Dynamics of habitat banking under changing conservation costs and habitat restoration time lags

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Abstract: Tradable permits are a popular instrument for environmental policy. Classical examples are emission control, but tradable permit systems are recently also promoted and applied to the conservation of biodiversity. This raises a number of challenges. One problem is that habitat turnover (the destruction of habitats and restoration elsewhere) is harmful to many species, even if the total amount of habitat is constant. Another problem is that the restoration of habitats often takes time, leading to time lags between the beginning of restoration activities and the time when the restored habitat is available for trading. It is therefore important to understand how restoration time lags and economic conditions affect habitat turnover. Using an agent-based model, we study the dynamics of a tradable permit market. In the model, conservation costs differ among agents and change in time, and habitat restoration takes time. Our results show the existence of trade-offs between conservation costs, the amount of habitat provided and the amount of habitat turnover. We discuss how habitat turnover can be controlled by an additional tax. We also find that restoration time lags can lead to feedback loops and oscillations in key variables and reduce the efficiency of the permit market. We conclude that temporal lags deserve a careful analysis when implementing tradable permit systems for the preservation of natural habitats and biodiversity.

Keywords: agent-based model, environmental policy, habitat turnover, time lag, tradable permits.

1. INTRODUCTION

Tradable permits have gained increasing popularity as a cost-efficient policy instrument for limiting the overuse of public or common natural resources. Examples of such schemes are the carbon emission trading schemes settled after the Kyoto Protocol, or water permits [Tietenberg 2006]. Recently, permit or credit trading systems have also been discussed and applied to control land use for species protection and biodiversity conservation (e.g., Fox and Nino-Murcia [2005], Latacz-Lohmann and Schilizzi [2005]). Under such a biodiversity credit trading system, the destruction of a natural habitat requires possession of a permit which can only be acquired by restoring a habitat of equal ecological value elsewhere or by buying a permit on the market.

Controlling the amount of natural habitat in a region by means of a tradable permit system raises a number of challenges as opposed, e.g., to the control of carbon emissions. The persistence of biodiversity is highly sensitive to the spatial and temporal allocation of natural habitat. While the spatial allocation has been addressed in various papers such as Drechsler and Wätzold [2009] and Hartig and Drechsler [2009], not much research exists on the temporal allocation. Two factors are particularly important here and special to biodiversity. The first is the presence of long time lags. The restoration of many relevant habitats may take decades or more. If the production of a market good involves a time lag, market participants must decide on their production level before they can sell. The relevance of time lags in markets has been emphasized already about 80 years ago by Hanau [1928] and Kaldor [1934] who showed that markets with time lags may exhibit cyclic fluctuations of prices and the supply of goods. The reason is a feedback loop: at a

current low price, production levels tend to be small, leading to a shortage of the good in the next period, which is associated with a higher price in the next period, which in turn triggers higher production levels in next period, leading to oversupply of the good in the following period, and so on. These cycles are not only undesirable from the point of view of consumers, but may also be inefficient in the sense that the same total amount of the good could be produced at fewer costs if productions levels were held constant in time.

The second problem is a very specific problem in conservation markets: While tradable permit markets lead to more flexibility and to cost savings, the associated activity in these markets is generally harmful for the species. The reason is that each trade implies the destruction of a patch of habitat *and* its local species populations, while created habitat patches have to be colonized by species before they can contribute to species survival. Even if the total number of habitat remains constant, and even if species are able to disperse between habitats, this spatial reallocation of habitats, called habitat turnover, is often detrimental for the species (e.g., Keymer et al. [2000]).

In this study, we develop a (non-spatial) agent-based model of a market for biodiversity credits. The key variables of this market are habitat restoration time, restoration costs, and the spatial and temporal variation of the opportunity costs of conservation. We ask three questions: How do ecologically and economically important quantities such as habitat turnover and the total costs of the permit scheme depend on these key variables? How can undesired habitat turnover be controlled? And finally, are permit markets for biodiversity likely to develop cyclic fluctuations, similar to other markets with production time lags? Section 2 explains the mathematical formulation of the model. Simulation results are presented in section 3 and discussed with their practical implications in section 4.

