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Abstract

Making conservation payment schemes permanent so that conservation efforts are retained even after the payment has been stopped, is a major challenge. Another challenge is to design conservation so that they counteract the ongoing spatial fragmentation of species habitat. The agglomeration bonus in which a bonus is added to a flat payment if the conservation activity is carried out in the neighbourhood of other conserved land, has been shown to induce the establishment of spatially contiguous habitat. I the present paper we show, with a generic spatially explicit agent-based simulation model, that the interactions between the landowners in an agglomeration bonus scheme can lead to hysteresis in the land-use dynamics, implying permanence of the scheme. It is shown that this permanence translates into efficiency gains, especially if discount rates are low and the spatial heterogeneity of conservation costs is high.

Key words: Agent-based model, agglomeration bonus, conservation payment, land use, permanence.

Introduction

Lock-ins usually describe states in social and social-ecological systems (SES) which are undesired, such as poverty traps (Dornelles et al. 2020) or the carbon lock-in (Unruh 2020). But what if environmental policies could lead SES into desired states in which they are locked, without further costly interventions? This could make environmental protection more cost-effective.

Lock-ins are often the result of collective phenomena occurring in complex systems. A classical example is ferromagnetism. Ferromagnetic materials such as iron can be made magnetic by applying an external magnetic field. Due to interactions in the ferromagnet's atomic structure the magnetism even prevails after the external field is switched off, a phenomenon referred to as hysteresis.

Hysteresis has been observed in natural and social systems which all have in common that individuals interact within some network and are affected by external drivers, such as the growth rate of a renewable natural resource (Sugiarto et al. 2015), the salary paid by an employer (Rios et al. 2017), the reproduction number (modifiable, e.g., through a vaccination program) of spreading contagious diseases (Chen et al. 2019), environmental conditions experienced by species populations (Cai et al. (2020) and the predisposition to adopt a particular social behaviour (Wiedermann et al. 2020). As in the ferromagnet, the interactions in the networks constrain the behaviour of the individuals, providing the system with the observed inertia to the change in the external drivers.

The hysteresis in ferromagnets can be explained by the interactions between the electron spins ("magnetic dipols"). The application of the external field aligns these dipols parallel to each other. Within this configuration the interaction of each dipol with its neighbours prevents it from leaving the parallel alignment – even if the external field is switched off. This effect is often described by the Ising model which assumes that a dipol can either point up or down (Chaikin and Lubenski 1995).

Here we show, using a similar model, that hysteresis and implied lock-in can also be triggered in SES, where the behavior of human actors corresponds to the orientation of the magnetic dipols in the ferromagnet, and the drivers affecting this behaviour correspond to the external magnetic field. The actors we are representing in the model are landowners who can manage their land either for economic purposes like intensive agriculture ("dipol down") or for the conservation of biodiversity ("dipol up"). The external driver is a conservation payment offered to landowners who conserve their land, as it is applied world-wide to halt and reverse the loss and fragmentation of natural or semi-natural habitat on private lands (Khanna and Ando 2009, Kleijn et al. 2011, Engel 2016).

A major challenge in the design of such payment schemes is the spatial heterogeneity in the costs associated with the conservation measures (Moxey et al. 1999, Smith and Shogren 2001, Wätzold and Drechsler 2005, Polasky et al. 2014). In order to be cost-effective this spatial heterogeneity would have to be addressed through spatially heterogeneous, site-specific payments. But for practical and equity reasons, conservation payments are usually spatially homogenous so that each landowner receives, for a given conservation measure, the same payment per area. Such spatially "blind" payments, of course, cannot control the spatial allocation of conservation measures and thus have only a limited ability to halt or reverse the process of habitat fragmentation.

To address this shortcoming, Parkhurst et al. (2002) proposed the so-called agglomeration bonus which consists of a standard homogenous payment that is paid for each conserved land parcel, plus a bonus for each adjacent land parcel that is under conservation, as well. This bonus induces the landowners into the spatial coordination of their land-use activities (Parkhurst et a. 2002, Parkhurst and Shogren 2007) and eventually leads to the conservation of contiguous areas (Parkhurst et a. 2002, Parkhurst and Shogren 2007, Albers et al. 2008, Drechsler and Wätzold 2009, Drechsler et al. 2010, Banerjee et al. 2012, Krämer and Wätzold 2018). Like the dipols in ferromagnets, the landowners form domains or clusters of like behaviour, and the sizes of the clusters depend on the size of the agglomeration bonus.

Although the effectiveness of the agglomeration bonus has been demonstrated in theory, experiment and practice, another major challenge in payment design remains: the schemes' lack of permanence – meaning that the landowners' conservation activities usually stop when the payment stops. Or, in other words, there is no hysteresis of the desired state of spatially agglomerated conservation efforts. As Pagiola et al. (2020) argue, with self-interested landowners, permanence of conservation can only be achieved if the long-run conservation costs are very low, so the temporary payment is needed only to offset high short-term conversion costs that arise, e.g., with the purchase of new machinery or the rescheduling of the farm's agricultural practices.

In contrast to this rather trivial but rare prerequisite for permanence, we will show that permanence can also appear due to a totally different process, which are the interactions among the landowners. Using a parsimonious spatial agent-based simulation, motivated by experiments on the agglomeration bonus by Parkhurst and Shogren (2007), we will show that the land-use dynamics induced by an agglomeration bonus scheme exhibit hysteresis so that even after the payment stops most of the conserving farmers will continue conserving. In our model analysis this implies that it is more cost-effective (in terms of long-run conservation for given conservation budget) to offer a large bonus for a short time to trigger a high amount of (spatially agglomerated) conservation efforts and then lower the bonus to exploit the hysteresis, than to apply a conventional payment design and offer a medium-sized bonus throughout.

Results

Hysteresis associated with the agglomeration bonus scheme

We consider a model landscape with land parcels $i \in \{1, \ldots, N = 30\times30\}$, arranged on a square grid with periodic boundary conditions, each of which may be conserved ($x_i = 1$) or in economic use ($x_i = 0$; more details about the model can be found in Appendix A). Conservation incurs a cost c_i, for example in terms of additional equipment of labour required, or reduced productivity. These costs are assumed to vary for each land parcel randomly and independently, sampled from a normal distribution with mean 1 and standard deviation σ (the results for spatially correlated conservation costs are qualitatively similar and shown in Appendix B). To offset these costs, a payment

$$p_i = x_i \left(p + b \sum_{j \in M_i} x_j \right) \tag{1}$$

is offered for each conserved land parcel i, where p is a spatially homogenous base payment and b an additional bonus that is paid for each conserved land parcel in the Moore neighbourhood M_i, i.e. the eight direct neighbour parcels around parcel i. Farmers change land use on a land parcel from economic to conservation if and only if the payment p_i exceeds the conservation cost c_i. After such a change, some of the economically used land parcels will have more conserved neighbours, increasing their p_i, so some of them will change to conservation, as well. These land-use dynamics continue until a final, static state is reached, which mimics observations from corresponding real-world experiments (Parkhurst and Shogren 2007).

