# On the cost-effective temporal allocation of credits in conservation offsets when habitat restoration takes takes time and is uncertain

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**Abstract**

Tradable permits or offsetting schemes are increasingly used as an instrument for the conservation of biodiversity on private lands. Since the restoration of degraded land often involves uncertainties and time lags, conservation biologists have strongly recommended that credits in conservation offset schemes should awarded only with the completion of the restoration process. Otherwise, as is claimed, is the instrument likely to fail on the objective of no net loss in species habitat and biodiversity. What is ignored in these arguments, however, is that such a scheme design may incur higher economic costs than a design in which credits are already awarded at the initiation of the restoration process. In the present paper a generic agent-based ecological-economic simulation model is developed to explore different pros and cons of the two scheme designs, in particular their cost-effectiveness. The model considers spatially heterogeneous and dynamic conservation costs, risk aversion and time preferences in the landowners, as well as uncertainty in the duration and the success of restoration process. It turns out that, especially under fast change of the conservation costs, awarding credits at the initiation of restoration can be more cost-effective than awarding them with completion of restoration.

**Key words:**
agent-based modelling, conservation offsets, ecological-economic modelling, habitat restoration, uncertainty.

**1 Introduction**

Biodiversity is still declining dramatically, with land use and land-use change being the most important anthropogenic drivers. Market-based instruments play an important role in the conservation of biodiversity on private lands (de Vries and Hanley 2016). An increasingly popular instrument are conservation offsets (Bull et al. 2018) which apply the concept of tradable permits (Panayotou 1994) to biodiversity conservation.

The charm of tradable permits is that they allow for land-use change and economic development while – at least in theory – guaranteeing that the cap (in the case of an environmental harm) or the target (in the case of an environmental benefit) is reached with certainty and at least costs. In the field of biodiversity conservation, this means that if the biodiversity target is set at the current level of biodiversity, there will be "no net loss" (NNL). In practical applications, however, conservation offsets have been observed to fail on the achievement of NNL (Maron et al. 2012, Quetiér et al. 2013).

On theoretical grounds, the ability of conservation offsets to deliver NNL has been heavily questioned by a number of leading conservation biologists, including, e.g., Moilanen et al. (2009), Bekessy et al. (2010) and Maron et al. (2012). A central line of criticism in these articles is that if credits are already awarded at the initiation of a habitat restoration process and can immediately be sold to developers then habitat is lost temporarily until the restoration process is complete. But even the assumption that at some time the habitat loss will be offset is overly optimistic given that restoration projects have frequently failed altogether in the past (Maron et al. 2012).

Although the raised concerns are valid, they only look on the ecological side of the issue, ignoring the economic side. While awarding credits with the initiation of restoration has ecological advantages, it may have several economic disadvantages. One is that credits that may be needed by a developer today will be available only at a later time, so the development cannot take place – incurring economic costs. Another one is that landowners investing in costly restoration earn the return only later, and moreover, this return is uncertain due to the above-mentioned risk that a restoration process fails.

Given the requirement of no net loss on the one hand and the potential economic problems associated with a late award of credits, so-called trading ratios have been proposed so that credits are awarded at the initiation of restoration but more credits are required to develop a certain amount of ecologically valuable land than are earned by the restoration of the same amount of degraded land. By this the loss of 1 ha of habitat now is compensated by the gain of $q$ >1 hectares of land later. This surplus compensates for the time delay between loss and gain as well as the uncertainty in the gain (caused by the uncertainty in the success of the restoration process), so that on average the amount of habitat does not decline. Trading ratios are increasingly applied in practice (Bull et al. 2017); a theoretical analysis of trading ratios, which however considers only their ecological effects, is provided by Moilanen et al. (2009).

The present paper takes up this concept and explores, in a systematic manner, under which circumstances no net loss can be achieved more cost-effectively by awarding credits with the initiation of restoration (*award-initiation*), considering appropriate trading ratios, or by awarding credits with successful completion (*award-completion*). As an alternative to the trading ratios I also consider that the (nominal) conservation target may be raised appropriately beyond the initial amount of habitat, which also may prevent the net loss of habitat in the *award-initiation* scheme. So altogether, both schemes are designed that the long-term average of habitat equals the initial amount, which is necessary for a meaningful comparison.

For the analysis I develop a generic agent-based ecological-economic model in which landowners can use their land parcels for conservation or for “economic” purposes like agriculture or housing, and strive for the maximisation of their net present value expected profit. Here they consider time discounting and profit uncertainty which arises in the *award-completion* scheme, because at the initiation of a restoration process the landowner does not know if and when the process will be complete and credits awarded.

The driver of the land-use and credits-trading activities are spatially heterogeneous and temporally changing profits associated with the economic land use. These changes imply that land parcels with comparatively low economic profits (which would typically be in conversational use) turn into high-profit land parcels (which would preferably be developed into economic use and require credits), while land parcels with comparatively high economic profits (which would typically be in economic use) turn into low-profit land parcels (which would preferably be restored into habitat to supply credits).

The different scheme designs are compared with respect to a number of performance criteria: (i) the average cost of the scheme, represented by the forgone economic profits of the landowners per habitat parcel and measuring the cost-effectiveness of the scheme, (ii) the temporal variation in the forgone economic profits, (iii) the temporal variation in the number of habitat parcels (considering that no net loss is defined as a temporal average which does not exclude the temporary shortfall of habitat), and (iv) the amount of habitat turnover incurred by the continuous economic development and restoration of habitats which usually has a significant – often adverse – impact on the survival of species (Hanski 1999, Drechsler and Johst 2010).

As outlined, the two types of conservation offset schemes differ by the time at which credits are awarded. This question loosely relates to the effect of inter-temporal trading (banking and borrowing) of credits in emissions trading discussed in the environmental-economic literature. Two main advantages are associated with inter-temporal trading. One is that it allows hedging against trends in emission abatement costs (Innes 2003). If abatement costs are currently low and expected to increase it is sensible to abate more emissions than necessary, bank the earned credits and sale them in the future at a higher price; while if abatement costs are currently high and expected to fall, it is sensible to borrow credits from future time periods to avoid current high abatement costs.

The second advantage of inter-temporal trading is that it allows hedging against price shocks, or more generally, against risks (Fell et al. 2012, Xu et al. 2014), because – similar to the expected price changes addressed above –, unexpected future increases or drops in credit prices can be buffered by banking or utilised by borrowing, respectively.

Although there is some similarity between these studies and the present one, one should, note an important difference: that the present study does not consider inter-temporal trading, but awarded credits are sold on the spot. Instead, the present study addresses a peculiarity in conservation offsets: that the restoration of ecological habitat causes time lags – of uncertain length – between the economic investment and the generated environmental benefit and/or even uncertainty in the level of the generated environmental benefit. Therefore, when ecologists (e.g., Bekessy et al. 2010) speak of "lending" and "savings banks" this should be understood as a "lending from" and "saving for" nature, respectively, rather than an inter-temporal trade between (human) market participants.

Furthermore, the present analysis does not focus on risk in the credits prices (cf. *Landowner decision making* in section 2.2) but on the success and duration of the restoration process. This, however, opens up a common question between the above-discussed inter-temporal emissions trading and the two present types of conservation offset schemes: how do the two schemes manage and distribute the ecological and economic risks associated with the restoration of habitats – which is addressed in the above questions (ii) and (iii).

While there are a few environmental-economic papers that address the spatial aspect of conservation offsets, such as Drechsler and Wätzold (2009), Parkhurst et al. (2016) and Needham et al. (2021), I am aware of only two that address the temporal dimension and in particular the issue of habitat restoration. One is Kangas and Ollikainen (2019) who presents an analytical model (numerically applied to forestry in Finland) of a conservation credits market in Finland. Although the authors address the concept of trading ratios, they do not provide a systematic comparison of the different offset scheme designs. The other paper is Drechsler and Hartig (2012) who developed a model of a similar (though slightly simpler) structure than the present one to explore effects of uncertainty in the cost (forgone profits) of conservation. Assuming a deterministic habitat restoration process, it is somewhat complementary to the present analysis.

## 2 Methods

### 2.1 Rationale

A region is considered that consists of a number of land parcels which can be used for conservation (habitat) or economic purposes, where in the latter case an economic profit is earned. Habitat can be developed into economic use while economically used land can be restored, which takes an uncertain time span or may fail altogether. Economic profits (or forgone profits if the land is used for conservation) differ among land parcels and change monotonically in time. That change, too, differs among the land parcels so that a currently relatively profitable land parcel may become relatively unprofitable (compared to other land parcels) or vice versa.

The basic idea of a conservation offset scheme is that owners of relatively profitable land that is currently under conservation may wish to develop their land. For this they require credits which they can buy from a landowners who earned credits by the restoration of previously economically used land. Such dynamics arise if there is a mismatch between profitability and land use so that some of the profitable land is used for conservation and some of the unprofitable land is used for economic purposes. Clearly, one reason for such a mismatch are the above-introduced changes in the land profitabilities.

As outlined above, credits from restoration may be awarded with the initiation (*award-initiation* scheme) or with (successful) completion of the restoration process (*award-completion* scheme). In the latter case the loss of habitat is avoided with certainty while in the former case net habitat loss is certain. To achieve no net loss in the award-initiation scheme, one can either introduce trading ratios, so more credits are required for the development of a land parcel than are earned for the restoration of a land parcel. Or alternatively, one may raise the conservation target. Similar to the cap in an emission trading scheme, the target in a conservation offset scheme specifies the number of habitat parcels – which under no net loss must not change relative to its initial level. To avoid no net loss in an award-initiation scheme one may raise the target beyond the initial number of habitat parcels. Both options are considered in the present analysis. The primary variable for the assessment of the performance of the different schemes is the average cost per habitat parcel that is associated with the no net loss requirement.

