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Exploring robustness of biodiversity policy with a coupled metacommunity and agent-based model

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This article reports results using a coupled agent-based model of land-use change and species metacommunity model. We used the coupled model to explore various mechanisms for giving incentives to farmers to manage for better biodiversity, including activity-based, outcome-based and clustered incentives, in which farmers potentially benefit from the activities of neighbours. In so doing, we demonstrate the benefit of using such models to explore 'in principle' questions pertaining to biodiversity policy. The results show that the effectiveness of government policies in protecting target vulnerable species can depend on a number of other factors influencing agricultural land-use decision-making, such as input costs, market variability and farmer aspiration levels. They also show that the way these factors influence species persistence can vary from species to species.

Keywords: agent-based modelling; metacommunity modelling; biodiversity; environmental agricultural incentives; coupled human–nature systems

1. Introduction

In most developed countries intensive agriculture has become the dominant land use, landscapes in high-intensity areas have been greatly simplified in structure and most habitats have been replaced by rather uniform arable fields or improved grassland (e.g. Robinson and Sutherland 2002; Kleijn and Sutherland 2003). Increased mechanisation has also led to the removal of linear feature, such as hedges, and the drainage of wetlands. As a consequence, habitats have been lost, or their quality degraded, and functional landscape connectivity compromised, in large areas, due to fragmentation (e.g. Fischer and Lindenmayer 2007). At the landscape scale, the decline of farmland species such as birds (Gregory, Noble, and Custance 2004), bees (Kwaiser and Hendrix 2008) and plants (Hald 1999) is due to the combined effect of this marked loss of functional heterogeneity and of more intensive land management practices (e.g. Benton, Vickery, and Wilson 2003).

Between-field landscape heterogeneity has been shown to be important, for example for butterflies (e.g. Weibull, Bengtsson, and Nohlgren 2000), spiders (e.g. Sunderland and Samu 2000) and birds (e.g. Galbraith 2000). Also in-field heterogeneity, favoured by lower intensity of agricultural practices, is known to be beneficial, for example, to plants (weeds), birds and insects (Thomas, Singer, and Boughton 1996; Benton Bryant, Cole, and Crick 2002; Morris, Bradbury, and Wilson 2002).

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Given the extent of the areas involved, reserve-based conservation needs to be integrated with conservation of the 'wider landscape'. From a theoretical point of view, there are two principal reasons why a reserve-based conservation paradigm might not be sufficient to save a large number of species from extinction. First, a static conservation paradigm, based on saving some important areas might, by itself, be ineffective in the long run due to the dynamic nature of landscapes. Second, there is a risk that such areas might not be able to accommodate viable populations, because habitat area is an important functional property of landscapes, to which species richness is related (e.g. Rosenzweig 2003). The conservation status of many species could be improved by targeting conservation measures to agricultural landscapes, recognising their highly dynamic state. In Europe, where low-intensity systems have existed for centuries, this would entail restoring a landscape mosaic in which land-cover and land-use practices interact in the provision of suitable habitat to species adapted to low-intensity agro-ecosystems, where landscape elements such as uncropped field margins, hedges and fallow areas provide habitat for many species (Benton *et al.* 2003). Agro-biodiversity in North America would also be likely to benefit from such measures: 380 of the 663 plant and animal species considered threatened in the United States, are listed for reasons linked to agriculture (USDA/ERS 1997), and similar benefits would be derived by most OECD countries (Warren, Lawson, and Belcher 2008).

Conservation requirements, however, need to be reconciled with the fact that land managers' decisions are mainly financially oriented, rather than biodiversity-oriented. This can be addressed through public policy, the fundamental purpose of which is to resolve conflicts between interests of individuals and society's goals (Ikerd 2006). Governments often try to incentivise the provision of biodiversity and other ecosystem services through payment schemes aimed at enhancing the sustainability of agro-ecosystems. This, however, presents a particularly complex policy situation, arising out of the combination of several interlocking problems. The 'supply' of environmental goods is dependent on the voluntary decisions of many individual agents acting with varied objectives and with different starting conditions, with the quality of environmental goods determined by ecological mechanisms that are imperfectly understood, using policy mechanisms which typically cannot mandate for collectively coordinated actions, yet in situations where the quality of ecological outcomes is often dependent on appropriate spatial and temporal sequencing of many different activities being undertaken on different parcels of land.

Moreover, particular challenges come from the fact that many populations have spatial dynamics at scales wider than the local management area (e.g. farm), so habitat value might be context-dependent (e.g. Robinson, Wilson, and Crick 2001; Concepción, Diaz, and Baquero 2008), and connectivity time-dependent (Clergeau and Burel 1997). Also, some land uses can constitute a demographic sink (Pulliam 1988) for organisms such as birds (e.g. Hatchwell, Chamberlain, and Perrins 1996; Chamberlain and Fuller 2000; Arlt and Pärt 2007), small mammals (Tattersall, Macdonald, Hart, and Manley 2004), butterflies (Boughton 1999; Öckinger and Smith 2007) and bees (Öckinger and Smith 2007).

In agro-ecosystems the landscape structure, which influences species diversity, emerges from the interaction of biophysical constraints and individual land managers' land-use decisions, influenced by factors such as crop prices, management input costs and economic aspirations. Agent-based modelling seems a natural tool to model the human portion of such systems, as analytical models would be much more difficult to formulate and solve. Agent-based modelling allows for more transparent, descriptive representations of phenomena than mathematical modelling, whilst still retaining the rigour of formal languages.

This makes it suited to accounting for social dynamics in environmental models and to use in policy-making scenarios.