An example of sucg dynamics is shown in the top row of Fig. 1. In the course of the land-use changes, clusters of conserved land parcels emerge gradually until a static land-use pattern is obtained. Figure 2 (solid lines) shows mean characteristics (taken over a number of simulation replicates) of that final land-use pattern as a function of the bonus b_1 (scaled in units of σ, since a doubling of σ, e.g., has the same effect as a doubling of b_1 – see Appendix A). Panel a shows the proportion q of conserved and parcels, while panel b shows the spatial agglomeration γ (details in Appendix A) of the conserved land parcels which ranges from zero (no conserved land parcel has any conserved neighbour) to one (all land parcels are completely surrounded by conserved neighbours). Beyond a certain threshold of b_1, the entire landscape is in conservation use. For a bonus level of $b_1 = 0.7\sigma$ (right vertical line in Fig. 2a), e.g., we obtain $q = 0.78$ and $\gamma = 0.92$ (cf. $t = 19$ in Fig. 1, top row).

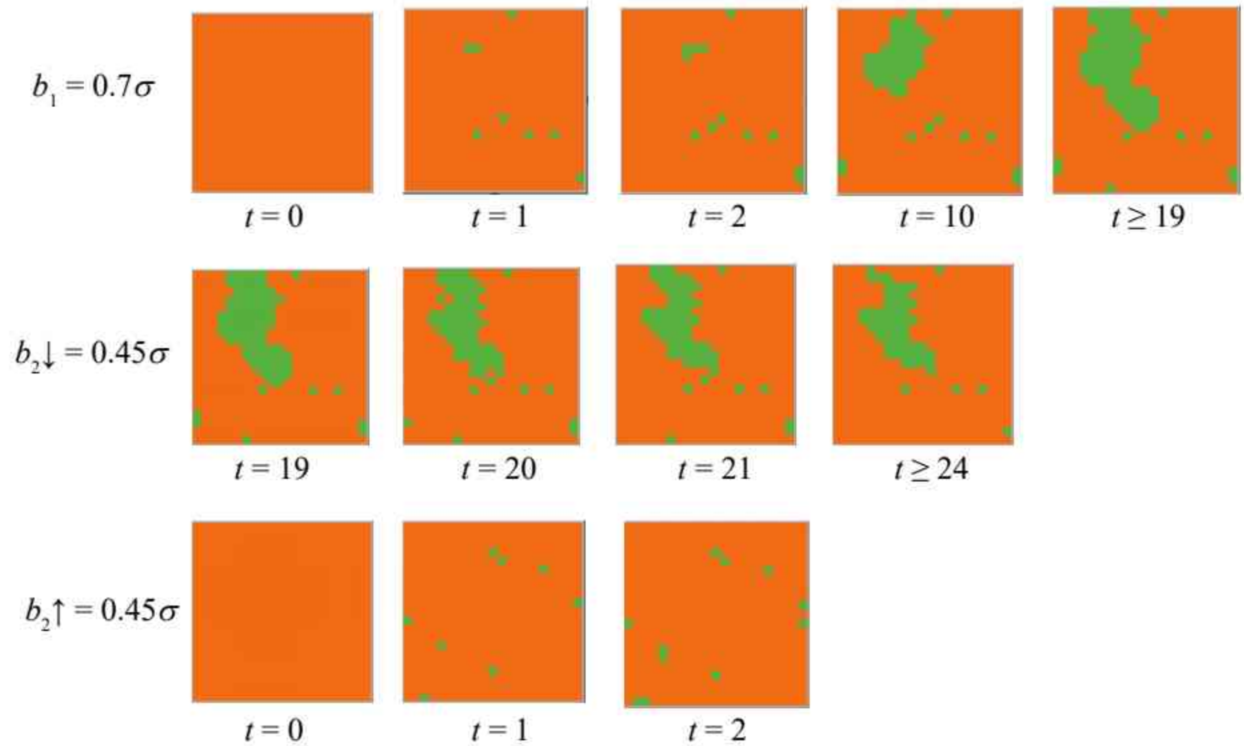

Figure 1: Land-use dynamics for selected bonus levels and initial and use. In the top row, the land use starts form an entirely economically used landscape (orange), and the bonus of size $b_1 = 0.7\sigma$ (base payment $p = 1 - 2\sigma$) induces land-use changes and the gradual emergence of clusters of conserved land parcels (green). After 19 time steps the land use has reached a final, static, pattern. Starting from this land-use pattern, the bonus is reduced to $b_2\downarrow = 0.45\sigma$ to obtain the dynamics in the second row. In the bottom row, the same bonus level is considered but raised from zero to $b_2\uparrow = 0.45\sigma$, and considering an initially economically used landscape (as in the top row).

To demonstrate the hysteresis, we start from this state and reduce the bonus to some value $b_2\downarrow < b_1$ (dashed lines in Fig. 2). For the example of $b_2\downarrow = 0.45\sigma$ (left vertical line on Fig. 2a) we obtain $q = 0.52$ and $\gamma = 0.72$ (cf. $t = 24$ in the second row of Fig. 1).

In contrast, had the same bonus level of 0.45σ been raised from zero and an economically used landscape (indicated by $b_2\uparrow = 0.45\sigma$) – i.e. without the "detour" via $b_1 = 0.7\sigma$ – the proportion and agglomeration of the conserved land parcels would have been only $q = 0.04$ and $\gamma = 0.18$ (solid lines in Fig. 2; cf. $t = 2$ in the bottom row of Fig. 1).

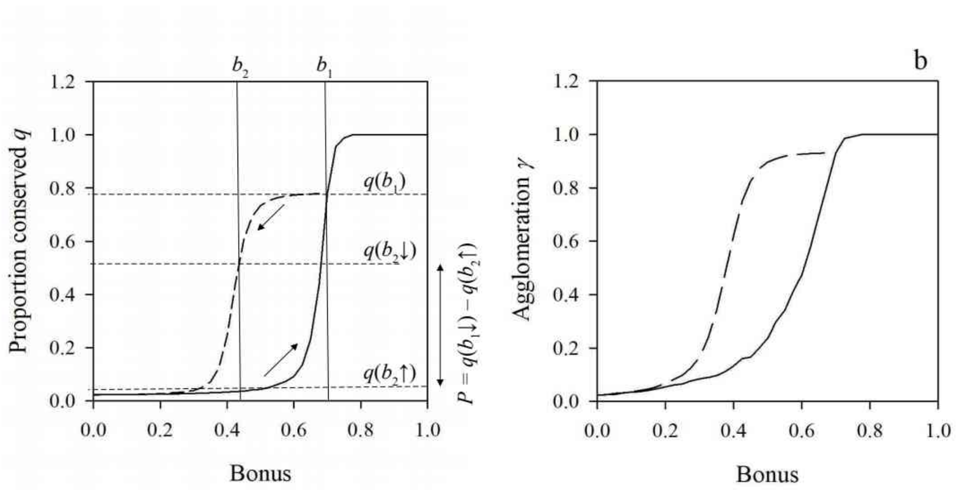

Figure 2: Proportion of conserved land parcels q (panel a) and spatial agglomeration γ (panel b) as functions of the bonus level b_1 if initially all land parcels are in economic use (solid lines); and q (panel a) and γ (panel b) as functions of the bonus level b_2 if before the bonus had been at a level of $b_1 = 0.7\sigma$ and q and γ at the associated values of 0.78 and 0.92, respectively. The base payment is $p = 1 - 2\sigma$. The bonus values measured on the horizontal axes are in units of the cost heterogeneity σ.

