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Optimal time series in the reserve design problem under climate change

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ABSTRACT

Climate change causes range shifts of species and habitats, thus making existing reserve networks less suitable in the future. Existing optimisation procedures hence need to be adapted in order to account for changes in the spatial distribution of habitat types as well as their relative occurrence. We develop a multi-objective optimisation procedure that considers these dynamic changes. We demonstrate the functioning of the model by applying it to a conceptual case study. In this case study, we aim to gain an understanding on the consequences of not adapting the reserve network despite climate change and the optimal adaptation pathways for different funding levels. Finally, we consider whether larger flexibility in terms of when to adapt the reserve network by providing a one-off payment instead of regular payment improves the outcome achieved. We find that the optimisation procedure is a suitable tool to identify adaptation pathways as the outcome is improved, especially for habitat types that become increasingly threatened. Initially providing a one-off payment instead of regular payments leads to higher habitat protection.

Keywords: Conservation planning; climate adaptation; climate-ecological-economic modelling; optimal time series; range shift; RD problem; spatial changes; temporal changes

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1 INTRODUCTION

Existing nature reserves are unlikely to protect their target species in the future unless they are adequately adapted to climate change (Heller and Zavaleta, 2009; Vincent et al., 2019). This is due to shifts in species' ranges and the distribution of habitats caused by changing climatic conditions (Creutzburg et al., 2015; Ponce-Reyes et al., 2017; Campos-Cerqueira et al., 2021; Dasgupta, 2021): habitats tend to shift poleward and towards higher altitudes. Reserve networks which are optimal today but remain unaltered are hence likely to deteriorate under changing climatic conditions, which may lead to the loss of certain habitat types. Reserve networks therefore need to be adapted spatially to climate change. Specifically, these adaptations need to take into account potential spatial changes in the distribution of habitat in the landscape and changes in the relative occurrence of different habitat types.

In the field of operations research, the reserve design (RD) problem (Ando et al., 1998; Polasky et al., 2001; Hamaide et al., 2014) is usually formulated as one of two archetypal problems: the Species Set Covering Problem (SSCP) and the Maximal Species Covering Problem (MSCP). In both cases, a landscape consists of potential sites containing different species. Regarding the SSCP, the problem is to find which sites to protect to conserve a set of desired species whilst minimizing costs (Moore et al., 2003; Jafari and Hearne, 2013; Snyder and Haight, 2016). Regarding the MSCP, the number of species to be protected is maximised given a certain budget constraint (Church et al., 1996; Polasky et al., 2005).

Previous research shows that the methodologies developed in this field may be applied to a variety of conservation problems (see Alagador and Cerdeira (2021) for an overview). One key area is research on the need to create (more or less) connected reserve networks. For example, Önal and Briers (2002) and Önal and Briers (2005) present integer programming approaches to reduce fragmentation of reserve sites, Önal and Briers (2006) develop a two-stage procedure to address connectivity, and Jafari and Hearne (2013) explicitly consider neighbourhood relations between sites in an adaptation of the RD-problem called the ”reserve network design problem”. Önal et al. (2016) further distinguish between physical and functional connectivity.

Other research in this field adds the temporal dimension in multi-period RD-problems (Jafari et al., 2017), considers multiple land uses (Dissanayake et al., 2011), the value of information (Polasky and Solow, 2001), changes in prices over time Dissanayake and Önal (2011), land restoration (Önal et al., 2016), and different strategies of conservation planning in adapting existing reserve networks (van Langevelde et al., 2002).While most of the above research focuses on finding the optimal solution, Önal (2004) and Önal and Briers (2006) explicitly address the trade-off between optimality and computation time by comparing optimal solution procedures and heuristics.

However, little research has been conducted so far in the field of climate adaptation of reserve networks. Alagador and Cerdeira (2020) provide a rare exception in their work on optimal migration corridors, and Dissanayake et al. (2012) develop an RD-problem considering the option of species relocation. Outside the field of operations research, climate-ecological economic modelling (Arafeh-Dalmau et al., 2020; Drechsler, 2020; Schöttker and Wätzold, 2022; Gerling et al., 2022) has been used to analyse optimal conservation strategies considering both ecological outcomes and conservation costs.

Apart from the above research, most research considering the challenges of adapting existing reserves under climate change to maintain chosen habitat types focuses on selected case study areas (Pyke and Fischer, 2005; Fung et al., 2017; Graham et al., 2019; Lawler et al., 2020). While most current research presents the additional, optimal reserve sites of a case study area necessary at some point in the future, this research does not consider the adaptations that have to be undertaken at every time step or a generic optimisation procedure that may deal with dynamic changes to the scarcity and spatial distribution of different habitat types. Specifically, the SSCP is of limited use under climate change when a species or habitat type that used to be present is impossible to maintain due to climatic changes and the resulting range shifts of species. Similarly, the MSCP is of little use if the goal is not just to conserve a species, but to also gain a certain habitat size as a single, small habitat may be of limited ecological value. This may be addressed by adding threshold values (Önal, 2004). However, when the potential habitat in a landscape decreases under climate change, this threshold value may no longer be adequate.

