Appendix A: Initial optimisation

We apply a goal programming approach in order to ensure that the conservation agency initially (i.e. in t=0) owns the optimal reserve network that conserves all habitat types given a budget constraint of 500MU (monetary units). This budget is approximately 7% of the value of all potential reserve sites in the landscape.

Following the approach of Jafari and Hearne (2013), we represent each site as a node. The budget is initially located at a source node outside of the grid. The problem is then regarded as a transshipment problem. Capital flows from the source to a node in the grid and from there to other connected nodes. Each node has a demand for capital equal to its cost and a reward equal to its ecological value. Capital cannot flow through a node without meeting its demand, i.e. without it being purchased. In this way contiguity is ensured while meeting some objective. Table A.1 provides an overview of the sets, indices, parameters and variables used in the mathematical formulation of the initial optimisation procedure.

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

Symbol	**Description**
Sets and Indices	
N	Set of all sites (nodes) in the *n x m* grid
0	The *source* node
N_+	Set of all sites (nodes) plus the *source* node
M_i	Set of all sites in the Moore neighbourhood of site $i \in N$
M_{i+}	Set of all sites in the Moore neighbourhood of site $i \in N$ plus the *source* node
Parameters	
p_i	Price of site *i*
h_{ki}	Ecological value of site *i* for habitat type *k*
B	Budget
Variables	
y_{ij}	equal to one if money flows from site *i* to site *j* (indicating site *j* is selected for purchase), 0 otherwise
x_{ij}	Amount of capital that flows from site *i* to site *j*

We first formulate the constraints of the problem.

$$(A.1) \sum_{j \in M_{i+}} x_{ji} - \sum_{j \in M_i} x_{ij} \geq p_i \times \sum_{j \in M_{i+}} y_{ji} \qquad \forall\, i \in N$$

$$(A.2) \sum_{j \in M_{i+}} y_{ji} \leq 1 \forall i \in N$$

$$(A.3)\ y_{ij} \leq x_{ij} \qquad \forall\, i \in M_{j+}, \forall\, j \in N$$

$$(A.4)\ x_{ij} \leq B \times y_{ij} \qquad \forall\, i \in M_{j+}, \forall\, j \in N$$

$$(A.5) \sum_{j \in N} y_{0i} = 1$$

$$(A.6)\ \ y_{ij} \in \{0,1\}, \qquad x_{ij}\ \geq 0, \quad \forall\, i \in N_{+}, j \in N$$

Constraint A.1 represents the flow of capital. The capital flowing into site *i* must be greater than or equal to the cost of the site plus the capital flowing out of it. Constraint A.2 ensures that capital can only flow into a site from one source. This ensures that each site is purchased only once. Constraints A.3 and A.4 ensure that capital will only flow from *i* to *j* if and only if y_{ij}=1, indicating that site *j* is purchased. Constraint A.5 together with A.3 forces capital to flow from the source and to only one site. As a result, we create one single connected reserve network. Constraint A.6 provides necessary function rules for x_{ij}, y_{ij}, *i* and *j*.

Objective and solution procedure

We have a multi-objective problem in that we would like to select sites to maximise the value with respect to each habitat type. Also in this step, we deal with this problem using goal programming. Solving to maximise each habitat type in turn subject to the constraints A.1- A.6, we obtain the goal g_k corresponding to each habitat type *k*. Thus:

$$(A.7)\ \ g_k = max \sum_{j \in N} \sum_{i \in M_{j+}} y_{ij} \times h_{kj} \qquad k = 1,2,3$$

The goal for each habitat is obtained while ignoring the other habitats. We now attempt to obtain habitat values as close as possible to the goals in a multi-objective setting by minimising ε (cp. equation A.8). Thus, we replace the previous objectives and add a new constraint to the previous constraints, as given below.

$\min \varepsilon$ subject to:

$$(A.8)\ \frac{g_k - \sum_{j \in N} \sum_{i \in M_{j+}} y_{ij} \times h_{kij}}{g_k} \leq \varepsilon \qquad for\ k = 1,2,3$$

Appendix B: Alternative utility function

We consider that the agency's utility function may not be adequately presented by eq. 6 in the main paper. However, how future biodiversity should be valued – in particular under climate change – remains an open question. Without considering the specific challenges arising under climate change, Gollier (2010) argues for a relatively small discount rate of less than half the discount rate for consumption – and hence an only slightly decreasing value over time (which however depends on current ecological and economic growth rates). Lewis et al. (2022) empirically estimate a discount rate of around 2%, which implies significant welfare gains for biodiversity conservation "now" rather than "later". The TEEB report argues that this is not only an economic question, but an ethical one (TEEB 2010) and hence further challenges to what extent the value of future biodiversity is lower than the value of current biodiversity. Future research could then examine how climate change influences this valuation: in times of high biodiversity extinction rates biodiversity becomes increasingly scarce. Given decreasing marginal utility, the value of preventing a marginal species' extinction hence increases (see Batabyal et al. (2003) for a discussion on the scarcity value, and Zhu et al. (2019) on the impact of scarcity on the appropriate discount rate). Overall, the question remains: what is the present value of future biodiversity?

