The value of flexibility in conservation management in the face of climatic uncertainty

Martin Drechsler

Abstract

Climate change is uncertain and has uncertain effects on the suitabilities of habitats for species. Conservation policies and strategies have to take this uncertainty into account. An approach to address uncertainty is flexibility. The present paper explores the value of flexibility using a stylized model with two regions in which conservation measures can be carried out. Two time periods, the present and a future time, are considered and a conservation manager has to decide how much of a conservation budget to spend in which period and in which region. The challenge is that the costs and benefits of conservation change in time in an uncertain manner. Two strategies are compared: a fixed one under which the conservation manager has to decide in the first period how to allocate the budget over the two periods and regions, and a flexible strategy under which s/he has to decide how much ofb the budget and where to spend in the first period, while the allocation of the remaining period-2 budget over the two regions has to be decided only in the second period when the costs and benefits functions in that period are known. The results show, among others, that the value of flexibility depends on the level of uncertainty but only insofar as it affects the relative performances of the different allocations.

Key words

allocation, climate change, conservation strategy, cost-effectiveness, flexibility, option value

1 Introduction

Climate change affects the spatial distribution of species and the suitability of habitats. The ranges of many species shift poleward or to higher altitudes (Parmesan et al. 1999, Root et al. 2003, Chen et al. 2011). The reason for these shifts is that previously suitable habitats become unsuitable while previously unsuitable habitats become suitable.

As a consequence, species protected in the current reserve systems will not be protected in the future (Burns et al. 2003, Araujo et al. 2004). A range of possible responses through conservation management has been compiled by Heller and Zavaleta (2009). Among the top-ranked (measured by the number of articles the authors found for each management option) are: integrate climate change into conservation planning, increase the number and sizes of reserves, protect the full range of bioclimatic variation, increase connectivity between reserves, and practice adaptive management.

Planning for conservation under climate change is challenging because the ranges of species and the suitability of habitats for the species will change and so do the ecological benefits of individual habitats. Furthermore, this change is uncertain (Faleiro et al. 2013) due to uncertainties in the climate projections (Kujala et al. 2013) and the ecological models that predict the implied habitat suitabilities for the species (Elith et al. 2006).

Outlining the previous research in the field, to conserve biodiversity under climate change, it is necessary to know the impact of climate change on the distribution of species and the suitabilities of potential conservation sites. Species distribution models have been used frequently to generate knowledge on this issue (Hannah et al. 2007, Faleiro et al. 2013, Lung et al. 2014). Such information can be used to prioritise sites for biodiversity conservation.

When planning for conservation under climate change the question arises which conservation target should be fulfilled at which point in time. So far, most studies only consider a single time period in the future, ignoring present ecological benefits and, more generally, time preferences of humans who value benefits at different times with different intensities.

As exceptions, Cavalho (2011) and Loyola et al. (2013) consider two points in time (present and future) and contrast the reserve network covering the species under present climatic conditions with the network covering future species distributions. Kujala et al. (2013) build a weighted sum of present conservation benefits and future conservation benefits to explore the trade-off between present and future benefits. Fuller et al. (2008) analysed a two-stage decision process in which reserves can be selected today and a second time in the future.

A challenge that has been addressed by various authors is uncertainty in the climate projections and the future suitabilities of potential conservation sites. Most papers consider this uncertainty by creating an ensemble of likely species distributions and base the reserve selection on certain averages or statistics of these ensembles, or they explicitly generate reserve networks for different scenarios. An explicit consideration of uncertainty is found, e.g., in Cavalho et al. (2011) and Loyola (2013) who construct some sort of risk-utility function that leads to the selection of conservation sites with higher expected ecological benefit and/or lower uncertainty.

The most explicit consideration of uncertainty is found in Ando and Mallory (2012) who employ modern portfolio theory to the selection of reserve sites under climatic uncertainty. Modern portfolio theory is a basic tool in the evaluation of financial investments. The task here is to select a portfolio of financial assets that minimises the uncertainty in the portfolio's total return for a given mean return. The assets may differ in their individual mean returns and the standard deviations of their returns, and the returns of different assets may be correlated.

While the mentioned studies contain a high level of realism and consider many specific features of their study region, the produced results and conclusions are mostly applicable only to the study area. An alternative approach is to consider a stylized landscape with only few potential sites that can be analysed systematically to gain general insights into the problem of species conservation under climate change.

The present study is based on such a simple model. The model considers two regions that are characterized by ecological benefit and economic cost functions, i.e. functions that describe how the regional ecological benefit and the economic cost depend on the amount of area conserved. The benefit and cost functions may have different shapes and may differ between the two regions. To include climate change, a future point in time is considered and the benefit and cost functions of the two regions change between present and future in an uncertain manner.

It is assumed that a conservation agency has to allocate a financial budget over the two time periods and the two regions. Money that is not spent in the present earns interest in the future. The amount of money spent in a particular period in a particular region determines the current ecological benefit in that region. The objective is to maximise the sum of the discounted ecological benefits where the ecological benefit in one period is the sum of the two regional benefits, and the discounting allows capturing time preferences between present and future benefits.

Two allocation strategies are considered: a fixed and a flexible strategy. In the fixed strategy the budget must be allocated once over both periods and both regions. Information about the expected change in the benefit and cost function as well as the degree of uncertainty and correlations are taken into account, but the exact shapes of the future cost and benefit functions are not known at the time of decision making. The flexible strategy is able to adapt to the climate change. In the first period the agency decides how much of the budget to spend in that period and who to allocate it over the two regions. The allocation of the remaining budget over the two regions in the second period then is chosen with precise knowledge of the benefit and cost function s of that second period.

Comparing the cost-effectiveness of the two allocation strategies allows assessing the value of flexibility, or the value of the information revealed in the future time. By this the study addresses the concept of option value relevant especially in financial but also other investment problems. An option is the right to perform a decision in the future, such as buying or selling a financial asset at a given price at a given point in time. Since the future (such as the future market price of the asset) is uncertain, the option has a positive value that declines to zero with time until the time of the future decision is reached. By this, options can hedge against future risks, and while being used in finance, they are sometimes also used in problems of dynamic environmental planning and biodiversity conservation (Kassar and Lasserre 2004). Since the optimal management of risk depends on the risk attitude of the decision maker (Eeckhoudt et al. 2005), different levels of risk aversion are considered in the present analysis.

