Climate change and the cost-effective governance mode for biodiversity conservation

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10 March 2020

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Abstract

Optimal planning of biodiversity conservation and habitat location is paramount for the cost-effective implementation of nature and biodiversity conservation measures. Established approaches for land use planning and conservation site selection however might not be optimal in a world with changing climatic conditions. Generally, conservation organizations can choose one of two main governance modes: (1) buy land to implement conservation measures themselves on their land, or (2) compensate landowners for their voluntary provision of conservation measures on their land. We analyse in a conceptual ecological-economic simulation four different conservation site selection strategies in either of the two governance modes. Afterwards, we investigate the ecological and economic effectiveness of each governance-mode-strategy combination in a climatically changing environment, and in particular the influence of climate change characteristics. We show that the choice of the two governance modes and four patch selection strategies influences the cost-effectiveness of the implementation, generally suggesting that buying land, combined with the a species targeting patch selection strategy generates the highest cost-effectiveness.

Keywords

agri-environment scheme, biodiversity, conservation payments, cost-effectiveness, land acquisition, make-or-buy decision, payments for environmental services, modes of governance

1 Introduction

Financial resources for biodiversity conservation projects are scarce. A cost-effective use of these resources – understood as maximising conservation goals for given financial resources or minimising financial resources to achieve given goals – is thus of utmost importance (Ando et al., 1998; Ferraro and Pattanayak, 2006). A growing field of research hence focuses on the cost-effectiveness analysis of biodiversity conservation policies (Ansell et al., 2016; Drechsler, 2017; Wätzold et al., 2016). Examples include studies on the cost-effective selection of habitat types (Petersen et al., 2016) and of land for conservation in an uncertain environment (Armsworth, 2018), on the cost-effective design of conservation payments (Drechsler et al., 2016, 2017), and on the empirical assessment of conservation contracts (Hily et al., 2015; Schöttker and Santos, 2019).

A novel perspective regarding the cost-effective design of conservation measures is related to the question of governance (Schöttker et al., 2016; Wang et al., 2016). Applying Williamson's analysis of the firm (Williamson, 1998, 1989) to biodiversity conservation, it is of interest how the conservation agency chooses among several alternative governance modes (GMs) representing different levels of vertical integration of conservation measure provision into the agency's organizational structure. Following Schöttker et al. (2016), we assume that conservation agencies in principle have the choice between two GMs: (1) to buy land and implement biodiversity conservation measures on this land themselves, or through delegating the actual implementation to a contractor, e.g. a farmer (*buy alternative*), or (2) to compensate landowners for voluntary implementing conservation measures on their own land by offsetting implementation costs with a compensation payment (*compensation alternative*).

Literature addresses aspects such as the conceptual analysis of optimal GM choice (Muradian and Rival, 2012), the development of ecological-economic models to assess the cost-effectiveness of different GM (Schöttker et al., 2016), specific conservation settings like forestry and corresponding GM options in developed (Juutinen et al., 2008) and developing countries (Curran et al., 2016), and cost assessments of specific GMs related to conservation projects (Schöttker and Santos, 2019;

Schöttker and Wätzold, 2018). These studies suggest a substantial impact of GM choice on the cost-effective implementation of conservation policies.

A key threat to global biodiversity, which has not been discussed in the context of cost-effective GMs, is climate change. According to Thomas et al. (2004) between 15% and 37% of species face a high risk of extinction due to climate change in sampled regions worldwide. Araújo et al. (2011) state that by 2080 58% of currently protected species in Europe will lose suitable habitat. In order to conserve biodiversity, the development of climate change compatible conservation strategies and policies is important (Heller and Zavaleta, 2009; Jones et al., 2016; Reside et al., 2018). However, most research in this field considers the ecological effectiveness of conservation policies (e.g. Zomer et al., 2015), and only a few studies analyse conservation policies from an economic perspective (Gerling and Wätzold, 2019; Hily et al., 2017; Lewis and Polasky, 2018; Mallory and Ando, 2014); and to our knowledge no study from the perspective of cost-effective GM.

The purpose of this work is to contribute filling this research gap. We analyse the effects of GM choices on biodiversity and conservation costs against the background of variations in climatic conditions. Our background is species conservation in cultural landscapes. This implies that a conservation agency has to provide land with appropriate climate characteristics for a species but also that it has to ensure that specific conservation measures are carried out on that land (for example specific mowing or grazing regimes for endangered grassland birds, Wätzold et al. 2016).

We develop a conceptual, spatially explicit ecological-economic model in a dynamic landscape. We calculate for the considered two GMs the cost-effectiveness of four different implementation strategies under climate change. These strategies include spatial targeting of conservation areas with respect to (a) implementation costs, (b) species abundance, (c) local climatic conditions and (d) climate change direction. The underlying ecological metapopulation model (Hanski, 1999) is used to determine the ecological benefit of the different GMs and site selection strategies.

In a Monte-Carlo simulation, we analyse the different GM options. The impact of varying model parameters is then assessed in sensitivity analysis, climatic characteristics such as spatial climate characteristics and climate change speed.

2 *The Model*

2.1 Landscape and conservation costs

We assume a landscape with $10 \times 20 = 200$ equally sized, square patches i (Table 1 provides an overview of all conceptual variables used in the model and Table 2 of all parameter values used in the computation). The landscape has a size of 10 patches in the east-west dimension and 20 patches in the south-north dimension (Fig. 1a).

We assume Euclidean distances d_{ij} between the midpoints of patches i and j, i.e. the distance d_{ij} between patches (x_i, y_i) and (x_j, y_j) is $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$. Without loss of generality, we assume for the eight nearest patches a distance of one, equalling the minimum dispersal distance of the target species.

Each patch in the landscape can potentially serve as a habitat for a target species under two conditions. First, each patch has a certain, time-dependent, climate suitability value, which determines to what degree the target species can find suitable habitat on the patch. Second, conservation measures need to be carried out on a patch i in a specific time-step t ($c_{i,t}^{cons} = 1$). This causes opportunity costs of conservation of OC_i which are assumed to be constant over all time steps. If no conservation measures are carried out ($c_{i,t}^{cons} = 0$) the patch may be used for economic purposes, e.g. intensive agricultural production, and no conservation costs arise.

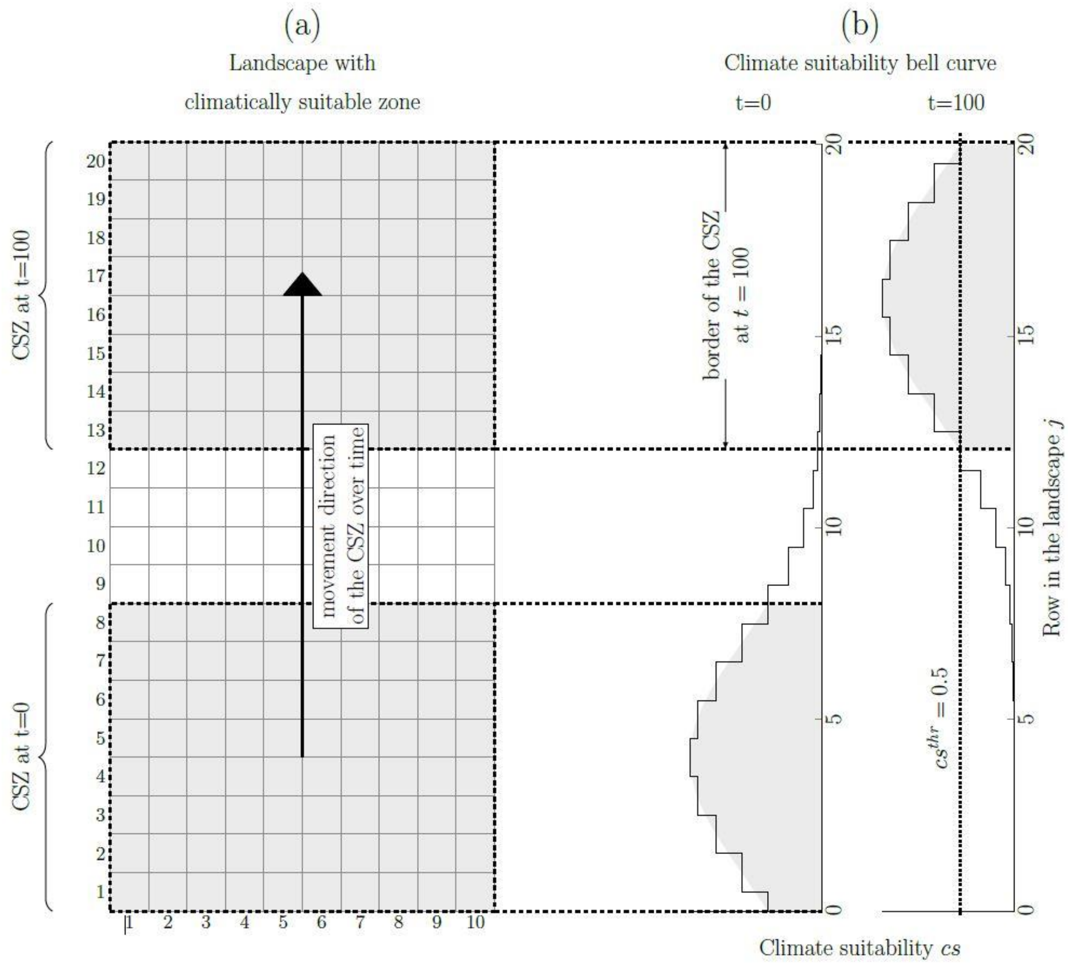

Figure 1: *(a) Spatially explicit landscape consisting of* 10×20 $patches$ *including the climatically suitable zone (CSZ, shaded area) at time-steps* $t = 0$ *and* $t = 100$, *(b) climate suitability bell curves according to Eq. (1) in their respective base case parametrization (see Table 2) and climate suitability threshold* $cs_{thr} = 0.5$, *leading to the CSZ at the different time steps* $t \in \{0,100\}$. *The shaded area and the corresponding borders represents the CSZ at each given time-step.*

Conservation costs are spatially heterogeneous and follow a random distribution within a range of $[\overline{OC} + \sigma_{OC}, \overline{OC} - \sigma_{OC}]$, where σ_{OC} is the standard variation and $\overline{OC}$ the mean conservation costs which equals 1.

Table 1: *Overview and description of model variables.*

Variable name	***Variable description***
B^{buy}	Budget for purchasing patches
B_t^{buy}	Budget to purchase land within a specific time-step t
B^{comp}	Budget to compensate landowners
B_t^{comp}	Budget to compensate landowners within a specific time-step t
$c_{i,t}^{cons}$	Conservation status of patch i
c_i^{comp}	Total expenses to compensate a single patch i for one time period
c_i^{buy}	Total expenses to buy a patch i
c_i^{sell}	Total amount of money received when selling a patch i
$cs_i(t)$	Climate suitability of patch i at time-step t
d_{ij}	Distance between patches i and j
ε	Residual budget in the *compensation alternative*
$h_{i,t}$	Dummy variable to indicate if a patch i is colonized at time-step t
$Im_{i,t}$	Immigration rate into patch i at time-step t
K	All patches within the climatically suitable zone
mc_i	Monitoring costs of patch i
OC_i	Opportunity costs of conservation of patch i
p_i^{buy}	Purchasing price of a patch i
$\overline{p^{buy}}$	Mean purchasing price of patches in the landscape
S	Number of all climatically suitable patches that can be reached by dispersal of the target species from already occupied patches
σ_{pbuy}	Standard deviation of purchasing prices
t	Time-step
$\tau_{i,t}$	Colonization probability of patch i at time-step t
tc_i^{buy}	Transaction costs of purchasing a patch i
tc_i^{comp}	Transaction costs to compensate the landowner of patch i
(x_i, y_i)	Coordinates of patch i

2.2 Climate Change

The modelling of climate change is based on Hily et al. (2017) and we slightly adapted it to fit our simulation model. We assign a climate suitability value $cs_i(t) \in [0,1]$ to each patch in the landscape, representing the probability with which habitat is provided if that patch is under conservation. Over time, the climate suitability of a patch $cs_i(t)$ changes in every time-step t such that

$$cs_i(t) = \exp(\frac{-(j-\mu_t)^2}{2\times\rho^2}) \tag{1}$$

with $\mu_t = \rho + t \times \frac{j-2\times\rho}{T}$ being the centre of the climate suitability bell curve at time-step $t \in [1,100]$, ρ an indicator for the bell shapes curvature and j the y-coordinate of patch i. The bell-shaped climate suitability distribution in the landscape moves through the landscape from south to north (Fig. 1b).

