Insights from Ising models of land-use under economic coordination incentives

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Abstract

Two Ising models are presented, of land-use induced by conservation payment schemes. Such payments reward the application of conservation measures on private land to conserve biodiversity. To counteract the fragmentation of species habitat, coordination incentives (CI) have been proposed that reward the spatial agglomeration of conservation efforts. The two main types of CI, the agglomeration bonus (AB) and the threshold bonus (TB), are considered. Depending on their design parameters, both scheme are shown to cause bistability in the induced land-use pattern, reflecting a coordination problem faced by the individual landowners.

Key words

agglomeration bonus, biodiversity conservation, coordination incentive, Ising model, threshold bonus.

Highlights

- An Ising-type agent-based model of coordination incentives is developed.
- The expected proportion of land conserved for biodiversity is calculated.
- The model behaviour reflects the coordination problem of the landowners.
- Attempts are made to establish references to real land-use systems.

1 Introduction

The application of methods and models from physics in economics has a long tradition [1]. From the very beginning of economics as a science, protagonists like Adam Smith and Léon Walras had been influenced by concepts of classical mechanics. Later examples include the modelling of the dynamics of the prices of financial assets, implying important contributions to financial economics [2,3].

More recently, another cross-disciplinary field has emerged: multi-agent systems [4–6]. The complexity of agents here ranges from perfectly informed rational profit maximisers (*homines economici*) to complex decision makers that sense and interact with their environment [1,7].

Within this research field, lattice models in which each agent occupies a node and interacts with its Euclidian neighbours have gained quite some popularity [8,9]. Within the social sciences the most famous example is probably Schelling's [10] model of social segregation where an agent's decision to stay or move to another site depends on the proportion of like agents in the focal agent's neighbourhood. Another application are opinion or voter models [11,12] in which each agent can have one out of two mutually excluding opinions. The opinion of an agent depends both on the agent's individual characteristics and on the opinions of the neighbouring "peers". Not surprisingly do these models have a strong similarity with Ernst Ising's model of the ferromagnet [13].

The present paper adds a new application of an Ising model in a socio-economic context, focusing on land use and biodiversity conservation. It is motivated by the fact that the loss and fragmentation of habitat is a major driver of the ongoing world-wide decline of biodiversity, and instruments are needed to halt these processes. Since on private lands biodiversity conservation measures can largely be implemented only on a voluntary basis, landowners must be incentivised to carry out these measures on their land.

The dominant policy world-wide here are conservation payments that are offered to conserving landowners who – if they are rational profit maximisers – carry out the conservation measure to receive the payment if and only if that exceeds the costs or profit losses associated with the conservation measure.

Yet, for reasons of practicality and equity, these payments are usually spatially homogenous, so that the spatial allocation of the induced conservation measures simply depends on the spatial distribution of the conservation costs which is often not known to the conservation agency and can even less so be controlled by it. Consequently, with homogenous payments the agency has no control over the spatial allocation of the conservation measures – which strongly limits the use of this instrument to counteract habitat fragmentation.

To allow for a better spatial targeting of conservation efforts, coordination incentives [14] have been proposed that reward the spatial coordination of land-use decisions, and in particular the spatial agglomeration of conservation measures. The first type, which has been analysed most frequently, is the agglomeration bonus (AB) by Parkhurst et al. [15] in which the conservation of a land parcel earns a (spatially homogenous) base payment, which is accompanied by a bonus for each conserved land parcel in the neighbourhood around the focal land parcel (for theoretical and applied modelling studies of the AB, see [16–21]; for empirical analyses, see [22–24]; for experimental analyses, see [15,25–28]).

Typical levels for the base payment here are of the order of a few hundred up to around one thousand €/ha [29,30], while typical bonus levels are about one tenth of that [29,31]. The number of land parcels per neighbourhood is eight in Panchalingan et al. [29], and most habitat connectivity projects ("Vernetzungsprojekte") documented by BÖA [32] for Switzerland have perimeter areas of the order of one thousand hectares (with a few projects having areas of a few hundred and a few having about ten thousand hectares).

The second main type of coordination incentive is the threshold bonus (TB) [33–35]. Here a bonus is not paid for each conserved land parcel in the focal land parcel's neighbourhood, but it is paid if the proportion of land parcels in a predefined region (in which the focal land parcel is situated) is exceeded. Connectivity projects in Switzerland, e.g., involve thresholds of 12 to 15 percent [36], typical sizes for focal regions were provided above. A variant of the TB is the threshold payment which can formally be regarded as a TB with zero base payment [37–40].