2 Methods

2.1 Model description

The model assumes two regions, i = 1,2, with areas of size A_i managed for conservation. The marginal economic cost accruing from managing an area of size A_i for conservation increases linearly with increasing A_i:

$$c_i(t) = \gamma_i(t) + eA_i(t), \qquad (1)$$

where γ_i is a constant with regard to A_i but depends on the time period $t \in \{1,2\}$ and e is the slope of the marginal cost curve (cf. Drechsler and Wätzold 2001). For simplicity the slope e is assumed identical in both regions and does not change in time. The ecological benefit generated from a conserved area of size A_i is

$$b_i(t) = g_i(t)A_i(t)^z, \qquad (2)$$

where the prefactor g_i depends on the period t, and the exponent z determines whether the ecological benefit function is convex in A_i ($z > 1$), linear ($z = 1$) or concave ($z < 1$) (for the ecological meaning of z, see Drechsler and Wätzold (2001)). For simplicity the exponent z is assumed identical in both regions and does not change in time.

Climate change modifies the cost and benefit functions from period 1 to period 2. For the cost functions I assume that the γ_i are multiplied with some climate change factor $\delta_i^{(\gamma)}$, so that

$$\gamma_i(2) = \gamma_i(1) \cdot \delta_i^{(\gamma)} \qquad (3)$$

for i = 1, 2. In an analogous manner, the benefit functions change according to

$$g_i(2) = g_i(1) \cdot \delta_i^{(g)}, \qquad (4)$$

where $\delta_i^{(g)}$ represents the relative change of g_i in the course of climate change.

To model uncertainty in the climate change I assume that the climate change factors $\delta_i^{(\gamma)}$ and $\delta_i^{(g)}$ are random numbers drawn from a uniform distribution with means $m_i(\delta\gamma)$ and $m_i(\delta g)$ and upper and lower bounds of $m_i(\delta\gamma)[1 \pm \sigma_i(\delta\gamma)$ and $m_i(\delta g)[1 \pm \sigma_i(\delta g)]$, respectively. In addition, the changes in the cost functions, $\delta_1^{(\gamma)}$ and $\delta_2^{(\gamma)}$, are correlated with correlation coefficient r_γ, and the changes $\delta_1^{(g)}$ and $\delta_2^{(g)}$ in the benefit functions are correlated with correlation coefficient r_g (the chosen approach for drawing correlated uniformly distributed random numbers is described in Appendix A1).

Now assume a conservation agency is confronted with the task to allocate a budget C over the two time periods and the two regions, so that $C_i(t)$ is the amount of money allocated to region i in period t. It is assumed that money not spent in period 1 earns interest, raising the budget available in period 2, so that

$$C_1(2) + C_2(2) = \rho_C\left[C - C_1(1) + C_2(1)\right] \quad (5)$$

The objective of the agency is to distribute the budget such that an ecological benefit B is maximised. Assuming that in each period the current ecological benefit is the sum of the benefits obtained in the two regions, the total benefit is modeled as the sum of the discounted benefits obtained in the two periods:

$$B = B_1(1) + B_2(1) + \rho_B\left[B_1(2) + B_2(2)\right] \quad (6)$$

where ρ_B is a discount factor weighting future benefits against present benefits. Due to the uncertainties in the processes of climate change and the impacts of the period-1 benefits on the period-2 benefits, for a given allocation of the budget the ecological benefit B is uncertain and has a mean m_B and a standard deviation σ_B. Risk-averse decision makers try to avoid variation and for given m_B prefer smaller σ_B to larger σ_B. The conservation agency attempts to maximise, for given budget C, the risk-utility function

$$U = m_B - s\sigma_B \quad (7)$$

where s is the degree of risk aversion. For $s = 0$ the standard deviation σ_B does not affect utility U, characterising the case of risk-neutrality, while increasing s reduces U if the standard deviation σ_B is non-zero.

2.2 Model analysis

To determine the cost-effective allocation of the budget, the $C_i(t)$ are systematically varied in small steps. For each combination of the $C_i(t)$ ($i = 1, 2$; $t = 1, 2$) the conserved areas $A_i(t)$ are determined through the inverse of eq. (1), and the resulting benefits $B_i(t)$ are calculated through eq. (2). To take the climate and colonisation uncertainties into account, the $B_i(t = 2)$ are calculated based on 100,000 random samples of $\delta_i^{(\gamma)}$, $\delta_i^{(g)}$. The means m_B and σ_B over the resulting total benefits (eq. 7) are taken and the allocation $C_i(t)$ that maximizes U (eq. 8) is the cost-effective one.

Two allocation strategies are analysed. In the fixed strategy all $C_i(t)$ are selected in the first period, based among others on the means, variations and correlations of the uncertain climate change factors $\delta_i^{(\gamma)}$, $\delta_i^{(g)}$ but without knowing the exact values of the climate change factors. In the flexible strategy the decision on the budgets $C_1(1)$ and $C_2(1)$ for the first period is the same as in the fixed strategy, i.e. in ignorance of the climate change factors $\delta_i^{(\gamma)}$, $\delta_i^{(g)}$. However, in contrast to the fixed strategy, the allocation of the remaining budget $C - C_1(1) - C_2(2)$ over the two regions in the second period (i.e., $C_1(2)$ and $C_2(2)$), is chosen only after the values of $\delta_i^{(\gamma)}$, $\delta_i^{(g)}$ and thus the precise shapes of the cost and benefit functions – have been observed. The cost-effective flexible strategy is determined through stochastic dynamic programming (Dixit and Pindyck 1994): For a given choice of $C_1(1)$ and $C_2(1)$, the cost-effective allocation of $C_1(2)$ and $C_2(2)$ that maximises risk-utility U is determined for each of the 100,000 random samples of $\delta_i^{(\gamma)}$, $\delta_i^{(g)}$ and the average over the obtained risk-utilities, E$U(C_1(1)$, $\mathrm{C}_2(1))$, calculated. This average is a function of $C_1(1)$ and $C_2(1)$), and to obtain the cost-effective flexible strategy, $C_1(1)$ and $C_2(1)$ are varied systematically and the values that maximise EU identified. The fixed and flexible strategies are analysed for the model parameter values shown in Tables 1 and 2.