A patch provides only suitable habitat for a target species, if the climate suitability of a patch at a specific point in time is larger than a threshold value ($cs_i(t) > cs^{thr}$). Due to the general bell shape nature of the climate suitability in the landscape, the introduction of a climate suitability threshold cs^{thr} generates a climatically suitable zone (CSZ), containing all patches in the landscape which are suitable for a target species' habitat. Smaller (larger) values of cs^{thr} generate a larger (smaller) CSZ by allowing the target species to colonize patches with lower (higher) climate suitability and the CA to set respective patches under conservation. The CSZ moves through the landscape form south to north over time, implying that the target species can only survive if it relocates northwards.

2.3 Ecological Dynamics

We assume the target species to populate the landscape and colonize new patches according to metapopulation dynamics (Hanski, 1999). The occupation of a patch by the target species depends on an immigration rate $Im_{i,t}$ of the species into that patch, an immigration threshold necessary for successful colonization θ, and a resulting colonization probability

$$\tau_{i,t} = \frac{Im_{i,t}^2}{Im_{i,t}^2 + \theta^2} \qquad \text{if } cs_i(t) \geq cs^{thr} \text{ and } c_{i,t}^{cons} = 1 \tag{2}$$

and 0 otherwise. The immigration rate is defined as

$$Im_{i,t} = \sum_{k=1}^{K} h_{k,t} \nu \frac{\exp(-d_{i,k}/\delta)}{S_t}, \tag{3}$$

with K being the number of all patches within the CSZ in principle available for colonization, $h_{k,t}$ a dummy variable indicating if a patch k is occupied at time t, ν the emigration rate from patch k, $d_{i,k}$ the distance between patches i and k, δ the dispersal distance of the target species, and S_t the number of climatically suitable patches in the neighborhood of patch k (the neighborhood of a patch consists of all patches within the dispersal distance of the target species). By migrating from an occupied patch i to an unoccupied patch j, the target species can colonize new habitat over time, while also facing the probability of extinction on already occupied patches. These colonisation and extinction processes generate dynamics in the metapopulation model.

Climatic conditions are updated for each patch in every time step. With a northward shift of CSZ the climate suitability of patches at the southern end of the CSZ falls below the climate suitability threshold cs_{thr} and these patches become unsuitable for the species.

We calculate the overall share of simulation runs in which the target species goes extinct as an indicator for the ecological outcome of our model. Hence, increasing (decreasing) extinction risks reduce (increase) the cost-effectiveness of a selected GM and implementation strategy.

2.4 Decision Problem of the Conservation Agency

In order to reach a desired conservation outcome, a conservation agency (CA) implements certain conservation measures in the landscape. The CA chooses between two GMs: (1) buy land and implement conservation measures itself (*buy alternative*), or (2) pay landowners for their voluntary provision (*compensation alternative*) of equally designed conservation measures. For the implementation of conservation measures, the CA has to develop a patch selection strategy (PSS) to decide which patches to conserve. We consider four strategies resulting for each of the two GM resulting in eight GM-PSS pairs. In the following, we first introduce the budget available for covering conservation costs and its allocation over time. We then explain how we model the two GMs and the corresponding budget equations, before we finally describe the four PSS.

2.4.1 ***Budget Comparability***

The implementation of conservation measures within a certain GM-PSS combination causes costs, which are covered by the agency's budget. For all 8 GM-PSS pairs we assume equal available budgets at the beginning and the end of the simulation to allow comparability of the ecological outcomes and thus be able to assess the relative cost-effectiveness of the GM-PSS pairs.

As the two different GM alternatives generate different cost streams, with high initial costs for buying and relatively high recurring costs for compensation, we assume that the present value (PV) of the two cost-streams has to be equal. The available budgets in each GM-PSS pair and each time-step thus differ and the relation of present values of the respective budgets, $PV\left(\sum_{t=0}^{T} B_t^{buy}\right) = PV\left(\sum_{t=0}^{T} B_t^{comp}\right)$, translates into :

$$B^{buy} = \sum_{0}^{t=T} B_t^{comp} \times d_t. \tag{4}$$

$$B_t^{comp} = \frac{-r \times (B^{buy} \times r^T - \varepsilon)}{1 - r^{T+1}}, \tag{5}$$

with B^{buy} being the budget available for patch purchase, T the length of the total timeframe (i.e. 100 time-steps), r the interest rate, and ε the residual budget at the end of period T (necessary to keep the budgets for the two GMs comparable over the complete timeframe). The whole budget is available at the beginning of time-step $t = 0$ for the *buy alternative*. For the *compensation alternative*, we assume that B_t^{comp} is set so that in each time-step t an equal monetary amount (*compensation annuity*) is available for the CA to be spend, i.e. B_t^{comp} of eq. 8 (for a detailed explanation, see Appendix A4).

The CA conserves as many patches as possible for a given budget in a certain period t. Any leftover budget at the end of a period is transferred to the next period and added to the respective budget, including interest.

2.4.2 *Buy Alternative*

The *buy alternative* characterizes the CA's option to purchase and consecutively manage patches for conservation. The costs of an individual patch purchase are defined as

$$c_i^{buy} = p_i^{buy} + tc_i^{buy}, \tag{6}$$

with $p_i^{buy} = \overline{p^{buy}} \pm \sigma_{pbuy}$ being the uniform randomly distributed purchasing price, $\overline{p^{buy}} = \frac{\overline{OC}}{r}$ the mean purchasing price of patches in the landscape, $\sigma_{pbuy} = \sigma_{OC} \times \overline{p^{buy}}$ the standard deviation of purchasing prices, $\overline{OC}$ the mean conservation costs, r the interest rate, σ_{OC} the standard deviation of conservation costs. Transaction costs for purchasing a patch $tc_i^{buy} = \overline{tc^{buy}} \pm \sigma_{tc}$ (such as notary fees, contract negotiation costs, legal counsel) are uniform randomly distributed. For simplicity, we assume that patch prices do not change over time.

The CA is able to purchase new patches as long as the remaining budget is high enough. The CA is not allowed to have negative budgets, i.e. taking loans to fund patch purchase. We assume myopic spending behavior of the CA, thus strategically saving budget for later periods is not allowed. Purchased patches are managed in the prescribed conservation sense. Following Schöttker et al. (2016) we assume, that the costs of managing patches are equal to potential income generated from these measures, hence we need to consider only the costs of purchasing patches in the *buy alternative.*

Depending on the chosen PSS species monitoring costs might occur. These are recurring monitoring costs of $mc_i = \overline{mc} \pm \sigma_{mc}$ per patch in each time-step, with $\overline{mc}$ the mean monitoring costs and σ_{mc} the variation bandwidth. Monitoring costs are initially drawn randomly, like transaction costs, from a uniform distribution (according to $\overline{mc}$ and σ_{mc}) and do not change over time..

After a patch i is purchased it is set under conservation, resulting in habitat generation on this patch, if climatic conditions for the target species on that patch are good enough, i.e. $cs_i(t) \geq cs^{thr}$. Patch purchase then results in $c_{i,t}^{cons} = 1$.

We assume that in all four PSS the agency only purchases patches within the CSZ as $cs_i(t) < cs^{thr}$ for all patches outside the CSZ. We also assume that if an earlier purchased patch after some time falls out of the CSZ due to climate change, the CA sells the respective patch and receives the amount

$$c_i^{sell} = p_i^{sell} - tc_i^{sell}. \tag{7}$$

Following from the assumption that purchasing prices do not change over time, the CA receives the same amount from selling a patch as it paid for its acquisition ($p_i^{sell} = p_i^{buy}$). However, it has to bear the transaction costs, which are assumed to be equal for patch purchase and sale ($tc_i^{sell} = tc_i^{buy}$).

2.4.3 *Compensation Alternative*

In the *compensation alternative*, the CA does not purchase areas for conservation, but offers a compensation payment to landowners to incentivize them to implement conservation measures voluntarily (equivalent to the measures in the *buy alternative*) on their land. Compensation payments are spatially homogeneous and are selected such that they equal the opportunity costs oc_i of the landowner who has the highest conservation costs of the participating landowners.

For each patch under conservation, the CA has to pay

$$c_i^{comp} = oc_i + tc_i^{comp} \tag{8}$$

in every time period, resulting in a periodical payment subtracted from the budget in each time-step, with tc_i^{comp} the transaction cost for each time-step for setting up and implementing a conservation measure (such as patch finding costs, contract negotiation, etc.).

After a patch is set under conservation ($c_i^{cons} = 1$), it remains in that state for one time-step. In the next time-step, the CA renegotiates conservation contracts. Depending on the PSS, the CA might want to keep certain patches under conservation for more than one time-step, or wants to alter the conservation location according to its priorities (see Section 2.4.4).

Comparable to the *buy alternative*, the CA also chooses potential conservation areas only within the CSZ. Hence, $cs_i(t) \geq cs^{thr}$ for all patches under conservation. The periodically renewed conservation decision of the CA results in potentially varying locations of patches under conservation.

2.4.4 ***Patch Selection Strategies***

To implement conservation measures, the CA has to identify suitable patches. We consider four different PSS for this purpose (‘price prioritization’, ‘species abundance prioritization’, ‘climate suitability prioritization’, ‘climate change direction prioritization’). The first PSS is motivated purely by cost concerns, whereas PSS 2-4 follows the notion that prioritization of potential habitats based on natural processes and characteristics (here species abundance and general climate-related suitability of potential habitats) most likely provides a cost-effective conservation strategy (Reside et al., 2019).

(1) ‘Price prioritization’ characterizes a PSS in which the CA prefers cheaper patches over more expensive ones. This translates for the CA, in case of the *buy alternative*, to buy the cheapest available patches in the CSZ. In case of the *compensation alternative*, the patches with the lowest compensation payment requests are added to the conserved patches (Fig. 2a). The resulting conservation patches do not necessarily consist of connected patches in which a target species can successfully migrate between patches under conservation, thus potentially inhibiting colonization. However, this PSS will generate the highest number of patches under conservation for a given budget.

(2) For the PSS ‘species abundance prioritization’ the CA only buys or compensates patches, which are within the dispersal distance of colonized patches (Fig. 2b). This generates a cluster of conserved patches around existing habitat and leads to connected areas for the target species to

colonize. However, as not all patches are available for conservation, more expensive patches might have to be added leading to a lower number of conserved patches than with PSS ‘price prioritization’. Due to the need to identify colonized patches in this PSS, monitoring costs of $mc_i = \overline{mc} \pm \sigma_{mc}$ arise for the CA in each time-step.