While the two options can guarantee that on average there will be no decline in the number of habitat parcels, they cannot guarantee that there will be no temporal fluctuations in the number of habitat parcels with temporary short-falls as well as temporary surpluses. Two other quantities of interest are the coefficient of variation in the habitat parcels and the habitat turnover, i.e. the average proportion of habitat parcels developed between consecutive time periods.

Lastly, not only can the number of habitat parcels be expected to vary in time, but variation may also occur in the total cost (total forgone economic profits) associated with the no net loss requirement. The different offset schemes are statistically compared with respect to these four performance variables.

**2.2 The model**

*The model region and system states*

The model region is assumed to consist of $N = 100$ land parcels, each owned by a single landowner who can use the land parcel for economic purposes or for conservation. A land parcel $i$ used economically in time step $t$ earns a profit $a_i(t)$ in that time step, while a conserved land parcel earns no economic profit. Economic profits $a_i$ vary among the different land parcels, which may, e.g., be due to spatially heterogeneous soil quality for agriculture or different distances to cities in the case of rents from housing development. A conserved land parcel may be habitat or in restoration, so altogether three states are distinguished: in economic use, conserved and in restoration, and conserved and habitat. Land parcels in economic use can stay in economic use or switch to conservation (with the initiation of a restoration process); habitat parcels may stay in conservation or switch to economic use; and land parcels in restoration stay in restoration until the restoration process is complete or has failed (see below). Transitions between economic use and conservation and transitions from habitat to economic use are instantaneous between consecutive time steps, while transitions from economic use to habitat are possible only via the state of restoration. Below the different processes in the model system are described. An overview is given in Fig. 1.

*Dynamics of the agricultural profits*

To model spatial heterogeneity in economic profits, the initial profit $a_i(0)$ at time $t = 0$ is sampled for each land parcel $i \in \{1, \ldots, N\}$ randomly and independently from a uniform distribution with lower and upper bounds of $1 - \sigma$ and $1 + \sigma$ (scaling all profits in units of the mean profit). The mean and the standard deviation of the $a_i(0)$ are denoted as $m_0$ and $s_0$, respectively (for $N \to \infty$ we obtain $m_0 = 1$ and $s_0 = \sigma/3^{1/2}$).

As described above, the credits market dynamics are driven by changing economic profits on the land parcels, because without that change there would be no reason to restore an economically used land parcel or convert a habitat parcel into economic use. For simplicity and analytical clarity, the dynamics of the $a_i$ are modeled such that their mean and standard deviation over the $N$ land parcels are constant over time. For this, a rate of profit change $r_i$ is introduced and sampled randomly and independently from a uniform distribution with lower and upper bounds of $-\gamma$ and $+\gamma$. An "unscaled" profit is calculated for each model time step $t$ via

$$z_i(t) = a_i(0) + r_i t \quad . \qquad (1)$$

Equation (1) implies that the standard deviation of the $z_i$ will increase with time, so the $z_i$ have to be rescaled in each time step $t$. With $m_t$ the calculated mean and $s_t$ the standard deviation of the $z_i$ in time step $t$, the rescaled economic profit is calculated via

$$a_i(t) = m_0 + \left(z_i(t) - m_i\right)\frac{s_0}{s_i} \quad . \qquad (2)$$

Fig A1a in the Appendix A shows a numerical example of the profit dynamics.

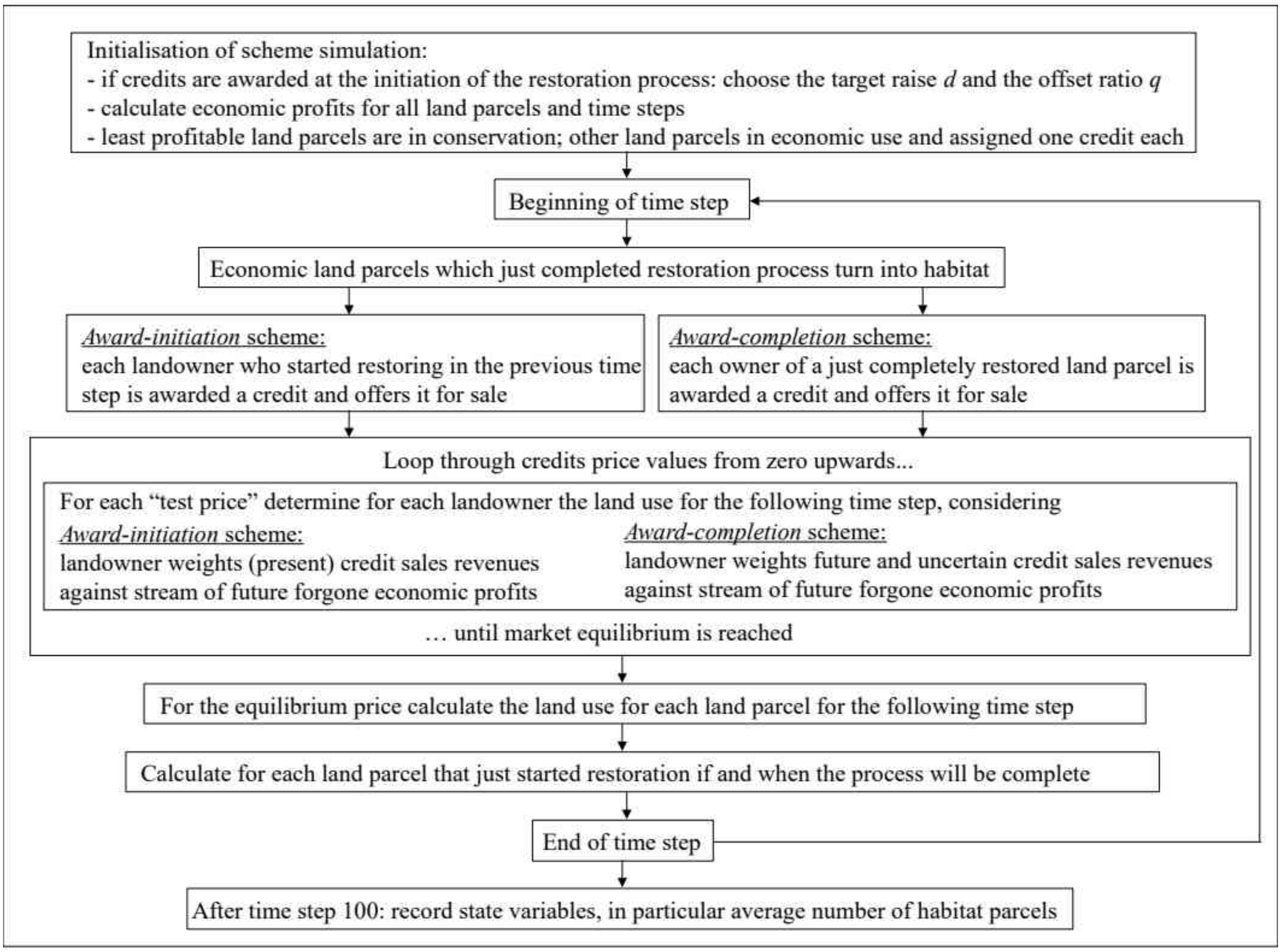


Figure 1: Overview on the simulation schedule.

Numerical inspection reveals that the obtained distribution of the economic profits over the *N* land parcels is, with negligible error, constant in time, which simplifies the analysis and the interpretation of the results. However, the validity of the results is not restricted to the assumption of a constant profit distribution. Consider, e.g., the case in which all profits $a_i(t)$ are multiplied by some factor $b^t$, (where *b* may be larger or smaller than one), which would imply that the mean and the standard deviation of the profit distribution would change between consecutive time steps by *b* (for a numerical example, see Fig A1b). However, despite these changes, the ratio between the profits of two land parcels *i* and *j*, $a_i(t)/a_j(t)$ would still be constant in time, and so would be the ratio of the parcels' land prices, i.e. their streams of all discounted future profits. Since the decisions of the landowners (see below) depend only on the relative profits of the available land-use measures, the dynamics of the credits market and the land use would not change. Only the credits price would nominally change by a factor *b* per time step, in accordance with the profits.

*Habitat restoration dynamics*

Two types of habitat restoration are considered that reflect typical uncertainties in an ecological restoration process: that the length of the process is uncertain and that the process may fail altogether (which includes the case that the previous destruction of the ecological value of the land parcel may not be reversible). For simplicity the two types are treated separately, so restoration processes that have both uncertain duration and may fail altogether in the end, are not considered.

For the modelling of uncertainty in the duration, it is assumed that the restoration of an economically used land parcel into habitat takes *m* time steps which are distributed according to

$$\Pr(m) = \mathrm{Pois}_{M-1}(m-1) = \frac{(M-1)^{m-1}}{(m-1)!}\exp\{-(M-1)\} \tag{3}$$

for $M \geq 1$ and $m \geq 1$. Here $P_{M-1}$ is the Poisson distribution with mean $M - 1$. The probability of observing instantaneous restoration is set to zero: $Pr(m = 0) = 0$. Basically, $Pr(m)$ is a Poisson distribution shifted by one to the right, so $Pr(m)$ has a mean of $M$ and a standard deviation of $M - 1$ (for a numerical example, see Fig. B1 in Appendix A). The setting of $Pr(m = 0) = 0$ is to ensure that an economically used land parcel cannot become a habitat and earn credits in the same time step. Otherwise a circularity would appear such that the decisions of the landowners in time step *t* (see below) affect the supply of credits in time step *t*, which through the market clearance (see below) affects the decisions of the landowners in the same time step. An alternative solution to entangle this circularity would be overly complicated, and the loss of generality implied by the restriction $m > 0$ seems acceptable.