Agent-based models are particularly useful when dealing with dispersed interaction of possibly heterogeneous agents (especially when such interactions are not centrally organised) and are frequently applied to modelling complex systems with features such as multiple levels of partially interacting structure, continual system adaptation, perpetual novelty and out-of-equilibrium dynamics that are challenging for more traditional modelling paradigms (Arthur, Durlauf, and Lane 1997; Manson 2001).

There is a growing body of work applying agent-based models to land-use and land-cover change (ABM/LUCC models) and there are several reviews of agent-based modelling in land-use change. The interested reader is referred to articles such as Hare and Deadman (2004); Bousquet and Le Page (2004); Parker, Manson, Janssen, Hoffmann, and Deadman (2003); and Matthews Gilbert, Roach, Polhill, and Gotts (2007). Recent interesting examples include Valbuena Verburg, Bregt, and Ligtenberg (2009), devoted to regional land-use change; Guillelm, Barnes, Rounsevell, and Renwick (2009), investigating the effect of land-use decisions on bird populations; and co-constructed models such as Becu, Neef, Schreinemachers, and Sangkapitux (2008) and Leclerc *et al.* (2009), which are often applied to management of ecological resources in situations of conflict. (See also the overview on this type of models provided by Bousquet *et al.* 2002.) Framework for the Evaluation and Assessment of Regional Land Use Scenarios (FEARLUS) (Polhill, Gotts, and Law 2001) is an agent-based modelling system designed to build models for studying land-use change. This is a modelling tool flexible enough to capture differences among individual land managers, but still able to produce relatively simple general models. It has been used to study various aspects of boundedly rational land-use decision-making algorithms and their interaction with differing degrees of spatio-temporal heterogeneity in factors influencing economic returns, including imitation (Polhill *et al.* 2001; Gotts and Polhill 2009) and aspiration (Gotts, Polhill, and Law 2003). For this work, we have coupled FEARLUS with a metacommunity model which is an extension of the Stochastic Patch Occupancy Model framework (Moilanen 1999, 2004). The resulting model is dubbed FEARLUS-SPOMM (FEARLUS with Stochastic Patch Occupancy Metacommunity Models).

This coupled modelling tool permitted us to build stylised models to investigate the space–time dynamics of a socio-ecological system. In this particular application the objectives were to investigate the interaction between incentive-based policies and persistence time in the landscape of species of interest.

We set up simulations of a relatively simple system where some species of conservation interest share habitat with other ‘less interesting’ species and in which conservation incentives reward either the choice of land uses providing the appropriate habitat or the occurrence of target species on a parcel of land. Land use here incorporates notions both of crop and management *practices* (as these partly determine the level of intensity) which have an effect on habitat suitability for species of interest.

2. Research methods

2.1. Model overview, design concepts and details

We describe the model using Grimm *et al.*’s (2006, n.d.) overview, design concepts and details documentation protocol. Sections 2.1.1.–2.1.3 constitute the overview; the design concepts are described in Section 2.1.4 and the details in Sections 2.1.5.–2.1.7.

2.1.1. Purpose

The purpose of the model is to explore the effectiveness of different agricultural incentive schemes in maintaining landscape-scale biodiversity.

2.1.2. Entities, properties and scales

Here, we deviate slightly from the ODD standard to describe all the key entities in the model and the properties they have. Some of these properties are low-level state variables, as per the ODD standard, others are exogenous driving variables – of the latter, some are constant over time. Exogenous driving variables are given directly as input to the model – none of the processes described in the model affect their value, except, in the case of non-constant exogenous driving variables, insofar as their value for the next time step is read from an input file. Tables 1–5 show the properties of the five entities: the environment (regional scale), land parcels/patches (field scale), land managers (farm scale), species (population scale) and government (national scale), respectively.

Table 1. Description of the environment entity in FEARLUS-SPOMM.

Property	Brief description	Exog?	Const?
Land uses	The set of land uses that land managers may apply to their land parcels	Y	Y
Economy	The (gross) price per unit yield returned to land managers for each land use	Y	N
Break-even threshold	Cost per unit area for all farm activity	Y	Y
Social spatial topology	How to determine neighbourhood for the purposes of social spatial interaction	Y	Y
Habitats	The set of habitats that species can exist on	Y	Y
Species list	The set of species	Y	Y
Distance function	How to determine distance for the purposes of species interaction	Y	Y
Land-use/habitat matrix	Mapping from land-use choice to habitat availability for species	Y	Y
Sink	Whether certain habitats operate as sinks for certain species.	Y	Y
Parcel transfer price	The price at which land parcels are exchanged	Y	Y

Note: Exog, exogenous.

Table 2. Description of the land parcel/patch entity in FEARLUS-SPOMM.

Property	Brief description	Exog?	Const?
Land manager	The land manager agent owning the land parcel	N	N
Land use	The current land use applied to the parcel	N	N
Habitat list	The habitats made available by the current land use	N	N
Species list	The species currently occupying the patch	N	N
Yield	The yield generated by the land use on the parcel	N	N
Area	The area of the patch (always 1)	Y	Y

Note: Exog, exogenous.

Table 3. Description of the land manager entity in FEARLUS-SPOMM.

Property	Brief description	Exog?	Const?
Land parcel list	The list of land parcels owned by the manager	N	N
Account	The accumulated wealth of the land manager	N	N
Aspiration	The mean profit (per unit area) aspiration of the manager	N	N
Change delay	The number of consecutive time steps of not meeting aspirations for which the manager will wait before reviewing land uses on the farm	Y	Y
Mean profit	The last profit made, divided by the area of the farm	N	N

Note: Exog, exogenous.

Table 4. Description of the species entity in FEARLUS-SPOMM.