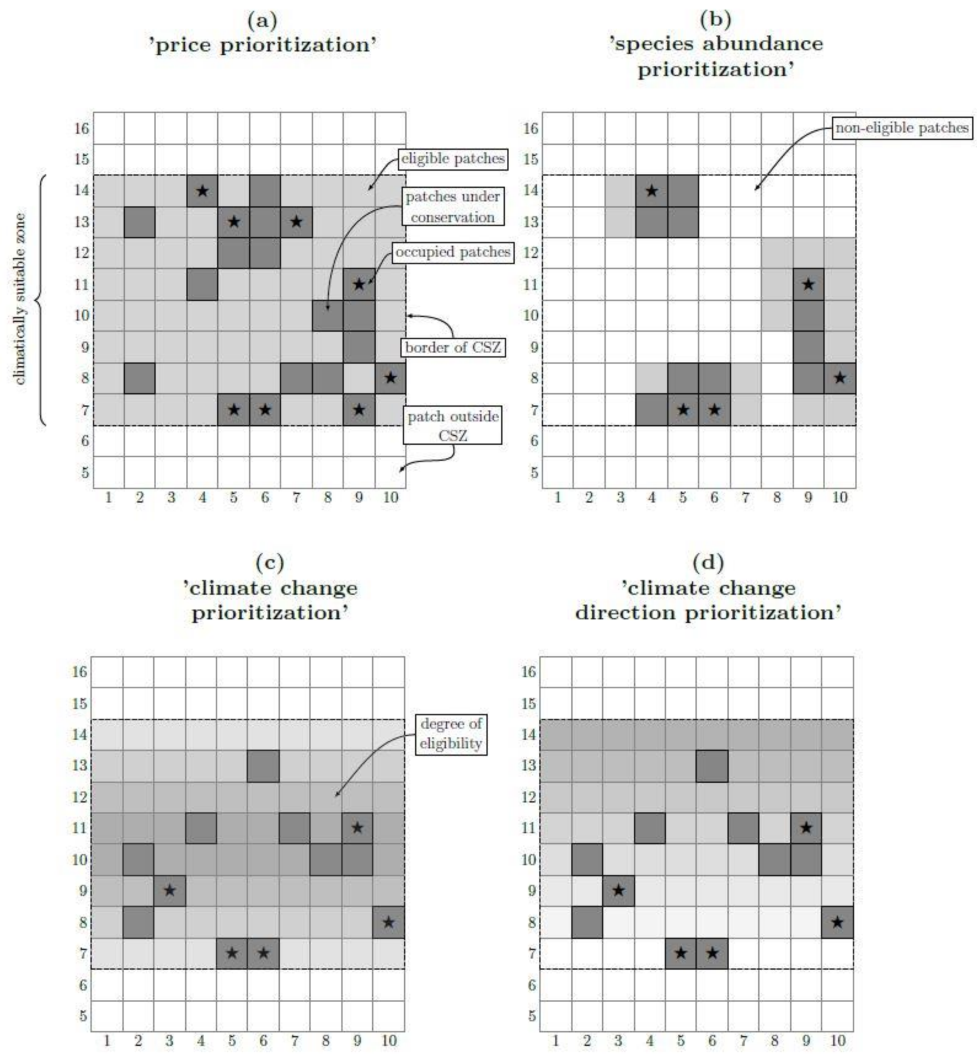

Figure 2: *Visualization of the four different PSSs and the corresponding patch location. (a) ‘Price prioritization’ allows for patch selection in the complete CSZ, only depending on the purchase price or compensation costs. (b) ‘Species abundance prioritization’ only selects patches within the dispersal distance of already occupied patches. (c) ‘Climate change prioritization’, prefers patches with higher climate suitability over patches with lower climate suitability, and (d) ‘Climate change direction prioritization’, prefers patches at the northern end of the CSZ over patches at the southern end of the CSZ.*

(3) We assume that the CA has full information of the climate suitability of all patches in the landscape. The PSS 'climate suitability prioritization' prefers patches with a high climate suitability (Fig. 2c), specifically, patches in the center of the climate suitability bell curve, as here the climate suitability value is highest. However, if only sufficiently cheap, also more northern or southern patches can be selected, allowing for a spatial spread of the conserved patches over the CSZ. By introducing a scaling factor λ (Eq. 7), we are able to foster or loosen this prioritization and thus either allow the CA to almost exclusively focus on the most centered patches (high λ), or to allow a broader spread of patches as (for given climate suitability) less expensive but further away patches are selected (low λ). In order to include costs into this PSS, we introduce the "suitability price" of each patch, which is a non-homogeneous payment, depending on a combination of the climate suitability of a patch and its opportunity costs. The "suitability price" includes both the (normalized) price and the (normalized) climate suitability of that patch as follows:

$$p_i^{suit} = p_i^{norm} + cs_i^{norm}(t) \times \lambda, \qquad (9)$$

with p_i^{norm} the price of patch i normalized on a scale of 0 to 1 (on which the cheapest patch price in the landscape is 0 and the most expensive price is 1), $cs_i^{norm}(t)$ the normalized climate suitability of patch i and λ the scaling factor. Instead of using only the price for patch selection (as in the PSS 'price prioritization'), now the suitability price is used as a selection criterion. Obviously, we use the regular price with respect to budgetary calculations.

(4) Due to the CSZ's movement into the northern direction over time, already selected and colonized patches move to the southern edge of the CSZ. By assuming that the CA has full information on the direction of climate change, we can design a fourth PSS in which the CA prioritizes patches closer to the northern edge of the CSZ (Fig. 2d). These patches will, due to the northward movement of the CSZ, stay in the CSZ for a long time with a high possibility of being colonized. The resulting conserved patches are comparable to the ones under the 'climate suitability prioritization', but biased towards northern patches. By introducing a scaling factor κ into this PSS, we can vary the

CA's prioritization strength and either allow for a more or less strict patch selection close to the northern edge of the CSZ. Similar to the PSS 'climate suitability prioritization', we calculate a "suitability price" for each patch, which includes both the (normalized) price and the (normalized) climate suitability of that patch and represents a non-homogeneous payment to the individual landowners:

$$p_i^{suit} = p_i^{norm} + csz_i^{row}(t) \times \kappa, \tag{10}$$

with p_i^{norm} the price of patch i normalized on a scale of 0 to 1 (on which the cheapest patch price in the landscape is 0 and the most expensive price is 1), and $csz_i^{row}(t)$ the normalized row number in which within the CSZ a certain patch i is located (more northern patches have higher row numbers and thus higher $csz_i^{row}(t)$ leading to the intended prioritization).

3 Analysis

For model analysis we apply a Monte-Carlo-simulation, in which each parameter set – i.e. selected combinations of parameters specified in Table 2 – is simulated 2000 times to allow an analysis of the whole bandwidth of potential outcomes and to avoid randomly extreme results resulting from the model inherent stochasticity. A simulation run refers to one single calculation of the model for one parameter set.

The parameters cs^{thr}, ρ, m_t, and θ influence the shape of the climate bell curve, and thus have potentially an effect on both GM and all PSS. In contrast, λ and κ affect the prioritization strength of the two climate sensitive PSS, and hence may only influence the outcome of these PSS. The economic parameters $\overline{OC}$, $\overline{tc^{buy}}$, and $\overline{mc}$ impact the different cost measures, while the interest rate r is used for discounting and budget calculations in all GM-PSS pairs. σ_{OC}, σ_{tcbuy}, and σ_{mc} determine the range of all randomly drawn cost parameters in the simulation. The ecological parameters ν and δ influence the dispersal ability of the target species affecting the ecological dynamics in all GM-PSS pairs.

***Table 2**: Overview and description of parameters and parametrization values specified for computation of the Monte-Carlo-Simulation and the sensitivity analysis.*

Parameter name	***Parameter description***	***Parametrization Value***	
i	Patch index	$\in [1,200]$	
μ_t	Centre of the climate suitability bell curve at time-step t	1	
σ_{OC}	Standard deviation of opportunity $\overline{OC}$	0.1	
σ_{tc}	Standard deviation of transaction costs	0.01	
σ_{mc}	Standard deviation of monitoring costs	0.01	
θ	Immigration threshold for successful colonization	5	
Economic parameters			
$\overline{OC}$	Mean opportunity costs in the landscape	1.0	
$\overline{tc^{buy}}$	Mean transaction costs of purchasing a patch	1.0	
$\overline{mc}$	Mean monitoring costs	0.1	
r	Interest rate	0.03	
Ecological Parameters			
ν	Emigration rate from any patch	100	
δ	Dispersal distance of the target species	1	
Climate Parameters		***Value Range***	***Base case***
T	Maximum number of time steps	$\in \{50,100,150\}$	100
cs^{thr}	Climate suitability threshold	$\in \{0.3,0.5,0.7\}$	0.5
ρ	Curvature of the climate suitability bell shape	$\in \{2,3,4\}$	2
λ	Scaling factor for PSS 'climate suitability prioritization'	$\in \{1.5,2.0,4.0\}$	2.0
κ	Scaling factor for PSS 'climate change direction prioritization'	$\in \{1.5,2.0,2.5\}$	2.0

We calculate a reference base case with a respective base case parametrization, which was selected to resemble economic, ecological, and climatic conditions, which allow the model to generate inherently consistent outcomes (see Table 2). Afterwards, we individually vary some parameters in specified ranges to values lower and higher than the base case value to identify the impact of each parameter on the cost-effectiveness of each GM-PSS pair (sensitivity analysis).

4 Results

We first present the results of the base case parametrization of the eight GM-PSS pairs as it already provides valuable and general insights into the choice of the cost-effective GM. To identify factors influencing the relative performance of the eight GM-PSS pairs, we then present results of a sensitivity analysis in which climatic model parameters are varied individually. The analysis of the results revealed four effects influencing the cost-effectiveness of each GM-PSS pair. Wätzold and Drechsler (2014) have identified already two of the effects – the patch restriction effect and the connectivity effect –, while the remaining two effects – the *climate prioritization effect* and *the flexibility effect* – are newly identified in this work. In particular, the effects are:

(1) The *patch restriction effect,* which exists as due to the limitation of eligible patches, if connected habitat network requirements or certain climate suitability restrictions are to be met by a specific GM-PSS pair. In these cases, most likely more costly patches are to be selected compared to a situation in which the CA can freely choose patches in the whole CSZ. Therefore, a restriction of eligible patches tends to increase conservation cost and hence to reduce cost-effectiveness.

(2) The *connectivity effect*, as with improved connectivity of conserved patches, the ecological outcome increases, and hence the cost-effectiveness increases.

(3) The *climate prioritization effect*, which leads to improved ecological conditions of patches under conservation as they are chosen in climatically more suitable areas within the CSZ.

(4) The *flexibility effect*, which exists as due to the selected GM, the adaptability of the conservation network (e.g. to changing climatic conditions) can be fast (for the *compensation alternative*) and slow (for the *buy alternative*). This adaptation possibility increases conservation costs, but allows for a flexible selection of suitable patches and hence increases ecological outcome. The net effect depends on the respective GM-PSS pair.

4.1 Scenarios

In the following, the influence of changes in climatic parameters on the cost-effectiveness and extinction probabilities of the different GM-PSS pairs is analysed. Results of the influence of ecological and economic parameters are found in Appendix A4.

4.1.1 ***Climate Change Speed***

The cost-effectiveness of three GM-PSS pairs was influenced by variations of climate change speed, i.e. variations of the overall simulation timeframe T. A short timeframe (small T) represents fast climate change as it takes less time steps for the climate suitability to vary and the CSZ to move across the landscape (Fig. 3).

Generally we find that patch selection in the *compensation alternative* is more flexible compared to the *buy alternative*. Patches can be reselected anew in every time step in the *compensation alternative*, depending on patch price, climate suitability and occupation status, while they are fixed for a longer time (until they are no more in the CSZ) in the *buy alternative* and thus cannot react to changing climatic conditions or occupation status. Hence, a strong *flexibility effect* exists which causes improved ecological outcome in the *compensation alternative* compared to the *buy alternative*.

For the 'price prioritization' strategy (Fig. 3a), we find that the cost-effectiveness of the *compensation alternative* decreases with increasing climate change speed whereas it remains constant for the *buy alternative*. We explain this result with the combination of a generally reduced ecological suitability of the landscape for the target species due to faster climate change, and the counteracting *flexibility effect*. In the *compensation alternative*, reduced ecological suitability and a strong *patch restriction effect* outperform the *flexibility effect* compared to the *buy* alternative, and hence lead to a reduced cost-effectiveness. In contrast, in the buy alternative the stability of the selected conservation network compensates the negative ecological effects of fast climate change on the cost-effectiveness. Furthermore, prioritizing patches by price generally results in more patches under conservation as cheaper areas are selected, which at the same time are not necessarily well connected

Increasing climate change speed, however, increases the cost-effectiveness of the 'species abundance prioritization' strategy for the *buy alternative* in comparison to the *compensation alternative* (Fig. 3b). This result is somewhat surprising, as this strategy prioritizes patch selection around already existing habitat and hence allows for easy migration to new nearby habitat. Differences in climate change speed should not interfere with this effect. An explanation may be that the *connectivity effect* is increasingly relevant with increasing climate change speeds, which also would explain, why the other strategies result in increasing extinction rates, as there the connectivity effect is less pronounced. Against the background of more volatile conservation networks in the *compensation alternative*, it is however unclear why no cost-effectiveness reduction can be observed in the 'species abundance prioritization' strategy in the *compensation alternative.*

We do not observe any influence of changing climate change speed on the extinction probability and hence cost-effectiveness in the 'climate suitability prioritization' strategy in any of the two GMs (Fig 3c). A possible explanation is that conserved patches are located in well-functioning conservation networks in case of the *buy alternative*, or adapt quickly enough to location changes of the CSZ in case of the *compensation alternative*, so that eventually extinction rates are not affected.