In this paper, we go beyond the mentioned approaches and develop a novel, climate-ecological-economic multi-objective optimisation model that considers dynamic changes to the scarcity and spatial distribution of different habitat types under climate change and calculates a time series of optimal habitat networks within these dynamic conditions. We then apply the model to an illustrative landscape to demonstrate a simple application of the model. In the application, we aim to gain some conceptual understanding on the consequences of not adapting the habitat network despite changing conditions the optimal adaptation pathways and the influence of different funding levels on the overall outcome.

In our results, we illustrate (1) how an optimal reserve network is affected by climate change if no adaptation takes place, (2) how the quality of the reserve can be improved by adapting the reserve network with different funding levels, and (3) whether larger flexibility in terms of when to adapt the reserve network by providing an appropriately discounted one-off payment initially rather than regular payments improves the achieved outcome.

We utilize the JuMP modelling language (Dunning et al., 2017) in the Julia programming environment (Bezanson et al., 2017) to set up the climate-ecological-economic model, and the Gurobi optimiser (Gurobi Optimization, LLC, 2021) to solve the optimisation for a global optimum. Standard packages of the R software are used for processing and visualization of results (R Core Team, 2018).

2 MATERIALS AND METHODS

2.1 Model formulation

The sets, indices, parameters and variables used in the formulation of the mathematical model that follows are given in Table 1.

We consider K habitat types on a landscape with multiple sites. On this landscape is a reserve network comprising a subset of connected sites. We expect the habitat quality of this initial reserve network to deteriorate with time under climate change. We therefore formulate a dynamic optimisation model that allows for adaption of the initial reserve network through buying and selling of sites over T time-periods, each of duration τ years.

Symbol	Description
Sets, Indices	
N	set of all sites, $i \in N$
M_i	set of all sites in the neighbourhood of site i
T	set of all time periods, $t \in T$
K	the set of all habitat types, $k \in K$
Parameters	
τ	duration of each time period (years)
a	transaction cost of buying or selling a site
p_{it}	price of property i at time t
h_{kit}	utility of habitat type k of site i at time t
r	annual interest (discount) rate
$c(t)$	capital available at time t
$d(t)$	additional capital (e.g. from grants or donations) available at time t
$\mathbf{M}$	a large number
Variables	
y_{it}	1 if site i is owned at time t, 0 otherwise
b_{it}	1 if site i is purchased during the period $(t,t+1)$, 0 otherwise
s_{it}	1 if site i is sold during the period $(t,t+1)$, 0 otherwise

Table 1. Overview of used sets, indices, parameters and variables in the dynamic optimisation.

$$\sum_{i \in N} (1+a) * p_{it} * b_{it} \leq c(t) \qquad \forall t \in T \tag{1}$$

$$\begin{aligned} c(t+1) = (1+r)^{\tau} * c(t) + d(t) + (1+r)^{0.5\tau} * \\ \sum_{i \in N} (1-a) * p_{it} * s_{it} - (1+a) * p_{it} * b_{it} \quad \forall t \in T \end{aligned} \tag{2}$$

$$y_{it+1} = y_{it} + b_{it} - s_{it} \qquad \forall i \in N,\ \forall t \in T \tag{3}$$

$$b_{it} \leq \sum_{l \in M_i} (y_{lt} - s_{lt}) \qquad \forall t \in T \tag{4}$$

$$b_{it} \leq 1 - y_{it} \qquad \forall i \in N,\ \forall t \in T \tag{5}$$

$$\mathbf{M}(1 - s_{it}) \geq \sum_{l \in M_i} y_{lt} - 1 \qquad \forall t \in T \tag{6}$$

Constraint 1 ensures that the cost of purchases in any time period cannot exceed the capital available at that time. Constraint 2 keeps track of the flow of capital. Capital carried over from the previous time-period earns interest during the new period (of τ years). We assume that buying and selling transactions occur in the middle of the time-period i.e. 0.5τ years before the start of the next period, thus sales and purchases must be adjusted according to the interest rate. Constraint 3 updates the sites forming the reserve after sales and purchases. To maintain connectivity constraint 4 will only allow a site to be purchased if there will be at least one other reserve site in its neighbourhood. Constraint 5 ensures that we do not buy a site already part of the reserve. Constraint 6 is introduced to reduce breaking up clusters. Only sites that have at most one reserve site in its neighbourhood are allowed to be sold. A standard 'big M' formulation is used here to ensure there is no unwanted constraint placed on the binary variables on the right hand side of the constraint in the event that site i is not to be sold. An appropriate value for $\mathbf{M}$ is the smallest number such that no site has more than $\mathbf{M}$ neighbours. For example, if the sites in a reserve comprise a grid of squares then there would be at most eight sites in the direct neighbourhood of any particular site. Thus in this case setting $\mathbf{M}= 8$ is sufficiently large to ensure that the constraint will always be satisfied at any time that site i is not sold.

