Jul 1st, 12:00 AM

Analysis of Incentive Schemes for Biodiversity Using a Coupled Agent-Based Model of Land Use Change and Species Metacommunity Model

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Abstract: We report results from roughly 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 four kinds of policy varying along two dimensions: activity-versus-outcome-based incentive, and individual-versus-collective incentive. The results reveal critical thresholds in incentive schemes, where a sudden increase in environmental benefit occurs for a small increase in incentive. Further, the context affects the level of incentive at which tipping 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 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.

Keywords: agents; biodiversity; land-use; policy; nonlinearity

1. INTRODUCTION

The Scottish Government has adopted the biodiversity 2010 agenda of reducing biodiversity loss from agriculture. We have developed FEARLUS-SPOMM to explore biodiversity incentive schemes, by coupling FEARLUS [Polhill et al., 2001; Gotts and Polhill, 2009], an agent-based model of agricultural land use change, with an enhanced version of Moilanen's [2004] Stochastic Patch Occupancy model, which is capable of simulating multiple species and interactions among them. In this paper, we show selected results from 20,000 runs of the coupled models, illustrating some of the sensitivities of biodiversity to farmer agent attributes, incentive scheme design, and other drivers of farmer behaviour.

2. METHOD

Here we give an overview of FEARLUS-SPOMM based on Grimm et al.'s [2006] ODD (Overview, Design concepts and Details) model description protocol, with the exception that to save space, the Design concepts are used to tag relevant sections of the Submodels. In the Details section, we outline the simulations conducted. A more detailed description of FEARLUS-SPOMM can be found in Gimona et al. [in press]. Note also that here we describe FEARLUS-SPOMM as configured for these experiments. Other configurations are possible.

2.1 Overview

Purpose: The purpose of the model is to explore how effective *in principle* various agri-environmental incentive schemes are at managing catchment biodiversity.

Entities, State Variables and Scales: The key entities in the model are an environment, consisting of a toroidal grid of 25×25 land parcels (a.k.a. patches), each owned by a land manager, who chooses a land use (conceptually, a combination of crop and land management strategy) for each parcel they own every year (the time step in the model). Land managers use a satisficing algorithm to choose land uses, in which no change is made to the land uses unless their profit is below an aspiration threshold. Each land use has a different yield, and this together with an exogenous economy time series and break-even threshold parameter determines the economic return from the market accumulated to the land manager's account. Each land use makes one or more habitats for species available where it is used. Each patch records the species living on it as presence or absence (i.e. numbers of individuals are not recorded). Each species has parameters affecting its dispersal distance and patch extinction probability. A government agent monitors the environment, and has a rule it uses to issue a reward to land managers, designed to prevent biodiversity loss.

Process Overview and Scheduling: Each time step (year), consists of: (i) Land managers choose land uses for each of the land parcels they own. (ii) The land uses are used to derive a habitat map for species. (iii) Species compute patch extinction and colonisation probabilities based on the habitat map and their prior distribution. (iv) The government agent uses its rule to issue financial incentives to land managers. (v) An economic return from the market is computed from the yield of the land use, and the current state of the economy, and added to the land managers' accounts. (vi) Land managers with a negative account are regarded as bankrupt, and sell their land parcels.

2.2 Details

Initialisation: The model is initialised with six land uses comprised of two classes having three levels of intensity: GL1, GL2 and GL3 (from low to high intensity; yielding 4, 5 and 6 respectively) representing grazing; AL1, AL2 and AL3 (low to high intensity; yields 4.5, 5.5, 6.6) representing arable. Land uses are mapped onto habitat provision: AL1 provides AH1, AL2 provides AH2, AL3 provides AH3, GL1 provides GH1, GL2 provides 20% GH1 and 80% GH2, GL3 provides GH3. There are ten species, with parameters in Table 1; all can survive on at least one of habitats AH1 or GH1, and all except a competitor species (C), which causes the local extinction of G1, G2 and G3 after three consecutive years of occupancy, can survive on at least one of AH1 or GH2. Thus the lower intensity land uses AL1, GL1 and GL2 are the most important for biodiversity, but they have the lowest yields. Note also that GL1, the lowest intensity 'grazing' land use provides the best habitat for species C—a setup designed to reflect real-world findings, such as those of Wallis de Vries et al. [1998], that biodiversity can be improved by grazing. This is consistent with the 'intermediate disturbance hypothesis' (Connell [1978]) in ecology: that biodiversity first rises, then falls, as the frequency and intensity of disturbance to an environment increases.