Moreover, we find faster climate change speed increases extinction rates in the 'climate change direction prioritization' strategy for the *buy alternative*, and hence a decrease in cost-effectiveness of the GM-PSS pair compared to the *compensation alternative* (Fig 3d). This result is expected as the period when patches are located inside the CSZ is reduced with a shorter timeframe. This is especially true for this strategy, which prioritizes patches at the northern-edge of the CSZ that stay in the CSZ longer compared to other PSS. Within the *compensation alternative*, for every parameter setting the survival rates are at 100%, indicating a strong *flexibility effect*, which leads to increased survival rates.

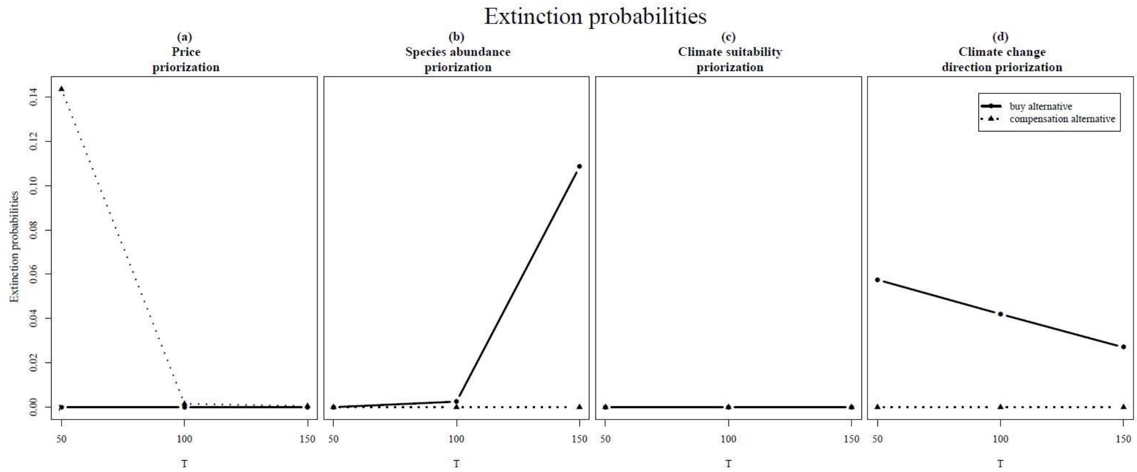

Figure 3: *Changes in extinction rates due to changes in maximum length of the simulation timeframe T, (i.e. climate change speed decreases with increasing T). (a)-(d) represent the extinction probabilities for all four strategies in the buy and compensation alternative.*

4.1.2 *Strength of climate prioritization*

Within the PSSs ‘climate suitability prioritization’ and ‘climate change direction prioritization’, patch selection takes place according to either climate suitability or climate change direction. We introduced a scaling factor λ for each strategy to define the strength of prioritization of respective patches. A higher λ (κ) results in a stronger prioritization for climate suitability (climate change direction) relative to patch prices. Thus, increases in either parameter generate a *patch restriction effect* and climate *prioritization effect* by narrowing the spatial extent of the conserved patches in the respective strategies. Changes in λ only affect the ‘climate suitability prioritization strategy’, and changes in κ only affect the ‘climate direction prioritization strategy’. The ‘prize prioritization strategy' and the 'species abundance prioritization strategy' remain unaffected, as both parameters do not alter their respective patch selection mechanism.

We did not find any influence of the climate suitability scaling factor λ, neither in the *buy* nor the *compensation alternative* within our parameter range (compare graphical analysis in Appendix A4). This is somewhat surprising as increasing values of λ cause a prioritization of patch selection in the center of the CSZ, and hence have a *patch restriction effect* and *climate prioritization effect*. Both effects are probably cancelling each other out in their influence on the cost-effectiveness.

However, changes in κ do show an influence on the cost-effectiveness of the 'climate change direction prioritization strategy' for the *buy alternative*, while the *compensation alternative* remains unaffected (see Fig. 4d). Low values of κ (low prioritization for climate change direction) result in an increased cost-effectiveness compared to larger values of κ due to the high *connectivity effect*. With increasing κ newly added patches are predominantly located in the most northern part of the CSZ while large portions of the CSZ remain unconsidered for selection. Hence, conserved patches are spread far across the complete CSZ, resulting in large distances between conserved patches and leading to an increase in extinction probability with increasing κ, and hence a reduction of cost-effectiveness. For lower values of κ however, new patches are selected in a larger proportion of the landscape, hence are more likely located closer to already occupied patches, which results in better migration possibilities and increased cost-effectiveness. Also, with larger (smaller) parts of the CSZ eligible for patch selection with smaller values of (larger) κ, the *patch restriction effect* becomes weaker (stronger), hence also increasing (decreasing) the cost-effectiveness.

We did not find any influence on the *compensation alternative* strategies by variations in κ. A possible explanation is the interplay between *connectivity effect* and *flexibility effect* in either alternative. Due to repeated reselection of new patches in the prioritized area they are relatively well connected in the *compensation alternative*, compared to the wide spatial spread in the *buy alternative*, leading to relatively good migration possibilities and hence a better cost-effectiveness of the *compensation alternative*, compared to the *buy alternative*.

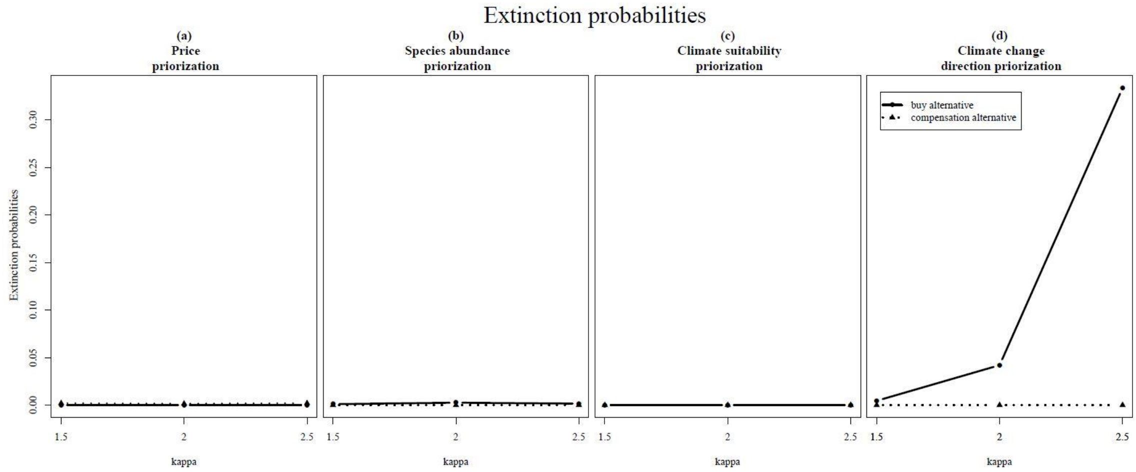

Figure 4: *Influence of changes in κ on the extinction probability in the buy alternative and the compensation alternative for each of the four PSSs.*

4.1.3 ***Climate suitability threshold***

Changes in the climate suitability threshold value cs^{thr}influence the cost-effectiveness of four GM-PSS pairs (Fig. 5). The value of the climate suitability threshold cs^{thr} determines the width of the CSZ and hence has potentially an effect due to the *connectivity* and *patch restriction effects*. Generally speaking, with an increasing CSZ (low cs^{thr}) the *connectivity effect* weakens, while the *patch restriction effect* is decreasing for all GM-PSS pairs.

We find with increasing CSZ size (decreasing cs^{thr}) for both GMs in the 'price prioritization strategy' (Fig 5a) a decrease in cost-effectiveness suggesting that the *patch restriction effect* dominates the *connectivity effect*. However, the reduction of cost-effectiveness in the *compensation alternative* is stronger than in the *buy alternative*. This effect may be explained as the size of the CSZ and hence the number of eligible patches increases with decreasing cs^{thr}. For the *compensation alternative*, more volatile patch selection (compared to the *buy alternative*) causes frequent changes of habitat location (potentially every period), and hence reduces migration possibilities as selected patches are potentially far apart. This effect is especially prominent in the 'price prioritization strategy' as patches are purely selected based on compensation costs and hence will be selected randomly across the whole CSZ. In other strategies (see details below), patch selection is restricted to a more narrow area within the CSZ, leading to a more compact conservation network and hence decreased extinction probabilities, compared to the 'price prioritization strategy'.

In the 'species abundance prioritization strategy' however, only the cost-effectiveness of the *buy alternative* decreases with increasing cs^{thr} (see Fig. 5b). A decreasing size of the CSZ due to increasing cs^{thr} limits the CA to purchase patches nearby already occupied patches. If a CA wants to select further patches within this strategy, it would be necessary to select patches outside of the dispersal distance of the target species and which thus could not be colonized in the current time step (though they would still be connected to the habitat network). Hence, a decreasing *connectivity effect* causes a reduction of the cost-effectiveness in the 'species abundance prioritization strategy' in the *buy alternative*. A higher *flexibility effect* in the *compensation alternative* positively contributes to the cost-effectiveness compared to the *buy alternative*. This impact is not present in the *buy alternative.*

In the 'climate suitability prioritization strategy', no negative effect occurs with a decreasing climate threshold on the cost-effectiveness of both GMs within the chosen parametrization range (Fig 5c). Our explanation is that the *patch restriction* and *connectivity effect* cancel each other out.

A strong negative effect on cost-effectiveness can be observed for small values of cs^{thr} (large CSZ), in the 'climate change direction prioritization strategy' (Fig. 5d) for the *buy alternative*, while no effect can be seen in the *compensation alternative*. This may again be explained by a combination of the *connectivity effect* and the *climate prioritization effect*. While patches remain under conservation in the *buy alternative* as long as they are located within the CSZ, this duration grows, as well as the resulting gaps between conserved areas and unoccupied patches, with a decrease in cs^{thr}, eventually leading to a lower cost-effectiveness. In the *compensation alternative*, patches under conservation in contrast might be reselected anew if they are unoccupied at the end of the time step. Reselection then happens in the northern part of the CSZ, automatically locating newly added patches close to other patches in the conservation network, hence leading to low extinction probabilities and high cost-effectiveness.

Generally, *compensation alternative* strategies perform well even with large CSZs because of the *flexibility effect* with the exception of the 'price prioritization strategy', in which the *flexibility effect* is counteracted by a small *connectivity effect*.