The baseline parameter values (Table 1) is chosen with the following logic. The cost and the benefit functions for both regions in the first period are assumed identical. The factors $\gamma_1(1) = \gamma_2(1)$ and $g_1(1) = g_2(1)$ are set to 1, which imposes no loss of generality. The slope of the marginal costs is set at a rather small value of $e = 0.02$, so the cost functions are only slightly convex. The benefit functions are assumed to be linear: $z = 1$. Uncertainty levels in all cost and benefit factors are moderate with $\sigma_1(\delta\gamma) = \sigma_2(\delta\gamma) = \sigma_1(\delta g) = \sigma_2(\delta g) = 0.5$, and the cost and benefit correlations are $r_\gamma = r_g = 0$. The budget is set at a value of $C = 100$ which in preliminary analyses turned out to be a value that allows extracting the behaviour of the model. Interest and benefit discount factors are set at $r_C = r_B = 1$, which means that saved money earns no interest and benefits are valued equally between the two periods. Lastly, the decision maker is risk-neutral: $s = 0$.

Table 1: Baseline values of the model parameters.

Parameter	Notation	Equation	Value
Cost offset	$\gamma_1(1) = \gamma_2(1)$	1	1
Slope marginal cost	e	1	0.02
Benefit prefactor	$g_1(1) = g_2(1)$	2	1
Benefit exponent	z	2	1
Mean climate change factor costs	$m_1(\delta\gamma) = m_2(\delta\gamma)$	cf. eq. (3)	1
Mean climate change factor benefits	$m_1(\delta g) = m_2(\delta g)$	cf. eq. (4)	1
Cost variation	$\sigma_1(\delta\gamma) = \sigma_2(\delta\gamma)$	cf. eq. (3)	0.5
Benefit variation	$\sigma_1(\delta g) = \sigma_2(\delta g)$	cf. eq. (4)	0.5
Correlation cost variation	r_γ	Appendix A	0
Correlation benefit variation	r_g	Appendix A	0
Budget	C	5	100
Interest factor	ρ_C	5	1
Benefit discount factor	ρ_B	6	1
Risk aversion parameter	s	7	0

Table 2: Varied values of the model parameters. Each model parameter, except for $m_1(\delta g)$ and $m_1(\delta g)$ which are varied systematically within their ranges, is varied from its baseline value up and/or down.

Parameter	Notation	Value
Cost offset	$\gamma_1(1)$	1.5
Slope marginal cost	e	0.05
Benefit prefactor	$g_1(1)$	1.5
Benefit exponent	z	0.5, 2
Mean climate change factor benefit 1	$m_1(\delta g)$	0.5, 0.71, 1, 1.41, 2
Mean climate change factor benefit 2	$m_2(\delta g)$	0.5, 0.71, 1, 1.41, 2
Cost variation	$\sigma_1(\delta\gamma) = \sigma_2(\delta\gamma)$	0.2
Benefit variation	$\sigma_1(\delta g) = \sigma_2(\delta g)$	0.2
Correlation cost variation	r_γ	–0.8, 0.8
Correlation benefit variation	r_g	–0.8, 0.8
Budget	C	400
Interest factor	ρ_C	5
Benefit discount factor	ρ_B	0.2
Risk aversion parameter	s	2

From these values selected model parameters are varied one by one. The cost offset is moderately increased to $\gamma_1(1) = 1.5$ which makes conservation in region 1 more expensive. Since the model system is symmetric, increasing $\gamma_2(1)$ (or reducing either of the two factors accordingly) would lead to equivalent results. The slope of the marginal costs is increased to a moderate value of $e = 0.05$, so the cost functions are significantly convex. Analogously to the marginal cost offsets, the benefit prefactor is increased to a moderate value of $g_1(1) = 1.5$, increasing the benefit in region 1 relative to that in region 2. The shape of the benefit function is varied from linear to concave ($z = 0.5$) and convex ($z = 2$).

Climate change may positively or negatively affect the benefits in region 1, region 2 and/or both regions. This is considered by varying the mean climate change factors $m_1(\delta g)$ and $m_2(\delta g)$ systematically from 0.5 to 2. This is done in four steps on a geometric scale so that from one step to the next $m_i(\delta g)$ ($i = 1, 2$) is multiplied by a factor of of $2^{1/2} \approx 1.41$. Cost and benefit uncertainties are varied in turn to small values of $\sigma_1(\delta\gamma) = \sigma_2(\delta\gamma) = 0.2$ and $\sigma_1(\delta g) = \sigma_2(\delta g) = 0.2$. The budget is increased to a rather large value of $C = 400$. The interest factor is increased to $\rho_C = 5$ which corresponds to an annual interest rate of about 5.5 percent if a period is assumed to have a duration of 30 years. Analogously, the benefit discount factor is reduced to $\rho_B = 0.2$ which corresponds to an annual discount rate of about five 5.5 percent over a period of 30 years. Lastly, the level of risk aversion is increased to a moderate level of $s = 2$.