Given the scant research on valuing future biodiversity, and in particular the lack of research on the issue under climate change (which we argue has a strong impact on this valuation), we decided to model a present-focused decision-maker who cares highly about present conservation outcomes (future biodiversity has no value to them) as a rather "extreme" case to complement the analyses conducted in the main paper. While in reality, the valuation of future conservation may lie in between the two considered extreme cases, we focus on these two cases to gain an understanding of the impact of this assumption on overall results. When considering the temporal dimension, the utility function given in eq. 5 in the main paper then becomes:

(B.1) $U_t = min.\{\mathrm{U}_{k=1,t}, \mathrm{U}_{k=2,t}, \mathrm{U}_{k=3,t}\}$

<u>Results</u>

Figure B.1 shows the development of U_t over time. It can be seen that the utility of conservation decreases as the mountain-top habitat H_3 becomes increasingly scarce. A higher budget leads to higher utilities achieved, especially during the later periods. Comparing this with the results from the utility specification analysed in the main paper, it can be seen that spatial flexibility has a lower value, and the differences in the value of spatial flexibility are more similar for different budget constraints.

The low utilities achieved in the final time steps are caused by the low conservation status of H_3 towards the end of the optimisation. In particular, even for a high budget, the outcomes achieved for H_3 are relatively low. The present-focused utility function, leading to myopic decision-making, hence leads to worse ecological outcomes, which in turn leads to lower utilities in the future.

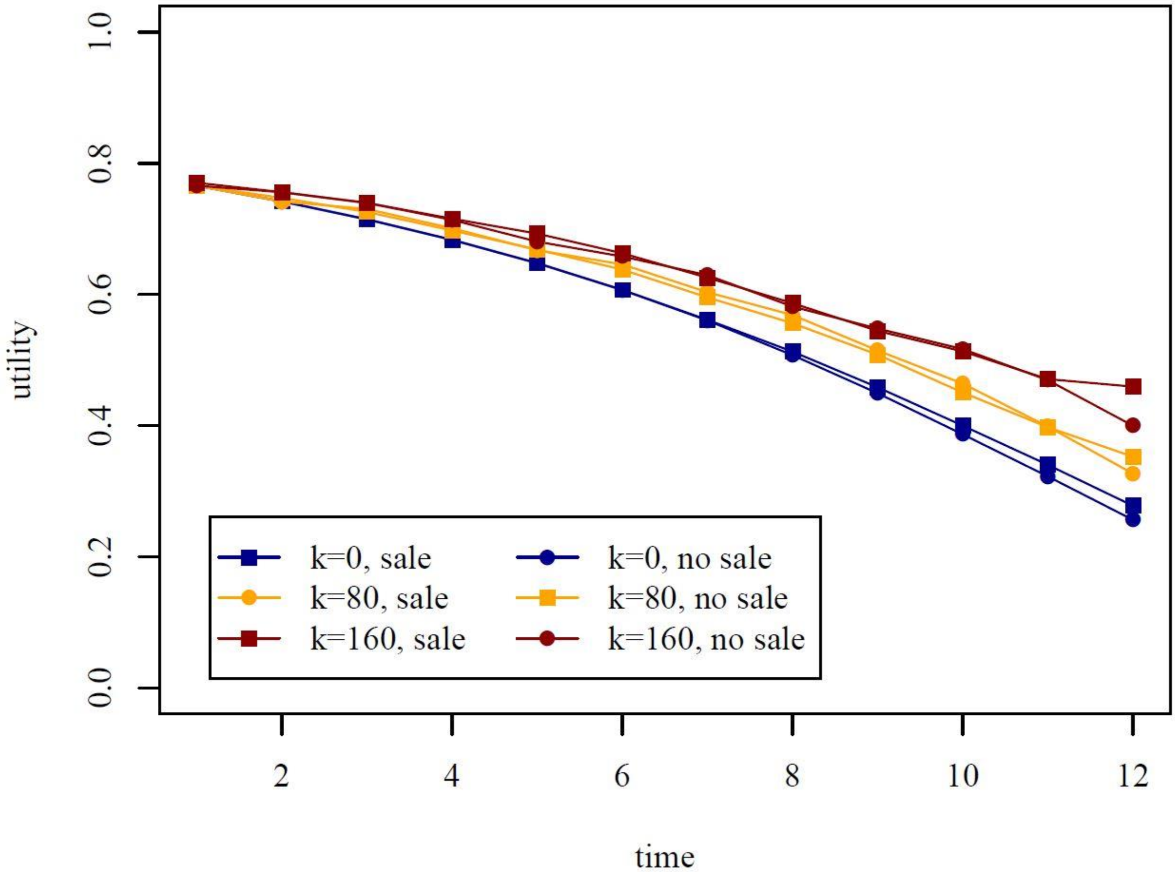

Figure B.1 Utility of conservation over time for a present-focused decision-maker.