The difference between the two outcomes,

$$
\begin{aligned}
P_q &= q(b_2 \downarrow) - q(b_2 \uparrow) \\
P_\gamma &= \gamma(b_2 \downarrow) - \gamma(b_2 \uparrow)
\end{aligned}
, \qquad (2)
$$

can be regarded as a measure of permanence, so that in the numerical example considered above, q does not fall down the full way from 0.78 to 0.04 but only to 0.52 when the bonus is reduced from 0.7σ to 0.45σ. The arrows in eq. (2) indicate that for the first term on the right hand side the bonus b_2 is reached from the larger bonus $b_1 > b_2$, while form the second term it is reached from a value of $0 < b_2$.

Obviously, permanence is equivalent to hysteresis: in the absence of hysteresis the solid and dashed lines in Fig. 1 would collapse and permanence would be zero. This is nearly the case for a rather large base payment such as $p = 1$ (not shown). Hysteresis emerges in this system because for high values of q and γ, the land use decision for each parcel is more strongly affected by the neighbours' land use than the level of the bonus, so the bonus can be reduced without severely loosing conservation in the landscape.

Static policy

The observations in Fig. 2 motivate the comparison of two conservation policies: a static and a dynamic one, both applied to a landscape with all land parcels initially in economic use. In the static policy a base payment p and a bonus b_0 are chosen and a land-use pattern emerges as described along eq. (1).

As described, after a number of time steps the land-use pattern evolves into a static state. Fig. 3 shows the proportion q and spatial agglomeration γ of conserved land parcels in that static state as functions of b_0 for two levels of p. For small p one can, with increasing b_0, observe a sharp transition between a landscape with few and spatially dispersed conserved land parcels to a landscape with many and spatially agglomerated conserved land parcels.

Next, especially for b_0 below that transition, the spatial agglomeration γ exceeds the proportion q of conserved land parcels. To interpret this observation, note that in a totally random allocation of the conserved land parcels the expected number of conserved neighbours is $\gamma = q$. So a spatial agglomeration of $\gamma = q$ is a mere "statistical" effect and does not indicate any "bonus-induced" agglomeration. That bonus-induced agglomeration is measured by the surplus

$$\Gamma = \gamma - q \quad (3)$$

In Fig. 3 (especially panel a) one can see that Γ first increases with increasing b_0 and then decreases, so that it assumes a maximum Γ_{max} at a bonus level denoted as $b_0(\Gamma_{max})$ (in the example of Fig. 3a, $\Gamma_{max} \approx 0.14$ and $b_0(\Gamma_{max}) \approx 0.63$). As Fig. 4 shows, both quantities decline with increasing base payment p, so high levels of bonus-induced agglomeration Γ are obtained only for small base payments; and the level $b_0(\Gamma_{max})$ at which that bonus-induced agglomeration is maximised, shifts to smaller values if the base payment is increased.

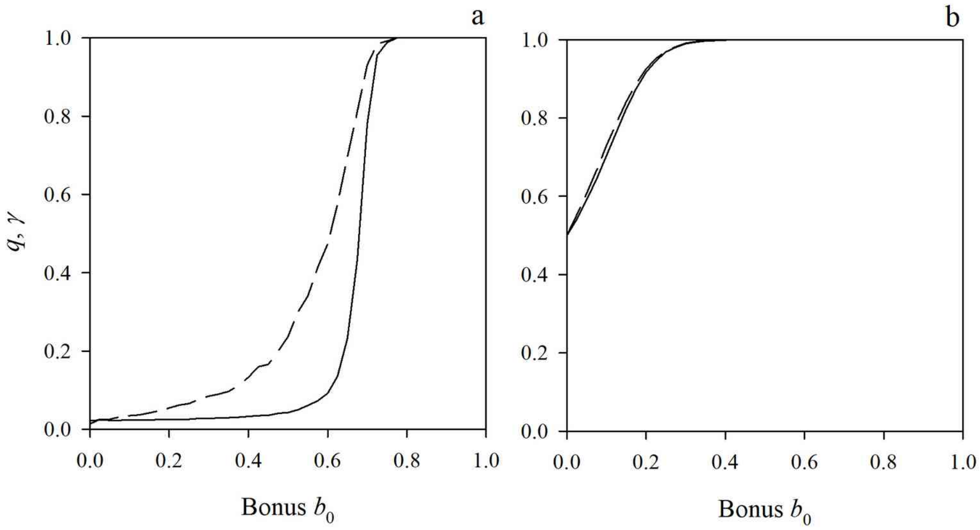

Figure 3: Proportion of conserved land parcels q (solid line) and spatial agglomeration γ (dashed line) as functions of the bonus b_0 (measured in units of the cost heterogeneity σ) reached from zero (see text). Base payment $p = 1 - 2\sigma$ (panel a) and $p = 1$ (panel b).

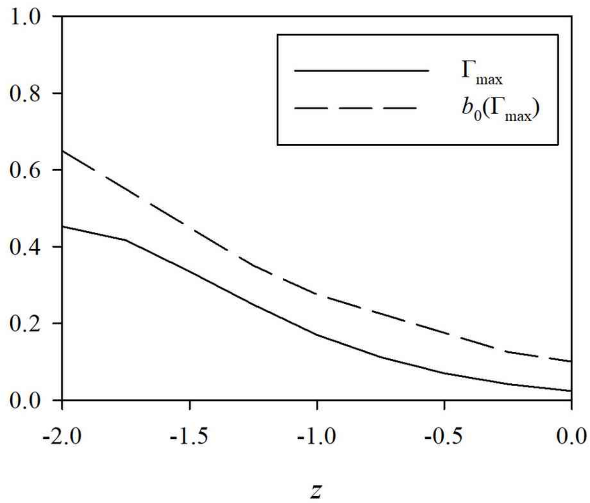

Figure 4: Maximum level Γ_{max} of bonus-induced agglomeration (solid line) and level of bonus $b_0(\Gamma_{max})$ (scaled in units of the cost heterogeneity σ) at which that maximum is obtained (dashed line) as functions of the base payment $p = 1 + z\sigma$.

Dynamic policy

The dynamic policy is motivated by the hysteresis in Fig. 2, particularly the observation that for given bonus b_2, the proportion and agglomeration of conserved land parcels is higher when b_2 is reached from some higher level $b_1 > b_2$ than when it is reached from a value of zero. The difference between the two outcomes is measured by the permanence P of eq. (3). As in the static policy, a base payment p and a bonus b_1 are applied to an initially economically used landscape. After a static land-use pattern has emerged, the bonus is reduced to the level b_2.