The AB has been shown to exhibit a strong similarity with the Ising model of the ferromagnet [16,20]. However, as I will show in the present paper, there are some differences which appear to have been overlooked in the cited papers. After this analysis I will explore outcomes of the AB as a function of the scheme design and the economic conditions in the modelled land-use system. In the same manner I will explore the land-use pattern emerging under a TB scheme which to my knowledge has not yet been analysed systematically. Below, the land-use models under coordination incentives will be introduced and analysed. The main results then are summarised and discussed.

2 Analysis

2.1 The land-use model

A stylised landscape is considered with N land parcels $i = 1, \ldots, N$, each of which can be used for economic purposes (such as profit-oriented agriculture) ($x_i = 0$) or for biodiversity conservation ($x_i = 1$). The economic land use, $x_i = 0$, generates an economic profit $c_i = c_0(1 + \varepsilon_i)$ where ε_i is an i.i.d random number with mean zero and standard deviation σ (so that σ is the relative standard deviation of the c_i). Conservation, $x_i = 1$, generates no profit (so c_i is the opportunity cost of conservation) but is rewarded by a payment p_i. In their comprehensive review of coordination incentives, Nguyen et al. [14] distinguish three different designs of p_i:

$$p_i = \begin{cases} p_0 + b\sum_{j\in L_i} x_j & \text{Agglomeration bonus} \\ p_0 + b\Theta\left(\sum_j x_j - Nm_c\right) & \text{Threshold bonus} \\ p_0\Theta\left(\sum_j x_j - Nm_c\right) & \text{Threshold payment} \end{cases}, \qquad (1)$$

where $\Theta(x) = 1$ for $x > 0$ and $\Theta(x) = 0$ otherwise.

In the agglomeration bonus scheme (AB) [15], each conserved land parcel i earns a base payment p_0 plus a bonus b for each conserved land parcel j in the neighbourhood L_i around land parcel i, where L_i (of magnitude L) denotes the set of indices j in this neighbourhood.

The interaction between landowners i and j is symmetric so that $i \in L_j$ implies and is implied by $j \in L_i$. A typical choice used in many of the papers cited in the Introduction is that L_i is the von-Neumann neighbourhood of the four land parcels to the north, south, east and west to land parcel i (e.g., [25]) or the Moore neighbourhood of the eight land parcels surrounding land parcel i (e.g., [29]).

Under the threshold bonus (TB), each conserved land parcel earns a base payment p_0, plus a bonus if the proportion $\Sigma_i x_i/N$ of conserved land parcels in the whole region exceeds some target value m_c. In the threshold payment [38] a conserved land parcel earns a payment p_0 if and only if m_c is exceeded. It is formally identical to a TB with zero base payment and therefore will not be considered explicitly below.

The economic benefit accruing from land parcel i under each land-use type, $x_i = 0$ and $x_i = 1$, then is

$$V_i = p_i x_i + (1-x_i)c_i = \begin{cases} x_i\left(p_0 + b\sum_{j\in L_i} x_j\right) + c_0(1+\varepsilon_i)(1-x_i) & \text{AB} \\ x_i\left(p_0 + b\Theta\left(\sum_{j\in L_i} x_j - Nm_c\right)\right) + c_0(1+\varepsilon_i)(1-x_i) & \text{TB} \end{cases} \quad (2)$$

Each landowner i chooses the land use x_i that maximises their expected benefit

$$E[V_i] = E[p_i] + (1-x_i)c_i = \begin{cases} x_i\left(p_0 + bE\left[\sum_{j\in L_i} x_j\right]\right) + c_0(1+\varepsilon_i)(1-x_i) & \text{AB} \\ x_i\left(p_0 + bE\left[\Theta\left(\sum_{j\in L_i} x_j - Nm_c\right)\right]\right) + c_0(1+\varepsilon_i)(1-x_i) & \text{TB} \end{cases} \quad (3)$$

where $E[]$ is the expectation operator.