Appendix C: Utility of increasing amounts of habitat

Increasing habitat or population size of a single species is often found to exhibit diminishing marginal utility. Hypothetical utility functions are therefore often assumed to be positive but concave (e.g. Davis et al. 2003, Davis et al. 2006). There are also a range of empirical studies assessing the willingness-to-pay (WTP) for increases in habitat or population size, which often find diminishing marginal utility. Rather than inventing a hypothetical utility function from scratch, we use published quantitative outcomes to develop a utility function that resembles empirical studies. This requires detailed, quantitative outcomes (such as information on the WTP for different increases in a certain conservation outcome, which also needs to be quantified (e.g. increase in habitat area)). Published studies that satisfy these data requirements are summarized in Table C.1.

Table C.1 Overview of studies used to develop utility functions (may add another one if the authors send me the full text).

Abbreviated name	Ecosystem studied	Reference
LG	Spotted owl habitat	Loomis & González-Cabán, 1998
BT	Elephant abundance	Bandara & Tisdell, 2005
LL	Gray whale population size	Loomis & Larson, 1994
LLR	Steller Sea Lion population size	Lew et al. 2010

To allow comparability between these very different studies, we scale the examined conservation outcome between 0 and 1, and scale the WTP or utility reported also between 0 and 1. These utility functions are shown in Figure C.1.