2. METHODS

2.1 State variables and model parameters

We assume that the model region consists of $N=1000$ land patches each of which is owned by one agent and managed in discrete time steps. During each period t, a patch can be either managed for agriculture: $r_i(t)=0$, or for conservation: $r_i(t)=1$. Conservation management incurs a patch-specific opportunity cost c_i per period. Opportunity costs $c_i(t)$ are modeled as a temporally correlated random walk with mean 1, standard deviation σ and temporal correlation α. A correlation of $\alpha=1$ means perfect temporal correlation so that $c_i(t+1)=c_i(t)$, and a correlation of $\alpha=0$ means that the costs between consecutive periods are uncorrelated. Costs are further assumed to be uncorrelated among different patches.

The ecological state x_i of patch i is given by a value between 0 and 1, with 1 being a habitat of maximum ecological value. The ecological state changes according to the type of management applied to the cell. Management for agriculture immediately changes the ecological state to 0. When managed for conservation, the ecological state is assumed to recover with a speed of $1/K$ per time step. Only a patch in state $x_i=1$ is assumed to be of ecological value ("habitat"). Thus, a formerly agriculturally managed patch has recovered to a habitat after a "restoration time" K. We assume that landowners may have to support restoration actively. In this case, they bear an additional cost of magnitude d per time period during restoration, additionally to the opportunity cost c.

We also assume that any landowner whose patch is not habitat ($x_i<1$) requires a permit. Landowners can, however, hold a permit even if their patch is habitat. Denoting the number of permits held by owner i as z_i, these conditions are expressed by demanding that each patch i fulfills

$$x_i + z_i \geq 1 \tag{1}$$

(the patch is either habitat, a permit is held, or both). Banking of permits for the purpose of speculation is not considered in our model, so z_i can be either 0 or 1. This assumption will be justified in the Discussion. The number of land-use permits possessed by all agents in

the model region is denoted as Z. The levels of x_i and z_i define the state $Y_i=(x_i, z_i)$ of patch i. Land-use permits are traded on a perfect market at an endogenous equilibrium price p^* (see section 2.2). Agents decide on their market and land-use actions under the objective of maximizing their long-term profit (section 2.3). This long-term profit is assumed to be the sum of the discounted profits earned in each period. The discounting factor is denoted as q.

2.2 Market dynamics

Each time period is composed of two phases. In the first phase, agents observe the conditions of the current period: the current opportunity costs, $c_i(t)$, and the state $Y_i(t)=(x_i(t), z_i(t))$ of the patch. Based on this information, agents engage in the permit market and adapt their land use which marks the beginning of the second phase of period t. The patch state in this second phase is denoted as $Y_i'(t)=(x_i'(t), z_i'(t))$. We assume that the first phase is short compared to the second phase, so that the change into the second phase is practically instantaneous for the purpose of calculating the change of the ecological state x_i.

Assuming that agents maximize their long-term expected profits, we can formulate for each agent i a demand function $b_i(Y_i, c_i, p)$ that tells for a given permit price p whether he is willing to buy a permit on the market ($b_i=1$), sell a permit ($b_i=-1$) or do nothing ($b_i=0$). The demand function will be derived in the next subsection. We assume a perfect market where supply and demand are completely settled at an equilibrium price $p^*(t)$ which is determined by a balance of demand and supply

$$\sum_{i=1}^{N} b_i(Y_i, c_i, p^*) = 0$$

(2)

As a consequence of the market interaction, the number of permits held by agent i changes from z_i to

$$z_i'(t) = \min\{\max\{z_i(t) + b_i(t), 0\}, 1\}$$

(3)

Next to the market interactions, agents decide on their land use type $r_i(Y_i, c_i, p)$, depending on the (current) patch state Y_i, opportunity cost c_i and permit price p. Land may either be management for agriculture: $r_i=0$, or for conservation: $r_i=1$. The choice $r_i(t)=0$ in time period t implies that the patch degrades to the lowest possible ecological state: $x_i(t) \to x_i'(t)=0$, regardless of its state $x_i(t)$ that was observed in the first phase of the time period. The decision model of the agents, i.e. the functions $b_i(Y_i, c_i, p)$ and $r_i(Y_i, c_i, p)$ will be presented in detail in the following section 2.3.