For the case in which restoration processes may fail, the probability of such failure is denoted by $\varphi$. A successful process (happening with probability $1 - \varphi$) completes after exactly *M* time steps.

*Scheme design*

Assuming that initially $n(0)$ land parcels are habitat and $N - n(0)$ land parcels are in economic use, the initial amount of credits in the market is set at $-d$ ($d \geq 0$). Under the choice of $d = 0$, a habitat can be developed once a credit has been created. The choice $d > 0$ describes an initial debt of *d* credits that must be balanced by the creation of *d* credits before any habitat parcel can be developed; this choice represents the raise of the target for the number of habitat parcels.

A habitat parcel may be converted to economic use by purchasing a credit. In the *award-completion* scheme a credit is awarded with successful completion of a restoration process when the previously economically used land parcel has turned into habitat. The credit can be sold at the current market price $p$ (banking of credits is ignored, so an earned credit is sold immediately). In the *award-initiation* scheme credits of an amount $1/q$ ($q \geq 1$) are earned with the initiation of a restoration process on an economically used land parcel. Here a value of $q > 1$ represents a trading ratio as described in the Introduction. Similar to the *award-completion* scheme, earned credits are sold immediately at the current market price $p$.

Landowners are not allowed to prematurely cease a running restoration process, so after the process has been initiated the land parcel remains in conservation for $m$ time steps (in the case of uncertain restoration duration) or $M$ time steps (in the case of uncertain restoration success). Only once a successful restoration process is complete and the land parcel has become habitat (after $m$ or $M$ time steps, respectively) the land parcel may be re-developed to economic use, which requires the purchase of a credit – as described above.

The future of a land parcel on which a restoration process had just turned out to fail depends on the scheme. In the *award-completion* scheme the landowner had not received any credits yet, so the land parcel may (and will: see below) switch back in the next time step from conservation to economic use without the necessity of purchasing a credit. In contrast, in the *award-initiation* scheme in which the landowner had received a credit with the initiation of the restoration process, the land parcel can be switched back to economic use only after the purchase of a credit.

To ensure in the *award-initiation* scheme that there is no net habitat loss at least in the temporal average, either the target must be raised ($d > 0$) or a trading ratio must be introduced ($q > 1$). To avoid numeral difficulties in the calculation on the credits market clearance (see below), $d$ and $q$ are chosen as integer numbers. Preliminary calculations reveal that if there is no uncertainty in the restoration success, even the smallest integer value above one, $q = 2$, generally leads to overly large average numbers of habitat parcels above the initial value (net habitat gain), which complicates the comparison between the *award-initiation* and *award-completion* schemes. Therefore in this case, $q$ $=1$ and $d > 0$ are considered. In contrast, if restoration processes can fail, it turns out that only $q > 1$ can prevent the continuing decline of the number of habitat parcels, and to avoid both net loss and net gain of habitat $d = 0$ and $q > 1$ are considered.

*Landowner decision making*

Since the economic profits are assumed to change in a deterministic manner, it is consistent to assume that the landowners perfectly know their future values. Further, in a perfect permit market, without time lags or uncertainty, the (equilibrium) permit price equals the marginal cost at the cap (or conservation target as in the present case) (e.g., Tietenberg (2006)). In the present model, time lags and uncertainty associated with the restoration process cause temporal fluctuations but no deterministic trends in the dynamics. Since there is also no temporal change in the profit distribution (eq. (2)), the credits price is nearly constant, with no trend and with comparatively small fluctuations around its mean (Fig. 4). Thus, it is consistent to assume that the landowners in their decisions assume a constant credits price that equals the current price.

As described above, in the *award-initiation* scheme the initiation of a restoration process earns one credit immediately which is sold at price $p$, earning a revenue of

$$R_{\text{aw-init}} = p / q \tag{4}$$

This equation holds for both cases of restoration uncertainty (in duration and in success). In the *award-completion* scheme the credit is earned with completion of the restoration process. In the case where the process succeeds with certainty but has uncertain duration, the revenue of initiating a restoration process on an economically used land parcel is given by the credits price $p$ discounted over the time lag $m$:

$$R_{\text{aw-compl, 1}} = p(1+\delta)^{-m} \tag{5}$$

In the case where the restoration process may fail the revenue of initiating a restoration process (of duration $M$) is

$$R_{\text{aw-compl,2}} = \begin{cases} p(1+\delta)^{-M} & \text{success} \\ A^{(M)} & \text{failure} \end{cases} \tag{6}$$

where

$$A^{(M)} = \sum_{\tau=M}^{\infty} a(\tau)(1+\delta)^{t-\tau} \tag{7}$$

is the discounted flow of economic profits starting from the time $M$ at which the failed restoration process ended (counted from the initiation of the restoration process; note that in eq. (7) and the equations below, for simplicity of notation, the land-parcel index $i$ is dropped and the current time step is assigned a value of $t = 0$). This considers that after a failed restoration process in the *award-completion* scheme, the land parcel may switch back to economic use for free, and since under conservation the land parcel earns zero revenue it is always profitable ($A^{(M)} > 0$) for the landowner to choose that option.

It is assumed that landowners may be risk averse to the uncertainty in $m$ (eq. 5) or $\varphi$ (eqs. (6). This is modeled by transforming the revenue $R$ into a von-Neumann-Morgenstern utility function

$$u(R) = \frac{R^{1-\rho} - 1}{1-\rho} \tag{8}$$

with constant relative risk aversion $\rho$ (Eckhoudt et al. 2005). The expected risk utility of changing an economically used land parcel to conservational use and initiate a restoration process then is, usings eqs. (4) and (6)–(8):

$$EU(\text{econ} \rightarrow \text{cons}) = \begin{cases} u(p/q) & \text{award-inititiation scheme} \\ \sum_m \Pr(m) u\left(p(1+\delta)^{-m}\right) & \text{award-completion scheme, uncertain duration } (m) \\ (1-\varphi) u\left(p(1+\delta)^{-M}\right) + \varphi u(A^{(M)}) & \text{award-completion scheme, uncertain success } (\varphi) \end{cases} \tag{9}$$

To decide whether a restoration process is initiated or not, this risk utility $EU$ is compared to the certain utility of keeping the land parcel in economic use

$$U(\text{econ} \rightarrow \text{econ}) = u(A) \tag{10}$$

where

$$A = \sum_{\tau=0}^{\infty} a(\tau)(1+\delta)^{-\tau} \tag{11}$$

is the present value of the land parcel's flow of profits under economic use (i.e., its land price).

Assuming that next to the foregone economic profits restoration incurs no additional costs, the restoration process is initiated and the economically used land parcel is conserved if $EU$(econ → cons) > $EU$(econ → econ). Otherwise the land parcel stays in economic use.

Considering the possible transitions of habitat parcels, a habitat parcel is developed to economic use if its land price $A$ exceeds the credits price $p$: $A > p$. Otherwise it remains habitat (and conserved). As described above, land parcels in restoration remain in restoration (and in conservational use) until the restoration process has either ended successfully or failed.

A final note: Landowners assume that once the land parcel has become a habitat it will not be developed again. This does not exclude that they will in fact develop the habitat back into economic use, which would require the purchase of a credit. However, since the economic profits $a_i$ change monotonically in time (eqs. (1) and (2)), it is unlikely that a restored land parcel will ever be re-developed. If alternative profit dynamics were assumed eq. (9) would model some kind of myopic behaviour that ignores the longer future beyond the duration of the restoration process.

*Market clearance*

The model is a partial equilibrium model in which the credits market clears in each time step. As implied by eqs. (5) and (6), at credits price $p = 0$ no land parcel will switch from economic to conservational use and the amount of credits equals the number of land parcels initiating a restoration process (*award-initiation* scheme) or completing the restoration process (*award-completion* scheme). At the same time, all conserved land parcels will be converted to economic use, so there will be an undersupply of credits. In contrast, at $p \to \infty$ all habitat parcels will stay in conservation and all economically used land parcels will switch to conservation, so demand for credits will be zero and credits oversupplied. Using a simple iterative numerical procedure, the unique positive and finite equilibrium credits price $p^*$ where supply equals demand is determined. As considered, e.g., by Needham et al. (2020), $p^*$ is at the intersection of the supply (marginal cost) and demand (marginal benefit) curves (for a numerical example, see Appendix C of the present paper).

*Model initialisation (t = 0)*

It is assumed that initially $n(0)$ land parcels are habitat and $N - n(0)$ are in economic use. There are two reasons why landowners would trade credits and change the initial land use in the course of the model dynamics. First, economically profitable land parcels are currently habitat and unprofitable ones are in economic use, so the current land use is not cost-effective. There will be a substantial immediate demand for credits to develop those profitable habitat parcels which would have to be met by the restoration of (unprofitable) economically used land parcels. In a static world in which the agricultural profits are constant ($a_i(t) = a_i(0)$ for all $t > 0$) this reallocation process would end once the cost-effective allocation in which the $n(0)$ least profitable land parcels are habitat has been reached. The extent of this reallocation process depends entirely on the match between the initial distribution of the habitat parcels and the least profitable land parcels. If there is perfect overlap there will be no change while if there is zero overlap all habitat parcels will in the end be developed to economic use and all habitat parcels had been in economic use initially.