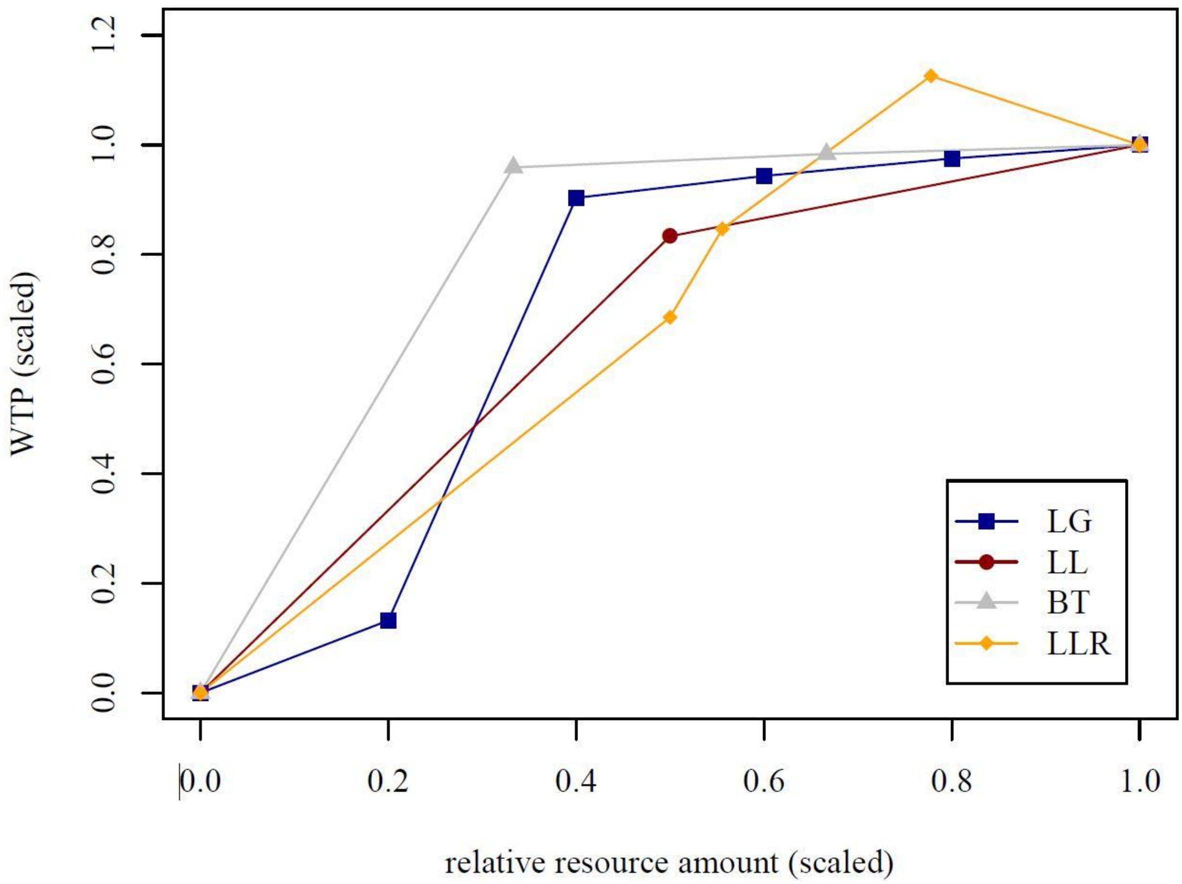

Figure C.1 Scaled utility of increases in resource amount (habitat or population size) based on the literature (see Table C1 for references to the four studies). Trend lines of data points have been added.

It can be seen that utility increases steeply in the first 40% or so of the conservation outcome, increases at a smaller rate until around 65% of the conservation outcome, and tends to level off for any further increases. Based on this pattern, we develop the utility function shown in Figure C.2. This function increases particularly steeply until 8 units of habitat area have been added (which represents around 40% of maximum habitat areas in case of no additional funding). It then increases less steeply for habitat areas up to 13 units, representing around 65% of this maximum value, and starts levelling off.

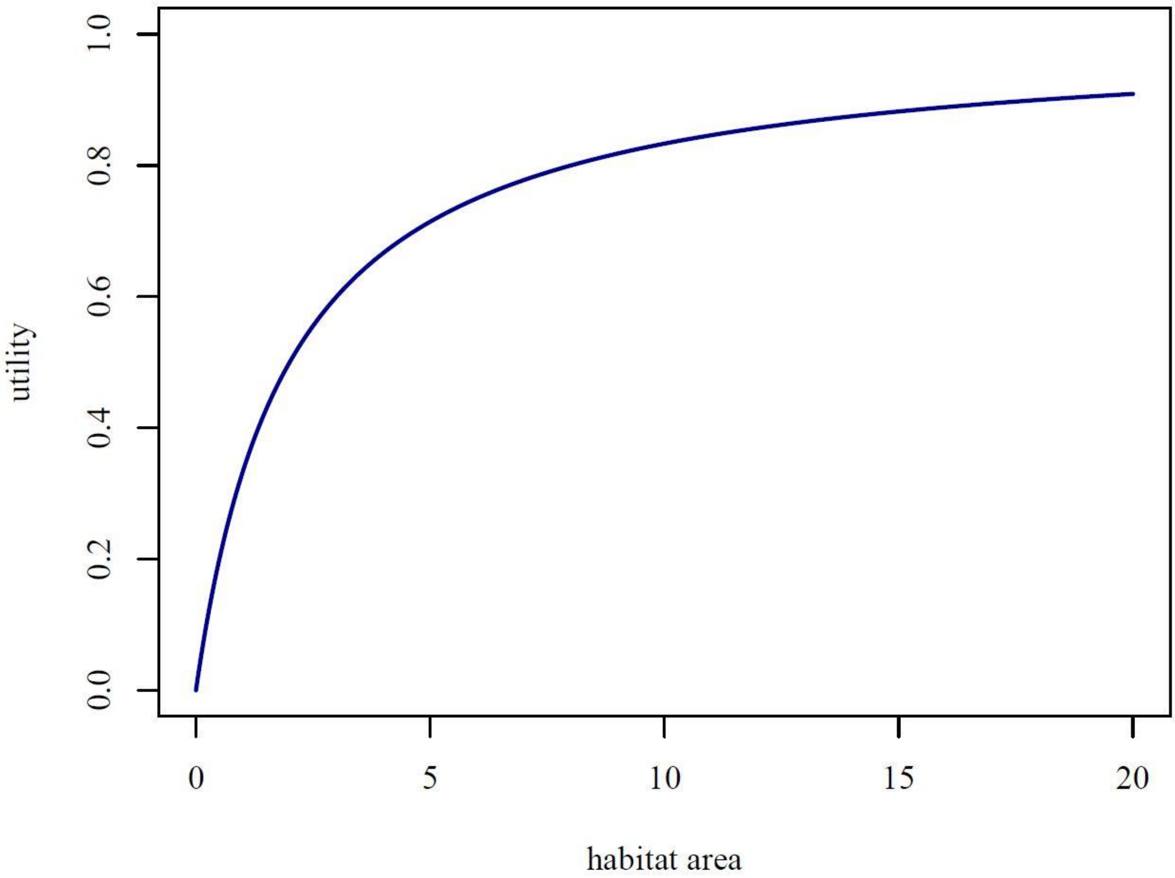

Figure C.2 Utility function exhibiting decreasing marginal utility

Appendix D: Neighbourhood

We assume that grid cells are only connected if they are located within a certain distance *d* defined by the combined Moore neighbourhood (Gray 2003) around already conserved grid cells. Any grid cells M_i which are located within this distance *d* around current reserve site *i* are those that are part of the combined Moore neighbourhood at time *t*. Those cells M_i are shaded yellow in Figure D.1 (c).