If $r_i(t)=1$ and $x_i(t)<1$, there are two options: habitat may be restored instantaneously, or it may be restored only after one or more periods. First we consider the second case and assume that patches recover at a rate of $1/K$ (with $K>0$) meaning that K is the time (number of periods) for a patch to recover from an economically used patch ($x_i=0$) to an ecologically valuable habitat ($x_i=1$) if it is managed for conservation ($r_i(t)=1$). Uncertainty in the restoration success (cf. Moilanen et al. [2008]) is ignored for simplicity. Since restoration takes at least until the next period, $t+1$, the choice $r_i(t)=1$ implies that the patch remains in its current state $x_i(t)$ for the rest of the current period t, so the ecological state in period t is

$$x_i'(t) = r_i(t) x_i(t)$$

(4)

Even though the state of the current period is not affected, the choice of r changes the ecological state $x_i(t+1)$ in the following period: if $x_i(t)<1$, the patch recovers to the next better state $x_i(t)+1/K$. If the patch is already habitat ($x_i(t)=1$), it remains in that state, so

$$x_i(t+1) = \min\{r_i(t)[x_i(t) + 1/K], 1\} = \min\{x_i'(t) + r_i(t), 1\}.$$

(5)

Restoration activities are assumed to be necessary until the ecologically valuable state, $x_i=1$ has been reached and so we assume that restoration costs occur whenever both $r_i=1$ and $x_i<1$.

The number of permits in the next period, $t+1$, is the number of permits after trading:

$$z_i(t+1) = z_i'(t) \tag{6}$$

With the state $Y_i(t+1)=(x_i(t+1), z_i(t+1))$ given by eqs. (5) and (6), we can move to the next period, $t+1$ and proceed in the same way as in period t.

Equations (4) and (5) consider the case where habitat restoration is not instantaneous. The case of instantaneous habitat recovery can be considered by replacing eqs. (4) and (5) by

$$x_i(t+1) = x_i'(t) = r_i(t) \tag{7}$$

obeying the constraints $x_i \in \{0,1\}$ and $x_i + z_i \geq 1$ (eq. (1)).

2.3 The agents' decision rules

We assume that each agent attempts to maximize his long-term aggregated profit, considering all periods from the present period till infinity and discounting with a discount factor $q=1/(1+\delta)$ where δ is the discount rate per time period. For the future periods the agent assumes that the permit price p and the opportunity cost c_i will stay the same as in the current period. For the case of non-instantaneous restoration the agents' optimal decision rules are obtained through dynamic programming (Drechsler and Hartig unpublished):

(a) If the patch is not habitat and a permit is held ($x_i<1$ and $z_i=1$) the agent can choose between restoration ($r_i=1$) or economic use of the patch ($r_i=0$). For the decision the agent has to weigh the discounted benefit of selling the permit at price p after restoration is complete against the sum of the discounted restoration costs that accrue from the present period until restoration is complete, and the discounted opportunity costs from the present period until infinity (the latter is henceforth termed the land price of the patch). If the former exceeds the latter $r_i=1$ is optimal, otherwise the agent chooses $r_i=0$.

(b) If the patch is habitat and no permit is held ($x_i=1$ and $z_i=0$) the agent can choose between buying a permit ($b_i=1$) and converting the patch to economic use ($r_i=0$), or buy no permit ($b_i=0$) and conserve the patch as habitat ($r_i=1$). If the current permit price p exceeds the land price of the patch the latter option is chosen; otherwise the former option is chosen.

(c) If the patch is habitat and a permit is held ($x_i=z_i=1$) the agent can choose between selling the permit ($b_i=-1$) and conserving the patch as habitat ($r_i=1$), or keeping the permit ($b_i=0$) and converting the patch to economic use ($r_i=0$). If the current permit price p exceeds the land price the former option is chosen; otherwise the latter option is chosen.