The second reason for credits market activity and land-use change is the temporal change in the agricultural profits, $a_i(t)$. The present analysis focuses on this second process. The first process of spatially aligning land-use with economic profitability depends, as described, entirely on the incidental correlation between economic profits and land cover. To eliminate this, I assume that initially the $n(0)$ least profitable land parcels are habitat and all others are in economic use. Further, no credits are available initially but are awarded once restoration processes are initiated (*award-initiation* scheme) or completed (*award-completion* scheme; except for the explicit consideration of a credit debt, $d > 0$).

In the *award-completion* scheme a habitat can be developed only if at the same time a restoration processes completes successfully, so net loss is excluded by scheme construction. In contrast, in the *award-initiation* scheme a habitat can be developed if at the same time a restoration process is initiated, leading at least to temporary net habitat loss. To ensure that at least on average there is no net loss, the target for the number of habitat parcels may be raised. This is achieved by initiating the dynamics with a debt of $d$ credits which has to be removed in the first model time step by initiating (at least) $d$ more restoration processes than habitat parcels can be developed (cf. the above section on scheme design).

*Model dynamics ($t > 0$):*

The model dynamics are simulated over $T = 100$ time steps. Depending on the agricultural profit $a_i(t)$, in each time step $t$ each landowners predicts the (expected) profitabilities of conservation and economic use as functions of the current state of the land parcel (habitat or in economic use; recall that land parcels in restoration remain conserved until the restoration process is complete or has failed) and the credits price $p$. From these functions the equilibrium credits price $p^*$ is determined as described above, which determines the land use for each land parcel. For those land parcels that switch from economic use to conservation, the duration of the restoration process is sampled according to eq. (3), or if restoration failure is considered, the duration of the restoration is set at the fixed value of $M$, and it is sampled whether the process will succeed (with probability $1 - \varphi$) or not.

For each land parcel under restoration the time step in which the restoration process completes is recorded, and for each time step the number of land parcels is counted that are just completing their restoration process and turn into habitat. As described above, in the *award-initiation* scheme this number represents the number of credits coming onto the market.

**2.3 Model analysis**

As described, the model dynamics are simulated for $T = 100$ time steps. In each time step the number of habitat parcels, the total forgone economic profit and the ratio of the two (i.e. the cost per habitat parcel) is recorded. For the comparison of the *award-initiation* and the *award-completion* schemes, the following statistics ("scheme performance variables") over the $T$ model time steps are calculated:

1. the average cost per habitat parcel (cost-effectiveness),
2. the cost variation, i.e. coefficient of variation in the forgone profits of all land parcels,
3. the habitat variation, i.e. coefficient of variation in the number of habitat parcels,
4. the habitat turnover, i.e. the proportion of habitat parcels developed per time step into economic use.

To account for the stochasticity in the model dynamics, the simulation is carried out 200 times and averages of the performance variables taken. As described, the two conservation offset schemes are compared under the constraint that both deliver the same long-term average of habitat parcels that is equal to the initial numbers – that is there is neither net gain nor net loss of habitat. While the *award-completion* scheme meets this constraint by construction, the *award-inititation* scheme must be tuned to no net loss or gain by an appropriate choice of the target raise $d$ (considered, as argued, if restoration success is certain but duration is uncertain) or the trading ratio $q$ (considered if the restoration duration is certain but success is certain). For this, $d$ or $q$ are incremented from their initial values $d = 0$ and $q = 1$ until there is no net loss (Fig. 2).

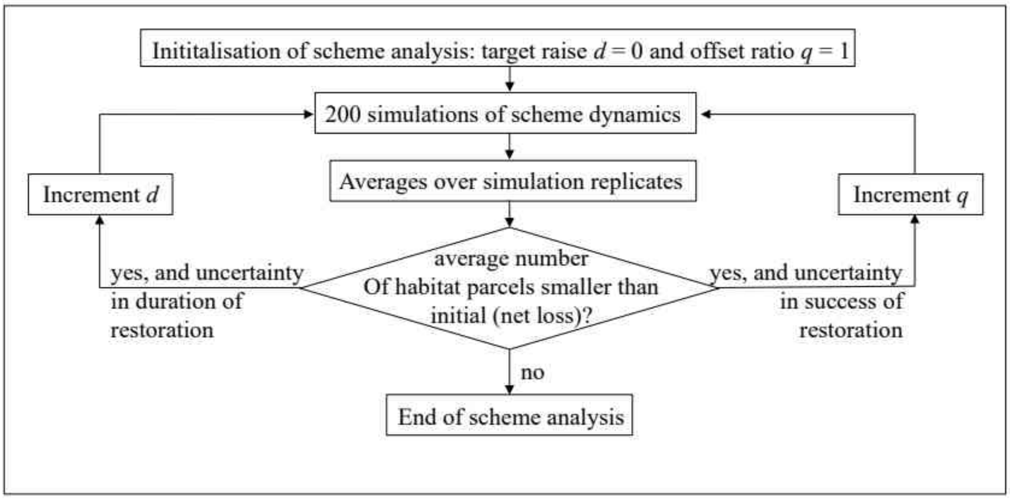


Figure 2: Analysis of the *award-initiation* scheme to achieve no net habitat loss or gain on average.

In a global sensitivity analysis (Saltelli et al. 2008), the described analyses are carried out for 500 random model parameter combinations where each parameter (in the case of the profit dynamics $\gamma$: the common logarithm) is drawn from a uniform distribution with bounds given in (Table 1). The mean restoration time and the risk of restoration failure are drawn as integer values while all other model parameters are real values.

The bounds in Table 1 are motivated as follows. A value of $\sigma = 0.2$ (0.8) correspond to a profit ratio between the most and the least profitable land parcels of of 1.5 (9), which covers a broad range of possible situations. Preliminary analyses revealed that reducing $(\lg(\gamma/(2\sigma))$ below –3 (i.e., $\gamma < 0.001 \cdot 2\sigma$) does not change the economic profit dynamics compared to that obtained for $(\lg(\gamma/(2\sigma) = -3$, while an increase of $(\lg(\gamma/(2\sigma)\ \gamma$ beyond –1 ($\gamma > 0.1 \cdot 2\sigma$) does not change the economic profit dynamics either compared to that obtained for $(\lg(\gamma/(2\sigma) = -1$.

The chosen discount rates are typical for private investment decisions, and a risk aversion of $\rho = 0.5$ can be regarded as quite strong (Derissen and Quaas 2013). The meaning of the values of $M$ depend on the time scale of the model. If land use is considered to change every year (or decade) than values of $M = 2, 10$ represent restoration times of 2, 10 years (or decades). A restoration failure probability of $\varphi = 0.8$ is regarded as severe uncertainty in the modelling framework of Moilanen et al. (2009).

Table 1: Bounds of the model parameters. If uncertainty is in the duration of the restoration process, the probability of restoration failure is fixed at $\varphi = 0$.

| Model parameter | Symbol | Lower and upper bounds |
|---|---|---|
| Economic profit heterogeneity | $\sigma$ | 0.2, 0.8 |
| Logarithm of economic profit dynamics | $\lg(\gamma/(2\sigma))$ | –3, –1 |
| Discount rate | $\delta$ | 0.02, 0.08 |
| Risk aversion | $\rho$ | 0, 0.5 |
| Mean restoration time | $M$ | 2, 10 |
| Probability of restoration failure | $\varphi$ | 0, 0.8 |
| Initial number of habitat parcels | $\lambda_0 \equiv n(t=0)/N$ | 0.1, 0.4 |

For each model parameter combination, the means and standard deviations, $mean_{aw\text{-}init}$, $mean_{aw\text{-}compl}$, $sdev_{aw\text{-}init}$ and $sdev_{aw\text{-}compl}$ of the performance variables defined above are calculated for the two offset schemes over the 500 parameter combinations, and from this an effect size is calculated via

$$E = \frac{mean_{aw\text{-}init} - mean_{aw\text{-}compl}}{\left(sdev_{aw\text{-}init}^{2} + sdev_{aw\text{-}compl}^{2}\right)^{0.5}} \qquad (12)$$

which measures the effect of a treatment with uncertain outcomes (Cohen 1988), where the treatment in the present case is the “replacement” of an *award-completion* scheme by an *award-initiation* scheme. A non-zero effect size is a sufficient condition for statistical significance (provided the sample size is sufficiently large) but in addition, $E$ tells how marked the effect is relative to the uncertainty in the outcomes.

The following quantities are calculated for each of the four performance variables:

- the mean of $E$ over the 500 model parameter combinations
- the standard deviation of $E$ over the 500 model parameter combinations
- the correlation of $E$ with the seven model parameters.

## 3 Results

### 3.1 Model dynamics for an exemplary scenario

The difference between the functioning of the *award-completion* and the *award-inititation* schemes is vividly demonstrated in Fig. 3. For average values of the model parameters (Table1), Fig. 3a,b shows typical examples of the stochastic dynamics of the *award-completion* scheme: the number of habitat parcels (black bars), the number of land parcels completing their restoration process and turning into habitat (grey bars stacked on top of the black bars), and the number of habitat parcels converted to economic use (grey bars stacked below the black bars). In the first few time steps, no land parcel turns into habitat, since by the initialisation of the model dynamics there are no land parcels in restoration at $t = 0$. In the example of Fig. 1a, only at $t = 8$ is one land parcel completing its restoration process (which must have been initiated in one of the previous time steps) and allows one habitat parcel to be developed to economic use. These processes continue over time, driven by the changing economic profits of the land parcels. Here it is noticeable that the number of habitat parcels is constant at the initial value of 20, which is achieved in each time step by an equality of the number of converted habitat parcels and the number of land parcels completing their restoration process.