For each parameter combination the following quantities are determined: for the fixed strategy (i) the cost-effective share of the budget allocated to period 1, (ii) the cost-effective share of the period-1 budget in region 1, and (iii) the cost-effective share of the period-2 budget in region 1; for the flexible strategy (iv) the cost-effective share of the budget in period

1, (v) the cost-effective share of the period-1 budget in region 1, and (vi) the cost-effective share of the period-2 budget in region 1; and (vii) the relative increase, $(U_{\text{flex}}-U_{\text{fix}})/U_{\text{fix}}$, in utility U (i.e., the efficiency gain) when switching from the fixed to the flexible strategy. Note that since in the flexible strategy the allocation of the period-2 budget is chosen adaptively in dependence of the observed climate change factors $\delta_i^{(\gamma)}$ and $\delta_i^{(g)}$, the cost-effective share of the period-2 budget in region 1 (quantity vi) is calculated as the mean over the cost-effective allocations obtained for the 100,000 realisations of $\delta_i^{(\gamma)}$ and $\delta_i^{(g)}$.

The impacts of the model parameters on the seven quantities are determined in the following order. Starting from the baseline parameter combination (Table 1) the mean climate change factors $m_1(\delta g)$ and $m_2(\delta g)$ are varied systematically as indicated in Table 2. Then all alternative parameter combinations defined in Table 2 are varied in turn and for each parameter combination, as in the baseline parameter combination, the mean climate change factors $m_1(\delta g)$ and $m_2(\delta g)$ are varied systematically.

Results

As a first result it turns out that for all parameter combinations the cost-effective allocation under the fixed strategy is identical to that under the flexible strategy, so below only the cost-effective allocation under the fixed strategy will be considered.

Baseline scenario (parameters values as in Table 1)

Cost-effective allocation:

For climate-change factors $m_1(\delta g) < 1$ and/or $m_2(\delta g) < 1$, so that benefits decline from period 1 to period 2, it is cost-effective to spend most of the budget in period 1, because here it generates higher benefits than in period 2 (Fig. 1a); and the period-1 budget should be spent evenly between the two regions (Fig. 1b), because the increasing marginal costs imply that an uneven allocation generates over-proportionally high costs without generating higher benefits (note that the benefit functions are linear: $z = 1$).

Conversely, for $m_1(\delta g) >1$ or $m_2(\delta g) > 1$), i.e. temporally increasing benefits, most of the budget should be spent in period 2 (Fig. 1a); and the allocation of the period-1 budget is not decisive because for those small budgets the cost functions appear nearly linear, and for linear cost and benefit functions any allocation is cost-effective (Fig. 1b).

The cost-effective allocation of the period-2 budget (Fig. 1c) simply follows the ratio $m_2(\delta g)/m_1(\delta g)$: the higher the climate change factor in a given region (relative to that in the other region) the higher the budget share that region should receive.

Efficiency gain:

The flexible strategy is more cost-effective than the fixed strategy for all levels of $m_1(\delta g)$ and $m_2(\delta g)$, with a maximum efficiency gain of about five percent (Fig. 1d). The efficiency gain decreases with increasing dissimilarity between $m_1(\delta g)$ and $m_2(\delta g)$ and is (close to) zero if (at least) one of the two climate change factors, $m_1(\delta g)$ and $m_2(\delta g)$ is very small. The reason is that here it is obvious already in period 1 that the region i associated with the small $m_i(\delta g)$ should receive no share of the period-2 budget, so there is not much gain if that decision is postponed to period 2.

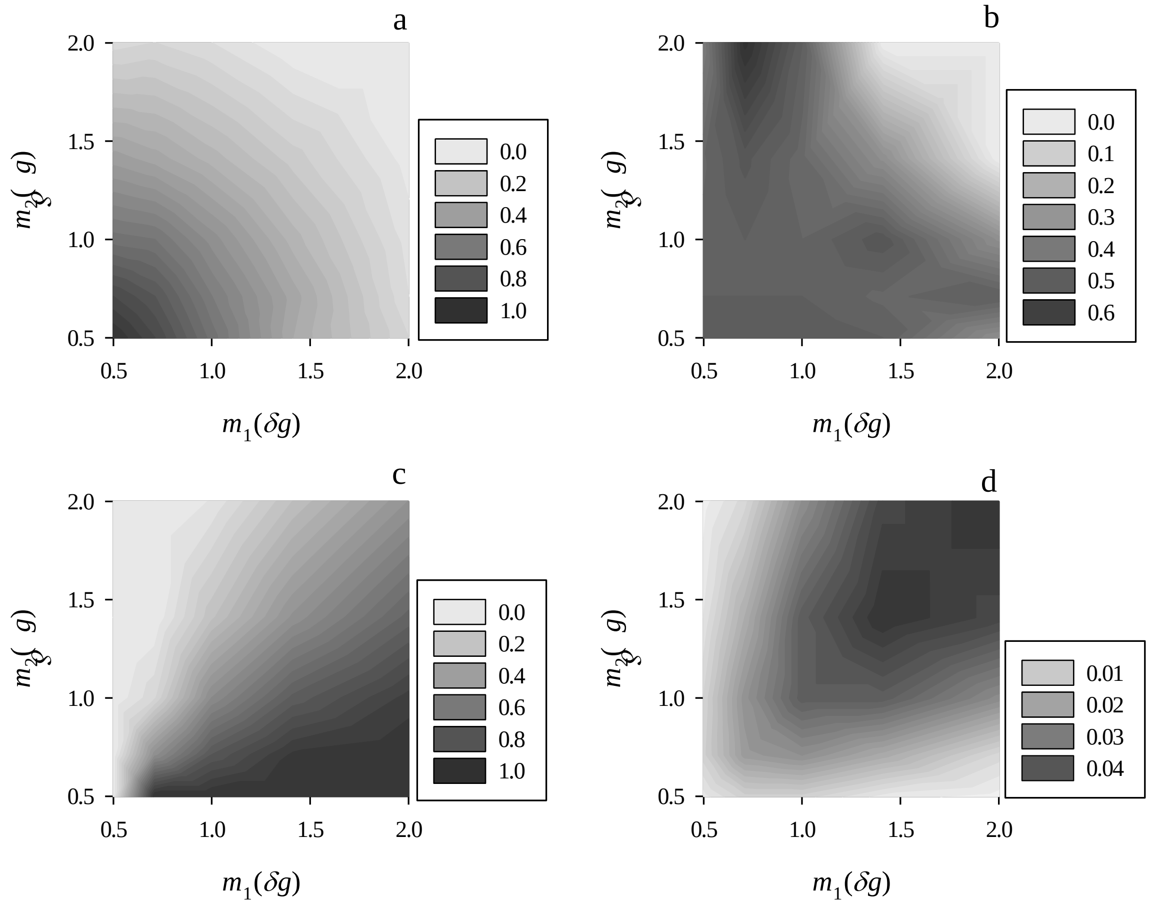

Figure 1: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the mean climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Other model parameters as in the baseline scenario.