The landscape is initialized to a random distribution of the land uses AL1 and GL1 chosen with equal probability on each parcel. All species are then allocated to those patches on which they can survive. Land managers are randomly assigned one parcel each, and have 0 initial account; their change delay is taken from a uniform integer distribution in the range [1, 9]. Aspirations are set according to the run (1 or 5), as is the break-even threshold (25 or 30).

We tried four rules for the incentive scheme. Each rule uses a reward level, computed from two parameters, reward (runs used integers in [1, 10]) and ratio ({1, 2, 10} tried), as follows:

- *Activity* rule: Pay reward to each land manager for each parcel using GL2 or AL1.
- *Outcome* rule: Pay reward to each land manager for each occupancy of A2, A3, G3, G5 or G6 on a parcel they own.

- *Cluster-Activity* rule: Pay reward/ratio to each land manager for each parcel using GL2 or AL1, plus reward/ratio for each (Moore) neighbouring parcel using the same land use.
- *Cluster-Species* rule: Pay reward/ratio to each land manager for each occupancy of A2, A3, G3, G5 or G6 on a parcel of land they own, plus reward/ratio for each neighbouring parcel also having the same species.

Table 1. Parameters for Species used.

| Spp. | α | μ | Habitats | | | | | | Competition (time) |
			GH 1	GH 2	GH 3	AH 1	AH 2	AH 3	
A1	1.3	0.1	-	-	-	Y	Y	Y	None
A2	0.9	0.1	-	Y	-	-	Y	Y	None
A3	0.8	0.1	-	Y	-	-	-	Y	None
C	1.3	0.05	Y	-	-	-	-	-	G1, G2, G3 (3)
G1	0.8	0.1	Y	Y	Y	-	-	-	None
G2	0.9	0.1	Y	Y	Y	-	-	-	None
G3	1.1	0.1	Y	Y	Y	-	-	-	None
G4	1.3	0.1	Y	Y	-	-	-	-	None
G5	1.3	0.1	Y	Y	-	Y	-	-	None
G6	1.3	0.1	Y	-	-	Y	-	-	None

Input: The economy time series is the only input to the model. In our experiments, we used two, dubbed 'flat' and 'var2'. The 'flat' market offered 5 units of wealth per unit yield of AL1, AL2 and AL3, and 5.5 per unit wealth of GL1, GL2 and GL3. The 'var2' market oscillated approximately sinusoidally between 3.25 and 6.75 with period 20 years for AL1, AL2 and AL3; and between 4 and 7 with period 16 years for GL1, GL2 and GL3. The regular oscillation was used rather than (for example) a random walk, to make the effects of variability easier to discern: note that the land managers lack the intelligence to learn temporal patterns.

Submodels:

(i) **Review land uses**. [*Adaptation*, *Interaction*, *Prediction*, *Sensing*, *Objectives*, *Stochasticity*] Each land manager computes the mean profit from their land parcels in the previous year, and if this has been less than their aspiration for at least as long as their change delay (the number of years they are prepared to tolerate below-aspiration profits), they will use case-based reasoning to choose a land use for each land parcel they own; otherwise they will make no changes. To make a (potential) change using case-based reasoning, managers consider each parcel in turn, and for each land use calculate expected profit by searching the case base for an experience of using that land use in the expected state of the economy (assumed to be the same as the previous year). If a case is found, the expected profit is that recorded in the case. If not, then if a neighbour[1] has a matching case, the profit recorded there is used, otherwise the aspiration itself is used (i.e. it is assumed that the land use for which there is no experience will just meet aspirations). The land use assigned to the parcel is that with maximum expected profit; if there are two or more such land uses, one is selected at random.