Figure 5 shows the permanence with respect to the proportion and the spatial agglomeration of conserved land parcels for two levels of the base payment p. For the small base payment (Figs. 5a and c) permanence is achieved only if b_1 had been raised to a sufficiently large value $b_1^{(\min)} \approx 0.7\sigma$. If that critical value has been reached the permanence does not change much with a further increase in b_1.

There is a wide range of values b_2, most of them smaller than $b_1^{(\min)}$, which are associated with high permanence close to one (white areas in the figures), so a reduction of b from b_1 to b_2 only partly reduces the proportion of conserved land parcels (a note to explain the small P observed for large $b_2 > b_1^{(\min)}$: in "relative" terms, measured by the ratio δ/Δ, the permanence is very high here, but the impact of the bonus is overall small, whether it is increased or decreased, so in absolute terms ($P = \Delta - \delta$) the permanence is only small). The results for the large base payment are qualitatively similar (Figs. 5b and d), but $b_1^{(\min)}$ is smaller, permanence is small and observed only for $b_2 \approx b_1^{(\min)}$.

Figure 6 shows the impact of the base payment on three characteristic quantities discussed along Fig 5: the critical bonus $b_1^{(\min)}$ beyond which permanence can be observed, the maximum level of permanence $P_{\max}$, and the level $b_2(P_{\max})$ at which that maximum is obtained. All quantities decline with increasing base payment p. In particular, $P_{\max}$ declines from about one to a much smaller value as the base payment is increased. Another important observation is that the critical bonus $b_1^{(\min)}$ beyond which permanence is observed has a very similar magnitude as the bonus $b_0(\Gamma_{\max})$ which had been defined above as maximising the bonus-induced agglomeration in the static policy (Fig. 4, dashed line).

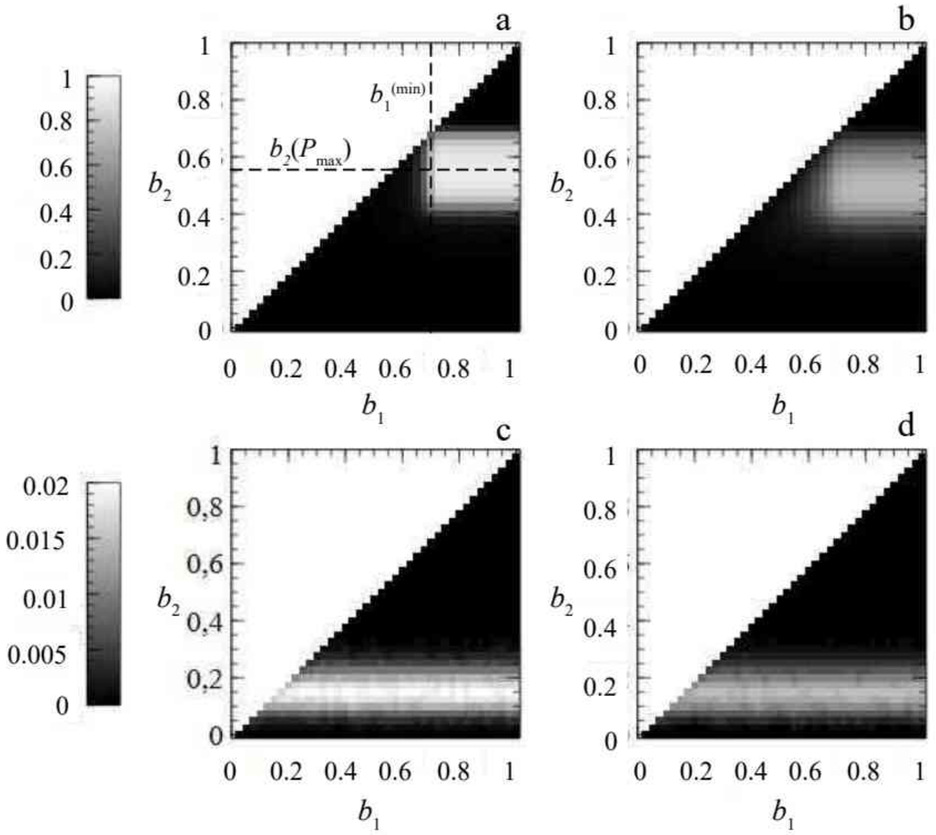

Figure 5: Permanence P after eq. (2) as function of the bonus levels b_1 and b_2 which are measured in units of the cost heterogeneity σ. Panels a and b show the permanence with respect to the proportion of conserved land parcels q, and panels c and d show it with respect to the spatial agglomeration of the conserved land parcels γ. The base payment is $p = 1 - 2\sigma$ (panels a and c) and $p = 1$ (panels b and d).

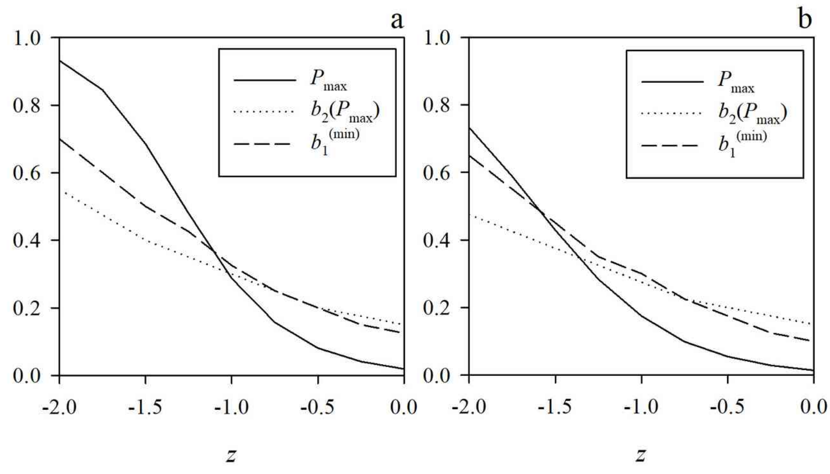

Figure 6: Maximum permanence P_{max} (solid line), critical bonus $b_1^{(min)}$ beyond which permanence can be observed (dashed line), and bonus $b_2(P_{max})$ where permanence is maximal (dotted line) as functions of the base payment $p = 1 + z\sigma$. Permanence is measured with respect to the proportion q (panel a) and spatial agglomeration γ (panel b) of conserved land parcels.

Cost-effectiveness of the static and dynamic policies

As demonstrated, the permanence observed in the analysis of the dynamic policy allows to reduce the bonus from b_1 to b_2 and still retain a rather high proportion and agglomeration of conserved land parcels – which reduces the necessary payments p_i (eq. (1)) and increases the cost-effectiveness of the policy, i.e. the magnitude of q or γ that are obtained for given conservation budget. However, this efficiency gain (compared to the case in which the bonus is not reduced from b_1 to b_2) would be useless if there was a static policy with some other bonus level b_0 that is even more cost-effective. Below we systematically consider a large number of dynamic policies and compare each with the most cost-effective static policy that incurs the same total cost (conservation budget).