Constraints 4 and 6 together encourage rather than guarantee contiguity.

Objectives and solution procedure

While maximising habitat is desirable, our primary concern is loss of habitat. We therefore aim to maximise the minimum values of each habitat type. As we consider K habitat types we have a multi-objective problem which we formulate using a goal programming approach. We begin by solving the following K problems subject to the constraints 1-6 given above.

For $\forall k \in K$ solve:

$$\Gamma_k = \max\ \theta \tag{7}$$

$$\text{subject to: } \sum_{i \in N} h_{kit} * y_{it} \geq \theta \qquad \forall t \in T \tag{8}$$

Having obtained the goals, Γ_k, we proceed to the multi-objective problem where we aim to minimise the deviations from the goals. Thus, still subject to the constraints 1-6, we have additional constraints 10 together with the objective 9 as given below.

$$\min \quad \varepsilon \tag{9}$$

$$\text{subject to: } (\Gamma_k - \sum_{i \in N} h_{kit} * y_{it})/\Gamma_k \leq \varepsilon \qquad \forall t \in T, \quad \forall k \in K \tag{10}$$

The solution to this last problem will yield the sites i that form part of the reserve at each time t as well as the sites that are to be purchased or sold at each time t.

3 ILLUSTRATION

3.1 Modelling of the landscape, habitat types and climate change

The landscape in our conceptual case study consists of a grid of $N = 10 * 20 = 200$ equally sized cells. In this landscape, three different habitat types exist (H_1, H_2, H_3). Each grid cell i has a specific utility value h_{kit} for each of the habitat types k at time t as the suitability of a site may change over time due to climate change.

Each of the three habitat types reacts differently to changing climatic conditions: H_1 expands, H_2 shifts through the landscape, and H_3 contracts as a result of climate change. Additionally, we assume that each habitat type is located in a specific part of the model landscape, with H_1 in the lower left, H_2 in the center, and H_3 in the top right. Each region provides ideal conditions for one of the three habitat types, while only providing sub-optimal conditions for the other habitat types. Hence, the locations of habitat types are not restricted to their ideal regions but partially overlap into the respective neighbouring regions.

We have chosen these patterns of spatial shifts as they represent typical movements observed in reality: One could imagine our model landscape as consisting of different altitudes, temperature or precipitation gradients (see Supplementary Material A and Fig. A.1 for details on the construction of the landscape). As climatic factors change – such as increasing temperatures in formerly cooler, high-altitude areas – the species' ranges and habitat types move uphill towards areas more suitable under the changed conditions, while the mountainous habitat types are increasingly threatened due to increasing competition and unsuitable climatic conditions (see for example Lamprecht et al. (2018)).

We assume that when a grid cell is conserved, the effective habitat area generated for the different habitat types is given by their respective utilities h_{kit} (see Supplementary Material B for details on the underlying functional relationship). As any grid cells that are not conserved do not provide any habitat, the conserved grid cells represent 'islands' of habitat surrounded by land of no ecological value with respect to the modeled habitat types.

In order to consider changing climatic conditions, the utility h_{kit} is time-dependent. Climate change is hence represented implicitly by the variable $t \in [2, T]$, which is the time step of the model simulation. We consider each time step t representing a five-year period, and $T = 13$. We hence examine a period of 60 years (note that $T = 1$ represents the optimisation generating the initial reserve network). Rather than modelling climate change explicitly, e.g. through changes in precipitation or temperature on a grid cell level, we hence model it implicitly by assuming that the climatic changes cause the suitability of each grid cell i for habitat type H_k to change.

We assume there is no time lag between the time when a grid cell is conserved and the time when the habitat of that grid cell is generated, i.e. as soon as conserving grid cell i, habitat types H_k are present according to their utilities h_{kit}.

3.2 Policy scenarios: variations in the timing and size of 'climate adaptation funds'

In order to gain an understanding on the optimal conservation strategy under climate change we compare the development of the values achieved for the three habitat types over the 60-year period.

The initial reserve network is generated with an initial budget of 500μ (throughout this section we use μ to indicate monetary units), representing approximately 7% of the total value of all sites in the landscape. Considering the regular 'climate adaptation' payments $k(t)$, we consider different budget constraints in order to see how the budget influences the adaptation. Specifically, we consider that the agency may have no, a low or a high additional budget $k(t)$ available in every time step to realise the reserve network adaptation in the dynamic optimisation. In the 'low funding' case we assume that the agency receives 50μ during each five-year period (i.e. $k(t) = 50 \ \forall t$, see equation 2). In the 'high funding' case the regular payments are increased to 100μ. Finally, we consider whether an appropriately discounted one-off payment initially improves the achieved outcome in comparison to the regular payments.