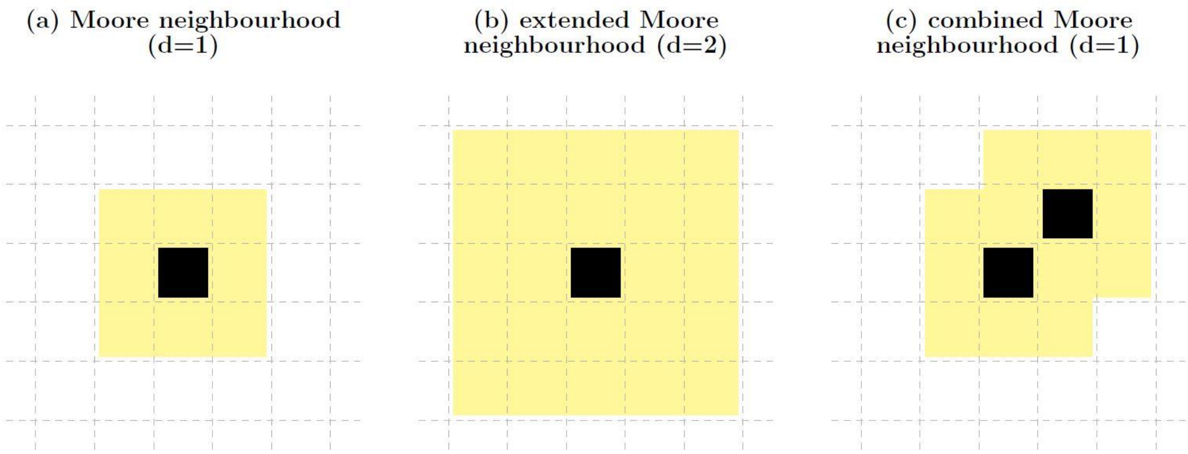

Figure D.1 Illustration of the (a) Moore neighbourhood (*d = 1*) of a grid cell, (b) the extended Moore neighbourhood (*d = 2*), and (c) the combined Moore neighbourhood of two cells (*d = 1*).

This assumption is reasonable as isolated habitats (i.e. grid cells too far away from the reserve network) might potentially provide habitat, but this may not be beneficial if the sites are not accessible by any target species relying on the potentially provided habitat type, as they lie beyond the species' dispersal abilities (Schöttker & Wätzold 2022). Hence, adding grid cells beyond a combined Moore neighbourhood would be ecologically ineffective and not cost-effective per se and is thus assumed impossible in our model.

Appendix E: Sensitivity analysis regarding climate change sensitivities of habitats

Figure E.1 shows results for different climate change sensitivities of the habitat types. Specifically, we consider that H_1 may not expand under climate change (as assumed in the main text), but rather shift uphill, similar to the other two habitat types. Figure E.1 shows that as in the main text, the utility of conservation increases as the available capital for adaptation increases. Moreover, the 'sale' policy is strictly preferable to the 'no sale' strategy, but the value of spatial flexibility decreases with increasing budgets. We conclude that the general trends observed in the main paper also hold for this distribution of habitat types.