(ii) **Update habitats**. The habitat map is computed from the land uses as described in *Initialisation* above.

(iii) **Update occupancy**. [*Interaction*, *Stochasticity*] Dispersal, colonization and local extinction are computed as per Moilanen [2004], with the extra property that if species C is present on a patch four consecutive time steps, it causes local extinction of G1, G2 and G3 if present, and prevents them recolonising whilst occupancy continues. The Moilanen equations are given below:

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[1] The neighbours of a land manager are those owning a parcel in the Moore neighbourhood of that land manager's parcels.

Let $S_{ps}(t)$ be the connectivity of species s on patch p at time t, computed as:

$$S_{ps}(t) = A_{ps}{}^c \sum_{q \neq p} O_{ps}(t-1) \exp(-\alpha_s d_{pq}) A_{qs}{}^b \qquad (1)$$

where A_{ps} is the amount of habitat made available on patch p for species s (see *Initialisation*), q iterates over all patches other than p, $O_{ps}(t)$ is an occupancy indicator variable (1 if patch p is occupied by species s at time t, 0 otherwise), α_s is a dispersal parameter for s (see Table 1), d_{pq} is the Euclidean distance between patches p and q (assuming a toroidal spatial topology), and b and c are parameters (both 1).

Then the probability that s colonises a patch p it currently does not occupy is given by (2), where y is a parameter (set to 1):

$$C_{ps}(t) = \left[S_{ps}(t)\right]^2 \bigg/ \left(\left[S_{ps}(t)\right]^2 + y^2\right) \qquad (2)$$

and the local extinction probability of s on a patch p it occupies is given by (3), where x is a parameter (set to 1), μ is the mortality parameter of s (Table 1), and A_{ps} is as per (1):

$$E_{ps} = \mu_s \big/ A_{ps}{}^x \qquad (3)$$

(iv) **Implement incentives**. [*Objectives*] Managers receive funds from the government agent according to the rules described above.

(v) **Economic returns and case-base update**. [*Learning*] Update the state of the economy from the economy file. This provides a market price p_i for each land use i. A yield, y_i for each land use is set as described in the initialization. If e is the break-even threshold, then the economic return for each land parcel is $p_i y_i - e$. If A is the aspiration threshold of a land manager, M is the total economic return they received from the market, P is the number of parcels they own, and R the amount of incentive the manager received in step (iv), then the aspiration threshold test in step (i) is that $(M + R) / P > A$. The case base is updated on a parcel-by-parcel basis, assuming an equal distribution of reward. A case is added for each parcel, containing the state of the economy, the land use chosen, and the outcome: $p_i y_i - e + R / P$. Any cases from more than 75 time steps ago are removed from the case base.

(vi) **Land exchange**. [*Objectives, Stochasticity*] If a land manager's account is less than zero, they are bankrupt, and all their land parcels are sold. For each parcel for sale, choose a new land manager at random from a set consisting of one new in-migrant land manager, and all land managers in the Moore neighbourhood of the parcel with an account > 40. Assign the parcel to the manager selected. If the new owner is the in-migrant manager, then initialize its other variables (as per initialization, above); if not, deduct 20 from the account of the new owner. Note that in-migrant managers cannot be assigned more than one parcel for sale.

Reporting. [*Observation, Emergence*] Government expenditure, bankruptcies, land use map (each time step), occupancy of species and landscape-scale biodiversity metrics (every 10 time steps).

2.3 Run set-up summary

Table 2 summarises the parameter exploration done for this paper. Each combination of parameters (960 in total) was repeated 20 times using different seeds for the pseudo-random number generator, making 19,200 runs overall. (Note that the Ratio parameter has no effect on the runs using Government rule 'Activity' and 'Outcome'. Effectively, there were 60 rather than 20 replications of these parameter settings—this was done to provide sufficient samples for any statistical tests comparing the Cluster-x rules with their non-clustered counterparts.) Each run was for 200 time steps.