Increased cost offset in region 1: $\gamma_1(1) = 1.5$ (cf. Fig. A3 in Appendix A2)

Cost-effective allocation: Compared to the baseline scenario the cost-effective budget share allocated to period 1 increases slightly for $m_1(\delta g) > m_2(\delta g)$, because here the more costly region has the higher benefit in period 2, reducing the cost-effectiveness of budgets in that period. Conversely, the cost-effective budget share allocated to period 1 decreases slightly for $m_1(\delta g) < m_2(\delta g)$, because here the less costly region has the higher benefit in period 2, increasing the cost-effectiveness of budgets in that period. Due to the cost advantage of region

2, the cost-effective share of the period-1 budget in region 1 is smaller than in the baseline scenario. The share of the period-2 budget in region 1 does not change compared to the baseline scenario.

Efficiency gain: The efficiency gain is similar to that found for the baseline scenario. For $m_1(\delta g) > m_2(\delta g)$ it is slightly increased compared to the baseline scenario while for $m_1(\delta g) < m_2(\delta g)$ it is slightly reduced. The reason is that for $m_1(\delta g) > m_2(\delta g)$ the benefit in period 2 is higher in the more costly region 1, leading to a trade-off between benefits and costs and enhancing the importance of an adaptive decision in period 2. The opposite applies for $m_1(\delta g) < m_2(\delta g)$.

Increased marginal-cost slope: e = 0.05 (cf. Fig. A4)

Cost-effective allocation: The cost-effective budget share in period 1 is similar to that in the baseline scenario. The increasing marginal costs imply over-proportionally increasing costs and favour an even allocation of the period-1 budget. The cost-effective allocation of the period-2 budget is similar to that in the baseline scenario.

Efficiency gain: The efficiency gain is similar to that found for the baseline scenario; it is slightly reduced for $m_1(\delta g) \approx m_2(\delta g)$ because due to the increasing marginal costs a more even allocation of the period-2 budget is cost-effective (as noted above), so the cost-effective allocation does not depend so sensitively on the climate change factors $\delta_1^{(g)}$ and $\delta_2^{(g)}$ and the advantage of an adaptive flexible management is reduced.

Increased benefit prefactor in region 1: $g_1(1) = 1.5$ (cf. Fig. A5)

Cost-effective allocation: Compared to the baseline scenario the cost-effective budget share in period 1 decreases for $m_1(\delta g) > m_2(\delta g)$, because here the region with the higher period-1 benefit (i.e., region 1) has the higher climate-change factor, increasing the cost-effectiveness of budgets in period 2. Conversely, the cost-effective budget share in period 1 increases for $m_1(\delta g) < m_2(\delta g)$, because here the region with the higher period-1 benefit has the smaller climate-change factor, reducing the cost-effectiveness of budgets in period 2. Due to the higher benefit in region 1, the cost-effective share of the period-1 budget in that region is large and even close to one for large $m_1(\delta g)$. The share of the period-2 budget in region 1 is slightly increased compared to the baseline scenario.

Efficiency gain: The efficiency gain is similar to that found for the baseline scenario. For $m_2(\delta g) > m_1(\delta g)$ it is slightly increased compared to the baseline scenario while for $m_2(\delta g) < m_1(\delta g)$ it is slightly reduced. The reason is that for $m_2(\delta g) > m_1(\delta g)$ the benefit increases between periods more strongly in region 2 with the lower initial benefit, so it is less clear in period 1 whether the period-2 budget should be concentrated in region 1 or region 2, enhancing the importance of an adaptive decision in period 2.

Reduced benefit exponent: z = 0.5 (cf. Fig. A6)

Cost-effective allocation: A reduced benefit exponent has the same effect on the cost-effective allocation of the budget as the increased marginal-cost slope (cf. above), because like a convex cost function, a concave benefit function favours a more even allocation of the budget.

Efficiency gain: The result is qualitatively the same as that obtained for an increased marginal-cost slope, because the concave benefit functions favour a more even allocation of the period-2 budget, independent of the exact values of the climate change factors $\delta_1^{(g)}$ and $\delta_2^{(g)}$, reducing the advantage of an adaptive decision in period 2.

Increased benefit exponent: z = 2 (cf. Fig. A7)

Cost-effective allocation: For $m_1(\delta g) < 1$ and $m_2(\delta g) < 1$ the entire budget should be allocated into period 1 because the convexity of the benefit functions favours the concentration of the budget in only one period, and due to $m_1(\delta g) < 1$ and $m_2(\delta g) < 1$, this concentration should be in period 1. Analogously, for $m_1(\delta g) > 1$ and $m_2(\delta g) > 1$ the entire budget should go into period 2. Due to the convexity of the benefit functions, the period-1 budget should be allocated entirely into one region (which by the design of the optimisation algorithm happens to be region 1 in Fig. A7), while the period-2 budget should go entirely into the region with the higher benefit (i.e., with the higher $m_i(\delta g)$).

Efficiency gain: The efficiency gain is maximal (around 0.2) for $m_1(\delta g) \approx m_2(\delta g)$. Otherwise it is small because in these cases it is obvious that the budget should be allocated entirely into the region with the higher $m_i(\delta g)$ (as explained above).

Reduced cost variation: $\sigma_1(\delta\gamma) = \sigma_2(\delta\gamma) = 0.2$ (cf. Fig. A8)

Cost-effective allocation: The cost-effective allocation is very similar to that in the baseline scenario.

Efficiency gain: The efficiency gain is very similar to that in the baseline scenario.