In the *award-inititation* scheme (Fig. 3c,d) habitat parcels are converted to economic use even before previously economically used land parcels have turned into habitat. In Fig. 3c, e.g., four land parcels are developed between times $t = 0$ and $t = 1$, reducing the number of habitats by four to a level of 16 in $t = 1$. Only between $t = 4$ and $t = 5$ some of the deficit is partly offset by the completion of two restoration processes, increasing the number of habitat parcels in $t = 5$ to 18. Between $t = 5$ and $t = 6$ two more land parcels turn into habitat while one habitat parcel is developed, increasing the number of habitat parcels in $t = 6$ to 19. From $t = 16$ to $t = 19$, the number of habitat parcels exceeds the initial value of 20. In this manner the dynamics continue with the number of habitat parcels varying around a mean of about 20.

The total economic profit, i.e., the sum of profits on the economically used land parcels, varies according to the exogenous change modeled in eqs. (1) and (2) and the induced land-use changes. Figure 4a shows some examples in which the total profit in the *award-inititation* scheme (bold lines) are quite similar for both types of restoration uncertainty. While in the *award-completion* scheme (thin lines) uncertainty in the duration of the restoration process (solid line) appears to generate lower total profit than uncertainty in the restoration success (dashed line).

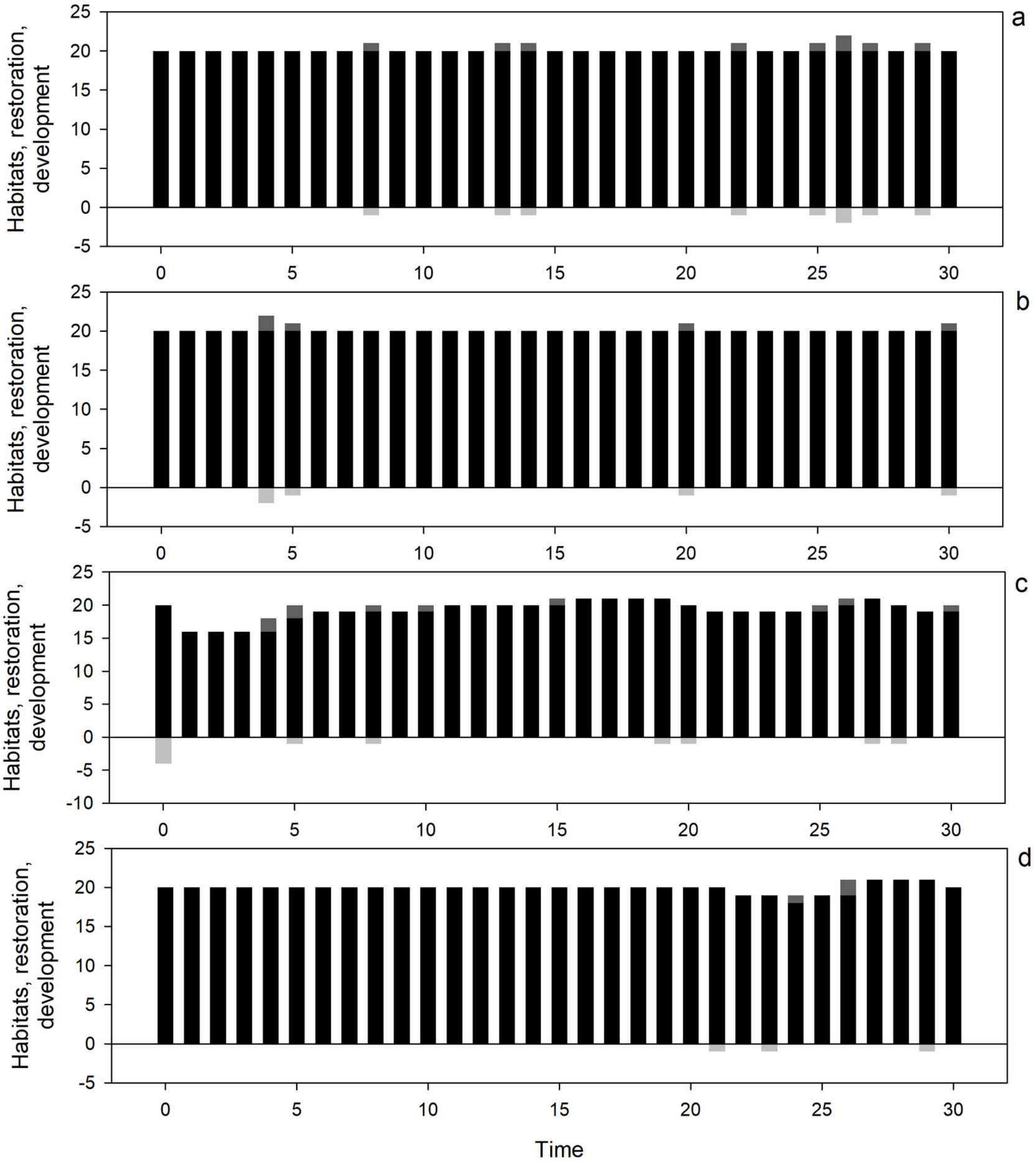


Figure 3: Random realisations of the dynamics of the number of habitat parcels (black bars), the number of land parcels completing their restoration process (grey bars stacked on top of the black bars), and the number of habitat parcels converted to economic use (grey bars stacked below the black bars). Panels a,b: *award-completion* scheme; panels c,d: *award-inititation* scheme. Model parameters (cf. Table 1): $\sigma = 0.5$, $\gamma/(2\sigma) = 0.01$, $\delta = 0.05$, $\rho = 0$, $M = 5$, $\lambda_0 = 0.2$. Panels a,c: uncertain duration of the restoration process ($\varphi = 0$); panels b,d: uncertain success of the restoration process ($\varphi = 0.4$).

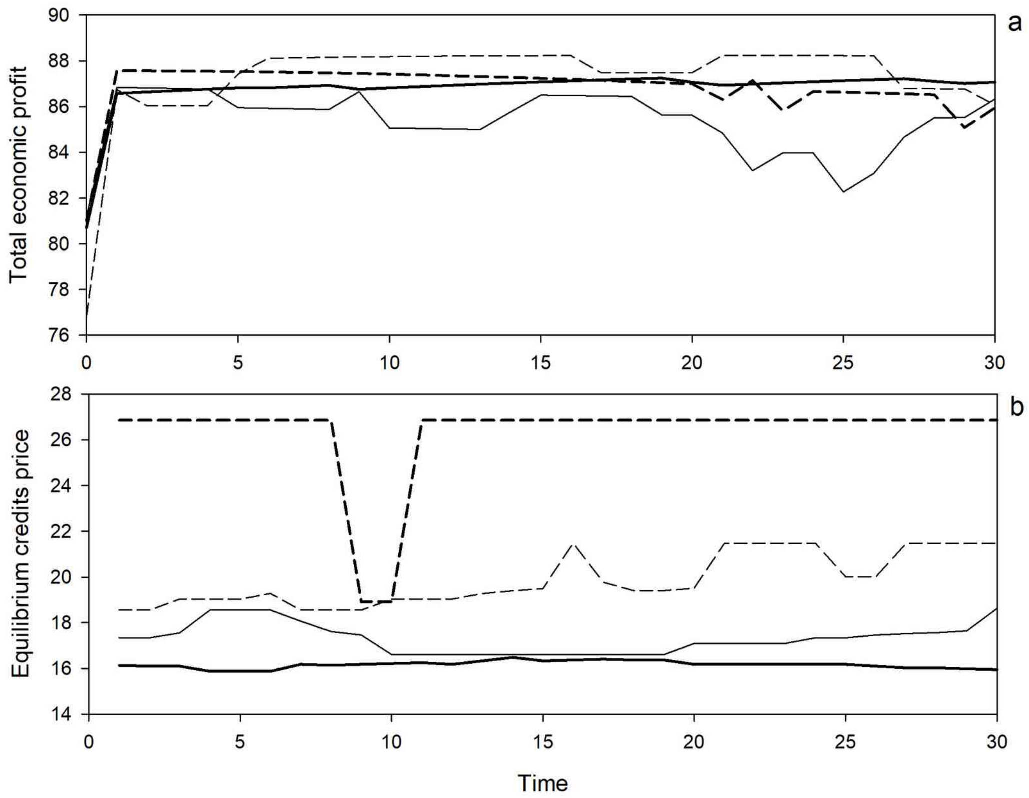


Figure 4: Examples of random trajectories of the total profit of the economically used land parcels (panel a) and the credits price *p** (panel b). Solid and dashed lines: uncertainty in the duration and the success, respectively, of the restoration process. Thin lines: *award-completion* scheme and bold lines: *award-inititation* scheme. Model parameters as in Fig. 3.

Figure 4b confirms the assumption formulated in the Methods section on landowner decision making, that the credits price is fairly constant over time, which – as explained – stems from the constancy of the distribution of the economic profits in the model region. Appendix C discusses differences between the two schemes within the classical economic framework of supply and demand functions.

### 3.2 Sensitivity analysis

The effect of replacing the *award-initiation* by the *award- completion* scheme on the four performance variables introduced in section 2 is measured by the effect size $E$, eq. (12), where a value below 0.5 can be regarded as low and a value above 0.8 as large (Cohen 1988). By this, I classify the results of the sensitivity analysis, Table 2, as follows: if $E > 0.8$ the associated performance variable is markedly larger in the *award-inititation* scheme than in the *award-completio*n scheme; if $-0.5 < E < 0.5$ both schemes perform similarly; and if $E < -0.8$ the associated performance variable is markedly smaller in the *award-inititation* scheme than in the *award-completion* scheme.