4 RESULTS

We start with an optimal reserve network that is worth 500μ. By optimal here we mean that no other subset of sites to the value of 500μ can yield a better habitat outcome than this initial reserve. We used the method described in Jafari and Hearne (2013) to obtain this initial optimal reserve. Figure 1(c) shows the spatial distribution of the three habitat types in the landscape. It can be seen that the most prominent locations of H_1 are located in the bottom left corner of the reserve network, the largest areas of H_2 can be found more in the center of the landscape, while H_3 is found mainly in the upper right corner of the reserve network.

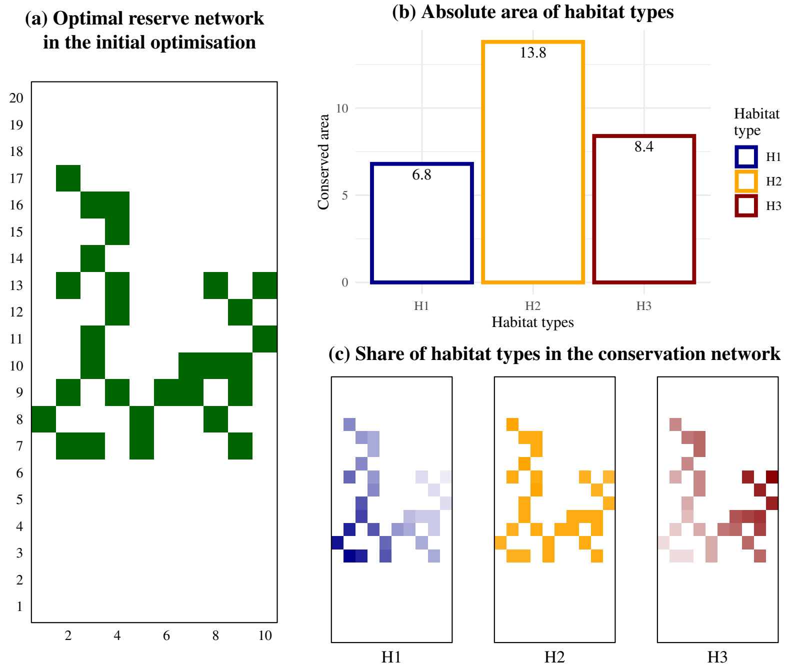

Figure 1. (a) Optimal reserve network within the landscape resulting from the initial optimisation. (b) Absolute area of the three habitat types within the initial optimal reserve network. (c) Share of each habitat type within the initial optimal reserve network. Lighter shaded areas represent a smaller share of the specific habitat type of a site, darker shaded areas represent larger shares.

In order to represent all three habitat types optimally, the initial reserve network turns out to be located in the center of the landscape, as was to be expected.

We now proceed to examine how the value of the reserve network changes if no adaptation takes place. Figure 2 shows that the static reserve network improves the outcome for the expanding habitat type H_1, but decreases the outcome for the shifting habitat type H_2 and the contracting habitat type H_3 over time. In particular, H_3 is almost lost in the final time step.

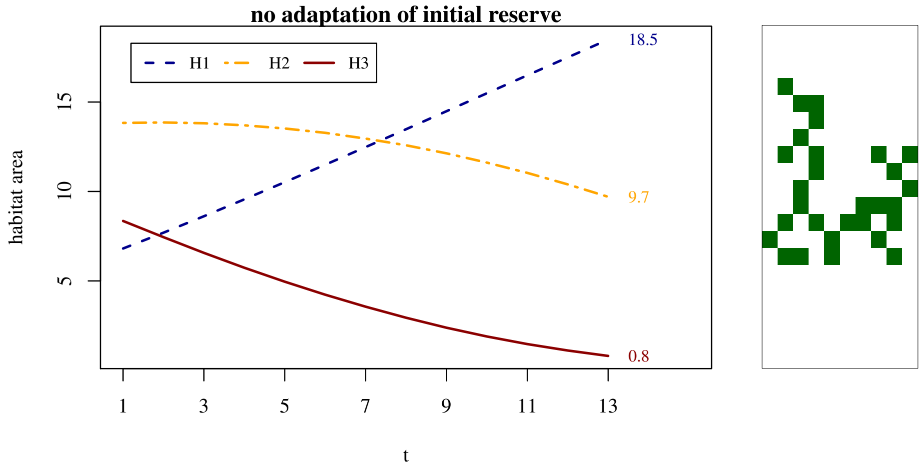

Figure 2. Development of habitat values for the ’static’ policy scenario. The number to the right of the lines shows the habitat value for each habitat type in the last time step. On the right, the initial reserve network is depicted.