Table 2. Summary of parameter exploration.

Parameter	Values
Government rule	Activity, Outcome, Cluster-Activity, Cluster-Outcome
Reward	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Ratio	1, 2, 10
Market	'flat', 'var2'
Break-even threshold	25, 30
Aspiration threshold	1, 5

2.5   Analysis

The results were analysed with three points of interest in mind: (i) non-linear relationships between Reward and biodiversity outcomes; (ii) any effect of government rule on the shape or turning points of these relationships; (iii) effects of context (market, aspirations and break-even threshold). We fitted Generalised Additive Models (GAMs, Hastie and Tibshirani [1990]) to the data to examine trends, using species richness over the whole landscape as a measure of biodiversity.

3.   RESULTS & DISCUSSION

Results are shown Figures 1, 2 and 3.

Although GAMs sometimes tend to overfit the data, fitting curves that could have fewer turning points, it is clear both from the curves and the data they fit that the relationship between incentive and biodiversity is far from trivial. A naïve expectation would be that more money buys more biodiversity. The relationship, however, is not linear. There seem to exist thresholds of expenditure, which relate to habitat provision, below which landscape-scale biodiversity remains low (i.e. many species extinctions occur, because their habitat is not sufficiently common). Spending money below such thresholds thus seems ineffective if the objective is saving species from extinction, and finding such thresholds is therefore important. It is not clear that fixed incentives or even mechanisms such as auctions would be able to find such thresholds, and schemes tend to be aimed at the individual farmer rather than the landscape scale. Hence they might be "efficient" in an economic sense in the short term, but are probably ineffective in the long term at maintaining landscape-scale species diversity. (Exploring these issues is the possible subject of future work.) A more sophisticated model would also recognise that there are limits to biodiversity, therefore suggesting a sigmoidal shape to the relationship. Some of the results do support such a shape, but others do not. Of particular interest are those results showing biodiversity reaching a peak at a point before maximum incentive/expenditure is reached—these suggest that biodiversity is not necessarily a monotone increasing function of incentive.

