with key stakeholders and decision-makers (Voinov and Bousquet, 2010). Recent examples include Anselme et al.'s (2010) work on shrub encroachment impacts on biodiversity conservation in the French Alps, and Lagabrielle et al.'s (2010) participatory process to integrate ecological knowledge into spatial planning on Réunion Island. A scenario approach is used here because FEARLUS–SPOMM is a typification: comparing results from as wide a range of scenarios as feasible with the computational power available is one way to avoid over-reliance on a specific instance of the model that has not been fitted to a particular case study in the real world.

Parker et al. (2008) outline various ways in which human and environmental systems can be coupled within a model, which can be divided into open-loop and closed-loop categories. In open-loop categories, submodels are executed sequentially, with no feedback from one submodel to another. Closed-loop categories feature such feedbacks, and although more challenging to implement, are clearly better fitted to capturing the complexity of the co-evolving landscape. An et al.'s (2005) IMSHED model, for example, is able to explore responses of households and panda populations to different conservation scenarios; they argue that the inclusion of feedbacks in their model leads to more representative results. Manson's (2005) SYPRIA model also features closed-loop human–environment interactions. FEARLUS–SPOMM currently features closed-loop interactions when outcome- rather than activity-based biodiversity incentive schemes are used.

2. Method

Here we give an overview of FEARLUS–SPOMM using Grimm et al.'s (2006; 2010) ODD (Overview, Design concepts and Details) model description protocol, with a slight modification to introduce the scenarios used as part of the overview. In