Table 2: Means and standard deviations of the effect size $E$ for the four scheme performance variables, over all 500 model parameter combinations; and Pearson's correlation coefficients between the effect sizes and the seven model parameters.

| | Uncertainty in restoration duration | | | | Uncertainty in restoration success | | | |
|---|---|---|---|---|---|---|---|---|
| | Cost per habitat | Cost variation | Habitat variation | Habitat turnover | Cost per habitat | Cost variation | Habitat variation | Habitat turnover |
| Mean $E$ | 0.29 | -2.76 | 5.49 | 1.00 | -0.08 | -0.16 | 1.91 | -1.17 |
| Standard deviation of $E$ | 0.51 | 1.67 | 1.01 | 2.10 | 0.72 | 1.58 | 1.15 | 1.68 |
| Correlation between $E$ and | | | | | | | | |
| Profit heterogeneity $\sigma$ | -0.25 | -0.07 | 0.04 | -0.40 | -0.10 | 0.00 | 0.41 | -0.15 |
| lg(Profit dynamics $\gamma/(2\sigma)$) | -0.35 | -0.71 | 0.73 | -0.44 | -0.45 | -0.42 | 0.31 | -0.60 |
| Discount rate $\delta$ | 0.11 | 0.34 | 0.03 | 0.55 | 0.43 | 0.35 | -0.12 | 0.40 |
| Risk aversion $\rho$ | -0.03 | -0.02 | -0.03 | 0.00 | -0.01 | 0.03 | -0.09 | 0.00 |
| Mean restoration duration $M$ | 0.32 | 0.00 | -0.05 | 0.37 | 0.40 | 0.16 | -0.01 | 0.37 |
| Prob. of restoration failure $\varphi$ | - | - | - | - | -0.19 | 0.16 | -0.70 | 0.04 |
| Initital proportion of habitats $\lambda_0$ | 0.06 | -0.10 | 0.35 | 0.17 | -0.03 | 0.11 | -0.01 | -0.03 |

In this manner, the following can be stated:

1. For both types of restoration uncertainty the cost per habitat parcel, i.e. in the cost-effectiveness, is similar in both schemes (mean $E$ of 0.29 and –008, respectively). However, with standard deviations of $E$ of 0.51 and 0.72, the magnitude of the performance difference between the two schemes varies substantially (allowing values of $E$ far above 1 or below –1) if the model parameters are varied within their ranges of Table 1. The correlation coefficients in Table 2 indicate that $E$ increases especially if the economic profit heterogeneity $\sigma$ or the economic profit dynamics $\gamma$ are reduced (indicated by the negative correlations) or if the mean restoration duration $M$ is increased (indicated by the positive correlation). Thus, for large $\sigma$ and $\gamma$ and small $M$ the effects size $E$ will be very large and negative, indicating that the *award-initiation* scheme is markedly more cost-effective than the *award-completion* scheme, while the opposite is observed for small $\sigma$ and $\gamma$ and large $M$.

2. In the case of uncertain restoration duration, the *award-initiation* scheme generates markedly less cost variation than the *award-completion* scheme over most of the model parameter space (the mean of $E$ is negative and its absolute value about twice the standard deviation). Large values of $E$ close to zero so that both schemes generate a similar cost variation are obtained (cf. the correlation

coefficients) for slow economic profit dynamics $\gamma$ and large discount rates $\delta$. In the case of uncertain restoration success, both schemes perform, on average, similar, but the standard deviation of $E$ is large, so the *award-initiation* scheme can generate both markedly higher or lower cost variation than the *award-completion* scheme. Analogous to the case of uncertain restoration duration, the former is observed for slow economic profit dynamics $\gamma$ and large discount rates $\delta$.

3. Habitat variation is markedly higher in the *award-initiation* scheme than in the *award-completion* scheme across the entire model parameter space in the case of uncertain restoration duration (the mean of $E$ is positive and much larger than the standard deviation of $E$) and across most of the parameter space in the case of uncertain restoration success. This is not surprising, given that the *award-completion* scheme by construction does not generate any habitat variation at all. In the case of uncertain restoration duration this effect is largest if the economic profit dynamics $\gamma$ are fast and the initial proportion of habitat parcels $\lambda_0$ high. In the case of uncertain restoration success the effect is largest if the economic profit heterogeneity $\sigma$ and economic profit dynamics $\gamma$ are high and especially if there is a high risk of restoration failure $\varphi$.

4. An interesting observation regards the habitat turnover. This is on the average of all model parameter combinations markedly larger in the *award-initiation* scheme than in the *award-completion* scheme if the uncertainty is in the restoration duration, while the opposite is observed if the uncertainty is in the restoration success. However, the standard deviation of the effect size is larger than its mean, so in both cases of uncertainty the opposite of the "average" behaviour can be observed. The effects of the model parameters are similar with both types of restoration uncertainty, so that a decreasing economic profit heterogeneity $\sigma$ or profit dynamics $\gamma$, increasing discount rate $\delta$ and increasing restoration time $M$ increase $E$, i.e. the habitat turnover in the *award-initiation* scheme relative to that in the *award-completion* scheme.

## 4 Discussion

In this paper a general agent-based ecological-economic simulation model is developed to explore whether conservation offsets should be implemented as "*award-initiation* schemes" in which credits from habitat restoration are earned immediately at the initiation of the restoration process, or as "*award-completion* schemes" in which credits are earned only with completion of the restoration process.

The model considers a region with 100 land parcels, each of which can be managed for conservation or for economic purposes such as agriculture. Economic use earns a profit which varies among land parcels and changes over time. The model dynamics start with a certain number of land parcels in habitat state and the others in economic use. As the (potential) economic profit on a habitat parcel increases, the owner of that land parcel may wish to develop the parcel to economic use, for which s/he needs to purchase a credit on a credits market. Credits are supplied, as described, by landowners who are initiating (*award-initiation* scheme) or completing (*award-completion* scheme) a restoration process on their previously economically used land parcel.

Two types of uncertainty in the restoration process are considered: uncertainty in the duration and uncertainty in the success of the process. The two offset schemes are compared for both types of restoration uncertainty with respect to (i) the cost (forgone economic profit) per habitat parcel (measuring the cost-effectiveness of the scheme), (ii) the variation in the scheme cost (coefficient of variation, over time, of the forgone profits incurred by the conservation of land parcels), (iii) the variation (coefficient of variation over time) in the number of habitat parcels, and (iv) the habitat turnover which is defined as the average number of habitat patches developed into economic use between consecutive time steps.

By construction, the *award-completion* scheme can guarantee that there is no net loss (NNL) of habitat, while in the *award-initiation* scheme there can be temporary or even permanent (if habitat restoration fails) habitat loss. To allow for a meaningful comparison of both schemes, NNL on the long term average is achieved in the *award-initiation* scheme by either raising the conservation target (applied here if the duration of the restoration process is uncertain) or by introducing trading ratios so that the development of a habitat parcels is compensated by the initiation of the restoration of more than one economically used land parcels (applied here if the success of the success of restoration is uncertain).

While previous ecological research strongly argues in favour of the *award-completion* scheme the integrated consideration of the ecological and the economic dimensions leads to more differentiated conclusions. On the average of the considered 500 random model parameter combinations, both schemes have a similar level of cost-effectiveness, but a more detailed inspection of the results reveals that (especially) if the economic profits on the land parcels change fast over time and/or the mean duration of the restoration processes is small the *award-initiation* scheme is more cost-effective than the *award-completion* scheme while the opposite is observed for slow profit dynamics and large mean restoration duration.

The variation in the scheme costs is generally (but not always!: cf. Section 3.2) higher in the *award-*

*completion* scheme than in the *award-initiation* scheme, while the opposite is observed for the variation in the number of habitat parcels. This points to a different allocation of the risk introduced by the uncertainty in the habitat restoration. Due to its tight regulation that a habitat cannot be developed before another land parcel has been successfully restored, in the *award-completion* scheme the uncertainties associated with habitat restoration translate into cost variation while the ecological benefit (NNL) is achieved with certainty. In contrast, the looser regulation in the a*ward-initiation* scheme implies that less of the restoration uncertainty translates into cost variation – at the expense that there is variation in the ecological benefit (temporary habitat loss). How critical such temporary habitat loss is depends on the traits of the species to be conserved (e.g., whether the species is “r-” or “K-selected”: Begon et al. (2005)).

In the case of uncertain restoration duration the amount of habitat turnover agrees with the habitat variation and is generally higher in the *award-initiation* scheme than in the *award-completion* scheme. Interestingly, the opposite is observed if the uncertainty is in the restoration success: the *award-initiation* scheme leads to *less* habitat turnover than the *award-completion* scheme. Thus, there is not only a trade-off between cost variation and habitat variation but also between habitat variation (minimised in the *award-completion* scheme) and habitat turnover (minimised in the *award-initiation* scheme). Again, it depends on the traits of the species, among others its ability to colonise restored habitat parcels (De Woody et al. 2005, Drechsler and Johst 2010), which of the two is more adverse.

Altogether, the two considered scheme designs appear to have different pros and cons which to quite some extent depends on the ecological and economic circumstances. Among the parameters of the present model, the speed by which the economic profits of the land parcels change is the most important one which tends to increase cost-effectiveness and habitat variation and reduce habitat variation in the *award-initiation* scheme relative to those in the *award-completion* scheme. The least important parameter is, interestingly, the level of risk aversion which was expected to strongly influence the decisions of the landowners and the dynamics under the *award-completion* scheme. An explanation for this unexpected finding is provided in Appendix B.