Property	Brief description	Exog?	Const?
α	Dispersal constant of the species (inversely proportional to dispersal)	Y	Y
μ	Mortality constant of the species	Y	Y
Habitat list	The list of habitats on which this species can survive	Y	Y
Competition list	A list containing those species that this species outcompetes on a patch, and for each outcompeted species, how long it takes this species to do so	Y	Y

Note: Exog, exogenous.

Table 5. Description of the government entity in FEARLUS-SPOMM.

Property	Brief description	Exog?	Const?
Activity or outcome	Whether to reward farmers for applying particular land uses (activity) or for having certain species on the farm (outcome)	Y	Y
Stop C	Whether to use an incentive structure (for activity or outcome) designed to prevent the spread of species C, a competitor species	Y	Y
Cluster	Whether to use an incentive scheme increasing the reward to farmers for activities/outcomes on neighbouring patches	Y	Y
Reward	Amount of incentive per activity/outcome	Y	Y

Note: Exog, exogenous.

2.1.3. Process overview and scheduling

The schedule consists of the series of events in Figure 1, repeated a specified number of times.

2.1.4. Design concepts

2.1.4.1. Emergence. The main emergent phenomena of interest in the runs conducted with this model were the landscape-scale species richness and for each species (and particularly the more vulnerable species) how long it survived before becoming extinct in

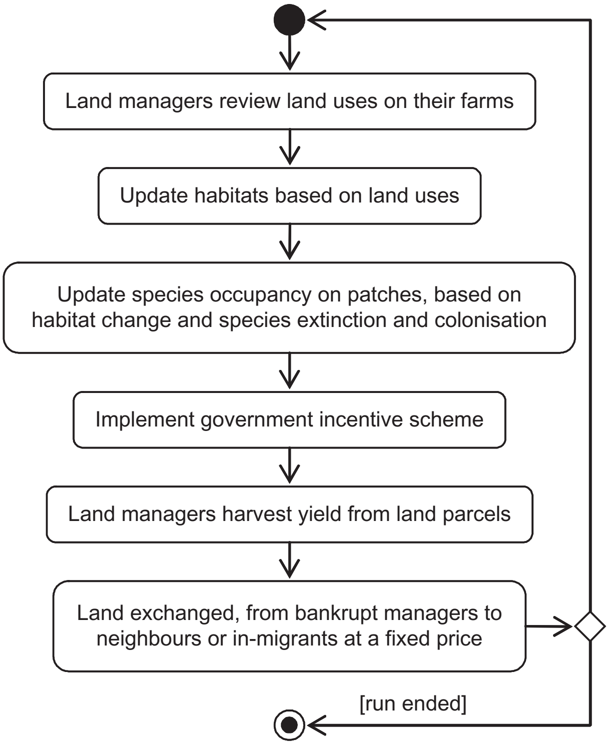

Figure 1. UML activity diagram depicting the FEARLUS-SPOMM schedule. The arrows indicate flow of activity in the algorithm. The diamonds are decision points in the code, with branches labelled according to the condition required for the flow to go in that direction (an unlabelled out-flow from a diamond has condition NOT that of any labelled out-flow). Solid circles are starting points, circles with a white border are ending points. Loops are organised in large boxes, and comments are associated with activities using a dashed line.

the landscape, as these are measures of the effectiveness of the incentive scheme. The bankruptcy rate of managers was monitored (runs using parameters leading to consistently high bankruptcy rates – more than 5% of the population – were rejected as being unrealistic). Also of interest was the landscape-scale fragmentation of land uses. Landscape structure was determined at each time step, by the collective decisions of land managers, given their objectives.

2.1.4.2. Adaptation. The only adaptive process operating is the land-use review process of managers. At a manager population scale, bankruptcy weeds out those managers making poorer decisions. As differences among managers are determined only by the value of their change delay (besides the neighbours they have), this population-level adaptive process can be expected to remove managers with change delays that confer a disadvantage. This, however, was not studied in the experiments reported herein.

2.1.4.3. Objectives. Land managers have the implicit objective of remaining in business. The government has the implicit objective of maintaining landscape-scale biodiversity. Species have an implicit objective of surviving in the landscape. (The government and species can, however, not make changes to their behaviour to achieve their objectives.)

2.1.4.4. Learning. The case-based reasoning algorithm stores land managers' experiences of using land uses. As these experiences are then drawn on when making subsequent decisions, this process may be conceived as learning.

2.1.4.5. Prediction. Land managers use case-based reasoning to predict the outcome of applying various land uses to their land parcels.

2.1.4.6. Sensing. Land managers are aware of the land uses they use, the parcels they own, and of their neighbours.

2.1.4.7. Interaction. Land managers directly interact through asking neighbours for advice when reviewing land uses on the farm, if they have no experience of using a particular land use. This advice consists of the neighbour's experience of using the land use, if available. Land managers also interact when acquiring new land, and where clustered incentive schemes operate, in choosing land uses that affect the incentives neighbours receive (though they are not aware of this). Species interact through competition. The government interacts with land managers in the incentive scheme through the reward given to (or withheld from) managers. If activity-based incentive schemes operate, the government also interacts with land managers through observing the land-use selections they make. Otherwise, the government interacts with species through observing their occupancy of patches.

2.1.4.8. Stochasticity. Stochasticity operates for land managers when multiple land uses have maximum expected outcome on a land parcel – here a random selection is made. Stochasticity also occurs when selecting new land managers for land parcels. For species, stochasticity is involved in the processes of extinction and colonisation. Stochasticity is also used extensively during initialisation.