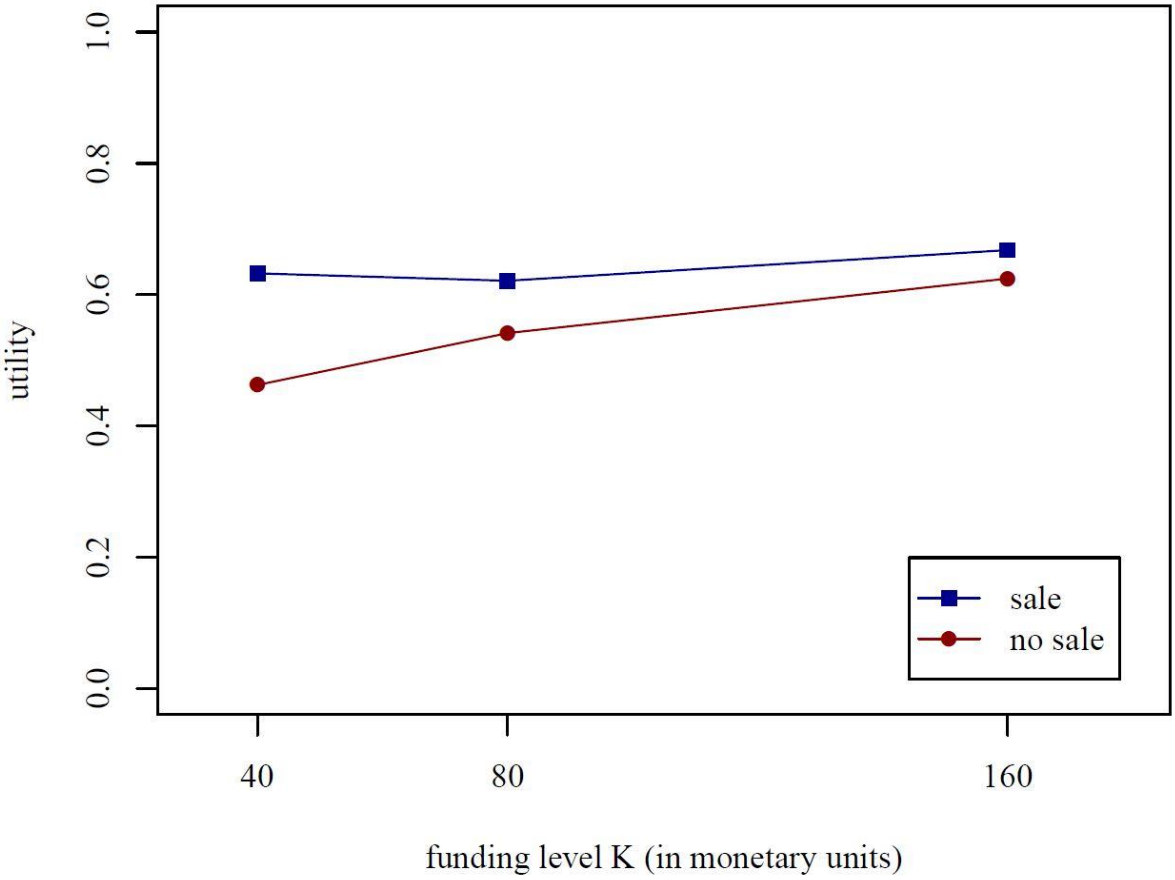

Figure E.1 Utility of conservation for the alternative habitat suitability specification.

Appendix F: Additional results on site habitat permanence

In this Appendix, we briefly discuss reasons why people may value site habitat permanence (Appendix F1) and show results for reserve permanence, i.e. the percentage area of the original reserve network maintained in all time steps (Appendix F2).

Appendix F1: The value of site habitat permanence

In the main paper, we assume that the conservation agency only cares about preventing species extinctions. However, people may also value site habitat permanence i.e. the percentage of initial habitat that is maintained in the same sites over time: Consider a region that has traditionally provided habitat for some species. People living in this region may have preferences for conserving the species that have traditionally been part of this region's habitat (e.g. Lundhede et al. 2014) and for maintaining the use value they derive from experiencing the species in question, e.g. via bird watching, or the cultural ecosystem services provided by the region's habitats. If the habitat shifts further away, distance-decay reduces the utility people gain from the habitat simply due to the increasing distance (Bateman et al. 2006, Danley et al. 2021). If people additionally exhibit loss aversion, losing biodiversity in their region may have to be compensated by a "larger amount" of "new" biodiversity to ensure indifference (Kahneman & Tversky (1979) and see Bartczak et al. (2015) for an example in the field of biodiversity valuation). Moreover, given the temporal dimension that needs to be considered inevitably in biodiversity conservation problems under climate change, people may have preferences for conserving a habitat to maintain a species' population within the region due to its option value, even if they may not experience any use value from the species' existence at present (Paul et al. 2020, Dasgupta 2021). Finally, people may even gain bequest value from ensuring the habitat's persistence as they may value future generations experiencing the ecosystem as they have (Turner et al. (2003), see O'Garra (2009) for an example).

In how far is it important that habitat sites are maintained in exactly the same locations then? For ecological reasons, maintaining habitat on a specific site may be important (Ranius et al. 2022). Regarding possible preferences for site habitat permanence discussed above, a regional focus may be appropriate in many cases: Regarding the use value derived from habitat conservation, it may be important to people to be able to access the habitat easily, but whether the exact location changes within a person's region may not matter as much. However, even within a region people may value specific habitat sites. For example, people may value an existing nature park, and if this park ceased to exist this loss may not easily be compensated by the creation of a new park in the region due to loss aversion.