For the case of instantaneous restoration the results are identical except that incase (a) the permit can be sold immediately after the decision to restore the choice is between restoring and selling on the one side and not restoring on the other.

2.4 Analysis methods

To analyze the stationary dynamics of the market model, we run the model for 1000 "burn in" periods, and then run it for another 1000 periods to generate the data for the analysis. We consider a base parameter combination $\sigma=0.3$ (medium variation of opportunity costs), $\alpha=0.8$ (large level of temporal correlation in the opportunity costs), $q=0.95$ (which corresponds to a discount rate of about five percent per period), $d=10$ (restoration cost equals half the average land price, $1/(1-q)$), and an allocation of $Z/N=0.75$ land use permits in the region. We simulate the market dynamics and record the temporal development of the following aggregated variables: the total amount of habitat prior to decision making (H_1) ("first phase": see section 2.2) and after decision making (H_2) ("second phase"), the amount of habitat turnover between consecutive periods (T) the total opportunity cost (C) which sums the opportunity costs (c_i) of all patches under conservation or restoration

(r_i=1), and the total restoration expense (*D*) that sums the restoration costs (*d*) of all patches under restoration (r_i=1 and x_i<1).

From the defined base case parameter combination we vary α between 0.1 and 0.5, *d* between 0 and 1/(1-*q*), *q* between 0.92 and 0.98 and *Z/N* between 0.6 and 0.9. For each varied parameter combination we determine the following statistics of the state variables: the average amount of habitat turnover (*ET*), the average total opportunity cost (*EC*), the average total restoration expense (*ED*). All costs are scaled in units of the mean opportunity cost (which was set to 1 in section 2.1)

These analyses are carried out for instantaneous restoration and for restoration delayed by one time period (*K*=1). We lastly consider cases of *K*>1 and investigate the effect of varying the patch number *N*. Some of the numerical results will be supported by analytical calculations.

3. RESULTS

3.1 The market dynamics

Iterating through the time periods with eqs. (3), (6) and (7) yields the temporal evolution of the state variables for the case of instantaneous restoration (Fig. 1a). One can see that all patches whose owners do not possess a land use permit are habitat: *H(t)=N-Z* (solid line; recall that *N* is the number of patches and *Z* the number of permits). The amount of habitat turnover is about 10% of the total amount of habitat (Fig. 1a, dashed line).

Iterating through the time periods with eqs. (3) – (6) yields the temporal evolution of the state variables for the case of delayed restoration (*K*=1) as shown in Fig. 1b. Compared to the case of instantaneous restoration the amount of habitat in the first phase of the time periods and the amount of habitat turnover are increased, and most strikingly, oscillate. The reason for this is the time lag in the habitat restoration: The decision to restore a habitat is made in period *t* on the basis of the current price and opportunity cost, but the habitat and associated land use permit is obtained only a period later where cost and price may have changed.
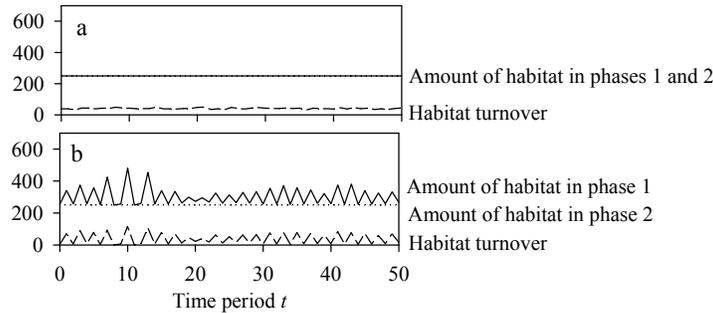

Figure 1: Amount of habitat in phases 1 and 2 (solid resp. dotted line) and habitat turnover (dashed line) as functions of time for the case of instantaneous habitat restoration (panel a) and for the case of delayed habitat restoration (*K*=1: panel b). Note that in the case of instantaneous restoration the amount of habitat in phase 1 (cf. section 2.2) of each time period equals that of phase 2 (panel a, solid line). The model parameters are: *N*=1000, *Z*=750, σ=0.3, α=0.8, *d*=0.25/(1-*q*) and *q*=0.95.