Findings from the conservation literature have already highlighted that if grazing intensity is too low, there can be a negative impact on biodiversity Wallis de Vries et al. [1998] and this is reflected in the set up for these simulations through the lowest intensity grazing land use (GL1) providing habitat for a competitor species (C) that outcompetes species G1, G2 and G3. However, in these simulations, the Government agent is assumed to know about this, and provides incentives for GL2 rather than GL1.
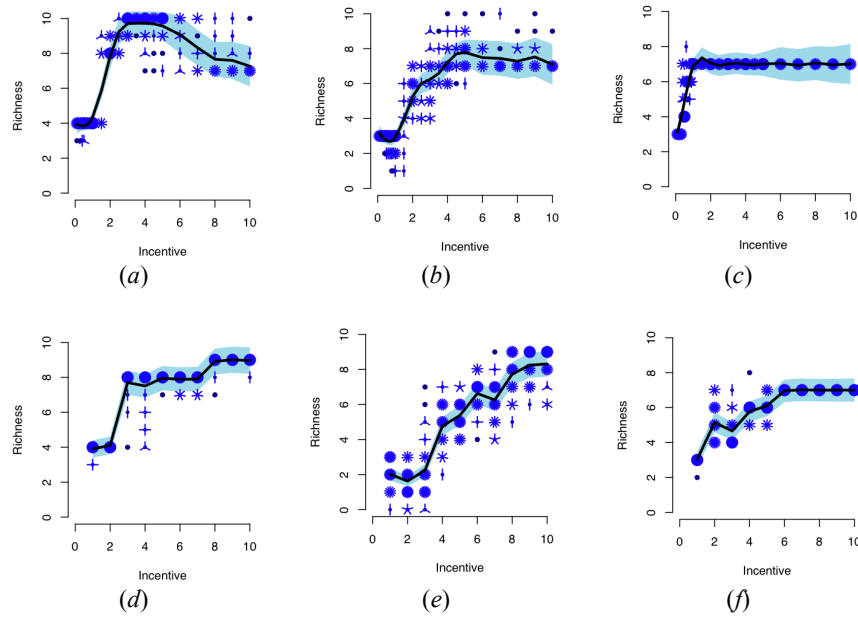
Figure 1. GAM fits of Incentive (Reward/Ratio for Cluster-*x* governments, Reward for others) to Richness for various families of runs, showing the range of behaviour found. The GAM is shown as a solid line with a shaded area for 95% confidence intervals. The raw data are shown as 'sunflower plots'—a single result at a point is shown with a small dot, otherwise, if multiple results have the same point, then one 'petal' of the sunflower is shown for each result. For each lettered subfigure, the government class, market, break-even threshold, aspiration, and deviance explained by the GAM are given in order: (*a*) Cluster-Activity, flat, 25, 5, 93%; (*b*) Cluster-Activity, var2, 30, 1, 86%; (*c*) Cluster-Outcome, var2, 30, 5, 82%; (*d*) Activity, flat, 25, 5, 94%; (*e*) Activity, var2, 25, 1, 80%; (*f*) Outcome, var2, 30, 1, 87%. Each graph shows the results from 600 runs.
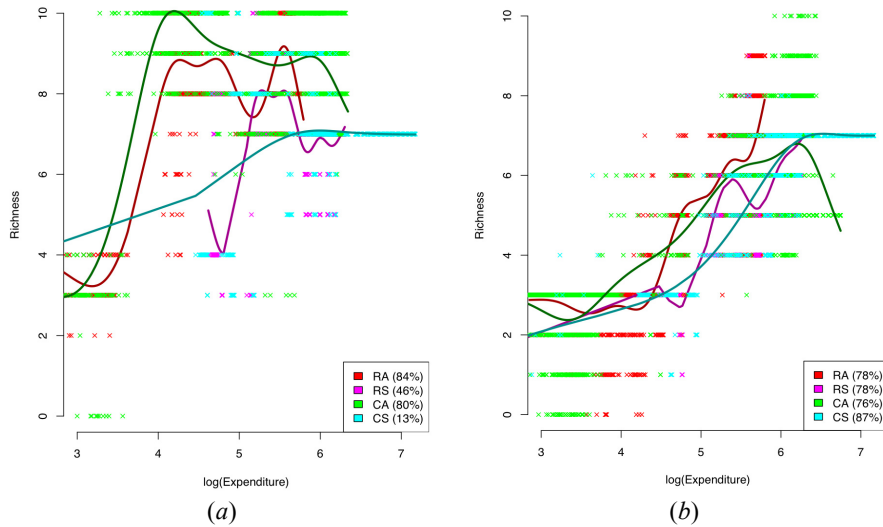

Figure 2. GAM fits of log(Expenditure) to Richness for (*a*) the flat market runs (*b*) the var2 market runs. GAMs for each Government class are done separately, and shown using a solid line in a different colour: RA = Activity, RS = Outcome, CA = Cluster Activity, CS = Cluster Outcome. The raw data are shown as a scatter plot. Percentages in the legend refer to the deviance in the data explained by the GAM.
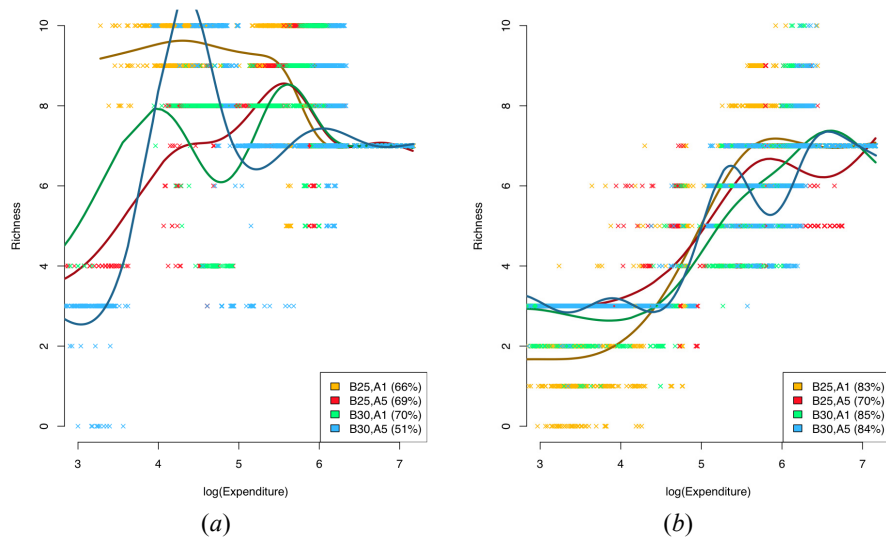
Figure 3. GAM fits of log(Expenditure) to Richness for (*a*) the flat market runs (*b*) the var2 market runs. GAMs for each combination of break-even threshold and aspiration are done separately, and shown using a solid in a different colour. The raw data are shown as a scatter plot. Percentages in the legend show the deviance in the data explained by the GAM.