2.2 Analysis of the agglomeration bonus (AB) scheme

The analysis of the AB scheme is similar to that in Phan et al. [41] of a social system with interacting individuals). Each landowner knows the size of the base payment p_0, the bonus b and the own economic profit (ε_i). However, s/he does not know the economic profits (ε_i) of their individual neighbours' but only their probability distribution as introduced above. Consequently, at the time of decision making the landowner does not know (with certainty) the neighbours' land uses x_j. The simplest model by which a landowner i would decide on the land use x_i is that s/he formulates expectations $E[x_j]$ on the land uses x_j in the neighbourhood L_i.

The expectation of the sum in the first line of eq. (3) then is the sum of the expectations $E[x_j]$ of the neighbours' land use:

$$E\left[\sum_{j\in L_i} x_j\right] = \sum_{j\in L_i} E\left[x_j\right] \quad (4)$$

Using a mean-field approach, the expectation E[x_j] is assumed to be the same for all neighbours:

$$E\left[x_j\right] = m, \forall j \in L_i \quad (5)$$

Given the distribution of landowner i's economic profit ε_i, the probability of observing $V_i(x_i = 1) > V_i(x_i = 0)$, so that the landowner i would choose $x_i = 1$, is

$$\Pr(x_i = 1) = \Pr\left(p_0' - 1 + b'Lm \geq \varepsilon_i\right) \quad (6)$$

with the dimensionless variables $p_0' = p_0/c_0$ and $b' = b/c_0$. Assuming that the ε_i are distributed logistically with

$$\Pr(\varepsilon_i \leq z) = \frac{1}{1+\exp\left\{-\beta z\right\}}, \quad \beta = \pi / (3^{1/2}\sigma) \quad (7)$$

we obtain

$$\Pr(x_i = 1) = \frac{1}{1+\exp\left\{-\beta\left(p_0' - 1 + b'Lm\right)\right\}} \quad (8)$$

Since the same applies to all landowners in the system, which except for the level of ε_i are identical,

$$\Pr(x_i = 1) = E\left[x_i\right] \quad (9)$$

In the present mean-field approach the landowners' expectations $E[x_j]$ equals the mean $\langle x_j \rangle$ over the random x_j in the model, allowing to equate eqs. (5), (8) and (9) to obtain

$$m = f(m) \equiv \frac{1}{1+\exp\left\{-\beta\left(p_0' - 1 + b'Lm\right)\right\}} \quad (10)$$

Figure 1 shows selected solutions of eq. (10) which below will be denoted by m^*.

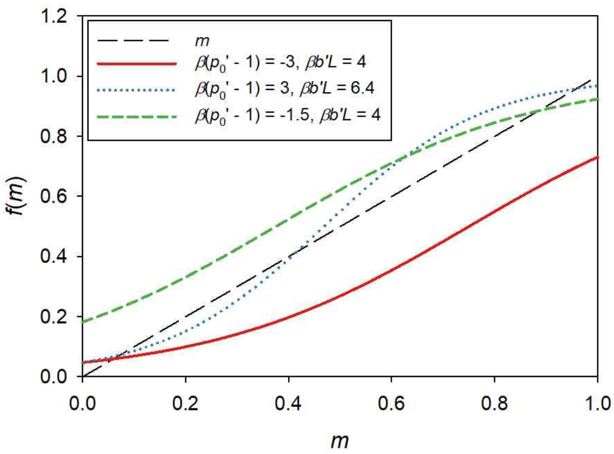


Figure 1: Left hand side (black dashed line) and right hand side (other colours) of eq. (10). The colours represent three different combinations of scaled base payment and scaled bonus.

Equation (10) is similar to the self-consistency equation for the level of magnetism obtained in the Ising model of the ferromagnet. Indeed, based on eq. (3) one could formulate a Hamiltonian for the land-use system

$$H\{x_i\} = -(p_0' - 1)\sum_{i=1}^{N} x_i - b'\sum_{i=1}^{N}\sum_{j\in L_i} x_i x_j \qquad (11)$$

with external field $p_0' - 1$ and interaction strength b'. The well-known mean-field calculations (but with $x_i \in \{0, 1\}$) yield for the probability of observing a particular land use x_i:

$$\Pr(x_i) = \frac{x_i \exp\left\{\beta\left(p_0' - 1 + b' L m\right)\right\}}{\exp\left\{\beta\left(p_0' - 1 + b' L m\right)\right\} + \exp\{0\}} \qquad (12)$$

which confirms eq. (8) and implies eq. (10).