Next, we apply the dynamic optimisation to examine the outcome for the different funding levels. Habitat type H_3 is the most negatively affected by climate change. Effectively this means that the optimisation problem is directed at maximising the minimum habitat values of H_3. In the ’no funding’ case, the outcome achieved by adapting the spatial location of reserve sites improves the final outcome from 0.8 (with no adaptation) (cp. Fig. 2) to 4.6 (cp. Fig. 3a). In the ’low funding’ case, the minimum value of habitat type H_3 improves further to 7.3, while in the ’high funding’ case H_3 no longer experiences any losses and remains constant at 8.2. It can hence be seen that additional funding improves the outcome for the most threatened habitat type, but the marginal improvement decreases with increasing funding.

Finally, we consider whether an increasing flexibility in terms of when to spend the money further improves the outcome achieved. To do so, we discount the regular payments of 100μ which the agency has so far received at the start of each of the twelve five-year periods. At the 5% interest rate level used throughout this work, this is equivalent to a present value of 437.22μ at the initial

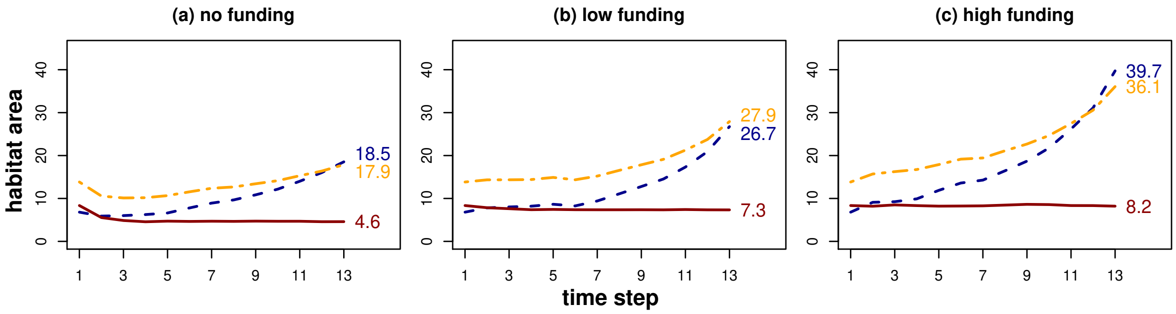

Figure 3. Development of the habitat values under the dynamic optimisation for (a) no funding, (b) low funding, and (c) high funding. The number to the right of the lines shows the habitat value for each habitat type in the last time step.

time, $t = 1$ [1]. We selected a level of 5% interest rates which is within the common range used in the field of conservation (Ando and Chen, 2011). Moreover, we tested other discount rates and found that they do not influence the qualitative outcome of results.

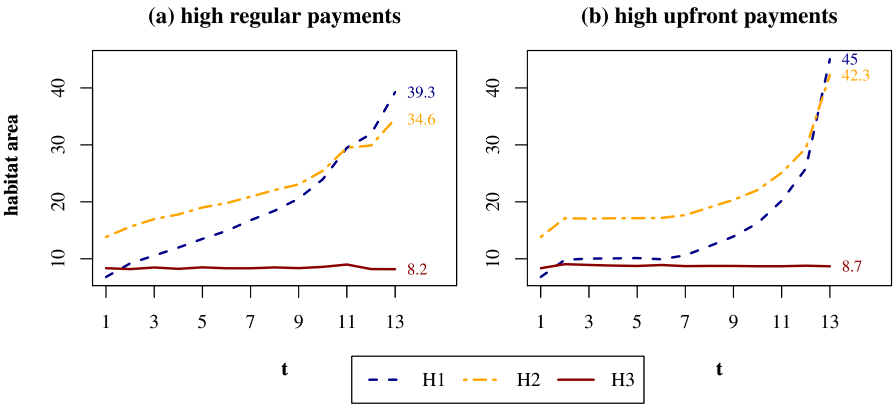

Figure 4. Development of the habitat values for the regular payments (a) and upfront payment (b) policy scenarios. The number to the right of the lines shows the habitat value for each habitat type in the last time step.

The results shown in figure 4 indicate that higher outcomes can be achieved with a single upfront payment than with the equivalent capital in regular payments. The habitat value for H_1, i.e. the expanding habitat, is initially the most threatened habitat type. With an upfront payment, its value

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[1] Note that in contrast to the previous cases, transaction costs differ (5% vs. 10%). Hence, results between Figure 3c and 4a differ slightly

in the early and late time steps improves compared to regular payments. In the final time step, habitat type H_3 (the contracting habitat) is the most endangered. The upfront payment leads to only a slightly larger protection of this habitat type in the final time step compared to the regular payments case. The final outcome for habitat type H_2 also improves in the upfront payment case. This suggests that the increased flexibility in terms of when to spend the money renders upfront payments superior to regular payments, especially concerning the conservation of habitat types that are most threatened in the early time steps.