A more detailed analysis of the runs themselves reveals two mechanisms by which higher expenditure can result in lower species richness. What matters in terms of satisficing for farm decision-making is the sum of the break-even threshold and the profit aspiration. With high break-even threshold plus aspiration and high incentive, land managers switch immediately from GL1 to AL1, the latter being the low-intensity arable land use that is incentivised. This provides habitat for five species; if all land managers adopt AL1, then this is the maximum richness achievable. With lower break-even threshold plus aspiration and high incentive, the land managers effectively subsidise continued use of GL1 with the incentives they receive for AL1; i.e. those land managers using AL1 and GL1 on two parcels will make enough money to achieve their aspirations. Here, C causes extinction of G1-3 through competition, and the maximum achievable richness is seven. In both cases, lower incentives make GL3 more attractive, providing a refuge for G1-3; however, if the incentives are not too low, AL1 and GL2 will sometimes satisfice, providing enough habitat for species besides C to enable them to persist in the landscape. In some cases it is even possible for farmers to cross-subsidise GL1, and a species richness of ten is observed. Such situations are possible because of various aspects of the land managers' decision-making algorithm: (a) satisficing of land use choice; (b) viewing profit at the farm-scale when considering aspirations; (c) an assumption that land uses of which the manager has no experience will exactly meet aspirations. Further analysis of simulation runs also revealed that the case retention time has an observable effect on land use dynamics, and hence under certain conditions on biodiversity. Whether these aspects of decision-making are artefactual or not, it is clear from our results that the success of an agri-incentive scheme is sensitive to the way farmers make decisions in subtle ways. Qualitative research of Scottish farmers has revealed that farmer identity can play a significant role in determining land use activity, and in particular, as shown by Burton [2004], a predominantly productivist mindset means that conservation activities are 'not farming'.

The results also show that the way the incentives are distributed by the government affect the outcome. The main turning point in government expenditure from lower to higher biodiversity changes according to the approach used. In a companion paper [Polhill et al., 2010], the possibilities of using adaptive control techniques to navigate the space of possible incentive schemes are given an initial investigation.

In Scotland, incentives for biodiversity are currently delivered as part of the Scottish Rural Development Programme, to which farmers make bids for funds. In our simulations,

incentives are aimed solely at biodiversity, and anyone performing an awardable activity gets the incentive. In the SRDP, farmers also receive incentives to assist with rural aspects of other policy goals, including economic and social sustainability, and farmers bid for funds that are constrained by a limited budget. Modelling both these aspects, and the potential impact on biodiversity, are the subject of future work.

4. CONCLUSION

We have shown that there are critical turning points in biodiversity delivered for incentive invested, and that, although these turning points depend partly on incentive scheme delivery, they also depend on other aspects of the ecological, economic and social agricultural environment that would be very difficult for a government to ascertain. In a companion paper to this, we consider some early experiments with methods by which governments could adjust incentives so as to achieve a biodiversity goal, such as that set by any follow-on to the Biodiversity 2010 agenda.

ACKNOWLEDGMENTS

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