One should note the difference between the present model and an Ising spin model at a given temperature $1/\beta$. Although the random component of the economic profit, ε_i, plays a similar role and is treated formally in the same way as the thermal fluctuations in the ferromagnet, there are actually no dynamics in the present model, since the economic profits do not change over time (for a related model with changing economic profits, see e.g. [16]).

The relation with the standard Ising model is more easily seen by making a change of variable, going from $x_i \in \{0, 1\}$ to the standard spin variables, $s_i = 2x_i - 1 \in \{-1, +1\}$. The Hamiltonian in eq. (11) becomes

$$H\{s_i\} = \frac{1}{2}\left[-(p_0' - 1 + b'L)\sum_{i=1}^{N} s_i - \frac{b'}{2}\sum_{i=1}^{N}\sum_{j\in L_i} s_i s_j\right] + \text{const.} \quad (13)$$

This Hamiltonian is the one of a standard Ising model with coupling constant $J = b'/2$, and external field $h = p_0' - 1 + b'L$. These two parameters are thus not independent, in particular the larger the coupling J the larger the external field h. Thus, for $J = 0$ and $p_0' - 1 = 0$ (implying $h = 0$) both states ($s_i = +1$ and $s_i = -1$) are equally likely, implying $m' \equiv E[s_i] = 0$. From here an increase in J leads to non-zero m', but the system is biased in favour of $s_i = 1$, so there is only a single solution with $m' > 0$. This can be seen from the self consistency equation associated with eq. (13) with $p_0' - 1 = 0$:

$$m' = g(m') \equiv \tanh\left\{\beta\left(b'L + b'Lm'/2\right)\right\} \quad (14)$$

Since g has a single root at $m' = -2$, and $dg/dm' \leq 1/2$ for all m', there can be no negative solution to eq. (14).

Returning to eq. (10), if this equation has three roots, the largest and smallest ones correspond to stable equilibria, separated by the intermediate, unstable, one. Figure 2 shows the stable equilibrium points m^* as functions of base payment and bonus and inverse economic profit variation β. For fixed β they increase with increasing base payment p_0 and bonus b (Fig. 2a). For $\beta b'L > 5$ and sufficiently small $\beta(p_0' - 1)$ (above the near-horizontal line and left to the near-vertical line) there are two equilibria, one close to zero and the other one close to one. For larger $\beta(p_0' - 1)$ there is only a single equilibrium, and the transition between these two regimes is sharp.

The effect of an increase in the inverse economic profit variation, with base payment and bonus fixed, can be read from Fig. 2 by increasing both $\beta(p_0' - 1)$ and $\beta b'L$, keeping their ratio fixed which is exemplified by moving along one of the white dashed lines. For $p_0' < 1$ (i.e. base payments below the mean economic profit) and very small bonus levels a decrease in the profit variation (an increase in β), reduces the base payment relative to the range of the economic profits and hence the proportion m^* of conserved land parcels. Conversely, for larger p_0' or b' an increasing β increases the total payment p_i (the sum of base payment and bonus: eq. (1)) relative to the range of economic profits, which increases m^*. An interesting case is that of $p_0' < 1$ and medium levels of b', where m^* is around 0.5. Here an increase in β has only little effect on m^* because of two opposing effects: on the one hand the base payment declines relative to the range of economic profits, but the bonus increases relative to that range.

For bonus levels of about $\beta b'L < 5$ there is only a single stable equilibrium m^*. It is near zero for small products of base payment and inverse profit variation, $\beta(p_0' - 1) < -2.5$, and gradually increases with increasing $\beta(p_0' - 1)$ until it reaches a value of near one for $\beta(p_0' - 1) > 1$.