Reduced benefit variation: $\sigma_1(\delta g) = \sigma_2(\delta g) = 0.2$ (cf. Fig. A9)

Cost-effective allocation: The cost-effective allocation is the same as in the baseline scenario.

Efficiency gain: The effect of $m_1(\delta g)$ and $m_2(\delta g)$ is the same as in the baseline scenario but the efficiency gain is much smaller, because lower variation means less uncertainty in the climate change factors $\delta_1^{(g)}$ and $\delta_2^{(g)}$, reducing the importance of an adaptive decision in period 2.

Negative correlation in the cost uncertainties: r_γ = –0.8 (cf. Fig. A10)

Cost-effective allocation: The cost-effective allocation is very similar to that in the baseline scenario.

Efficiency gain: The efficiency gain is very similar to that in the baseline scenario.

Positive correlation in the cost uncertainties: r_γ = 0.8 (cf. Fig. A11)

Cost-effective allocation: The cost-effective allocation is very similar to that in the baseline scenario.

Efficiency gain: The effect of $m_1(\delta g)$ and $m_2(\delta g)$ on the efficiency gain is the same as in the baseline scenario, but the efficiency gain is slightly reduced overall. The reason is that the cost-effective (adaptive) allocation of the period-2 budget over the two regions, among others, depends on the relative magnitudes of the climate change factors $\delta_1^{(\gamma)}$ and $\delta_2^{(\gamma)}$. If these two factors are strongly positively correlated, they will always be of similar magnitude in both regions and altogether have a minor influence on the cost-effective allocation of the period-2 budget.

Negative correlation in the benefit uncertainties: r_g = –0.8 (cf. Fig. A12)

Cost-effective allocation: The cost-effective allocation is very similar to that in the baseline scenario.

Efficiency gain: The efficiency gain is very similar to that in the baseline scenario.

Positive correlation in the benefit uncertainties: r_g = 0.8 (cf. Fig. A13)

Cost-effective allocation: The cost-effective allocation is very similar to that in the baseline scenario.

Efficiency gain: The effect of $m_1(\delta g)$ and $m_2(\delta g)$ on the efficiency gain is the same as in the baseline scenario, but the efficiency gain are strongly reduced overall. Similar to the case of r_γ = 0.8 above, the reason is that the cost-effective (adaptive) allocation of the period-2 budget over the two regions, among others, depends on the relative magnitudes of the climate change factors, $\delta_1^{(g)}$ and $\delta_2^{(\gamma)}$. If these two factors are strongly positively correlated, they will always be of similar magnitude in both regions and altogether have a minor influence on the cost-effective allocation of the period-2 budget.

Discounting of ecological benefit: ρ_B = 0.2 (cf. Fig. A14)

Cost-effective allocation: The entire budget should be allocated to period 1 because the future benefits are valued muss less than the present ones. The period-1 budget should be allocated equally among both regions because of the increasing marginal costs which render an uneven allocation more costly.

Efficiency gain: Since no budget goes into period 1, the efficiency gain is zero.

Gaining interest on saved budgets: ρ_C = 5 (cf. Fig. A15)

Cost-effective allocation: Except for very small $m_1(\delta g)$ and $m_2(\delta g)$, the entire budget should be allocated into period 2, because saving in period 1 increases the overall budget. As in the baseline scenario, the cost-effective share of the period-2 budget into region i increases with increasing benefit factor $m_i(\delta g)$ in that region.

Efficiency gain: The efficiency gain is increased (decreased) compared to the baseline scenario for those values of $m_1(\delta g)$ and $m_1(\delta g)$ at which the efficiency gain in the baseline scenario is small (large), so altogether the efficiency gain depends less strongly on $m_1(\delta g)$ and $m_1(\delta g)$ and always ranges between 0.01 and 0.025.

Increased budget: C = 400 (cf. Fig. A16)

Cost-effective allocation: The cost-effective allocation of the budget among periods 1 and 2 is similar to that in the baseline scenario, but its range as a function of $m_1(\delta g)$ and $m_1(\delta g)$ is more contracted around an even allocation. The reason is that higher budgets lead to higher marginal costs and the convexity of the cost functions (increasing marginal costs) becomes more relevant. The period-1 budget should be spent evenly while the period-2 budget should be allocated in a similar manner as in the baseline scenario.

Efficiency gain: The effect of $m_1(\delta g)$ and $m_2(\delta g)$ is the same as in the baseline scenario, but the efficiency gain is smaller overall by about 50 percent.

Risk aversion: s = 2 (cf. Fig. A17)

Cost-effective allocation: Compared to the baseline scenario the cost-effective share of the budget in period 1 is much higher, and only for large $m_1(\delta g)$ and $m_1(\delta g)$ some of the budget should go into period 2. The reason is that a higher budget share in period 1 reduces the available budget in period 2 and the associated risk if that budget is misallocated, so a risk.-averse decision maker will prefer a larger budget in period 1 and an accordingly smaller one in period 2. The period-1 budget should be spent evenly in both regions due to the increasing marginal costs, and in those cases where a non-zero period-2 budget is cost-effective that budget should be spent evenly among both regions, too.

Efficiency gain: The efficiency gain is (naturally) zero in the cases of small or moderate $m_1(\delta g)$ and $m_1(\delta g)$ in which the cost-effective period-2 budget is zero. In the cases of large $m_1(\delta g)$ and $m_1(\delta g)$ in which a non-zero period-2 budget is cost-effective, the efficiency gain is similar to that in the baseline scenario.

4 Discussion

The above results may be summarized into a few general rules, starting with more and ending with less intuitive ones.