In the main paper, we examine site habitat permanence (on a specific location) over the entire model timeframe. This may be an appropriate consideration of preferences in some cases, and also for ecological reasons. However, in other cases, a more nuanced consideration of whether habitat is maintained in a certain region (rather than in a specific location/ grid cell) may be more adequate.

Appendix F2: Reserve permanence

Here, we provide detailed results on the policies' reserve permanence, which directly influence the site habitat permanence results presented in the main paper. This additional analysis allows us to gain an understanding on the trade-off between the 'sale' policy (which provides flexibility at a cost in terms of habitat turnover) and the 'no sale' policy (which maximises site habitat permanence but does not account for changes in comparative advantages of sites over time) for adapting biodiversity conservation to the challenges of climate change.

Figure F.1 shows the share of conservation sites that are maintained throughout the run-time of the model, i.e. the degree of reserve permanence for different funding levels for the 'sale' and 'no sale' policies. In the 'no sale' policy, 100% of sites are maintained due to the restriction on sales for all funding levels. In the 'sale' policy however, permanence is lower than in the 'no sale' policy, but increases with the amount of additional funding available from approx. 79% (*K = 0MU*) to approx. 86% (*K = 160MU*).

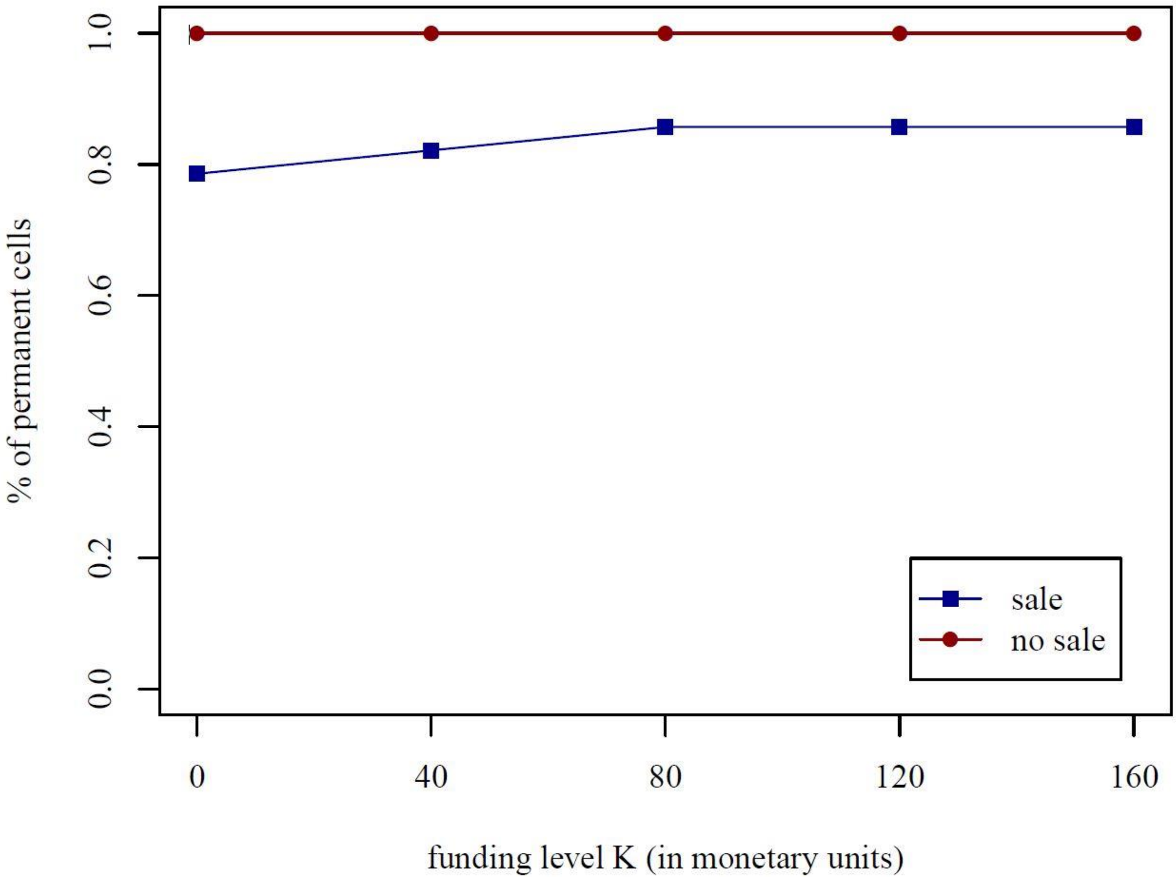

Figure F.1 Reserve permanence measured as the % area of the original reserve network maintained in all time steps depending on the level of funding.