Obviously, this comparison requires a dynamic consideration, since $q(t)$ and $\gamma(t)$ are time-dependent, as well as is the total cost (conservation budget) that accrues to the conservation agency

$$B(t) = \frac{1}{N}\sum_i x_i(t)\left[p + b_k \sum_{j \in M_i} x_j(t) \right], \qquad (4)$$

where $k = 0$ for the static policy, and $k = 1$ and $k = 2$ for the first and second phases of the dynamic policy, respectively (by the factor $1/N$ in eq. (4), the budget is measured per land parcel).

For the assessment of a stream of time-dependent costs or benefits, the classical economic approach is to consider the stream's present value PV which is the sum of the discounted costs or benefits, respectively (cf. Appendix A). In the present analysis we consider two levels of the discount rate (per model time step): $\delta \in \{0.1, 0.01\}$ which span typical values of annual discount rates used by private and public decision makers. A value of 0.1 is quite large and – considering annual time steps – implies that, e.g. a cost accruing in ten years is valued only about one third relative to the same cost in the present. A value of 0.01, in contrast means that the cost in ten year is valued ninety percent of the present cost. Additional analyses (not shown) revealed that reducing δ to 0.001 did not change the results compared to $\delta = 0.01$.

In contrast to the previous sections, via eq. (4) the results of the analysis depend on the cost heterogeneity σ, so three different levels $\sigma \in \{0.05, 0.15\ 0.3\}$ are considered for generality of the results. The chosen levels represent 95%-confidence intervals of the costs of about 1 ± 0.1, 1 ± 0.3 and 1 ± 0.6 and span a wide range of real-world spatial variations in agricultural land prices (ref?).

For each of the six scenarios (δ, σ) we consider a large number of systematically formed dynamic and static policies and measure the cost-effectiveness of each policy by its ratio of present-value benefit (proportion PV_q and agglomeration PV_γ of conserved land parcels, respectively) and present-value budget PV_B (see Methods). As a function of the present-value budget PV_B, we determine the static and dynamic policy that maximises the benefit-cost ratio and determine the relative cost-effectiveness gains G_q and G_γ of the dynamic policy relative to the static policy (Appendix A).

Figure 7a shows the efficiency gain G_q with respect to the proportion of conserved land parcels q. Gains above one percent are obtained for large cost heterogeneity and increase with decreasing discount rate. Similar is observed with respect to the spatial agglomeration of the conserved land parcels (Fig. 7b) where the efficiency gain G_γ increases with increasing cost heterogeneity and decreasing discount rate.

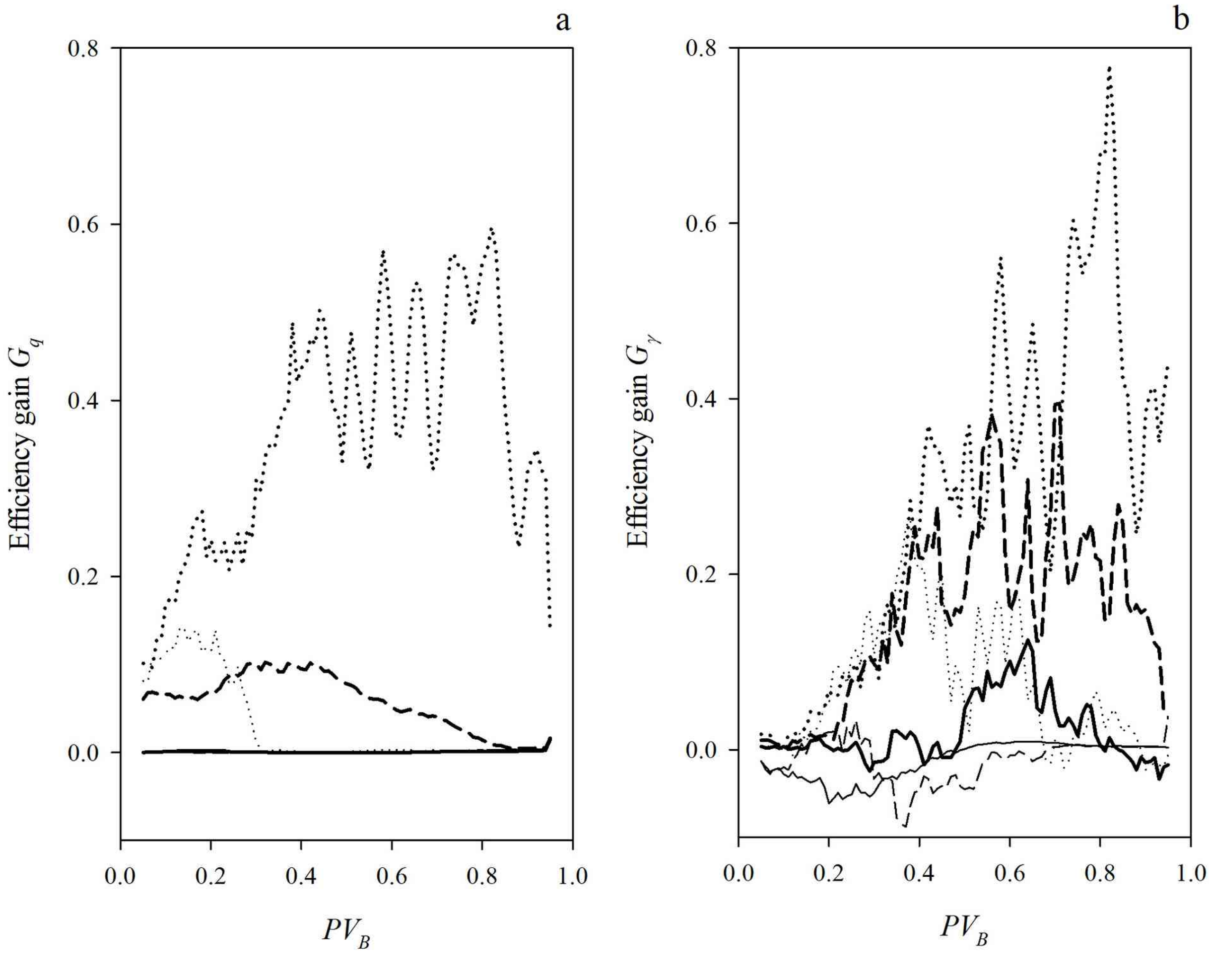

Figure 7: Efficiency gain of the dynamic policy with respect to the proportion of conserved land parcels (G_q, panel a) and the land parcels' spatial agglomeration (G_γ, panel b) as a function of the conservation budget (PV_B, scaled in units of $1/\delta$). The cost heterogeneity is $\sigma = 0.1, 0.2, 0.4$ (solid, dashed and dotted lines) and the discount rate is $\delta = 0.01$ (thin lines) and $\delta = 0.1$ (bold-faced lines).