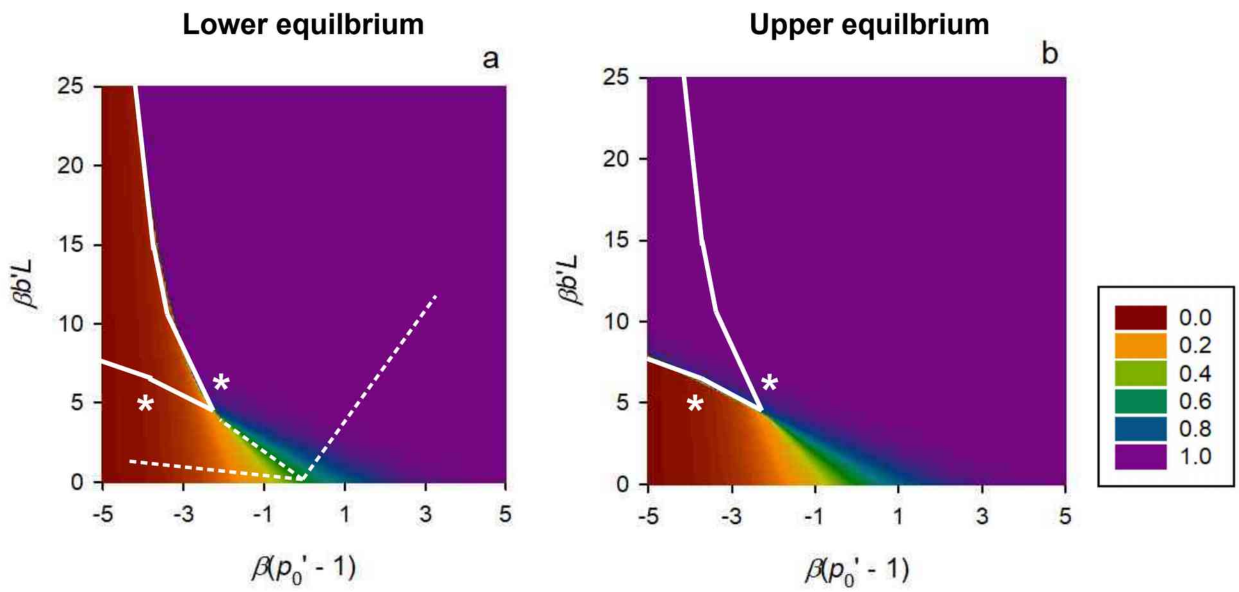


Figure 2: Equilibrium value m^* (proportion of conserved land parcels in the system), by colour scale between zero (brown) and one (purple), as a function of scaled base payment $\beta(p_0' - 1)$ and scaled bonus $\beta b'L$. If there are two stable equilibria the smaller one is given in panel a and the larger one in panel b (area in the upper left, encompassed by the while lines). If there is only a single equilibrium its value is given in both panels. The dashed lines represent points of fixed ratios between $(p_0' - 1)$ and $b'L$, with β being varied. For the meaning of the white asterisks, see section 2.4.

2.3 Analysis of the threshold bonus (TB) scheme

In the TB scheme the probability of land parcel i being conserved depends on whether the proportion m of conserved land parcels exceeds the target m_c or not:

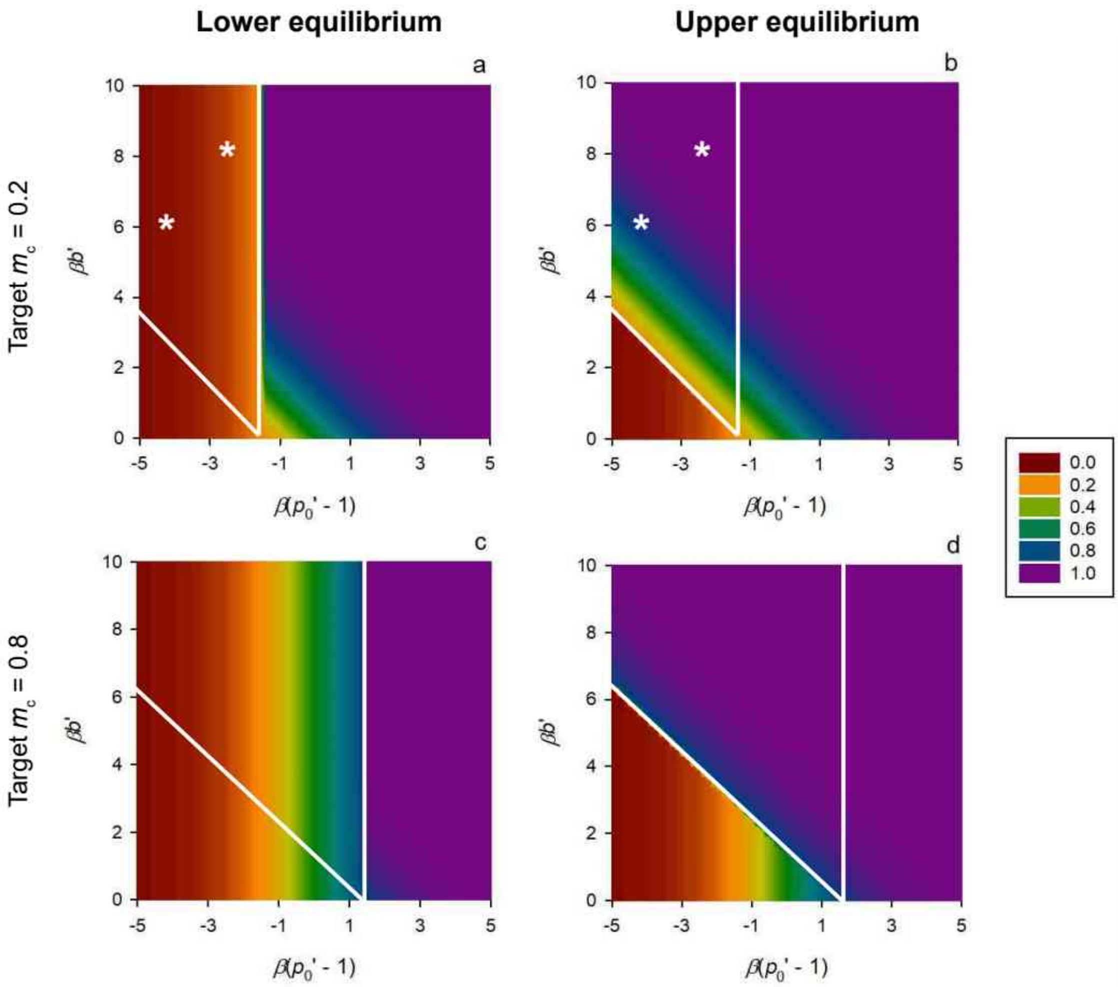
$$m \equiv \Pr(x_i = 1) = \begin{cases} \dfrac{1}{1+\exp\left\{-\beta\left(p_0{}'-1\right)\right\}} & m \le m_c \\ \dfrac{1}{1+\exp\left\{-\beta\left(p_0{}'-1+b'\right)\right\}} & m > m_c \end{cases} \tag{15}$$

Equation (15) implies that for small b' below some critical level b_c, the target m_c is not reached and m has the rather small value given in the first line of eq. (15). Above b_c the target is exceeded and m jumps to the value given in the second line. The value of b_c is given by equating the second line of eq. (15) with m_c, which yields

$$b_c = 1 - p_0{}' - \frac{1}{\beta}\ln\frac{1-m_c}{m_c} \,. \tag{16}$$

Quantity b_c increases with decreasing base payment p_0 and increasing conservation target m_c. The influence of β is ambiguous. For $m_c < 0.5$ the ln in eq. (16) is positive and b_c increases with increasing β; while the opposite is observed for $m_c > 0.5$. Due to the inverse relationship between β and the economic profit variation σ, increasing σ reduces b_c under a low target, and increases b_c under a high target. The result is intuitive, because at large profit variation a low target can be achieved even with a small bonus, while a high target is easily missed unless the bonus is large. It implies that that the size of the target has a non-trivial influence on the system behaviour.

Figure 3 shows that for small bonuses ($\beta b'$) and small base payments ($\beta(p'_0 - 1)$ (left-below the downward-sloping white line which represents eq. (16)) the proportion of conserved land parcels m^* is rather small and only increases as the base payment reaches levels near the mean conservation cost ($p_0' \approx 1$). Right to the vertical while line (which represents the critical p_0 required to reach the conservation target m_c at zero bonus) m^* is large and generally near one. For large $\beta b'$ and small $\beta(p'_0 - 1)$ (above the downward-sloping line and left to the vertical line) there are two equilibria, one large m^* and one small m^*. Interestingly, for small m_c (panels a and b) the smaller of the two m^* is near zero in the entire upper left area of the panels and the larger one increases with increasing $\beta(p'_0 - 1)$ and $\beta b'$; while for large m_c (panels c and d) the upper m^* is near one in the entire upper left area and the smaller one increases with increasing $\beta(p'_0 - 1)$.