5 DISCUSSION AND CONCLUSION

We present a specific case of the reserve design problem (RD-problem) in which the suitability of potential reserve sites changes over time due to climate change. We adapt the Maximal Species Covering Problem (MSCP) to maximise the conservation outcome given a budget constraint in a two-step optimisation procedure: we first solve the static optimisation problem to generate the optimal reserve network under current climatic conditions. We then solve a dynamic optimisation problem to adapt the reserve network over time. We adopt a *maximin* approach (Montoya et al., 2020) to solve the multi-objective optimisation using goal programming. Our optimisation procedure considers specifically the adaptations that have to be undertaken at every time step. We apply the model to a conceptual case study of conserving three habitat types. We consider different funding levels and timings of funding.

First, and in line with ecological research (see for example Heller and Zavaleta (2009); Vincent et al. (2019)), our results show that a static reserve network optimised for initial climatic conditions becomes increasingly less valuable for some habitat types, while the expanding habitat type benefits from this approach. Thus, the habitat type that becomes the most threatened under climate change is the least well protected in this static approach. This case implicitly assumes that the conservation agency is unable to adapt the existing reserve network due to budget and legal restrictions or is unaware of the need to do so. While in reality, many conservation actors are aware of the need to consider climate change in conservation decision-making, this is often not done due to a lack of information necessary for ”climate-smart” decision-making (Hannah et al., 2002; Prober et al., 2017). Our results therefore provide further evidence for the call of ecologists that reserve networks need to be expanded to maintain the protection of habitat under climate change (Heller and Zavaleta, 2009; Vincent et al., 2019). Additionally, with this scenario we aim to increase awareness of the importance of including climate change impacts as a variable in optimal reserve design problems. So far, this is only rarely included.

Second, our results show that our optimisation procedure is able to find improvements to the reserve network in the dynamic optimisation by taking into account spatial changes in potential habitat sites and changes to their relative occurrence. As the level of funding increases, the outcome achieved improves. However, marginal improvements decrease with an increase in funding. Our results show that even when no additional capital is provided, considering climate change-induced changes in the reserve adaptation may improve the conservation outcome, and that the model developed in this paper is a suitable tool to identify the necessary changes. It may hence be used in real-world case studies to contribute to filling the information gap currently hindering climate adaptation.

Third, we investigate in how far the flexibility of receiving additional funds as a one-off payment rather than regular payments throughout the runtime of the model influence the optimal outcome. Our results show that indeed the increased flexibility in terms of when to spend the money improves the overall outcome that can be achieved. This is in line with previous research on the topic (Costello and Polasky, 2004). However, if the conservation agency does not have perfect foresight (as it does in our model), the optimal investments in any time step may not be in line with the optimal investments given perfect information (Drechsler and Wätzold, 2020). In the case of imperfect foresight, the role of the quasi-option value of delaying irreversible investments (Arrow and Fisher, 1974) therefore provides an interesting avenue for future research on the optimal adaptation pathways of reserve networks under climate change (cp. Brunette et al. (2014) and Brunette et al. (2020)).

The presented adaptation of the RD-problem is able to model the impact of different policy scenarios on conserving threatened habitat types under climate change. In this paper, we have applied the model to a conceptual case study to examine the role of the size and timing of budget. In future research, the model may be used to analyse other relevant conservation questions.

One relevant question that may be addressed with our model in future research includes whether or not the conservation agency should be allowed to sell habitat sites. In this paper, we examined a conservation planning context in which the agency is able to add new habitat sites and exclude habitat sites from the reserve network only subject to a budget (and proximity) constraint. However, in reality, conservation agencies often do not sell previously purchased habitat sites due to negative ecological consequences in terms of habitat turnover (Ando and Hannah, 2011; Lennox et al., 2017; Gerling and Wätzold, 2021) and transaction costs such as taxes and the search for suitable sites for selling and buying (Schöttker and Wätzold, 2018). Future research may hence use the model to assess the suitability of specific policy instruments such as land purchase to adapt biodiversity conservation to the challenges of climate change.

In future research, the model may moreover serve as a tool to study the complexities of specific case studies in greater detail. For example, given the implementation of the optimisation, the model may easily be expanded to consider the parametrisation of specific case studies, landscapes that do not consist of grid cells but vectors of any shape and size (Jafari and Hearne, 2013), time lags in the generation of habitat after a site is conserved (Watts et al., 2020), and changing opportunity costs.