Discussion and Conclusion

The agglomeration bonus which particularly rewards biodiversity conservation measures neighbouring to (like) conservation measures, has been proposed as a market-based instrument to address the problem of the continuing fragmentation of species habitats. While the suitability of the agglomeration bonus for that very purpose has been documented in various theoretical and applied studies, the concept appears to have a number of positive side effects (Drechsler et al. 2010, Bell et al. 2016) that arise from the fact that the agglomeration bonus induces the interaction and cooperation of landowners. Since networks of interacting entities are well-known to exhibit complex dynamics, we hypothesise that the agglomeration bonus induces a particular feature of complexity, hysteresis, which may be exploited to raise the cost-effectiveness of conservation payment schemes.

In the present analysis a parsimonious spatial agent-based simulation model was used to explore hysteresis effects that – within the context of conservation payment schemes – translate into permanence such that desired land-use measures persists even after the payment was reduced or stopped. In line with Pagiola et al. (2020) who argue that permanence can be achieved if the long-term costs of biodiversity conservation measures are lower than the upfront costs and the payment scheme is introduced especially to offset the latter, we show that it is cost-effective in the long run to temporarily choose a rather large bonus b_1 to establish a spatially agglomerated network of conserved land, which allows to reduce the bonus again to a rather small level b_2 and still retain a large share of the network.

The analysis indicates that the cost-effective level of b_1 is about where the "bonus-induced" level of agglomeration, i.e. the agglomeration relative to the level that occurs just by chance (Γ in Fig. 3), is maximal. The reason is that a smaller b_1 will not be sufficient to generate permanence, while a larger value will be costly without further increasing the level of permanence. A cost-effective choice of b_2 is where permanence as defined along Fig. 2 is maximal.

The gain in cost-effectiveness relative to a static scheme in which the bonus is chosen at a fixed value b_0 is highest for large spatial variation in the conservation costs and – not surprisingly – low discount rate (which places a high weight on the long-term performance of the policy). The general results prevail even in the case of spatially correlated conservation costs (Appendix B), although all effects, in particular the level of permanence and the cost-effectiveness gain of the dynamic over the static policy, are reduced. The reason is that here the spatial agglomeration is already partly induced by the spatial correlation of the costs while, as argued in the section *Dynamic policy*, permanence (and the implied cost-effectiveness gains of the dynamic policy) relates to the bonus-induced agglomeration.

To conclude, selfish and non-cooperative behaviour of humans is a major – if not the dominant – cause for humanity's current environmental problems. While appeals to moral behaviour do have their justification, it is naïve to assume that selfish behaviours can be reduced to a level that is sufficient to solve our environmental problems. A promising alternative thus are instruments like the agglomeration bonus that induce selfish individuals into persistent modes of cooperation.

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Appendix A: Methods

Land-use decisions and the role of the cost heterogeneity σ

In the model landscape, a base payment $p = 1 + z\sigma$ and bonus $b = y\sigma$ are offered to offset conservation costs $c_i = 1 + \sigma\varepsilon_i$, where ε_i is a normally distributed random number with mean zero and standard deviation one. For given land-use pattern $\{x_i\}_{i=1,\ldots N}$, each landowner i maximises profit

$$\Pi_i = p_i - c_i x_i = x_i\left(1 + z\sigma + y\sigma\sum_{j\in M_i} x_j - 1 - \sigma\varepsilon_i\right) \tag{A1}$$

and conserves ($x_i = 1$) if and only if

$$z + y\sum_{j\in M_i} x_j - \varepsilon_i > 0 \tag{A2}$$

Thus, by scaling p in units of σ relative to 1 (the mean conservation cost) and b in units of σ, the dynamics of the static and the dynamic policies are independent of σ. A value of $\sigma = 0.2$ is used throughout the numerical analyses, except for the cost-effectiveness analysis where three different levels, $\sigma \in \{0.05, 0.15, 0.3\}$, are considered.

Definition of the spatial agglomeration of the conserved land parcels

The spatial agglomeration of the conserved land parcels is calculated as the mean number of conserved land parcels in the eight-cell Moore neighbourhoods M_i around conserved land parcels:

$$\gamma = \frac{\sum_i \left(x_i \sum_{j\in M_i} x_j \right)}{8\sum_i x_i} \tag{A3}$$

Definition of the critical bonus $b_1^{(min)}$

The critical bonus $b_1^{(\min)}$ is defined as the bonus at which the permanence is half its maximum value (obtained for $b_1 = \sigma$, i.e. at the right borders of the panels of Fig. 4). Strictly speaking, the maximum permanence as a function of b_2 slightly depends on b_1 (so the "ridge" of maximum permanence within the white areas of Fig. 4 is not exactly a straight line parallel to the b_1-axis). However, this error can be ignored within the scope of the present analysis.

Cost-effectiveness analysis

The present values of the proportion and the agglomeration of the conserved land parcels as well as the conservation budget are determined as

$$PV_y = \sum_{t=0}^{\infty} \frac{y(t)}{(1+\delta)^t} \quad \text{(A4)}$$

with $y \in \{q, \gamma, B\}$. The cost-effectiveness of a policy with respect to the proportion and the agglomeration of conserved land parcels is measured by the benefit-cost ratios

$$R_{q,\gamma} = PV_{q,\gamma} / PV_B \quad \text{(A5)}$$

These ratios are determined for static and dynamic policies $\{p, b_0\}$ and $\{p, b_1, b_2\}$ with $p \in [1 - 3\sigma, 1]$ and $b_{1,2,3} \in [0, \sigma]$, where for the dynamic (static) policy the policy parameters p and $b_{1,2,3}$ are varied in 100 (40) equidistant steps. To encompass the stochasticity in the model dynamics, averages over 20,000 (static policy) and 5,000 (dynamic policy) replicates are taken. The resolution of the policy parameters and the number of replicates were chosen to optimise the trade-off between the minimisation of output stochasticity and computation time.

For the budget stream PV_B, a range of $[0, 1/\delta]$ is considered, where the upper bound equals the discounted average conservation cost of a single land parcel, so that with this budget half of the land parcels in the model landscape could be conserved through a homogenous payment $p = 1$. The chosen budget range is split into 100 equidistant intervals. For each of these budget intervals the static and dynamic policies are determined that maximise the benefit-cost ratio of eq. (A5). Denoting these maximum ratios as $R_q^{(\text{stat})}$, $R_q^{(\text{dyn})}$, $R_\gamma^{(\text{stat})}$, $R_\gamma^{(\text{dyn})}$, respectively, the relative efficiency gains (as functions of the conservation budget) of the dynamic over the static policy are determined as

$$G_{q,\gamma} = \frac{R_{q,\gamma}^{(\text{dyn})}}{R_{q,\gamma}^{(\text{stat})}} - 1 \quad \text{(A6)}$$

Appendix B: Effects of spatial correlation in the conservation costs

Generating a model landscape with spatially correlated conservation costs

To obtain spatially correlated conservation costs, a random number x_i is drawn independently for each grid cell i from a normal distribution with mean zero and standard deviation one. Then for each grid cell the average w_i of the x-values in a square of dimension $2l + 1$ around cell i is calculated for each i via

$$w_i = \frac{1}{(2l+1)^2} \sum_{j=i-l}^{i+l} \sum_{k=i-l}^{i+l} x_j \,, \qquad \text{(B1)}$$

(which represents a moving window average in 2D space). To provide the w_i with the desired mean 1 and standard deviation σ, their mean m_w and standard deviation s_w (over all i) are calculated and the w_i are transformed via the z-transformation to have a mean of zero and a standard deviation of one:

$$y_i = \frac{w_i - m_w}{s_w} \,. \qquad \text{(B2)}$$

The final values for the conservation costs are calculated via

$$c_i = 1 + \sigma y_i \,. \qquad \text{(B3)}$$

Visual inspection (cf. Fig. A1) reveals that l quite well approximates the correlation length r defined by the correlation function[1]

$$C(r) = \mathrm{E}\left(c_i \cdot c_{i+r}\right) - 1 \,, \qquad \text{(B4)}$$

where E() is the expectation operator.