2.1.4.9. Observation. A record is made of the government expenditure, bankruptcies, amount of land-use change, extinction times of species, patch occupancy of species and landscape-scale species richness. A record is also kept of the land-use history.

2.1.5. Initialisation

The land uses, yields and habitats they make available (A_{is} in Equation (1)) are as defined in Table 6. For the purposes of this work, we made available two main land-cover types 'G' and 'A', in three levels of intensity (from '1' low to '3' high) giving land uses labelled GL1, GL2, GL3, AL1, AL2, AL3. Six corresponding habitats were specified in the SPOMM model, GH1, GH2, GH3, AH1, AH2, AH3. The more intense the land use, the fewer species were able to use the corresponding habitat.

The species and their habitats are as defined in Table 7. To create a potential refuge from competition, land uses GL1, GL3, AL1, AL2 and AL3 provided habitats GH1, GH3, AH1, AH2 and AH3, respectively, whereas land use GL2 provided two habitat types: GH1 (20% of the patch area) and GH2 (80% of the patch area). Only GH1 was available to the competitor species C. The relatively more vulnerable species are G5, G6 and A2, A3, having more specialised habitat requirements and in the case of G5 and G6, short dispersal distances. Land uses AL1, GL1 and GL2 are thus important for biodiversity – note, however, that they also have the lowest yields.

Table 6. Land uses, yields and habitats used.

		Habitat					
Land use	Yield	AH1	AH2	AH3	GH1	GH2	GH3
AL1	4.5	1					
AL2	5.5		1				
AL3	6.5			1			
GL1	4				1		
GL2	5				0.2	0.8	
GL3	6						1

Table 7. Species used.

Species	α	μ	Habitats	Competition
A1	1.3	0.1	AH1, AH2, AH3	None
A2	0.9	0.1	AH1, AH2, GH2[a]	None
A3	0.8	0.1	AH1, GH2 [a]	None
C	1.3	0.05	GH1	G1, G2, G3 after three time steps
G1	0.8	0.1	GH1, GH2, GH3	None
G2	0.9	0.1	GH1, GH2, GH3	None
G3	1.1	0.1	GH1, GH2, GH3	None
G4	1.3	0.1	GH1, GH2	None
G5	1.3	0.1	AH1 [a], GH1, GH2	None
G6	1.3	0.1	AH1 [a], GH1	None

Note: [a]Habitats are sinks for the associated species, if sinks are operating in this particular run.

The competitor species C is able to outcompete and exclude some of the species (G1–G3) if present on the same patch. This was intended to simulate a situation in which a complete lack of management would result in lower patch-based species richness (alpha diversity) with respect to a moderately intense regime. This is the case of many grassland systems, where grazing can promote diversity (e.g. Wallis de Vries, Bakker, and van der Wieren 1998).

All species have a characteristic dispersal distance, a probability of extinction from a patch and a probability of colonisation which depended on the configuration of occupied patches in the landscape.

The landscape is initialised to a random distribution of land uses chosen uniformly from {AL1, GL1}. All species are then allocated to those patches on which they can survive (i.e. on initially AL1 patches: A1, A2, A3, G5 and G6; on initially GL1 patches: C, G1, G2, G3, G4, G5 and G6). This was to maximise the probability of species surviving whilst the initial land manager agents are learning.

Land managers are randomly assigned one parcel each and have 0 initial account. Their ‘change delay’ (see Table 3) is taken from a uniform integer distribution in the range [1, 9]. Aspiration thresholds are set depending on the run (treatment 1 in Table 10). The break-even threshold was set according to treatment 2 in Table 10.

The incentive scheme is initialised as per the desired policy to explore for the run (treatments 4, 5 and 6 in Table 10). The level of incentive is set according to treatments 7 and 8 in Table 10. Table 8 shows the entities rewarded for given policy dimensions.

Table 8. Entities rewarded by different types of government.

	Stop C = true	Stop C = false
Activity	AL1, GL2	AL1, GL1, GL2
Outcome	A2, A3, G3, G5, G6	A2, A3, G5, G6

2.1.6. *Input*

The input to the model consists of the state of the economy for each time step. The economy is expressed as the price given per unit yield of each land use – the yield depending on intensity as per Table 6. Runs used one of two options: 'Flat', in which there were no changes in the state of the economy, and 'Var', in which the economy varied according to the time series in Figure 2. The means of the Var and Flat time series were the same. The settings for the Flat economy and Var settings are shown in Table 9.

2.1.7. *Submodels*

2.1.7.1. Review land uses. For these experiments, land managers were implemented with a satisficing (Simon 1955) approach to decision-making (rather than aiming at making the maximum possible profit). Satisficing is a commonly used heuristic approach to represent human decision-making. Departure from profit maximising is known to occur for a variety of reasons. Parker, Hessl, and Davis (2007) cite evidence of several factors that lead to farmers not making fiscally optimal decisions, such as meeting subsistence requirements and cultural norms. To this may be added questions of identity as a farmer from qualitative social research (Burton and Wilson 2006), in which 'keeping the name on the farm' and being recognised by one's peers as a 'good farmer' (Burton 2004) are also motivating influences on decision-making orthogonal to purely pecuniary concerns.