References

Bandara R, Tisdell C. 2005. Changing abundance of elephants and willingness to pay for their conservation. *Journal of Environmental Management, 76*(1):47-59.

Bartczak A, Chilton S, Meyerhoff J. 2015. Wildfires in Poland: The impact of risk preferences and loss aversion on environmental choices. *Ecological Economics, 116*:300-309.

Batabyal AA, Kahn JR, O'Neill RV. 2003. On the scarcity value of ecosystem services. *Journal of Environmental Economics and Management, 46*(2):334-352.

Bateman IJ, Day BH, Georgiou S, Lake I. 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. *Ecological Economics, 60*(2):450-460.

Danley B, Sandorf ED, Campbell D. 2021. Putting your best fish forward: Investigating distance decay and relative preferences for fish conservation. *Journal of Environmental Economics and Management, 108*:102475.

Dasgupta P. 2021. *The Economics of Biodiversity: The Dasgupta Review*. HM Treasury: London.

Davis FW, Costello C, Stoms D. 2006. Efficient Conservation in a Utility-Maximization Framework. *Ecology and Society, 11*(1).

Davis FW, Stoms DM, Costello C, Machado EA, Metz J, Gerrard R, Andelman S, Regan H, Church R. 2003. *A framework for setting land conservation priorities using multi-criteria scoring and an optimal fund allocation strategy*. Report. Available at: https://www.researchgate.net/profile/Frank-Davis-9/publication/238712362_A_framework_for_setting_land_conservation_priorities_using_multi-criteria_scoring_and_an_optimal_fund_allocation_strategy/links/00b4952787886d40c5000000/A-framework-for-setting-land-conservation-priorities-using-multi-criteria-scoring-and-an-optimal-fund-allocation-strategy.pdf

Gerling C, Schöttker O, Hearne J. 2023b. The multi-period reserve design problem under climate change. *Sustainability Analytics and Modelling 3*:100025.

Gollier C. 2010. Ecological discounting. *Journal of Economic Theory, 145*(2):812-829.

Gray L. 2003. A mathematician looks at Wolfram's new kind of science. *Notices-American Mathematical Society, 50*(2):200–211.

Jafari N, Hearne J. 2013. A new method to solve the fully connected reserve network design problem. *European Journal of Operational Research, 231*(1):202–209.

Kahneman D, Tversky A. 1979. Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, 47(2):263-292.

Lew DK, Layton DF, Rowe RD. et al. 2010. Valuing Enhancements to Endangered Species Protection under Alternative Baseline Futures: The Case of the Steller Sea Lion. *Marine Resource Economics, 25*(2).

Lewis DJ, Kling DM, Dundas SJ, Lew DK. 2022. Estimating the value of threatened species abundance dynamics. *Journal of Environmental Economics and Management, 113*:102639.

Loomis JB, González-Cabán A. 1998. A willingness-to-pay function for protecting acres of spotted owl habitat from fire. *Ecological Economics, 25*(3):315-322.

Loomis JB, Larson DM. 1994. Total Economic Values of Increasing Gray Whale Populations: Results from a Contingent Valuation Survey of Visitors and Households. *Marine Resource Economics, 9*:275-286.

Lundhede TH, Jacobsen JB, Hanley N, Fjeldså J, Rahbek C, Strange N, Jellesmark Thorsen B. 2014. Public Support for Conserving Bird Species Runs Counter to Climate Change Impacts on Their Distributions. *PLOS One, 9*(7):e101281.

O'Garra T. 2009. Bequest Values for Marine Resources: How Important for Indigenous Communities in Less-Developed Economies? *Environmental and Resource Economics, 44*:179–202.

Paul C, Hanley N, Meyer St, Fürst C, Weisser WW, Knoke T. 2020. On the functional relationship between biodiversity and economic value. *Science Advances, 6*(5)

Ranius T, Widenfalk LA, Seedre M, Lindman L, Felton A, Hämäläinen A, Filyushkina A, Öckinger E. 2022. Protected area designation and management in a world of climate change: A review of recommendations. *Ambio*, *52*:68–80.

Schöttker O, Wätzold F. 2022. Climate change and the cost-effective governance mode for biodiversity conservation. *Environmental and Resource Economics, 82*:409–436.

TEEB. 2010. *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. Available at https://teebweb.org/publications/teeb-for/synthesis/ (accessed 11.05.2023).

Turner RK, Paavola J, Cooper P, Farber S, Jessamy V, Georgiou S. 2003. Valuing nature: lessons learned and future research directions. *Ecological Economics, 46*(3):493-510.

Zhu X, Smulders S, de Zeeuw A. 2019. Discounting in the presence of scarce ecosystem services. *Journal of Environmental Economics and Management, 98*:102272.