1 e.g., Wikipedia contributors, 2022. Autocorrleation. In Wikipedia, The Free Encyclopedia. Retrieved Oct 25, 2022, from https://en.wikipedia.org/wiki/Autocorrelation.

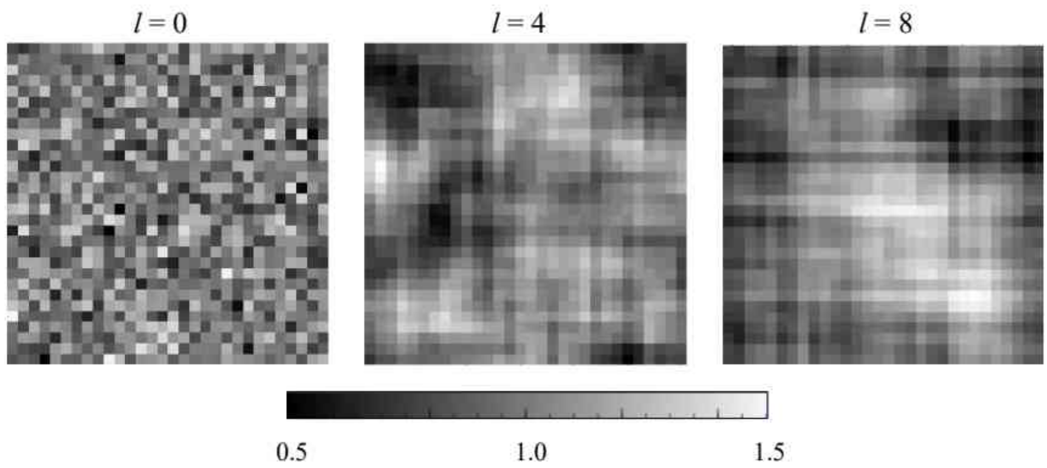

Figure B1: Three random cost landscapes with costs' mean and standard deviation of 1 and 0.2, respectively, and spatial correlation lengths $l = 0, 4, 8$.

Results for spatially correlated conservation costs

Qualitatively, the influence of the base payment ($p = 1 + z\sigma$) on Γ_{max} defined along eq. (3) is independent of the spatial cost correlation l (Fig. B2), and thus almost correctly represented by Fig. 4. Increasing l increases Γ_{max} because, in addition to the bonus b_0, the spatial cost correlation itself induces some spatial agglomeration of the conserved land parcels in the "cost sinks" (thus, for $l > 0$ the interpretation of Γ_{max} as a pure "bonus-induced" spatial agglomeration is not quite correct).

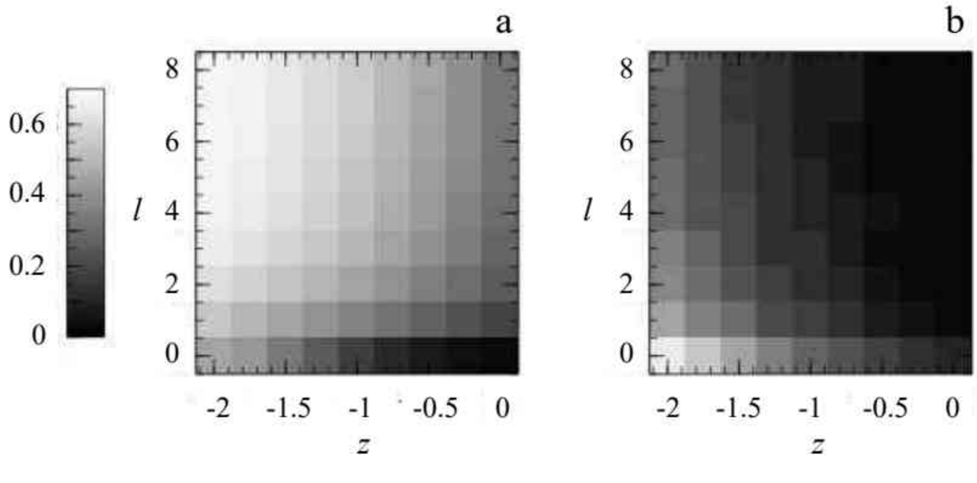

Figure B2: Maximum level Γ_{max} of bonus-induced agglomeration (panel a) and level of bonus $b_0(\Gamma_{max})$ (scaled in units of the cost heterogeneity σ) at which that maximum is obtained (panel b) as functions of the base payment $p = 1 + z\sigma$ and the spatial cost correlation length l.

Qualitatively, the influence of the base payment ($p = 1 + z\sigma$) on the maximum permanence $P_{\max}$, the critical bonus $b_1^{(\min)}$ and the bonus of maximum permanence $b_2(P_{\max})$ is independent of the spatial cost correlation l (Fig. A3), and is almost correctly described by Fig. 6 – with one exception: for medium $l \approx 4$, z has a small influence on $b_1^{(\min)}$ and for large $l \approx 8$, it even slightly increases with increasing z, in contrast to the observation for $l = 0$. Correspondingly, for small z an increasing l reduces $b_1^{(\min)}$, while otherwise, increasing l increases the bonus values $b_1^{(\min)}$ and $b_2(P_{\max})$. The qualitative influence of l on the maximum permanence $P_{\max}$ itself is the same for all z such that increasing l reduces $P_{\max}$.