Land managers reviewed their choice of land uses on all their parcels if the mean profit per unit area did not meet their financial aspirations for a specified number of consecutive years. When deciding whether to change land use, managers used their experience, that

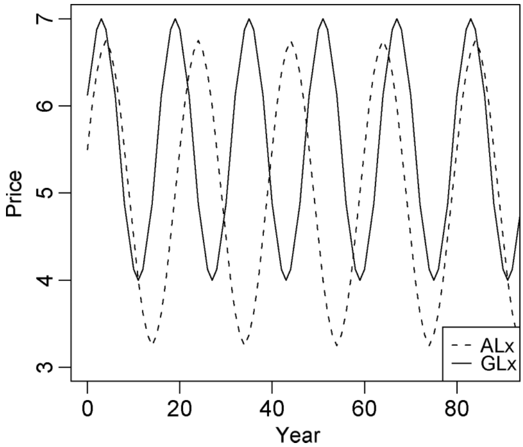

Figure 2. Time series of prices used in the Var market. The 80-year cycle is repeated over the course of the run.

Table 9. Prices per unit yield for land uses in the Flat market, and mean, minimum and maximum prices in the Var market.

Land use	Price (Flat; mean Var)	Minimum price (Var)	Maximum price (Var)
AL1, AL2, AL3	5	3.25	6.75
GL1, GL2, GL3	5.5	4	7

is, they employed case-based reasoning (Aamodt and Plaza 1994), to choose a land use based on their expectations of the economy in the coming year and their experience of the land use in the past, which includes its economic return. Managers with no experience of a land use were given the opportunity to ask neighbours for their experience of it, and use that as a basis for decision-making. If neighbours had no experience of a land use either, then managers assumed that that land use would meet their aspirations: When other land uses had poorer expected outcomes, this allowed land managers to experiment. Expected outcomes (profit) are obtained for each land use and a selection made at random from those land uses with maximum expected profit. Land managers are therefore satisficing regarding the decision to change land use but maximising once they have decided to change. As profit includes any subsidies from the government, policy has an influence on land-use selection by managers.

Each manager decides the land uses of the parcels they own as per Figure 3.

More detail on the decision algorithm can be found in the FEARLUS 1.1.5 user guide (Polhill, Gotts, and Izquierdo 2008), CBRDelayedChangeLandManager land manager class.

2.1.7.2. Update habitats. Use the land-use/habitat matrix (Table 6) to update the habitat on each patch.

2.1.7.3. Update occupancy.. Dispersal, colonisation and local extinction are modelled as in Moilanen (2004), but briefly covered below. Local extinction can also be caused by competition. In the runs used here, species C caused the local extinction of species G1, G2 and G3 on a patch after three consecutive time steps of occupancy.

For species s and patch i, the connectivity at time t, $S_{is}(t)$, is computed as per Equation (1):

$$S_{is}\,(t) = A_{is}^{c} \sum_{j \neq i} O_{js}(t-1) \exp(-\alpha_s d_{ij}) A_{js}^{b} \tag{1}$$

where A_{is} is the amount of habitat made available on patch i by the present land use for species s (see Table 6), j iterates over all patches other than i, $O_{js}(t)$ is an occupancy indicator variable (1 if patch j is occupied by species s at time t, 0 otherwise), α_s is the dispersal parameter of species s (Table 7), d_{ij} is the Euclidean distance between patches i and j (assuming a toroidal spatial topology), and b and c are parameters (both set to 1).

The colonisation probability of s onto unoccupied (by s) patch i, $C_{is}(t)$, is then given by Equation (2):

$$C_{is}(t) = \frac{[S_{is}(t)]^2}{[S_{is}(t)]^2 + p^2} \tag{2}$$

where p is a parameter (set to 1).

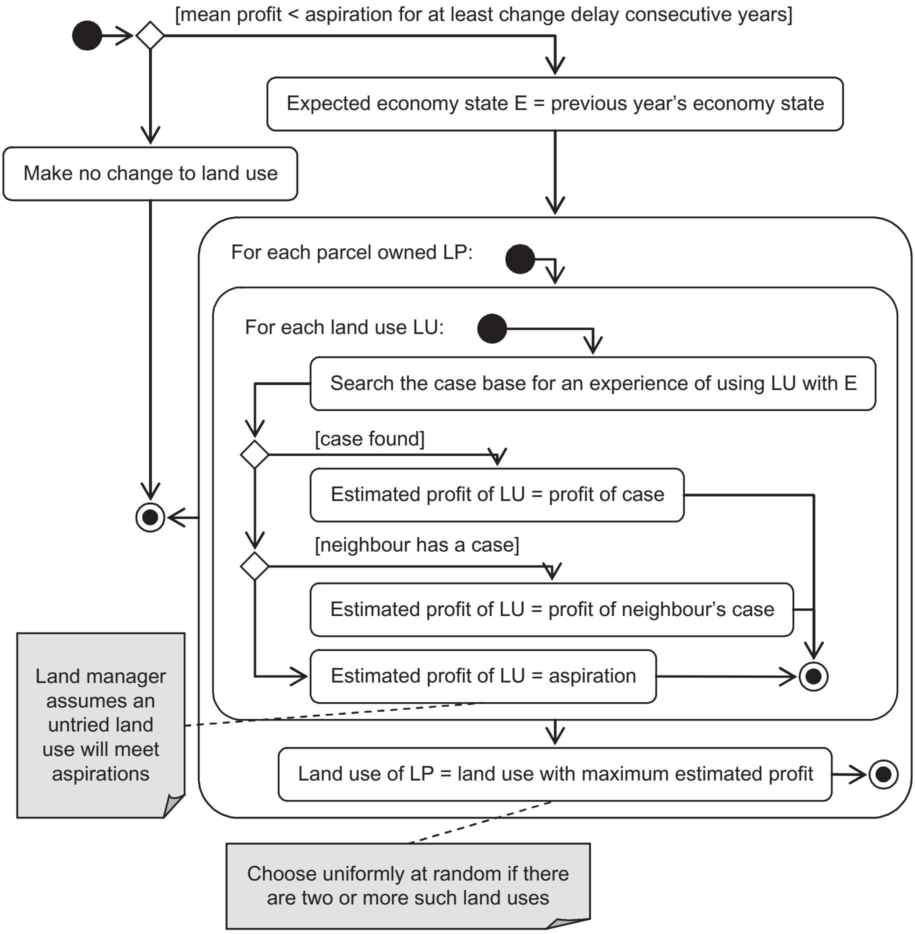

Figure 3. UML activity diagram showing the land-use decision algorithm.