The discussion above points to some questions for future research. One follows from the identified trade-offs between the amount of habitat that can be provided for given economic cost (determined by the cost per habitat), and the amount of habitat variation and turnover, which all affect the survival of species. Coupling the present model to an ecological population model would reveal which scheme design is eventually able to deliver species conservation most cost-effectively, and how this depends on the characteristics of the species.

Next to this, one could consider that the survival of species not only depends on the dynamics but also on the spatial distribution of their habitat (Hanski 1999). On the economic dimension, the importance of the spatial distribution of habitat for species has motivated the introduction of the agglomeration bonus that rewards the conservation of land close or adjacent to other conserved land (Parkhurst et al. 2002). In a static setting, Hartig and Drechsler (2009) incorporated the agglomeration bonus into the coupled ecological-economic simulation model of a conservation offset scheme, but the joint consideration of both the spatial and the temporal dimensions is still a matter of future research.

Another question of interest is how the present results and arguments carry over to "net gain policies" which aim at a net increase in ecological benefits (Bull and Brownlie 2015). Within the present framework there appears no obvious reason why this should not be the case, but future research may explore this issue in more detail.

For simplicity, the considered model assumes two land-use types, economic use and conservation, and development of conserved sites into economically used site must be compensated for by restoring economically used sites. By this, the present analysis is similar to those of Chomitz (2004) and Kangas and Ollikainen (2019) where conservational use represents forestry and economic use represents (intensive) agriculture and industry like mining, respectively. A slightly more complex setting was considered by Needham et al. (2020) who assumed three land-use types: conservation (with high ecological benefit), agriculture (with medium ecological benefit) and housing development (with zero ecological benefit), and where economic development changes agricultural sites to housing areas, while ecological restoration changes agricultural sites into conserved sites. Despite this difference, restoration uncertainty and time lags should have similar effects as in the present study, but it would be worth while to extend the model analysis to more than two land-use types.

While inter-temporal trading such as the banking of credits is not considered in the present analysis (where earned credits are sold on the spot), it plays a role in real conservation offset schemes (Levrel et al. 2017). Bekessy et al. (2012) consider it as a means for insuring investors against the risks associated with the habitat restoration in *award-completion* schemes. Yet, to the authors knowledge there is no modelling study that explores the effects of banking in conservation offsets, which is another avenue of further research.

To conclude, the present analysis provides another example, next to seminal ones like Ando et al. (1998), that the integrated consideration of both the ecological and the economic dimensions of a conservation problem can lead to quite different conclusions from those obtained in disciplinary ecological or economic analyses. The answer to the question of whether credits in conservation offsets should be awarded at the initiation or the successful completion of habitat restoration is much less clear than suggested by previous ecological research. Both scheme designs appear to have their pros and cons which depends on the circumstances. Especially in the face of fast economic change the award-completion scheme has considerable advantages on the economic cost side due to its higher flexibility – which however come at an increased ecological risk. In line with arguments by zu Ermassen et al. (2020), one should not strike out these cost advantages lightly but invest the saved costs to compensate for the increased ecological risks, such as by financing conservation efforts in phases of temporary habitat loss.

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**Supplementary Material: On the cost-effective temporal allocation of credits in conservation offsets when habitat restoration takes takes time and is uncertain**

**Appendix A: Dynamics of the economic profits**

Equations (1) and (2) models the changing profits $a_i(t)$ on the land parcels $i$ in dependence of the parameters $\sigma$ and $\gamma$. Figure A1a shows a numerical example. In section 2.2 *Dynamics of the agricultural profits* I argue that the model dynamics are largely independent of an overall trend where between consecutive time steps all profits multiply by the same factor $b$. Figure A1b shows a numerical example of such profit dynamics.

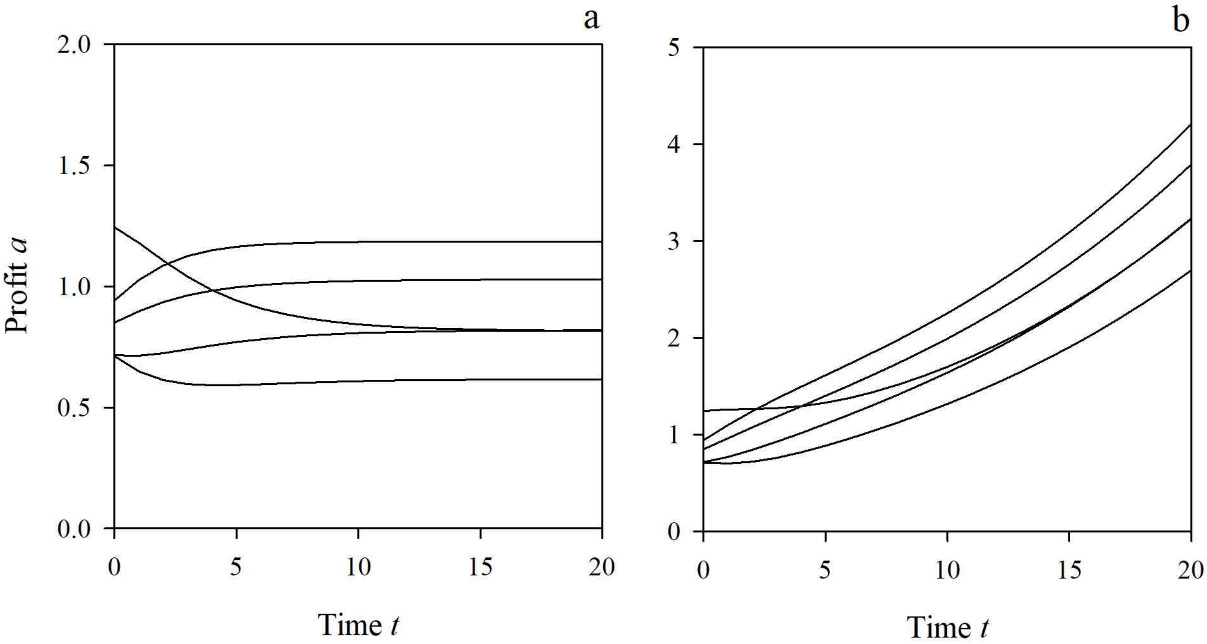


Figure 1: Dynamics of the economic profits $a_i(t)$ for $i = 1, \ldots, 5$ land parcels of eqs. (1) and (2), with cost variation $\sigma = 0.4$ and cost dynamics parameter $\gamma = 0.2$ (cf. section 2.2 *Dynamics of the agricultural profits*) (panel a). In panel b, the profits of panel a are multiplied by $b^t$ with $b = 1.05$, so between consecutive time steps all profits multiply by a factor of 1.05.

**Appendix B: On the impact of risk aversion $\rho$ on the example of uncertainty in the duration of the restoration process**

To understand why the level of risk aversion has little influence on the landowners' decisions and the model dynamics, consider Fig. B1 which assumes for the *award-completion* scheme the baseline value for the discount rate, $\delta = 0.05$ and a credits price of $p = 23$.

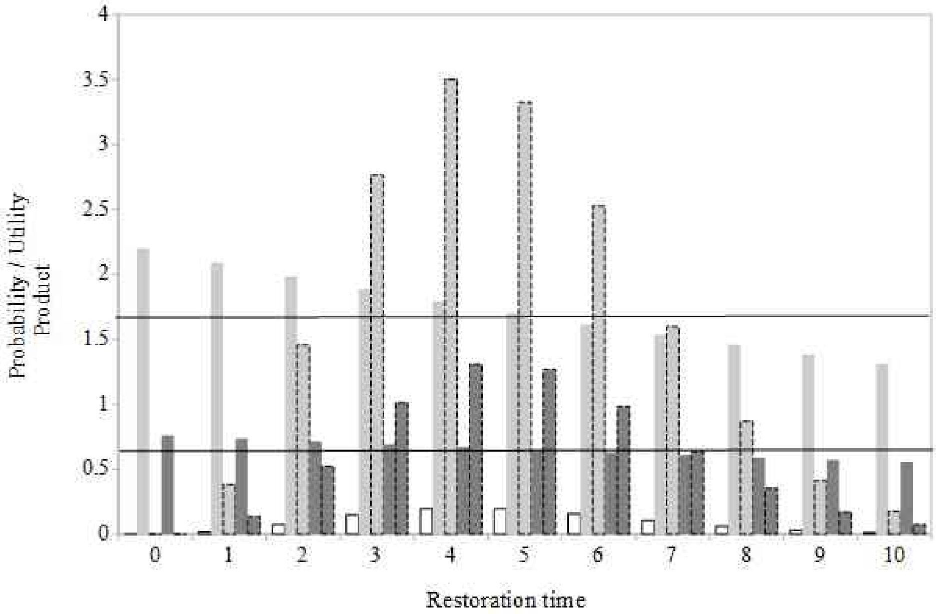


Figure B1: Various quantities in the *award-completion* scheme as function of the restoration time *m*. Discount rate $\delta = 0.05$, credits price $p = 23$. White bars: probability $P_M(m)$ of observing *m* for the baseline mean restoration time $M = 5$ (eq. 3). Open light grey bars: one tenth of the utility of switching from economic use to conservation (cf. eq. (9)) if the level of risk aversion is $\rho = 0$. Open dark grey bars: same as the open light grey bars but for $\rho = 0.5$. Closed (by dashed line) light grey bars: product of the corresponding white bar and open light grey bar, which is the *m*-th summand of the expected utility of eq. (9) for $\rho = 0$. Closed dark grey bars: analogous to closed light grey bars but for $\rho = 0.5$. Upper horizontal line: one tenth of the sum of the light grey dashed-bordered bars, i.e. one tenth of the expected utility of conservation (eq. 9) for $\rho = 0$. Lower horizontal line: analogous as the upper horizontal line but for $\rho = 0.5$.