Global biodiversity extinction rates continue to be high (IPBES, 2019; Dasgupta, 2021), and adapting existing reserve networks to climate change is an important aspect of conserving species in the future (Pyke and Fischer, 2005; Fung et al., 2017; Graham et al., 2019; Lawler et al., 2020). We hence believe that future research on the RD-problem that considers the specific challenges of climate change is of high value.

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A MODELLING THE LANDSCAPE

The elevation level $elev_i = 1 + \Big(sin\big((n(i)-5)(\pi/5)\big) + sin\big((m(i)-10)(\pi/10)\big)\Big)/2$ is assigned on a functional basis in a way that the landscape features three different regions, i.e. a valley, plains of medium elevation, and a mountain. In the elevation function, $n(i) \in [1,..,10]$ represents the column of the landscape in which cell i is located, while $m(i) \in [1,..,20]$ represents the row (Fig. A.1).

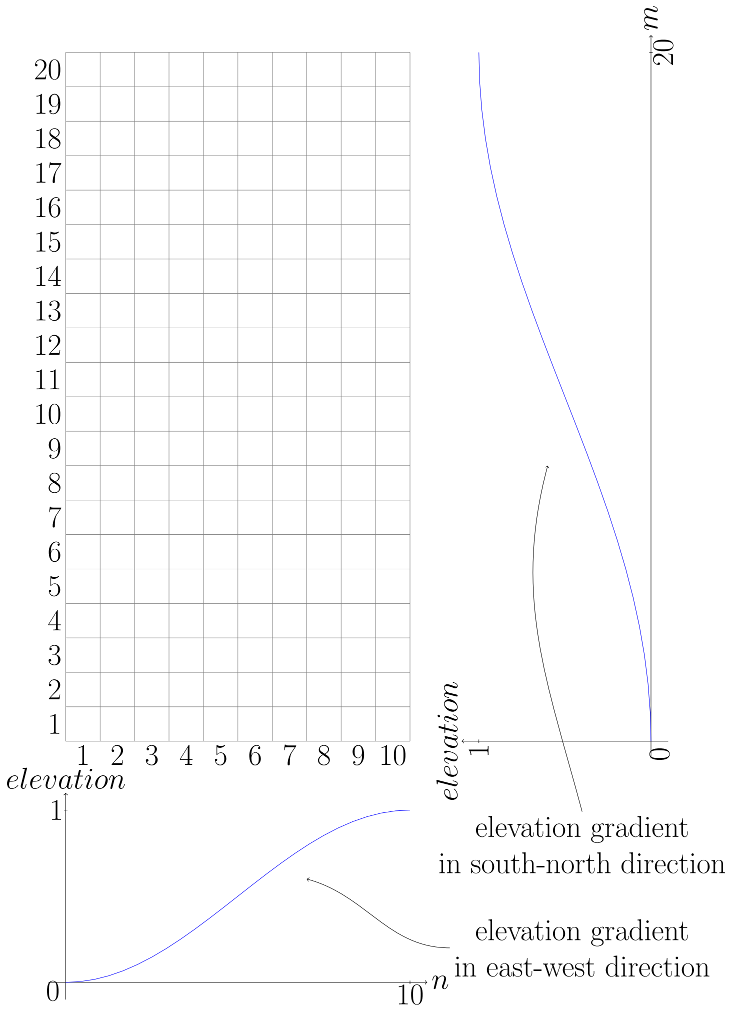

Figure A.1. Landscape grid in which conservation areas are selected (n=10 × m=20 cells), with the functional relationship describing the landscape's elevation in the east-west direction (below) and south-north direction (on the right).

B UTILITY AND HABITAT TRANSITION FUNCTIONS

We measure the utility h_{kit} of a grid cell for habitat type H_k by considering a grid cell i's suitability $S(H_{k,i}(t))$ at time t: the utility h_{kit} of a grid cell for a chosen habitat type equals the percentage share of that habitat type's suitability on the summed suitabilities of all three habitat types, i.e. $h_{kit} = \frac{S(H_{k,i}(t))}{\sum_{k=1}^{K} S(H_{k,i}(t))}$. We use a functional relationship of $S(H_{k,i}(t))$ to describe the individual climate-change-induced habitat shift of the three considered habitat types k over time between $t = 2$ and $t = T$. The relationship depends on the elevation $elev_i$ of cell i. We model $S(H_{1,i}(t))$ as follows:

$$S(H_{1,i,t}) = \begin{cases} 0 & \text{if } elev_i < 0 \\ -B_1 + (1 + A_1 + B_1) elev_i * \frac{T - s_1 * t}{T} & \text{if } 0 \leq elev_i < 1 \\ 1 & \text{if } 1 \leq elev_i \end{cases} \tag{B.1}$$