The local extinction probability of s on a patch i it presently occupies, E_{is}, is given by Equation (3):

$$E_{is} = \frac{\mu_s}{A_{is}^x} \tag{3}$$

where x is a parameter (set to 1), μ_s is the mortality parameter of species s (Table 7) and A_{is} is as per Equation (1).

2.1.7.4. Implement incentives.. Four of the policies for rewarding managers are given in Table 8: When an activity-based policy was used, managers received a payment for each parcel in which they deployed certain land uses. When an outcome-based policy was adopted, managers received a payment for each occurrence of certain species on a parcel they owned. For each of these two, incentives could be aimed at stopping species C or not. For each of the resulting four policies implemented as direct payments to land managers, we also simulated a case where reward was spatially clustered – managers received extra rewards if they and their neighbours deployed a rewarded land use or had a species of concern on their land, according to whether an activity- or outcome-based incentive scheme was used, respectively. Here, the land manager gets the stated reward once for themselves, and then n times for each neighbour doing the same awardable activity or having the same outcome.

2.1.7.5. Harvest. The net income I_m from the harvest for a farmer m is given by Equation (4):

$$I_m = \sum_{i \in W_m} [y(u_i)p(u_i, t) - BET] \tag{4}$$

where W_m is the set of parcels owned by m, u_i is the land use of parcel i, $y(u)$ is the yield of land use u (Table 6), $p(u, t)$ is the price of land use u at time t (Table 9 and Figure 2) and BET is the break-even threshold (Table 10). A manager's account increases each year by $I_m + R_m$, where the latter is the reward the manager receives from the government. The mean profit used for deciding whether aspirations are met is computed as $(I_m + R_m)/\#W_m$ (where $\#S$ is the cardinality of set S).

Land managers' case bases are updated to include the experience of using each land use, consisting of a data structure containing the economy, the land use chosen and the profit at the parcel scale assuming an equal distribution of reward $= [y(u_i)p(u_i, t) - BET] + R_m/\#W_m$. Any cases from more than 75 time steps ago are removed from the case base.

2.1.7.6. Land exchange. A land manager whose account is less than zero is regarded as bankrupt, and all their land parcels are put up for sale. For each land parcel for sale, the procedure for finding a new owner is shown in Figure 4.

2.2. Experiment design

The model was initialised to all combinations of the treatments in Table 10, and for each combination, run for 300 time steps with 20 replications using different seeds for the random number generator. This makes 34,560 runs in total. From these runs, 960 were rejected because the particular combination of treatments resulted in unrealistically high levels of bankruptcy, meaning that a total of 33,600 runs were included in the final analysis.

We used FEARLUS version 1.1.5 coupled with SPOMM version 2.3. The output of the software was analysed using regression trees (Breiman, Fredman, Olshen, and Stone 1984), with the treatments as the explanatory variables, and the landscape-scale species richness and time to extinction (for each species) as the outcome.

Table 10. Parameter values used in experiments.

Treatment	Affected property	Values used
1	Aspiration threshold	0.5, 1, 5
2	Break-even threshold	25, 30
3	Sink habitats	Yes, no
4	Policy	Activity-based, outcome-based
5	Policy	Per parcel, per parcel with clustered incentive
6	Policy	Stop C = true, stop C = false
7	Incentive (outcome)	0, 5, 10
8	Incentive ratio	Activity/outcome = 1/3, 1/2, 1/1
9	Market	Var, Flat

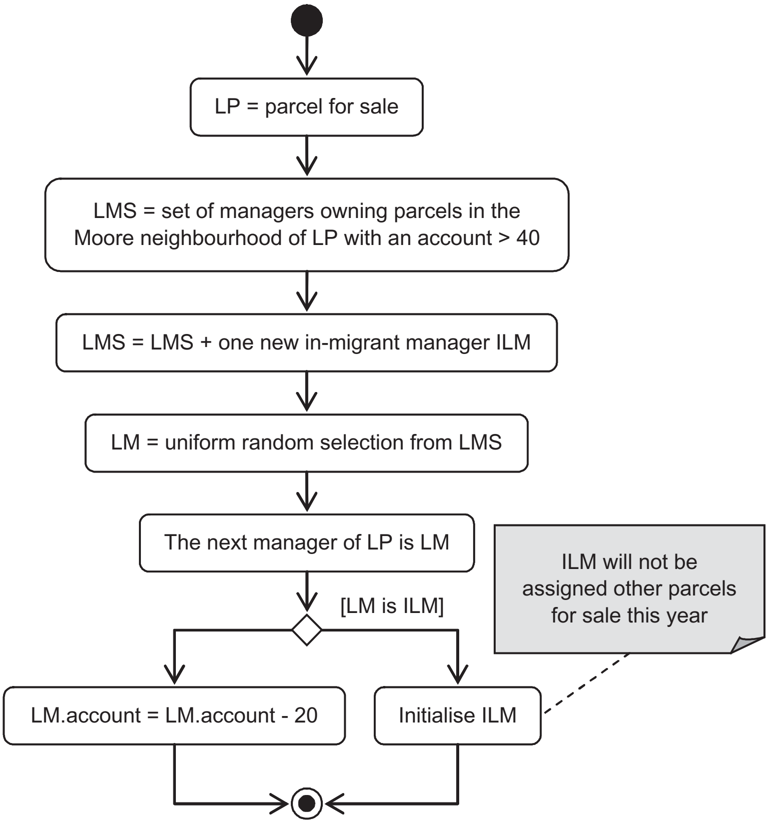

Figure 4. UML activity diagram showing the procedure for finding a new owner for a land parcel for sale.