The uncertainty in the restoration time is considered by the risk utility function of eq. (8) with risk aversion coefficient $\rho$. The light grey bars correspond to $\rho = 0$ and the dark grey bars to $\rho = 0.5$. The impact of increasing $\rho$ from zero to 0.5 on the expected risk utility of eq. (9) is on the one hand a trivial one that reduces the risk utilities *u* of eq. (8) for all *m* on average to about 40 %; and on the other hand a change in the dependence of *u* on *m*, which for $\rho = 0$ is a little more pronounced ($u(m = 0) \approx 22$ and $u(m = 10) \approx 14$; $22/14 \approx 1.6$) than for $\rho = 0.5$ ($u(m = 0) \approx 7.6$ and $u(m = 10) = 5.7$;

7.6/5.7 ≈ 1.3). These variations of 1.6 and 1.3, respectively, in $u$ over the different levels of $m$, however, is small compared to the variation in the probabilities $P_M(m)$ (white bars in Fig. B1), so that the variation of the product $u(m)P_M(m)$ over the levels of $m$ (closed bars in Fig. B1) is largely determined by the variation in the $P_M(m)$.

This implies that the effect of $\rho$ is mainly the trivial one that independent of its argument $x$, the risk utility $u(x)$ declines with increasing $\rho$ – finally implying that in the example of Fig B1 the expected risk utility declines from $EU(\rho = 0) \approx 17.1$ (upper horizontal line in Fig. B1) to $EU(\rho = 0.5) \approx 6.50$ (lower horizontal line in Fig. B1).

As described in Section 2.1, to decide whether the land parcel should stay in economic use or be switched into conversational use, this expected risk utility $EU$ has to be compared with the utility $U$ of the parcel's land price $A$ (eqs. (10) and (11)). Assuming a profit of $a = 1$with the chosen discount rate of $\delta = 0.05$ yields $U(\rho = 0) = 19$ and $\mathrm{U}(\rho = 0.5) \approx 6.94$. Thus, the utility $U$ associated with the parcel's land price declines by almost exactly the same factor of 6.94/19 as the expected risk utility $EU$ which declines by the factor 6.50/17.1 when $\rho$ is increased from zero to 0.5. Consequently, the relative advantage of restoration over economic use is almost independent from the level of $\rho$.

An equivalent result is obtained for the case of uncertain restoration success. Assuming, the baseline parameter values of $\delta = 0.05$, $M = 5$ and a credits price of $p = 23$ the utility of restoration in the *award-completion* scheme is in the case of restoration success, with eqs. (6)–(8): $u(\text{success}, \rho = 0) = 23(1 + 0.05)^{-5} - 1 \approx 17.0$ and $u(\text{success}, \rho = 0.5) = \{[23(1 + 0.05)^{-5}]^{0,5} - 1\}/0.5 \approx 6.49$; and in the case of restoration failure $u(\text{failure}, \rho = 0) = (1 + 0.05)^{-6} + (1 + 0.05)^{-7} + \ldots - 1\} \approx 14.7$ and $u(\text{failure}, \rho = 0.5) = \{[(1 + 0.05)^{-6} + (1 + 0.05)^{-7} + \ldots]^{0,5} - 1\}/0.5 \approx 5.92$. With eq. (9) and $\varphi = 0.4$ this yields an expected utility of restoration of $EU(Y = 0) \approx 16.08$ and $EU(r = 0.5) \approx 6.26$. Thus, increasing $r$ from 0 to 0.5 reduces $EU$ by about the same factor of 6.26/16.08 as it decreases the utility $U$ of keeping the land parcel in economic use (factor 6.94/19 as derived above).

**Appendix C: Supply and demand functions in the case of uncertainty in the duration of the restoration processes**

As outlined, in the *award-initiation* scheme landowners can immediately adapt to the changing economic profits on their land parcels because demand for credits can immediately and with certainty be satisfied by the initiation of the required number of restoration processes. So there are no restrictions on the land-use change and in each time step the land parcels with the lowest economic profits are in conservational use. For (an arbitrarily chosen) time step $t = 20$ the corresponding supply function which gives the forgone profits of the $\lambda_0 N = 20$ least least costly (i.e. least profitable) land parcels is shown in Fig. C1a (solid line). The vertical solid line marks the conservation target of $\lambda_0 N = 20$ habitat parcels, representing the regulator's demand function, and the intersection of the two lines yields the equilibrium credits price in this time step.

However, as discussed, due to the uncertainty in the duration of the restoration process, a target of $\lambda_0 N$ cannot deliver no net loss of habitats even on the temporal average. Therefore the target has to be increased by an amount $d$ (cf. *Scheme design* in section 2.1). For the model parameters of Fig. C1, the necessary and sufficient value to prevent both net loss and net gain and deliver an average number of habitat parcels equal to the initial one ($\lambda_0 N$) is $d = 1$; so the target is raised to 21, represented by the dash-dotted line. Due to the positive slope of the supply curve, the corresponding equilibrium credits price is slightly increased.

Alternatively to the raise of the conservation target, one can replace the *award-initiation* scheme by the *award-completion* scheme by awarding credits only with the successful completion of a restoration process. In this scheme, the demand of landowners who wish to develop their conserved land parcel into economic use cannot (always) be satisfied immediately but only once a restoration process has completed successfully. Thus, at least for a while land parcels with relatively high economic profits must remain in conservational use, raising the overall cost of the scheme and shifting the supply function that gives the (forgone) profits of the conserved land parcels upwards (Fig. C1a, dashed line). As a consequence, the intersection with the regulator's demand function (solid vertical line; not to be confused with the landowners' demand function), i.e. the equilibrium credits price, is increased relative to the original situation in which there was no restriction on the land-use change.

The same quantitative results are obtained if not only a single time step but the average over all $T$ model time steps is considered (Fig. C1b). An interesting observation is that in the *award-*

*completion* scheme the credits price is higher than in the *award-initiation* scheme. The same is observed in all of the 500 considered model parameter combinations. Interestingly, the opposite is observed in the case of uncertainty in the restoration success which was addressed by the introduction of trading ratios. Here in the *award-completion* scheme the credits price is lower than in the *award-initiation* scheme. Unfortunately, within the present modelling approach it is not possible to entangle the two issues and decide whether the changed price rank order is due to the different type of restoration uncertainty or the different type of *award-initiation* scheme (with trading ratios compared to raised conservation targets). Future research may address this question.

One reason why it is difficult to systematically compare both types of award-initiation scheme for both types of restoration uncertainty is that under uncertain restoration success, a raise of the conservation target cannot prevent the continuing net loss of habitat. This also explains why the analysis of Fig. C1 cannot be applied to the case of uncertainty in restoration success.

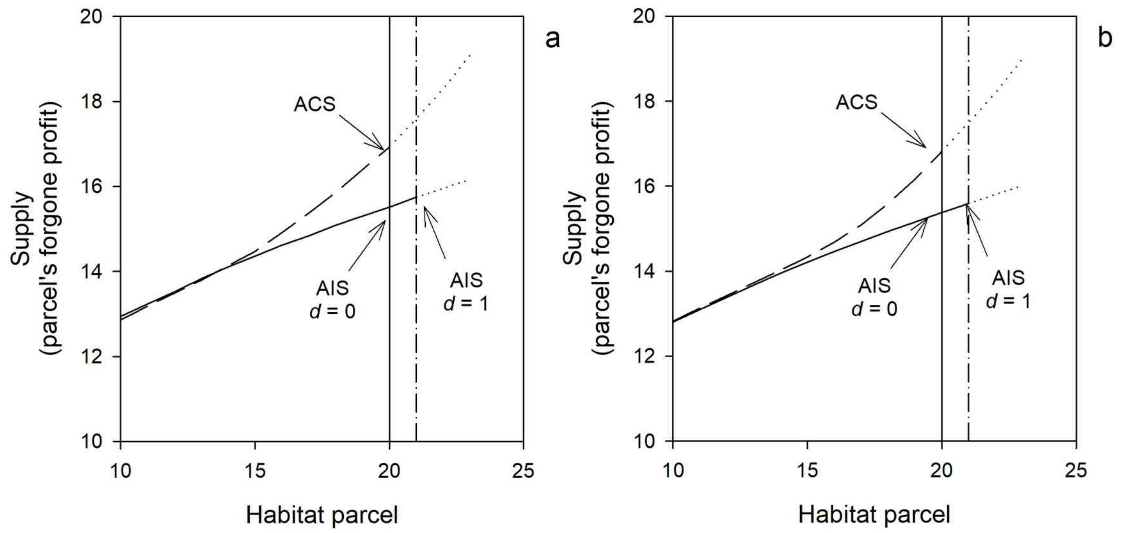


Figure C1: Supply and demand function for the *award-initiation* scheme (AIS) (solid line) and the *award-completion* scheme (ACS) (dashed line). The vertical lines mark conservation targets of 20 and 21 habitat parcels, respectively, and the intersections give the equilibrium credits prices (see text). Panel a shows the results for time step $t = 20$, and panel b shows the averages over all $T = 100$ time steps. Model parameters as in Fig. 3.