Lower equilibrium
Upper equilibrium
a
b
c
d
Target m_c = 0.2
Target m_c = 0.8
$\beta b'$
$\beta(p_0' - 1)$
10
8
6
4
2
0
-5
-3
-1
1
3
5
0.0
0.2
0.4
0.6
0.8
1.0

Figure 3: Equilibrium value m^* (proportion of conserved land parcels in the system) by colour scale between zero (brown) and one (purple) in the TB scheme, as a function of scaled base payment $\beta(p_0' - 1)$ and scaled bonus $\beta b'$. Conservation target $m_c = 0.2$ (panels a and b) and $m_c = 0.8$ (panels c and d). As in Fig. 2, if there are two stable equilibria the smaller one is given in the respective left panel and the larger one in the respective right panel (upper left areas, encompassed by the white lines). If there is only a single equilibrium it is given in both panels. For the meaning of the white asterisks, see section 2.4.

2.4 Numerical examples

Together with some arguments of plausibility, Panchalingam et al. [29] and BLW [30,36] allow for some crude, partly hypothetical, parameterisation of the models. For normally distributed conservation costs, a relative standard deviation of $\sigma = 0.2$ implies that the upper 2.5-percentile of the costs is about 2.5 times higher than the lower 2.5-percentile, which is a quite reasonable estimate and agrees, e.g., with Fig. 3c in Gerling et al. [42]. With eq. (7) this corresponds to $\beta \approx 10$.

If a proportion q of N land parcels should be conserved by a spatially homogenous payment p_0 (i.e. in the absence of any bonus), this payment must exceed the cost of the most costly land parcel of those qN least costly land parcels. Assuming the conservation costs are normally distributed (approximated by eq. (7)), payment levels p_0 of $c_0(1 - 2\sigma)$ and $c_0(1 - \sigma)$ induce the conservation of 2.5 and 16 percent of all and parcels, respectively, which appears like a reasonable estimate for conservation payment schemes [43]. With the above $\sigma = 0.2$ and $\beta \approx 10$, the two payment levels equal $\beta(p_0/c_0 - 1) \approx -4$ and $\beta(p_0/c_0 - 1) \approx -2$, respectively.

As noted in the Introduction, a reasonable estimate for the bonus b in an AB scheme may be one tenth of the base payment. With the above estimates and $L = 8$ we obtain $\beta bL/c_0 \approx 5$ for the small payment level and $\beta bL/c_0 \approx 6.4$ for the larger payment level. The first level implies a very small proportion of conserved land parcels m^* and the second one a large m^* (left and right asterisks in Fig. 2a).

The connectivity bonuses listed in BLW [30] are generally of the magnitude of the corresponding base payments. Unfortunately, the spatial scope of these bonuses is not clear. If one assumes that it refers to those projects that involve a threshold (12 to 15 percent, which is rather close to the value of 0.2 chosen in Fig. 3a) this would provide an estimate on the bonus b in the TB scheme, such that $b \approx p_0$. For the two above levels of the base payment, $\beta(p_0/c_0 - 1) = -4$ and $\beta(p_0/c_0 - 1) = -2$, with $\beta = 10$ one would obtain $\beta b/c_0 = \beta p_0/c_0 = 6$ and 8, respectively. According to Fig. 3a (asterisks) these schemes would induce rather high levels of m^*.

3 Discussion

Two Ising models of the land-use induced by coordination incentives were analysed: an agglomeration bonus (AB) that financially rewards conservation of a land parcel (grid cell) by a base payment p_0 plus a bonus b for each conserved land parcel in the neighbourhood; and a threshold bonus (TB) in which the bonus b is paid if the proportion of conserved land parcels in the region exceeds a given target m_c. If a land parcel is used "economically", such as profit-maximising agriculture, it earns a profit that varies among land parcels in an uncorrelated manner. The distribution of the profits was modelled by the logistic distribution whose slope β is inversely related to the standard deviation of the economic profits.

The models were analysed within wide ranges of the model parameters that well encompass typical values of real conservation schemes (section 2.4). In the analysis of the AB scheme, three regimes of model behaviour could be identified (Fig. 2). The first is obtained for rather small base payments p_0 and small bonus levels b which leads to very small proportions m^* of conserved land parcels. To obtain higher m^*, the base payment p_0 has to be increased considerably to induce a high proportion of conserved land parcels m^* (note that the required p_0' of about 0 in Fig. 2 represents a base payment equal to the average conservation cost in the model region, which would imply a large $m^* = 0.5$ even at a zero bonus).