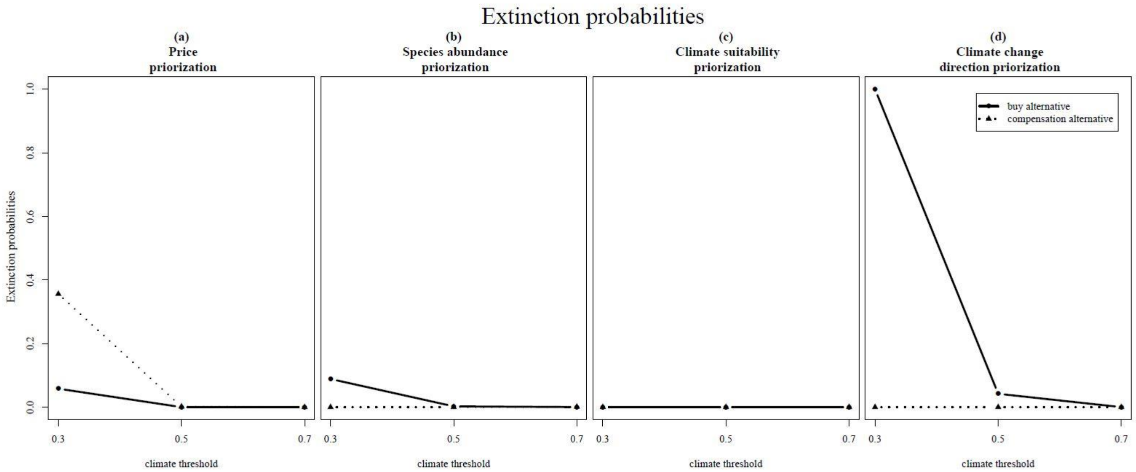

Figure 5: *Extinction probabilities of the different GM-PSS pairs with changing climate threshold, resulting in changing CSZ< sizes.*

4.1.4 *Shape of the climate suitability bell curve*

We only find small effects of variations in ρ (influencing the curvature of the climate suitability bell shape) on the cost-effectiveness of the GM-PSS pairs. A possible reason might be that the climate suitability bell shape determines the climate suitability in the complete landscape, while only a relatively narrow strip around the center (which the CSZ covers) is actually eligible for patch selection. Because changes in the curvature of the bell shape are not necessarily very strong within the CSZ and only have marginal effects on CSZ size, the effects on GM-PSS pairs performances is negligible (compare graphical analysis in Appendix A4).

5 *Summary and Discussion*

The purpose of this paper was to analyse with a conceptual model the impact of changes in climate parameters on the cost-effectiveness of different governance modes (GM) and specific implementation strategies (PSS). We assume that conservation agencies (CA) have two alternative GM to select. (1) Buy conservation areas and implement conservation activities on this land (*buy alternative*), and compensate private landowners for their voluntary provision of conservation measures on their own land (*compensation alternative*). We further assume that the CA chooses from four PSS. (1) Select the cheapest patches in the landscape ('price prioritization'), (2) select patches close to areas already populated by a target species ('species abundance prioritization'), (3) select patches with highest climate suitability ('climate suitability prioritization'), and (4) select patches which remain climatically suitable for the longest time ('climate change direction prioritization').

We wish to highlight the following two general key insights. First, buying areas for conservation produces a relatively rigid spatial selection of conserved patches due to the long-term commitment for certain conservation areas within the landscape. While more rigid patch location improves the ecological effectiveness by e.g. reducing habitat turnover it does not allow swift adaptation to changing climatic conditions. In contrast, the c*ompensation alternative* is more flexible, i.e. patches are potentially changing their conservation status more often as compensation contracts are typically only valid for short time periods (cp. also Gerling and Wätzold, 2019). More specifically, differences in flexibility result in a higher possibility of the *compensation alternative* to adapt to changing conditions and thus being a more robust choice against uncertain and changing climatic conditions than the *buy alternative*.

Second, we find that against the presence of changing climatic conditions, the cost-effectiveness of GM strongly depends on the choice of the PSS. In this context, to buy conservation areas yields a higher cost-effectiveness against changing climatic conditions when focusing on the cheapest available conservation sites (i.e. applying the 'prize prioritization strategy'), while private landowner compensation seems to be more cost-effective with more specific PSS (i.e. the 'species abundance prioritization', 'climate suitability prioritization' or 'climate change direction prioritization' strategy). While purchasing areas for conservation typically generates high up-front and one-off costs, the resulting areas should stay under conservation for as long as possible. Prioritizing cheaper patches then allows for an increase in total conservation areas as more patches can be selected, which in turn improves the ecological outcome and increases cost-effectiveness. Given the advantages in terms of flexibility of the *compensation alternative*, a more specific site selection by prioritizing either ecological or climatic characteristics has a stronger influence than in the *buy alternative* and, hence, price prioritization is comparatively less relevant.

In designing the ecological-economic model, we made several simplifying assumptions, which deserve discussion. We only considered two GMs, which are polar types of governance structures and ignored hybrid GMs. For example, a CA might split its budget and spend part of it to buy areas and the rest on compensation contracts with landowners. By doing so, benefits of both GMs might be combined (e.g. fixed location of purchased patches with ecologically beneficial effects, and flexibility of compensated areas with fast adaptability to changing climatic conditions). However, to what extent this happens and what other effects occur is a matter of further research.

We further assumed that landowners are willing to sell their land or take part in compensation contracts as long as the monetary benefits from participation exceed the costs. Some authors question the assumption that landowners are always willing to sell their land and suggest strategies to optimally time the purchase of land for reserves in insecure ecological and economic conditions (Costello and Polasky, 2004; McDonald-Madden et al., 2008), and with changing land prices (Dissanayake and Önal, 2011). Moreover, literature suggests factors which influence the general willingness to participate in compensation schemes (e.g. contract duration and flexibility, land productivity, and farm size; cp. Greiner (2016) and Unay-Gailhard and Bojnec (2016)), and indicate that the willingness to participate may also be reversed due to e.g. cost-related learning effects (Frondel et al., 2012). A reduced willingness to participate would directly increase the costs of conservation projects, as more costly areas would have to be chosen. In addition, the ecological effectiveness might be reduced, as less suitable patches might have to be selected or due to increased habitat turnover (cp. Schöttker et al., 2016). Ultimately, both effects negatively influence the cost-effectiveness of the corresponding GM. However, more research is required to understand which GM is likely to suffer from higher cost-effectiveness losses of modified assumptions on landowners' behaviour.

We also assumed that conservation costs in the landscape are constant over the complete timeframe and unaffected by the CA's behaviour. By assuming constant costs we ignore any kind of strategic behaviour, for example from landowners by overstating conservation costs to achieve higher payments or a higher price if they intend to sell their land (Banerjee et al., 2016; Gerling and Wätzold, 2019; Kuhfuss et al., 2016). A strategic overstatement of conservation costs could increase patch prices in both GMs, in turn reducing their cost-effectiveness. Further research is necessary to understand which GM is more prone to strategic behaviour and how to design possible mechanisms to reduce it.

We further assumed that the CA is allowed to sell patches in the *buy alternative*, as patches which are no longer in the CSZ for a specific species do not provide any more suitable habitat for this species. Thus, the potentially regained budget by selling these patches can be utilized to purchase new patches at more suitable locations. It has to be mentioned however that selling conserved land may not be possible in reality for a CA due to legal restrictions regarding the permanence of conservation areas (Schöttker and Wätzold, 2018).

The conceptual nature of our model limits the possibility for direct policy implications of our results. Nevertheless, our model improves the general understanding of the influence of climate change on the cost-effective choice of GMs for biodiversity conservation. We show that the cost-effectiveness of GMs and PSS may be influenced by changing climatic conditions and thus policy makers are advised to explicitly include climate change concerns in their design. The availability of respective conservation strategies to allow for specific targeting of species or climatic conditions is important in this context.

In addition, the more flexible or more rigid character of conservation networks due to different GMs and the resulting implications on cost-effectiveness should be accounted for in the decision about the optimal GM choice. Similarly, dependent on climatic characteristics, the optimal choice for CA may vary, as may the optimal choice of PSS.

Further research may investigate the topic of this work with more empirical data in real landscapes. Climate models are able to provide precise estimations about future climate developments on a regional level, species-specific ecological models are able to assess the impacts of conservation measures in a changing climate and the development of scenarios about future costs is feasible. Such models and data may be combined in empirical climate-ecological-economic models providing policy makers with important recommendations about cost-effective GM and PSS choices. We hope our model motivates such future work and provides a useful basis for it.

Acknowledgements

We thank Astrid Sturm, Emeline Hily and the other participants of the research colloquium at the Chair of Environmental Economics at the BTU Cottbus-Senftenberg for their valuable and detailed feedback on early stages of our work.

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Appendix

A1 Distance Calculation

We define the distance between the midpoints of any two patches i and j as follows:

$$d_{ij} = \begin{cases} 1 & if: |x_i - x_j| = 1 \; and \; |y_i - y_j| = 1 \\ \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} & for \; all \; other \; i \; and \; j \end{cases} \quad \text{(A1)}$$

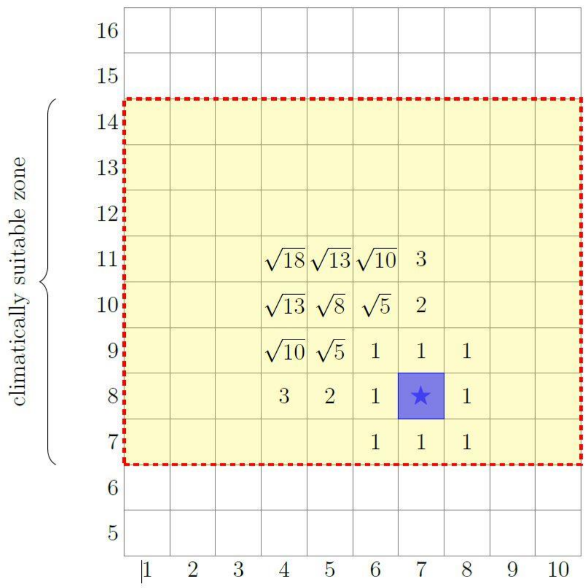

Figure F1: *Distance between two patches calculated by Eq. (A1). The yellow-shaded and red-framed area represents the climatically suitable zone (CSZ). The blue- shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species. Numbers indicate the distance of the respective patch to the highlighted blue patch. Note that the distance for all patches directly neighbouring the blue patch is 1.*

We chose this method of distance calculation, as it seems agreed upon in the literature and is relatively easy to handle in the implementation of the model. The exception made for the distance of diagonally neighbouring patches to calculate as 1 instead of $\sqrt{2}$ results in an overestimation of species dispersal, especially if the dispersal distance of a species is only 1. Without this exception, in this case a dispersal would only be possible to vertically and horizontally neighbouring patches but not to the diagonally neighbouring ones, causing distortions and model artefacts.

A2 Patch Selection Strategies

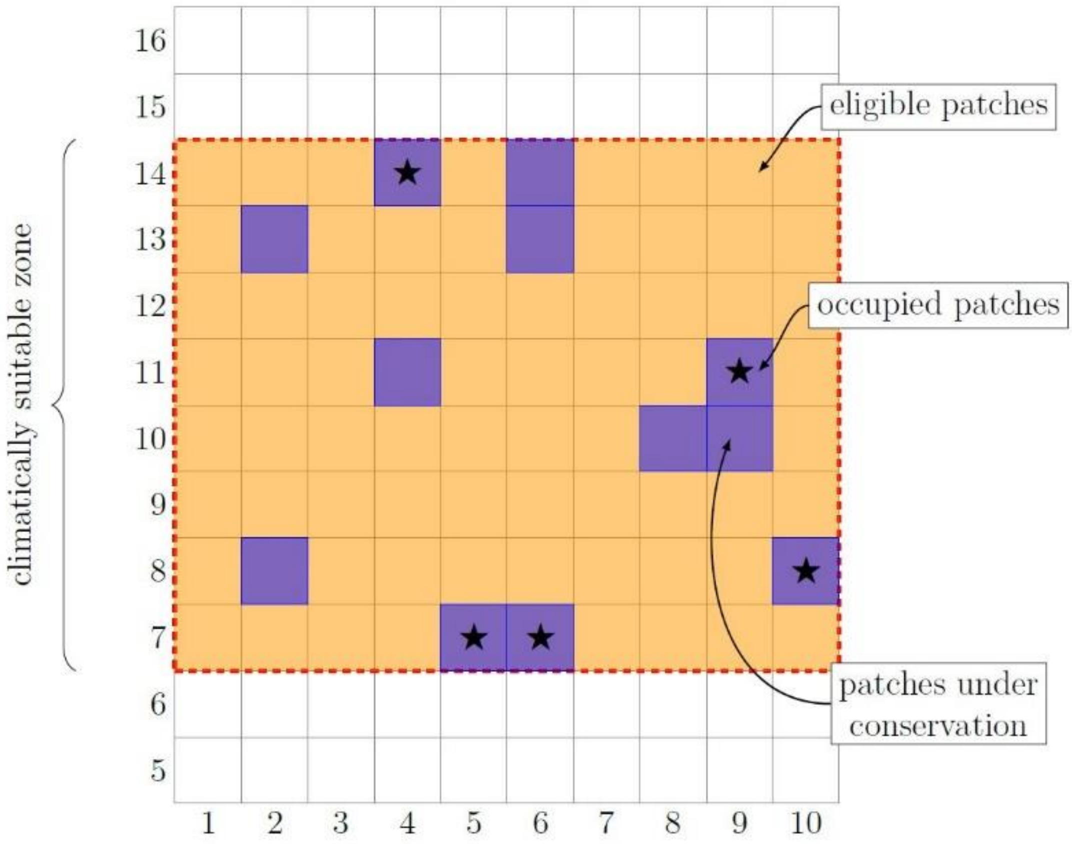

Figure A2: *'Prize prioritization strategy'. The red-framed area represents the climatically suitable zone (CSZ), within which the orange-shaded area represents patches eligible for patch selection in the 'prize prioritization strategy'. The blue-shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species.*

Figure A2 illustrates a conservation network in the model landscape, created by the 'prize prioritization strategy'. Within the CSZ potential conservation areas are located. Patches marked with a star are patches occupied by the target species.