The time lag leads to a feedback loop: In a period with much excess habitat permit prices are small leading to little restoration activities so the amount of excess habitat declines to the next period, while in a period with little excess habitat permit prices are relatively high, leading to a higher level of restoration activities and more excess habitat in the next period.

3.2 Influence of opportunity cost variation and restoration costs on the market behavior

To analyze the influence of opportunity cost variation and restoration costs on the market behavior, we focus on three variables of the market as introduced in section 2.4: the long-term average amount of habitat turnover, ET, the long term average total opportunity cost, EC, and the long-term average total cost which is the sum of opportunity cost and restoration expenses, $EC+ED$. For the case of instantaneous restoration, Figure 2a shows that habitat turnover ET increases with increasing cost variation σ and decreasing restoration cost d, because at large σ cost savings from reallocating habitat are large and at small d the costs associated with these reallocations are small. The same result is obtained for the case where restoration is delayed by one time period (Fig. 2d).
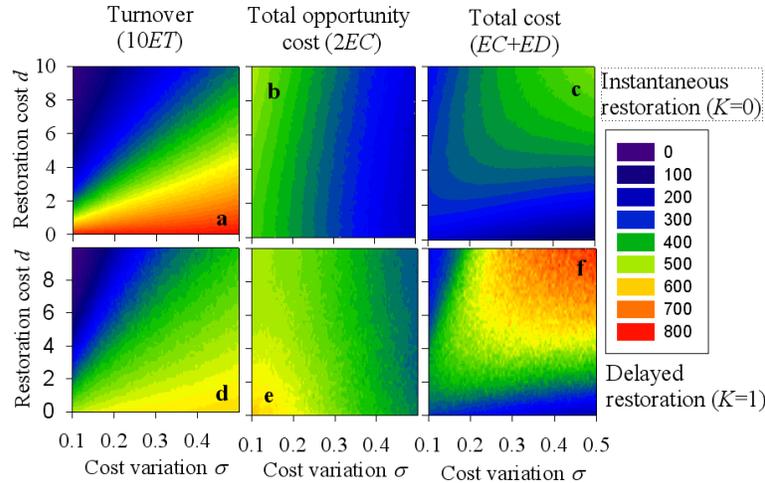

Figure 2: Average amount of habitat turnover (ET), total opportunity cost (EC) and total cost ($EC+ED$) for instantaneous habitat restoration (upper row)) and delayed restoration (lower row) as functions of the cost variation (σ) and the restoration cost (d). All quantities are represented by color scale. To obtain the same colour range for all figures, we plot $10ET$ in panels a and d, $2EC$ in panels b and e, and $EC+ED$ in panels c and f. Other model parameters as in Fig. 1.

One would expect that larger restoration costs are generally associated with low habitat turnover and a high total opportunity cost. And indeed, in the case of instantaneous restoration, this is observed (Fig. 2b). However, in the case of delayed restoration we observe that increasing restoration cost d not only decreases turnover (Fig. 2d) but also the total opportunity cost (Fig. 2e). The reason for this is that in the case of delayed restoration habitat turnover is associated with the restoration of excess habitat, which is associated with excess costs during the phase of restoration (see above). Increasing restoration cost (d) therefore reduces both habitat turnover and the associated excess cost.

For small σ<0.2, the total cost ($EC+ED$) first increases, approaches a maximum and then decreases when the restoration cost d is increased (moving from the bottom to the top of Figs. 2c and 2f). As σ increases the maximum moves towards larger values of d so that for σ>0.2 total cost monotonically increases with increasing d in the interval $0 \le d \le 10$.

The effect of the cost variation σ on the total cost depends on the magnitude of the restoration cost. At small d<2 the total cost decreases with increasing σ (moving from left to right in Figs. 2c and 2f), because the total cost is dominated by the total opportunity cost EC which was found to decline with increasing σ (Figs. 2b and 2e). At large d we find the opposite: that the total cost increases with increasing σ. The reason is that at large d the total cost is dominated by the total restoration expense ED, which increases with increasing habitat turnover ET, which was found to increase with increasing σ (Figs. 2a and 2d).