From this first regime, by increasing the bonus there is a sharp transition into a second regime in which there are two stable solutions for m^*, a rather small and a rather large one (upper left marked area in Fig. 2). And from there, an increase in the base payment leads, via another sharp transition, into the third regime in which there is a single equilibrium with large m^*.

These three regimes reflect the three types of game that can be formed by varying the scheme parameters p_0 and b. For the case of two players in which conservation ($x = 1$) incurs a cost c but earns the base payment p_0 which is increased by the bonus b if the other player conserves, as well, Table 1 shows the payoff V_1 (eq. (3)) of player 1 in dependence of the own and player 2's land use.

Three game types can be formed. For $p_0/c + b/c < 1$ the economic use ($x = 0$) is the dominant strategy, which corresponds to regime 1 above. For $p_0 > c$ conservation ($x = 1$) is the dominant strategy, which corresponds to regime 3 above. While the condition $1 – b/c < p_0/c < 1$ leads into a coordination game [42,43] in which each player maximises his/her payoff by choosing the same land use as the other player.

Table 1: Payoff V_1 of player 1 in a 2-player game based on eq. (3).

	$x_2 = 1$	$x_2 = 0$
$x_1 = 1$	$p_0 + b – c$	$p_0 – c$
$x_1 = 0$	0	0

The two associated Nash equilibria, $x_1 = x_2 = 0$ and $x_1 = x_2 = 1$, correspond to the two solutions of small and large m^* in the second regime of Fig. 2. Overcoming the coordination problem and inducing the agents into the coordinated equilibrium with many or all of them playing $x_i = 1$ is a major challenge in coordination incentives (e.g., [25,27]). One reason for this is that conservation is a risky choice whose payoff depends on the uncertain action(s) of the other agent(s). Useful policy measures addressed in the two cited articles are to gradually build up the network of conserved land by a sequence of conservation contracts (in a way, moving from a static game to a dynamic or iterated game) and facilitating communication among the agents.

The land use induced by the TB scheme is similar to the behaviour of Schelling's [44] dying-seminar model in which the attendance of a seminar depends on the excess of a critical mass of students [8,9]. The main message from the present model analysis is that base payment and bonus must exceed certain thresholds in order to achieve moderate or large levels of conservation m^*. Both scheme parameters are compensatory in the sense that the larger the one parameter, the smaller the threshold value in the other.

Similar to the AB scheme, there are three different regimes of model behaviour. For small base payments and small bonuses there is a single solution with small m^*; for large base payments there is a single solution with large m^*; while for small base payments and large bonuses there are two stable equilibria m^*, reflecting a coordination problem as in the AB scheme.

Comparing AB and TB, both schemes are subject to a coordination problem with two alternative stable solutions for the proportion of conserved land parcels if the base payment is small and the bonus large – which is the situation where conservation is most risky for the landowners compared to economic use. One difference between the two schemes is that the behaviour of the m^* in the AB scheme in that bistable regime is rather simple: either m^* is close to zero or close to one, while in the TB scheme one of the two stable m^* depends on the base payments and/or the bonus. The second major difference is that in the TB scheme the boundaries between the three discussed regimes of system behaviour (white lines in Fig. 3) are "straight" and determined exogenously, while in the AB scheme they have a more complicated shape and are determined endogenously from the interactions of the landowners in response to the scheme parameters.

The main limitation of the present study is its use of a mean-field approach. This includes, among other things, the assumption that all landowners all make the same assumption about the land use in their neighbourhood (eq. (5)) and that the (coordination) game played with the neighbours is a one-shot game, so there is no learning [40] nor informed expectations about the neighbours' future land use [45] nor evolutionary or iterated game playing [46]. As a consequence, the present study can only determine possible endpoints of the land-use dynamics but not which end point is actually reached from a given initial land-use pattern and how long it takes to reach that endpoint. Future research may focus on these transient dynamics, assuming more complex agent decision behaviour, including learning, strategic behaviour and communication. Nevertheless, even the analysis of the endpoints allows for some useful insights that may inform policy makers in the design of coordination incentives.

Acknowledgements

I am grateful for comments by Christian Wissel and Volker Grimm on an earlier version of this manuscript. Two anonymous reviewers greatly helped in the revision of this manuscript.

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