3. Results

The regression trees in Figure 5 show, in order of strength of influence (measured by decrease in variance) starting at the top, the parameters that affect the persistence of two vulnerable target species (A3 and G6) for a combination of treatments in Table 10. Regression trees were 10-fold cross-validated using 90% of the observations for training each time. This procedure was used to find the most parsimonious tree models fitting the data.

In Figure 6, we use a box plot to show how the species occupancy (NP) changes over time for one of the target species (G6) in two of the treatments, comparing clustered (b) and non-clustered (a) incentives for aspiration threshold 1, break-even threshold 25, market Var, reward activity, reward 5, no sinks, stop C true and incentive ratio 1/2. The box plots capture the variability of results over 20 replications, with the thick line in the boxes representing the median.

4. Discussion

From Figure 5a and b, for both species A3 and G6, the clustered policy more consistently promoted longer persistence times than the non-clustered in that other treatments had no significant influence on persistence, but this is most likely due to the extra costs involved. This matter will be discussed further in relation to Figure 6, below. In the non-clustered

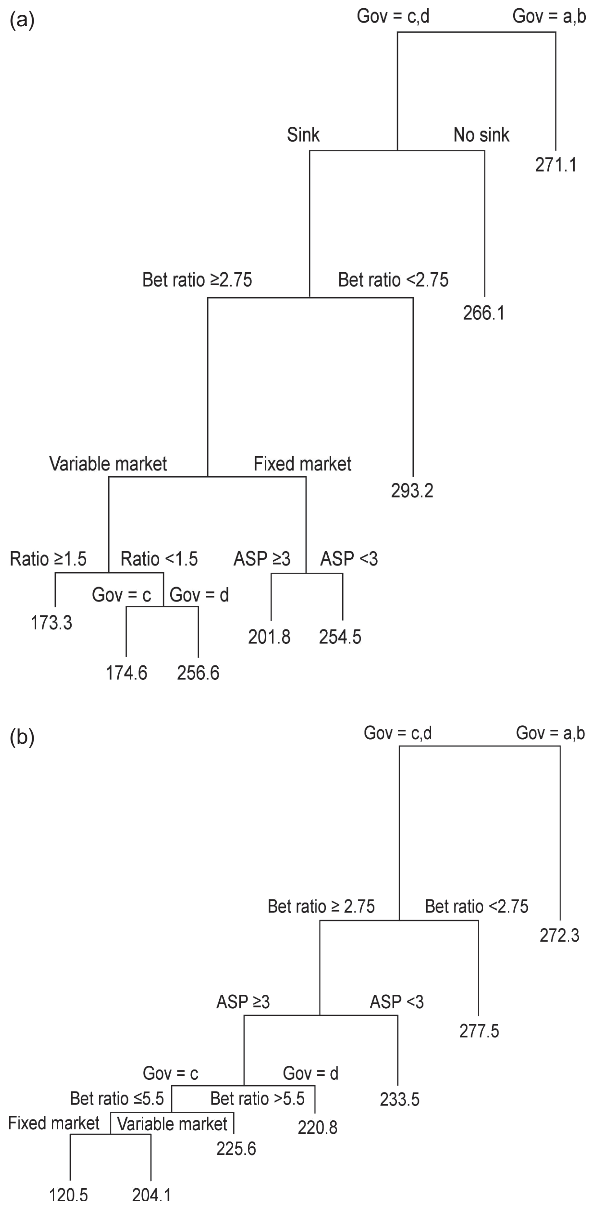

Figure 5. Regression trees showing the influence of various combinations of treatments in Table 10 on persistence of two vulnerable target species: (a) A3 and (b) G6. Treatments 2 (BET) and 7 (Incentive) have been merged into a single ratio, as BET/Incentive. Those treatments not mentioned in the tree do not significantly influence persistence. Gov a = clustered incentives for activity, Gov b = clustered incentives for outcome, Gov c = incentives for activity, Gov d = incentives for outcome. Bet ratio = ratio between break-even threshold and unit of incentive provided. Ratio = incentive ratio, see also Table 10.

policy, success was sensitive to the other treatments. A3, for example proved sensitive to the presence of sinks, and, as might be expected, both species' persistence was reduced for higher BET/Incentive ratios. Further down the trees, variation in market prices, aspirations