4. DISCUSSION AND CONCLUSIONS

4.1 Summary of the main results

We investigated how the variation in the opportunity costs among land users (σ), the restoration cost (d) and the proportion of issued land use permits (Z/N) influence the amount of habitat turnover (ET) and the cost of the policy which is composed of the total opportunity cost (EC) and the total restoration expense (ED) (respectively summed over all agents).

Habitat turnover generally increases with increasing cost variation (because at large cost variation the cost savings associated with the reallocation of conservation activities and the trade of land-use permits is high) and decreases with increasing restoration cost and habitat recovery time (because large restoration costs and recovery times make restoration unattractive to land users, reducing the supply of permits on the market).

Low habitat turnover, however, leads to higher total opportunity costs, because conservation activities are not allocated to the least costly sites. Total cost (total opportunity cost plus total restoration expense) is maximized at medium levels of the restoration cost d, because at large d habitat turnover is small and so is the total restoration expense which is the product of habitat turnover and restoration cost. If d is small increasing cost variation reduces the total cost, because cost-savings from the reallocation of conservation activities are large. If d is large increasing cost variation increases the total cost, because it generates high habitat turnover which leads to a high total restoration expense.

If restoration is not instantaneous but implies a time lag, the modeled permit market exhibits cyclic fluctuations of habitat and costs (Fig. 1). This behavior has similar causes as, e.g., the well-known pork cycle (e.g., Kaldor [1934]). A feedback loop exists so that in time periods where little of the good (habitat) is present the implied high market prices sets an incentive to produce more goods for the next period, which leads to excess provision of the good in the next period. Conversely a large amount of goods in the present period reduces incentives to produce the good, leading to a shortage in the next period. In our model, any non-zero restoration time increases the total opportunity cost, because it leads to excessive restoration activities (for details, see the discussion of Fig. 1 in section 3.1). This effect however declines if the time and/or cost of restoration become large, because as noted above, large restoration costs and times render habitat restoration unattractive to land users.

4.2 Policy implications

Our results allow drawing some conclusions relevant for the design of permit markets for conservation. In a static setting, one will generally find that a high variation in opportunity costs among land patches offers high efficiency gains through the allocation of conservation to the least expensive patches (e.g., Ando et al. [1998]). In a dynamic analysis, however, it is important to examine how the opportunity costs develop in time, because changes in opportunity costs may lead to ecologically unfavorable habitat turnover.

We find that the cost of habitat restoration is an important factor that determines habitat turnover rates. Therefore, changing this cost by raising a tax on restoration (which within the scope of our model is equivalent to raising a tax on habitat destruction) would reduce habitat turnover. For instantaneous restoration this would be costly, implying a trade-off between total cost and habitat turnover. For delayed restoration, in contrast, the tax would reduce the cyclic fluctuations and on net reduce both turnover and total costs..

4.3 Model assumptions and future research

An important assumption of the model is that landowners base their expectations about future costs and prices solely on their current observations. In contrast to this assumption, it appears also plausible that agents are able to look further back to the past, observe the long-term behavior of costs and prices and include this information into their decision making. Such a memory of agents would probably affect our results in several ways. First, our observation that long restoration times reduces market fluctuations and excessive restoration activities is partly explained by the fact that some agents who engage in restoration in one period may pull out in the next period – a behavior that would become less likely if our model agents were smarter. On the other hand, given that restoration times may be substantial and uncertainty in future costs and prices large, simply extrapolating the current conditions may still be the best option for a real actor. Since the agents face a decision problem under uncertainty, it could also be interesting to allow for errors in the decision process by making the decision rules stochastic or fuzzy.

Another assumption is that spatial issues are neglected. These can be internalized through spatial trading rules which may have consequences on the dynamics of a permit market (Drechsler and Wätzold [2009], Hartig and Drechsler [2009]). Future research should study the interaction between spatial trading rules and rules that target the market dynamics, such as a restoration tax. One can, however, expect that the general conclusions of the present analysis will be retained even if spatial interactions and trading rules are included.

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