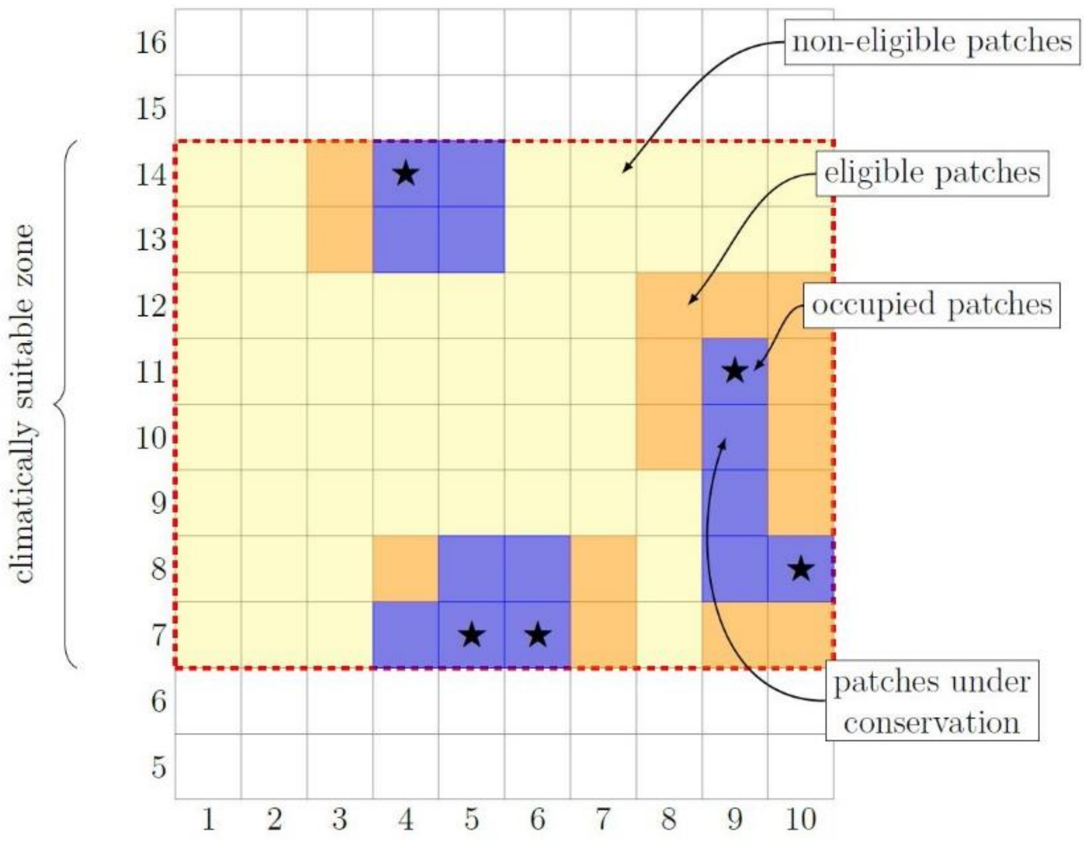

Figure A3: *'Species abundance targeting strategy'. The red-framed area represents the climatically suitable zone (CSZ), within which the orange-shaded area represents patches eligible for patch selection in the 'species abundance targeting strategy'. The yellow-shaded areas represent patches, which are non- eligible for selection in this strategy. The blue shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species.*

Figure A3 illustrates a potential conservation network generated by a 'species abundance targeting strategy'. Conservation areas are clustered together around occupied patches. Patches eligible for future extension (i.e. newly bought or compensated areas) represent all patches within the dispersal distance of the target species. All yellow shaded areas, although within the CSZ, are outside the dispersal distance of the target species and thus not eligible for conservation

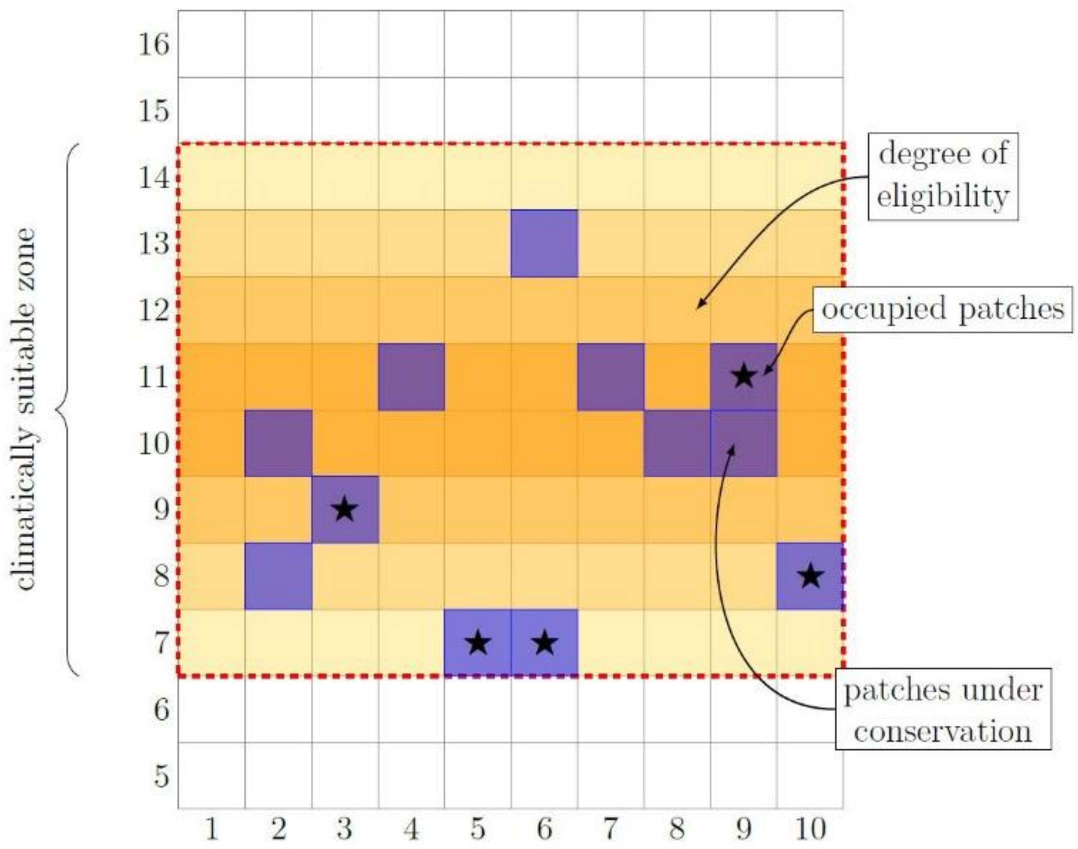

Figure A4: *'Climate suitability prioritization strategy'. The red-framed area represents the climatically suitable zone (CSZ), within which the orange-shaded area represents patches eligible for patch selection in the 'climate suitability prioritization strategy'. The degree of orange depicts the level of eligibility of a particular patch; darker-shaded areas have a higher eligibility than lighter-shaded areas. The blue shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species.*

Figure A4 visualizes a habitat network created by a 'climate suitability prioritization strategy'. Patches cluster around the centre of the CSZ, representing the area with highest climate suitability for the target species. Due to the closer proximity of conservation area location, the complete network has a higher degree of connectedness, and the target species is more likely to be able to migrate to other conservation areas in the network, compared to the price prioritization strategy (Fig. A2). For simplicity, we ignored the eligibility differentiation made in combination of climate suitability and conservation opportunity costs per patch as described and used in the simulation model, and only depicted the climate differentiation aspect here.

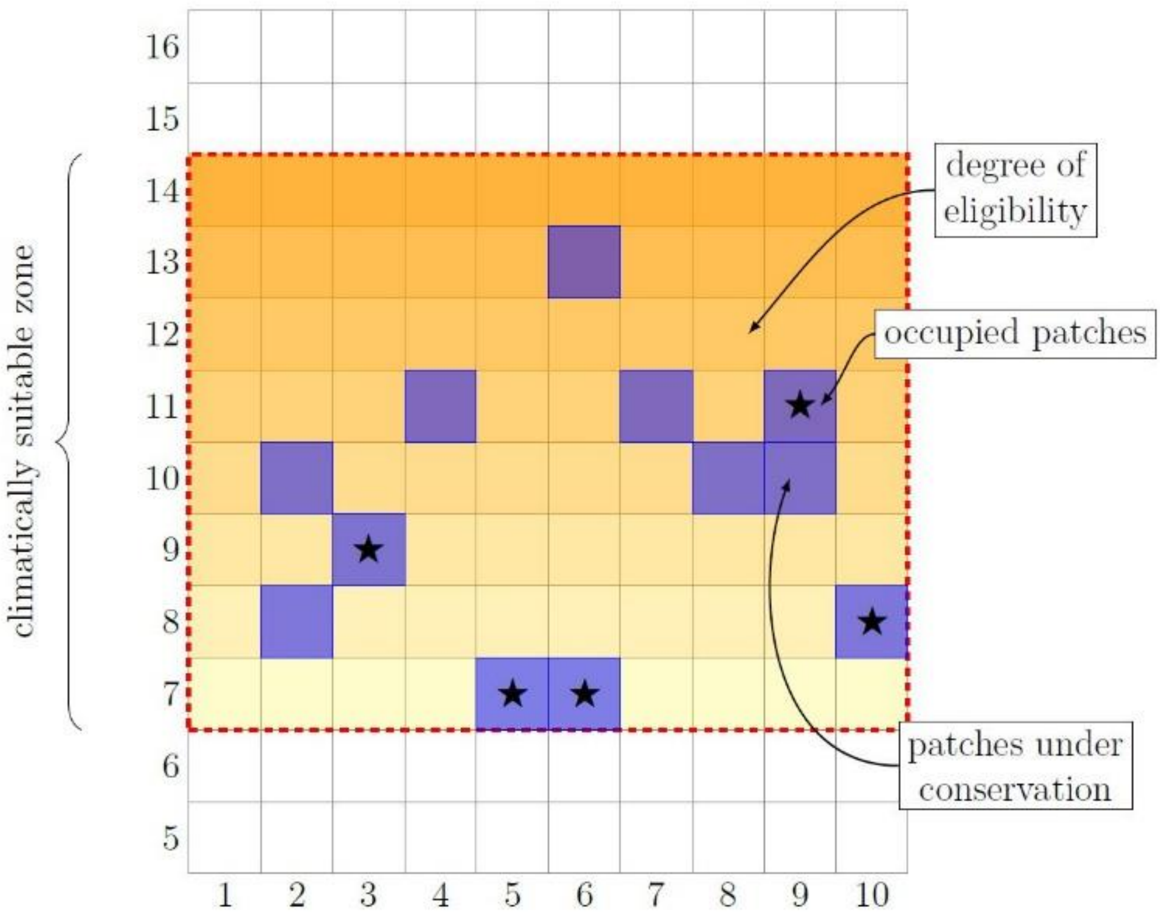

Figure A5: *'Climate change directional prioritization strategy'. The red-framed area represents the climatically suitable zone (CSZ), within which the orange-shaded area represents patches eligible for patch selection in the 'climate change directional prioritization strategy'. The degree of orange depicts the level of eligibility of a particular patch; darker-shaded areas have a higher eligibility than lighter-shaded areas. The blue shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species.*

Figure A5 illustrates the 'climate change direction prioritization strategy'. This strategy locates newly generated patches in the more northern range of the CSZ compared to the 'climate suitability prioritization strategy'. Patches selected closer to the northern border of the CSZ are located within the CSZ for the longest time. This is due to the northwards propagation of the CSZ through the landscape as a result of climate change. If a patch close to the northern border is selected for conservation, it takes longer for the CSZ to move across this patch and to eventually drop out of the CSZ, compared to a patch closer to the southern border which drops out of the CSZ earlier. This results in a generally more stretched out conservation network as patches can potentially be located throughout the whole

CSZ, while being added most likely at the norther edge, compared to the climate suitability prioritization strategy.