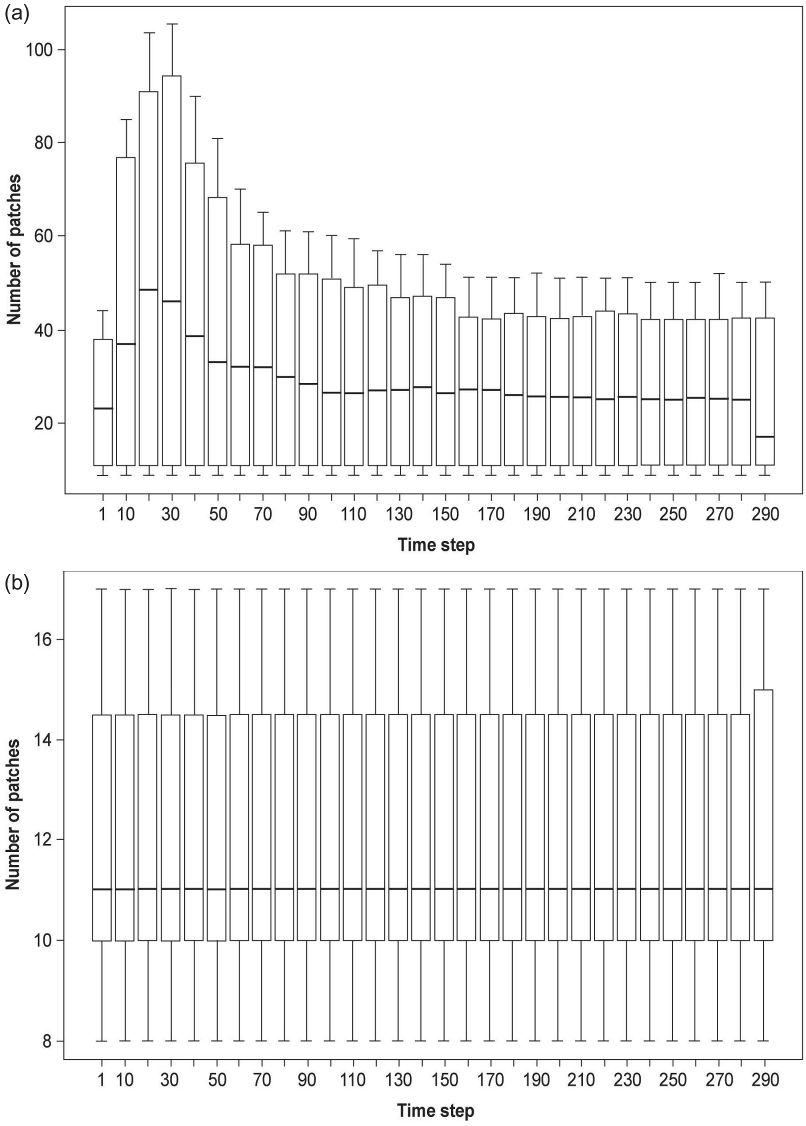

Figure 6. Box plots showing how the species occupancy of species G6 changes with time over 20 runs in each of two particular treatments using (a) no clustered rewards and (b) clustered rewards. In the box plot, the thick line marks the median, the box indicates the 95th percentile and the error bars show the full range of the data.

and outcome-based rather than activity-based incentives all had an effect, but in differing order of significance. As might be expected, in both cases, higher aspirations tended to reduce average persistence. Where the market had an influence, for species G6 persistence times were reduced in the variable market, whereas for species A3 the variable market, if anything, was a slight advantage. Outcome-based incentive schemes had higher average persistence times than activity-based, where this made a difference.

These results suggest a number of general points for government policies aimed at protecting target species, each of which should form the subject of more targeted experiments in future work:

- Species can be influenced differently by the various drivers of farm decision-making. An incentive scheme that works well to protect one species may not work for another.
- The success of an incentive scheme can be affected by factors that can be specific to particular regions and farmer types, such as input costs and aspirations. Although this suggests that an incentive scheme that works well in one region may not work in another, another interesting possibility to explore is whether mixtures of farmer types in a region can promote landscape-scale biodiversity. Increasing pressure on farm businesses could reduce the diversity of enterprise types.
- The more money is spent on protecting a species, the less influence other drivers with a positive or negative impact on its survival will have.

Although the box plots in Figure 6 show that clustered incentives are considerably more successful in maintaining a stable habitat for one species, this has to be taken against the fact that clustered incentives also cost a lot more: If nine neighbours in a 3 × 3 cell area of the environment all have the same awardable species or activity, the central manager will receive nine times the incentive under a clustered regime than they would under a non-clustered. Indeed, particularly in the case of activity-based incentives, the fact that there are six land-use options for managers to choose among means in the random case that the probability that no land managers in the neighbourhood of a manager use the same land use is $(5/6)^8$ – less than 25%. However, the initial starting condition of 50% GL1, 50% AL1 means that probability is less than 1%, and hence from the very beginning of the run, land managers will most likely be receiving a larger incentive in the clustered than the non-clustered case. Comparing expenditure is not trivial, however: although it is true that the comparison between clustered and non-clustered incentives in this case is not strictly fair, in general more successful schemes will require the government to make more payments, and thus cost more than less successful schemes.

The matter can of course be addressed by reducing the incentive in the clustered case, but this presents something of a dilemma: If the incentive is reduced too much, there will be little uptake of the scheme, threatening biodiversity. The impact of the problem can be reduced by making the payment to the farmer for their own activity greater than that given to the farmer for the clustered neighbouring activity. However, if the difference is too great, the incentive for clustering biodiversity-friendly activities will be reduced too much to make it worth implementing such a scheme in comparison with a simpler non-clustered one. These issues can be explored further in future work.

The practicalities involved with implementing clustered incentive schemes in the real world have not been discussed. The administrative burden in calculating payments for farmers if neighbouring activity is to be taken into consideration could be regarded as prohibitive. Particularly in the case of outcome-based incentive schemes, using clustered incentives could prove too costly in the level of sampling required to ensure payments were made fairly. However, it is precisely for these reasons that modelling such questions ‘in principle’ is an advantage: it is possible to explore, without annoying farmers or civil servants, how effective different incentive schemes might theoretically be in bringing about improvements in biodiversity. We can explore ‘life as it could be’ (Langton 1989), as well as life as it is. That we can do so in a manner that is more narratively realistic in its representation of agricultural land-use change and biodiversity than is tractable with more traditional modelling approaches emphasises the benefits that agent-based modelling of coupled human–nature systems have to offer.

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