$$S(H_{2,i,t}) = \begin{cases} 0 & \text{if } elev_i < 0 \\ 2 * elev_i * \frac{T - s_2 * t}{T} & \text{if } 0 \leq elev_i < 0.5 \\ (2 - 2 * elev_i) * \frac{T - s_2 * t}{T} & \text{if } 0.5 \leq elev_i < 1 \\ 0 & \text{if } 1 \leq elev_i \end{cases} \tag{B.2}$$

$$S(H_{3,i,t}) = \begin{cases} 1 & \text{if } elev_i < 0 \\ 1 + B_3 - (1 + A_3 + B_3) elev_i * \frac{T - s_3 * t}{T} & \text{if } 0 \leq elev_i < 1 \\ 0 & \text{if } 1 \leq elev_i \end{cases} \tag{B.3}$$

See Figure B.1 for a graphical explanation of A_k and B_k. s_k represents a scaling factor regarding the strength of the influence of climate change and hence the speed of the northwards shift of $S(H_{k,i}(t))$ over time. For our study case we selected $A_1 = A_3 = B_1 = B_3 = 0$, $s_1 = s_3 = 1$, and $s_2 = 0.5$

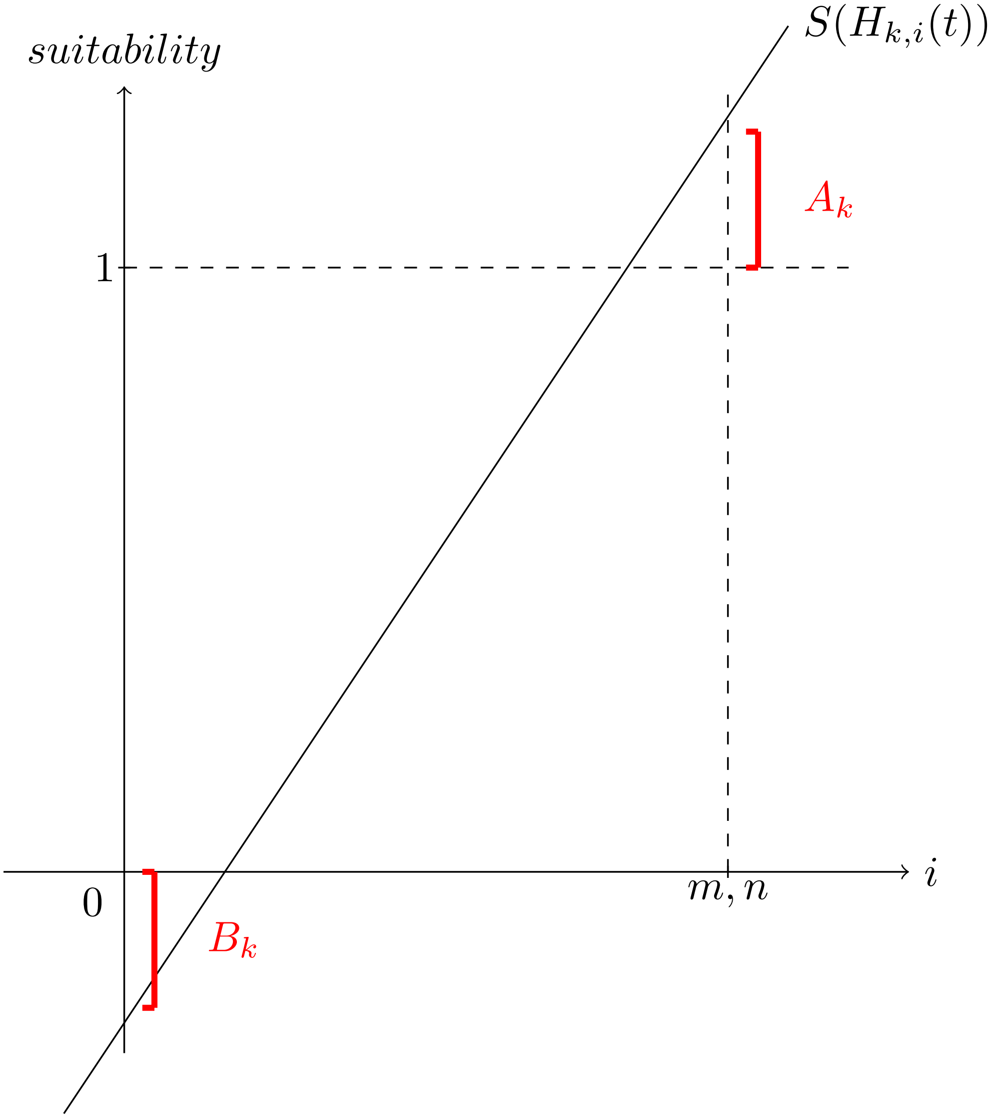

Figure B.1. Graphical illustration of parameters A_k and B_k.