1. The budget should generally be allocated into the region which has the higher benefit and/or the lower cost (as, e.g., in the baseline scenario where the cost-effective budget share in period 1 declines with increasing mean climate change factors $m_1(\delta g)$ and $m_1(\delta g)$, and where the share of the period-2 budget in region 1 increases with increasing $m_1(\delta g)$).
2. Strongly increasing marginal costs and/or concave benefit functions favour an even allocation of the budget over periods and/or among regions (as, e.g., in the cases of marginal cost slope $e = 0.05$ or benefit exponent $z = 0.5$ in which the period-1 budget should be allocated evenly among the two regions.
3. In the presence of convex benefit functions (e.g., $z = 2$), in contrast, the budget should be more concentrated in one period and one region.
4. If future benefits are weighted less than present benefits ($\rho_B < 1$) the budget should be spent predominantly in period 1.
5. If saved budgets earn interest ($\rho_C > 1$), less money should be spent in period 1, because this increases the overall budget that can be spent in both periods (but see the considerations below).
6. Higher uncertainty in the climate change factors increases the efficiency gains associated with the flexible strategy.
7. If climate change increases especially the benefit in the region with the higher cost and/or lower initial benefit the share of the budget allocated to period 2 should be reduced because the effectiveness of budgets spent in that period is reduced (as, e.g., in the case of an increased cost in region 1, $\gamma_1(1) = 1.5$ but higher mean climate change factor, $m_1(\delta g) > m_2(\delta g)$; or the case of a higher benefit factor, $g_1(1) = 1.5$ and a lower mean climate change factor, $m_1(\delta g) < m_2(\delta g)$).
8. Higher budgets imply higher marginal costs, implying that more even allocations over periods and/or among regions become cost-effective.
9. A risk-averse decision maker (risk aversion $s > 0$) will spend more of the budget in period 1 to avoid the uncertainty in the outcomes obtained in period 2.
10. The efficiency gain associated with the flexible strategy increases with the sensitivity of the cost-effective allocation of the period-2 budget to the uncertain climate change factors, in particular the factors $\delta_1^{(g)}$ and $\delta_2^{(g)}$. In the following several cases are highlighted in which this sensitivity is particularly high or particularly low:

a. If the mean climate change factor $m_i(\delta g)$ is higher in the region with the higher initial cost $\gamma_i(1)$, a trade-off occurs in period 2 between minimising costs per conserved area and maximising benefits per conserved area, enhancing the sensitivity of the cost-effective allocation to climate change.
b. If the mean climate change factor $m_i(\delta g)$ is higher in the region with the lower initial benefit $g_i(1)$ it is not clear in period 1 whether it will be better to concentrate the period-2 budget in region *i* or not, enhancing the sensitivity of the cost-effective allocation to climate change.
c. Concave benefit functions or strongly increasing marginal costs favour more even allocations, avoiding extreme allocations in which the period-2 budget is allocated only into one of the two regions. This reduces the sensitivity of the cost-effective allocation to the climate change factors.
d. Convex benefit functions imply a concentration of the budget in one of the two regions. If the mean climate change factors have similar magnitudes it is difficult to predict in period 1 whether in period 2 region 1 or region 2 should be preferred, enhancing the sensitivity of the cost-effective allocation to climate change.
e. A large positive spatial correlation between the climate change factors (in particular, a large ρ_g) implies that although the climate change factors ($\delta_1^{(g)}$ and $\delta_2^{(g)}$) are uncertain, they will be of similar magnitude in both regions, reducing the sensitivity of the cost-effective allocation to these factors.

Relating statements 6 and 10e points to an interesting and probably general conclusion. Although uncertainty generally increases the importance of adaptive management and the option value of flexibility (statement 6), it is not the uncertainty per se that raises option values but it is that component of the uncertainty which determines the relative favourabilities of the decisions to be made. While a high spatial correlation in the climate change factors does increase the uncertainty in the total benefit that can be attained in period 2, it reduces the uncertainty in the relative magnitudes of the climate change factors (e.g., the uncertainty in the ratio $\delta_1^{(g)}/\delta_2^{(g)}$) – and thus reduces the value of flexibility.

The model is based on a number of assumptions. The most relevant is probably the neglection of spatial and temporal interactions. Under spatial interactions the ecological benefit in region 1 could affect the ecological benefit in region 2 and vice versa. Such interactions have been considered, e.g., by Wu and Boggess (1999) and Wätzold and Drechsler (2005). A biological motivation of spatial interactions is the metapopulation concept that considers that local populations on individual habitat patches interact through the dispersal of individuals, so habitat patches that have become empty due to the extinction of the local population can be colonised by other local populations. The two cited studies indicate that spatial interactions call for a more even allocation of conservation budgets, as it has been obtained in the present study for the cases of concave benefit functions ($z > 1$) and strongly increasing marginal costs ($e >> 0.01$).

Temporal interactions include, e.g., the influence of the ecological benefit in period 1 on the ecological benefit in period 2. Managing a species population in a good state in period 1 (measured by a high ecological benefit in that period) increases the likelihood of the species being in a good state in period 2. Conversely, if no area is conserved in period 1 so the species goes extinct before period 2, it will not recover by any conservation effort in period 2 (unless individuals from other local populations immigrate) and the ecological benefit in period 2 will always be zero. This is an example of path dependence (Liebowitz and Margolis 1995, Drechsler and Wätzold subm.) where an action in the past affects the present set of possible actions and the effects of these actions. Preliminary analyses of a model variant with such a temporal interaction led to expected results: that the cost-effective budget share in period 1 increased compared to the case without temporal interaction because higher period-1 benefits allowed for higher period-2 benefits, while the share in period 2 decreased because the period-2 benefits had no influence on the period-1 benefits.

Despite these arguments, future research might consider a model with three or more regions that interact through dispersal of individuals, and include temporal interactions, e.g., through the explicit consideration of species population dynamics. This would also move the rather abstract present analysis closer to real-world application. A real case study to which the present approach could be applied rather readily is Ando and Mallory (2012) mentioned in the Introduction.

Nevertheless, the present results already indicate that flexibility is an important criterion of conservation policies and strategies in the face of climate change. The shapes of the benefit and cost functions seem to be important determinants for the option value of flexibility. Uncertainty is by definition an important factor, too, but it determines the value of flexibility only insofar it affects the *relative* performances of the alternative policies and strategies.