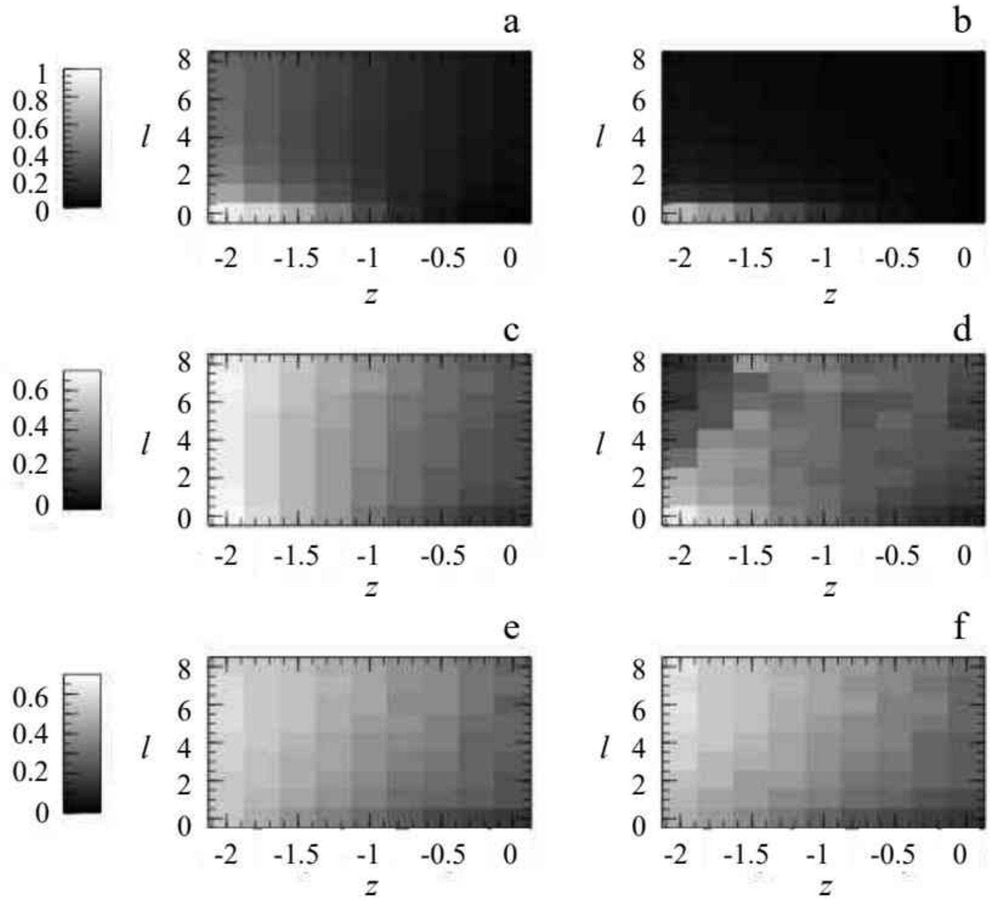

Figure B3: Maximum permanence $P_{\max}$ (panels a and b), critical bonus $b_1^{(\min)}$ beyond which permanence can be observed (panels c and d), and bonus $b_2(P_{\max})$ where permanence is maximal (panels e and f) as functions of the base payment $p = 1 + z\sigma$ and the spatial cost correlation length l. Permanence is measured with respect to the proportion q (left-hand panels) and the spatial agglomeration γ (right-hand panels) of the conserved land parcels.

The results for the cost-effectiveness analysis are qualitatively similar as those for $l = 0$, so that the cost-effectiveness gain of the dynamic over the static policy increases with increasing cost heterogeneity σ and decreasing discount rate δ (Fig. B4). However, the gains are generally below one percent, except for $\sigma = 0.4$ and $\delta = 0.01$ where the gain can be up to a few percent.

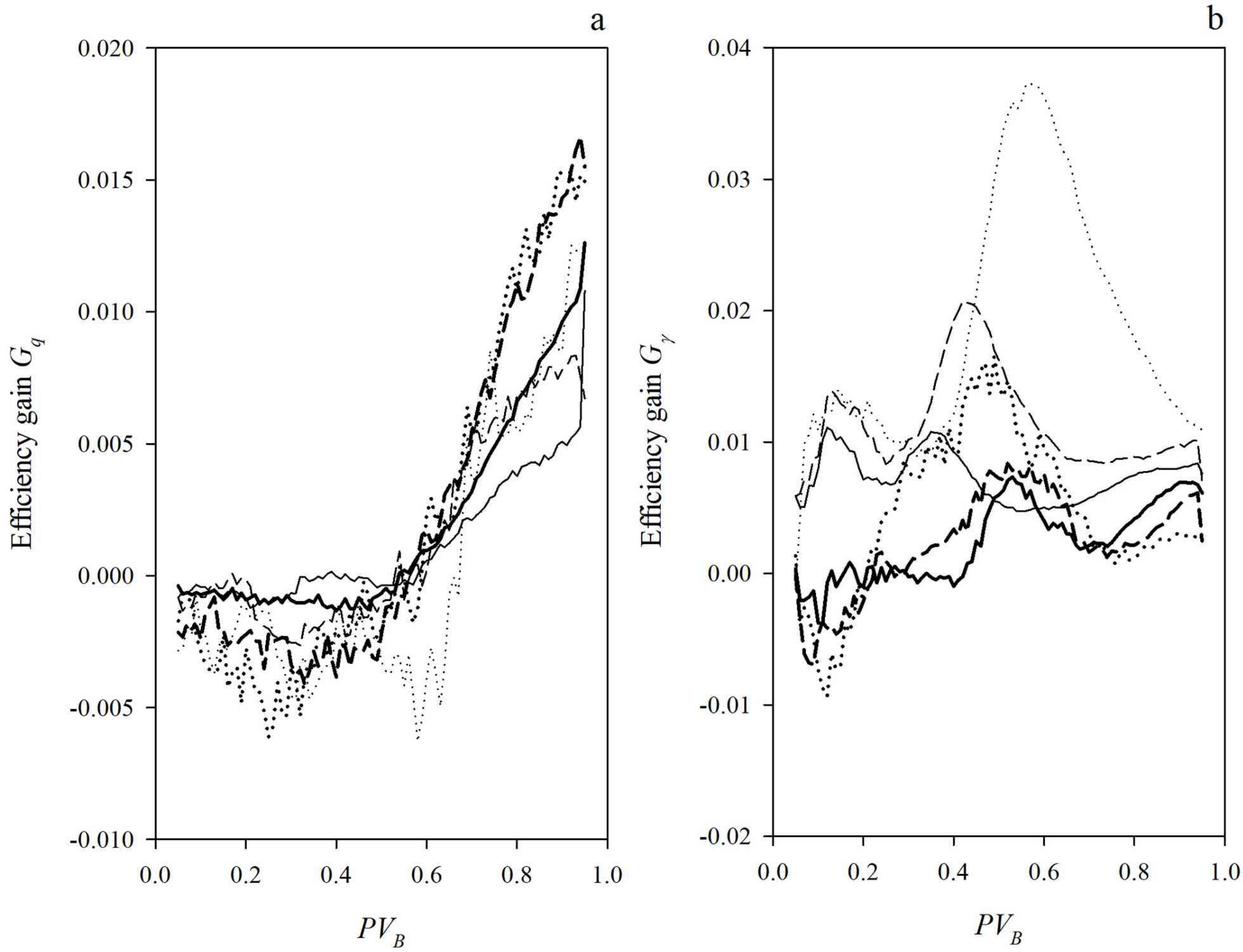

Figure B4: Efficiency gain of the dynamic policy with respect to the proportion of conserved land parcels (G_q, panel a) and the land parcels' spatial agglomeration (G_γ, panel b) as a function of the conservation budget (PV_B, scaled in units of $1/\delta$). The cost heterogeneity is $\sigma = 0.1, 0.2, 0.4$ (solid, dashed and dotted lines) and the discount rate is $\delta = 0.01$ (thin lines) and $\delta = 0.1$ (bold-faced lines). The correlation length is $l = 4$.