A3 Patch restriction effect

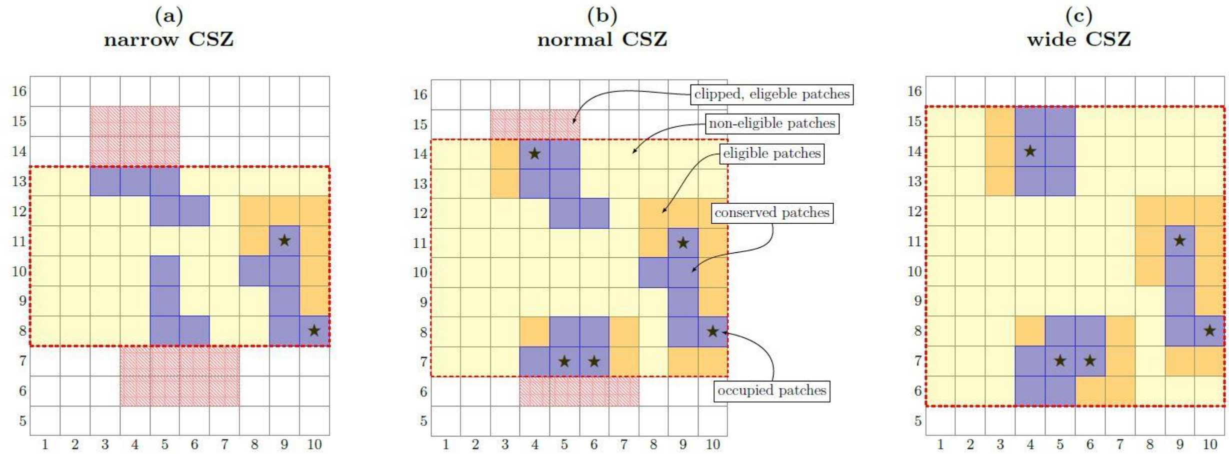

Figure A6*: Patch restriction effect in the 'species abundance prioritization strategy' due to changes in CSZ sizes due to varying cs^{thr}. The red-framed area represents the climatically suitable zone (CSZ), within which the orange-shaded area represents patches eligible for patch selection in the 'species abundance prioritization strategy'. The degree of orange depicts the level of eligibility of a particular patch; darker-shaded areas have a higher eligibility than lighter-shaded areas. The blue shaded area represents a patch selected for conservation; the star-symbol indicates that this patch is occupied by the target species. The red-shaded areas represent patches which could have been selected by the respective strategy, if the CSZ was large enough, but in fact are restricted in eligibility by the patch restriction effect.*

Decreasing the climate suitability threshold parameter cs^{thr} leads a decreasing extend of the CSZ (see Fig A6.a; visualized for the '*species abundance prioritization strategy'*). In any strategy, this can lead to an exclusion of otherwise potentially eligible patches from the selection mechanism. The result is a *patch restriction effect* (see main paper, Section 4) leading to an increased necessity to select patches in the remaining (smaller) CSZ, which in consequence are likely to be more expensive. Additionally, a *connectivity effect* can be observed, as the selected patches are closer together in case of a smaller CSZ and thus more likely to be well connected.

A4 Influence of economic and ecological variables

Additional to the sensitivity analysis for changes in climatic model parametrization presented in Section 4 of the main paper, we performed a sensitivity analysis with respect to changes in ecological and economic parameters, presented in the following. The corresponding parameter values can be seen in Table A1.

Table A1: *Overview about the parametrization value and value ranges specified for computation of the Monte-Carlo-Simulation and used in the sensitivity analysis for non-climatic factors.*

Parameter name	*Parameter description*	*Parametrization Values Range*	*Base case*
Economic parameters			
$\overline{OC}$	Mean opportunity costs in the landscape	$\in \{0.8,1.0,1.2\}$	1.0
$\overline{tc^{buy}}$	Mean transaction costs of purchasing a patch	$\in \{0.8, 1.0, 1.2\}$	1.0
$\overline{mc}$	Mean monitoring costs	$\in \{0.08, 0.10, 0.12\}$	0.1
r	Interest rate	$\in \{0.01, 0.015, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05\}$	0.03
Ecological Parameters			
ν	Emigration rate from any patch	$\in \{90,100,110\}$	100
δ	Dispersal distance of the target species	$\in \{1,2,3\}$	1

Regarding the impact of interest rates on the cost-effectiveness of the different GM-PSS pairs we find that with decreasing interest rates, the cost-effectiveness is reduced in all GM-PSS pairs. These result is expectable, as reductions in the parameter eventually decreases the CA’s possibility to buy or compensate new patches, either by reducing their available budgets or by increasing patch prices or compensation requirements through increases in the discount factor (compare Schöttker et al. 2016). A graphical analysis can be found in Figure A7.

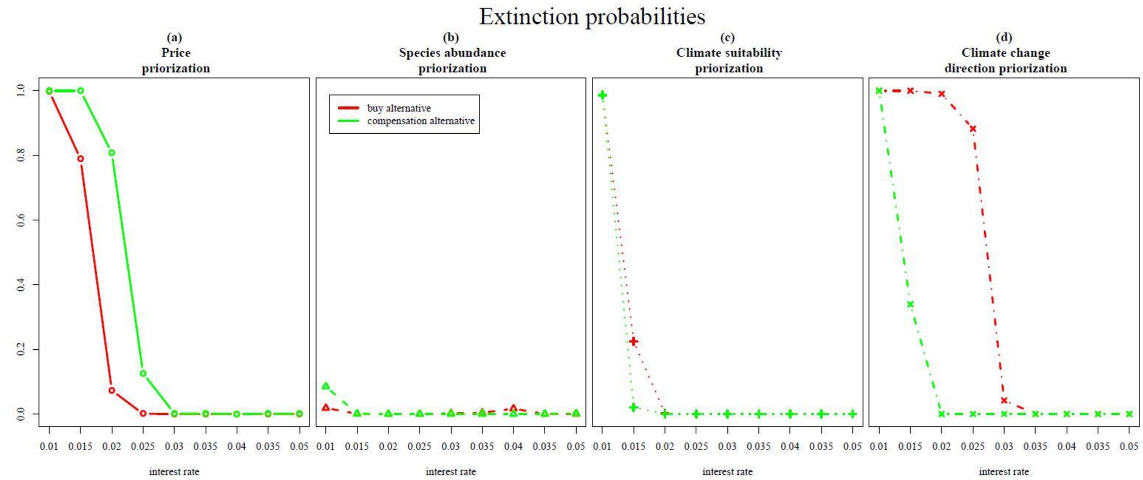

Figure A7: *Extinction probabilities of the different GM-PSS pairs with changing interest rates, resulting in changes in available budgets and discount rates. The red line represents results for the buy alternative, the green line for the compensation alternative.*

A direct increase of patch prices (by increasing $\overline{OC}$) has a negative effect on the cost-effectiveness of the GM-PSS pairs (see Figure A8).

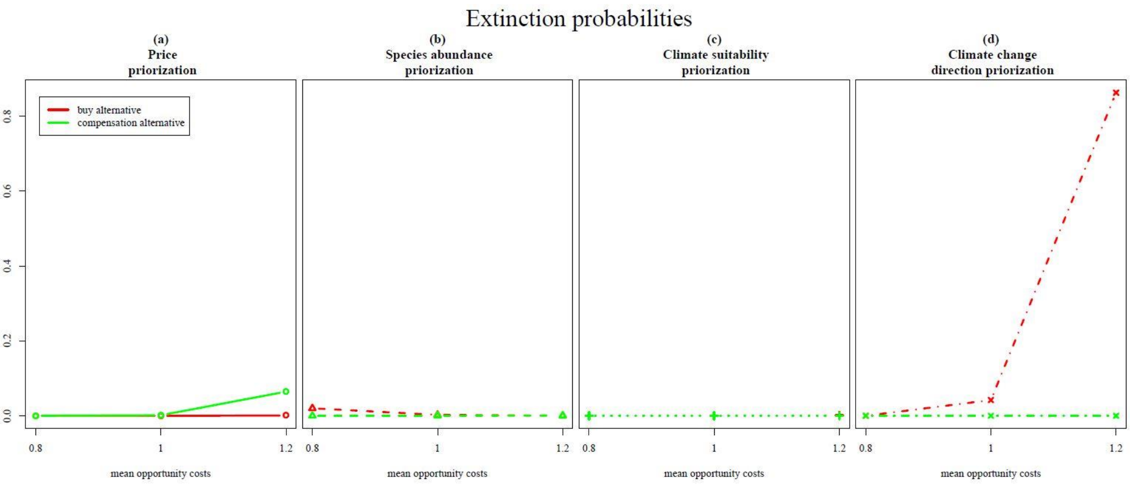

Figure A8: *Extinction probabilities of the different GM-PSS pairs with changing mean opportunity costs. The red line represents results for the buy alternative, the green line for the compensation alternative.*

Variations in the emigration rate (ν) did not result in observable changes of the extinction rates of the GM-PSS pairs (Fig. A9), and increasing the dispersal distance (δ) slightly reduced the extinction rate of the *buy alternative's* 'climate change direction prioritization strategy', while the other GM-PSS pairs remained unaffected (Fig. A10).

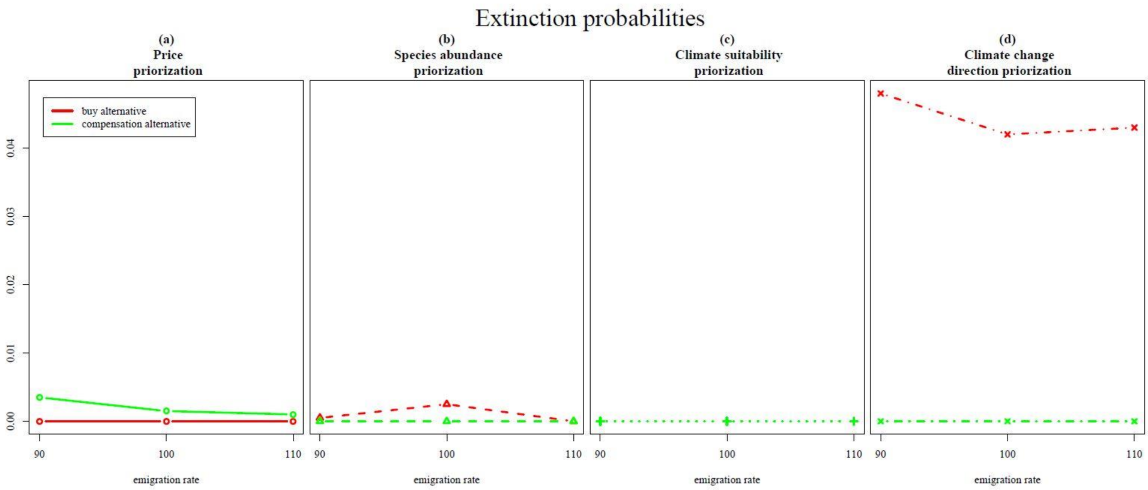

Figure A9: *Extinction probabilities of the different GM-PSS pairs with changing emigration rates. The red line represents results for the buy alternative, the green line for the compensation alternative.*

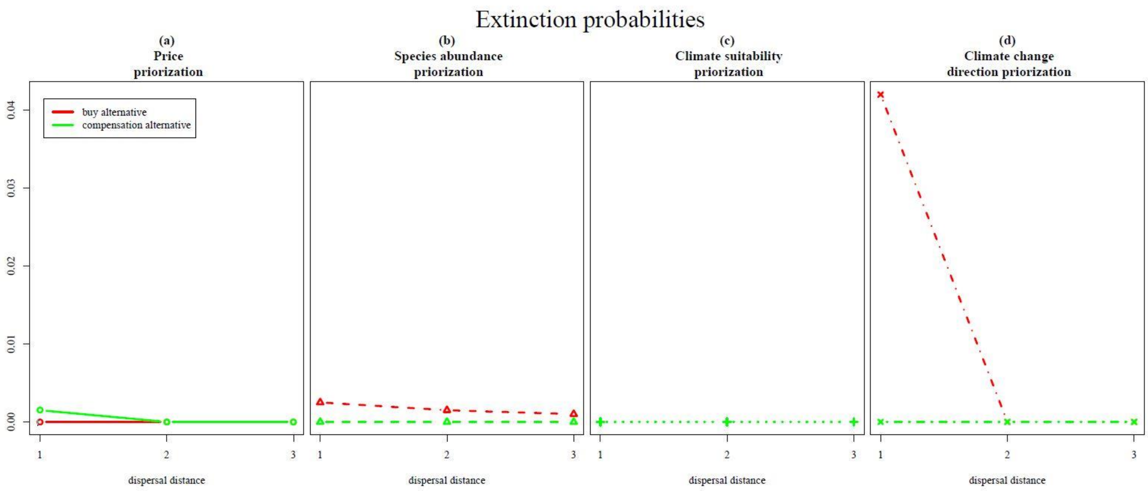

Figure A10: *Extinction probabilities of the different GM-PSS pairs with changing dispersal distances. The red line represents results for the buy alternative, the green line for the compensation alternative.*

Decreasing land purchase related mean transaction costs $\overline{tc^{buy}}$ only showed an influence on the in the climate direction prioritization strategy where cost-effectiveness increases (see Fig. A11). Other strategies where not influence by changes in mean transaction costs as the underlying model parametrization already resulted in complete species survival and no changes in cost-effectiveness where observable.

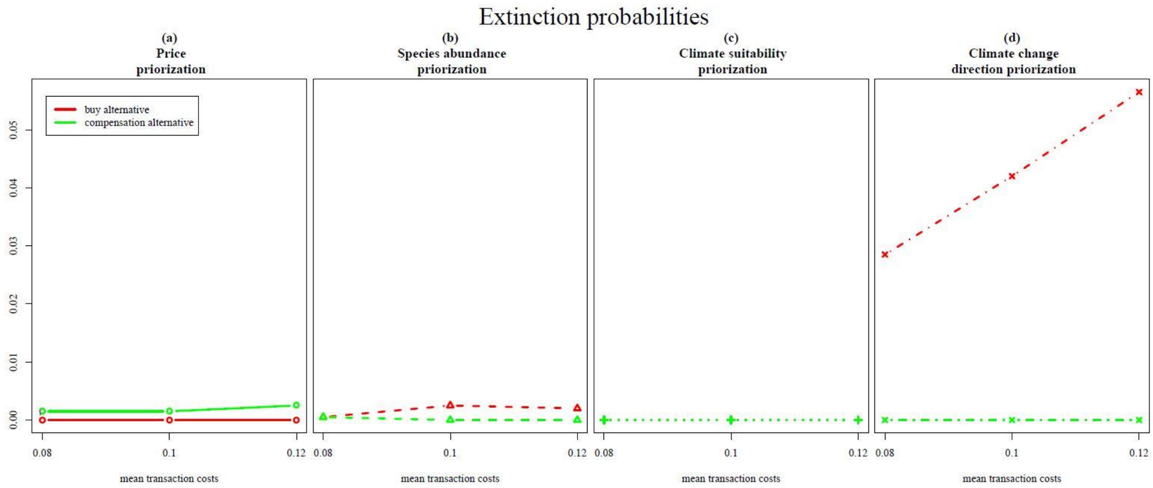

Figure A11: *Extinction probabilities of the different GM-PSS pairs with changing mean transaction costs. The red line represents results for the buy alternative, the green line for the compensation alternative.*

Similarly, a decrease in mean monitoring costs resulted in an increase in cost-effectiveness as general conservation costs where reduced (Fig. A12).

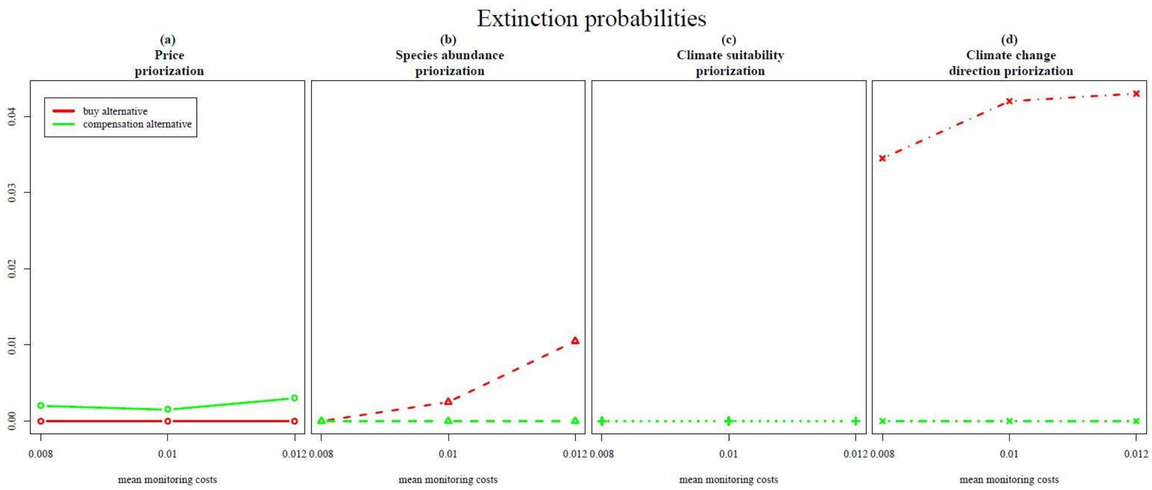

Figure A12: *Extinction probabilities of the different GM-PSS pairs with changing mean monitoring costs. The red line represents results for the buy alternative, the green line for the compensation alternative.*

As discussed in the main part, changes in the parameter ρ, influencing the curvature of the climate suitability bell shape, can be considered negligible (see Fig A13). Variation in ρ only influences the size of the CSZ and the absolute values of patch level climate suitability within the CSZ. These effects however are only marginal.

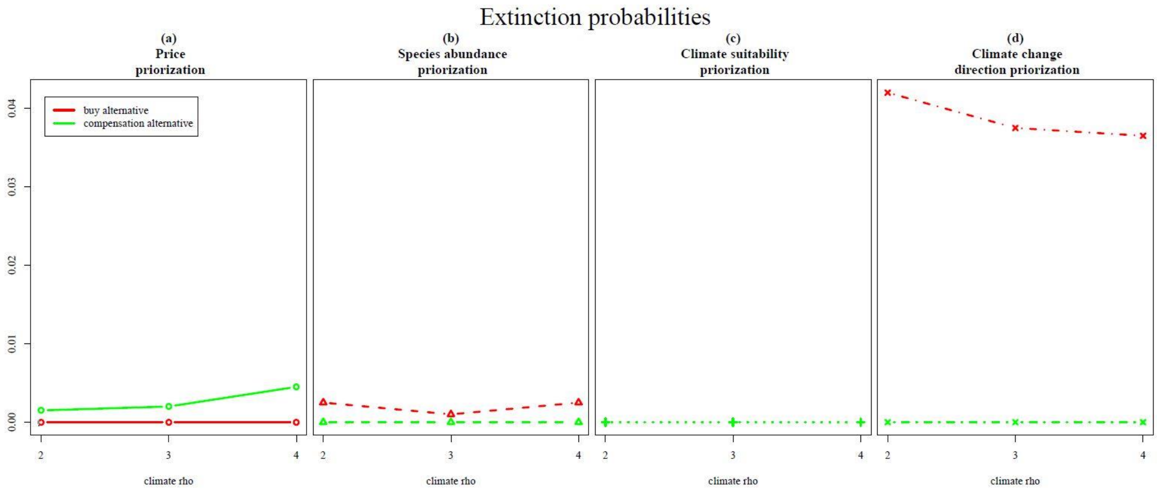

Figure A13: *Extinction probabilities of the different GM-PSS pairs with changing climate suitability bell curvature parameter* ρ. *The red line represents results for the buy alternative, the green line for the compensation alternative.*

Variations in the climate direction prioritization strength parameter λ only have an effect on the respective PSS (compare Figure A14). In particular, a marginal increasing effect on the cost-effectiveness of the buy alternative due to decreases in λ can be observed. The direction of this effect is reasonable, as a decreasing value of λ results in a less restrictive and thus less costly patch selection within the CSZ. This in turn increases the cost-effectiveness of the corresponding GM-PSS pair.

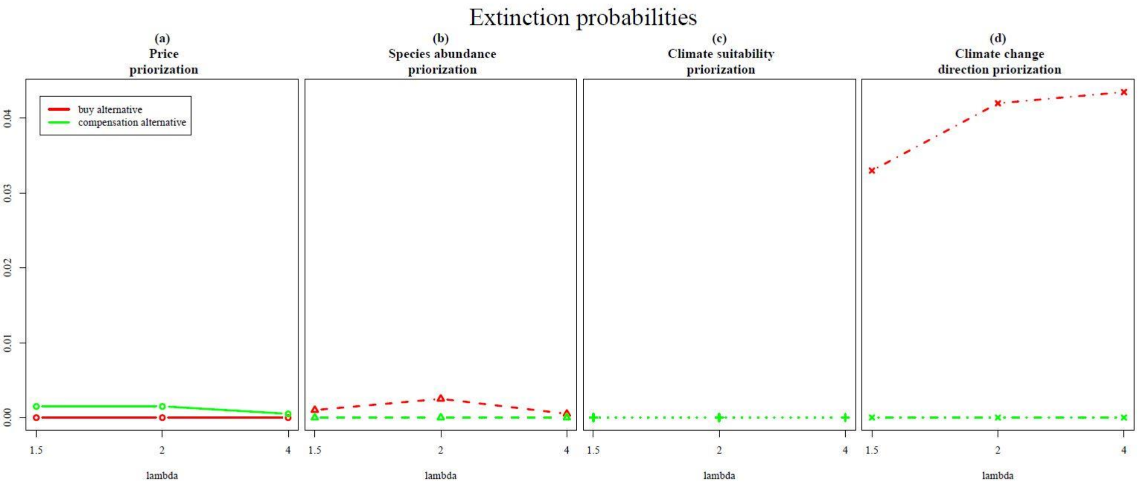

Figure A14: *Extinction probabilities of the different GM-PSS pairs with changing climate direction prioritization strength λ. The red line represents results for the buy alternative, the green line for the compensation alternative.*

A5 References

Schöttker, O., Johst, K., Drechsler, M., Wätzold, F., 2016. Land for biodiversity conservation — To buy or borrow? Ecol. Econ. 129, 94–103. https://doi.org/10.1016/j.ecolecon.2016.06.011