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Appendix A1: Drawing correlated random numbers from uniform distributions

If pairs (x,y) of random numbers are drawn in an uncorrelated manner from an interval [0,1], their values can be plotted in the two dimensional space spanned by x and y, resulting in a pattern of points that fill the unit square shown in Fig. A1. If there is a positive correlation $r \in$ [0,1] between the two numbers combinations with large x and small y and with small x and large y (represented by points near the upper left or lower right corner of the unit square) are less likely than combinations with large x and large y or small x and small y (represented by points near the diagonal running from the lower left to the upper right corner of the unit square). With increasing positive correlation the points in the unit square contract along the diagonal.

To qualitatively model increasing positive correlation r, I contract the unit square into a diamond by shifting its boundary (as well as the points in the interior) towards the diagonal, with the shift being carried out perpendicular to the diagonal (Fig. A1a). A correlation of $r = 0$ is represented by a zero shift; a maximum correlation of $r = 1$ is represented by a full shift so that all points end up on the diagonal; and a correlation of $r = r_0$ is represented by a shift of $(1\text{-}r_0)d$, where d is the initial distance of the point to the diagonal. By this, all points on the boundary of the unit square end up on the boundary of the diamond, and all points in the interior of the unit square end up in the interior of the diamond, accordingly.

With some basic analytical geometry, the new coordinates of a point (x,y) from the unit square become

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} (x+y)/2 + (1-r)(x-y)/2 \\ (x+y)/2 + (1-r)(y-x)/2 \end{pmatrix} \qquad \text{(A1)}$$

Since the points (x,y) represent pairs of random numbers sampled from the interval [0,1] these random numbers have means of 0.5 and are uniformly distributed around these means with widths of ±0.5. The transformation, eq. (A1), does not change the shape of these distributions, and so the transformed points (x',y') are uniformly distributed with means of 0.5 and widths of ±0.5, too. To obtain correlated pairs of points from uniform distributions with means μ_x and μ_y and upper and lower bounds $\mu_x(1 \pm \sigma_x)$ and $\mu_y(1 \pm \sigma_y)$, respectively, the values (x',y') of eq. (A1) have to be transformed to

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix} = \begin{pmatrix} \mu_x(1-\sigma_x + 2\sigma_x x') \\ \mu_y(1-\sigma_y + 2\sigma_y y') \end{pmatrix} \qquad \text{(A2)}$$

The two numbers x'' and y'' are now uniformly distributed with means μ_x and μ_y and upper and lower bounds $\mu_x(1 \pm \sigma_x)$ and $\mu_y(1 \pm \sigma_y)$, respectively, and are positively correlated with a degree of r.

For negative correlations, $r \in [-1,0]$, the procedure is analogue but now the points from the unit square are contracted towards the diagonal running from the upper left to the lower right corner (Fig. A1b), considering that a negative correlation implies that combinations of large x

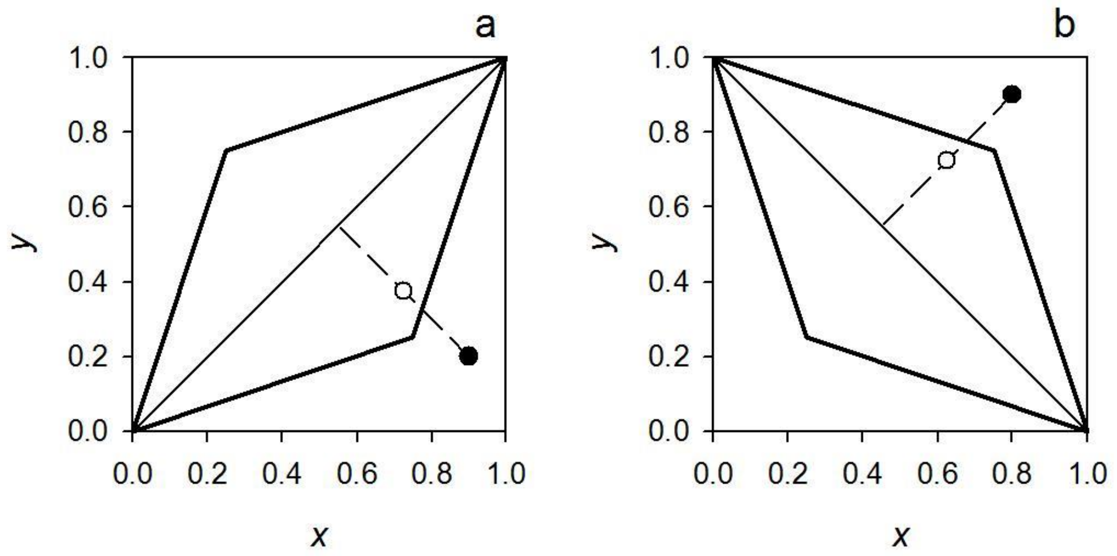
and small y or small x and large y are more likely than combinations of large x and large y or of small x and small y.

This transformation is described by

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} (1+x-y)/2+(1+r)(x+y-1)/2 \\ (1-x+y)/2+(1+r)(x+y-1)/2 \end{pmatrix} \tag{A3}$$

and negatively correlated random numbers with means μ_x and μ_y and upper and lower bounds $\mu_x(1 \pm \sigma_x)$ and $\mu_y(1 \pm \sigma_y)$ are obtained by transforming x' and y' via eq. (A2).

Figure A1: Graphical representation of drawing uniformly distributed correlated random numbers. Panel a: positive correlation; panel b: negative correlation. Pairs (x,y) of random numbers are represented by points in x-y-space. At zero correlation, the points evenly fill the entire unit square. At a positive correlation the set of possible points (x,y) contracts to the interiour plus boundary of the diamonds. In the example of panels a and b the diamonds represent correlations of r = 0.5 and r = –0.5, respectively. By the contractions, the two exemplary points represented by the filled circles are transformed to the points represented by the open circles.



Appendix A2: Results of the sensitivity analysis

Figure A2 (coloured version of Fig. 1): Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Other model parameters as in the baseline scenario.

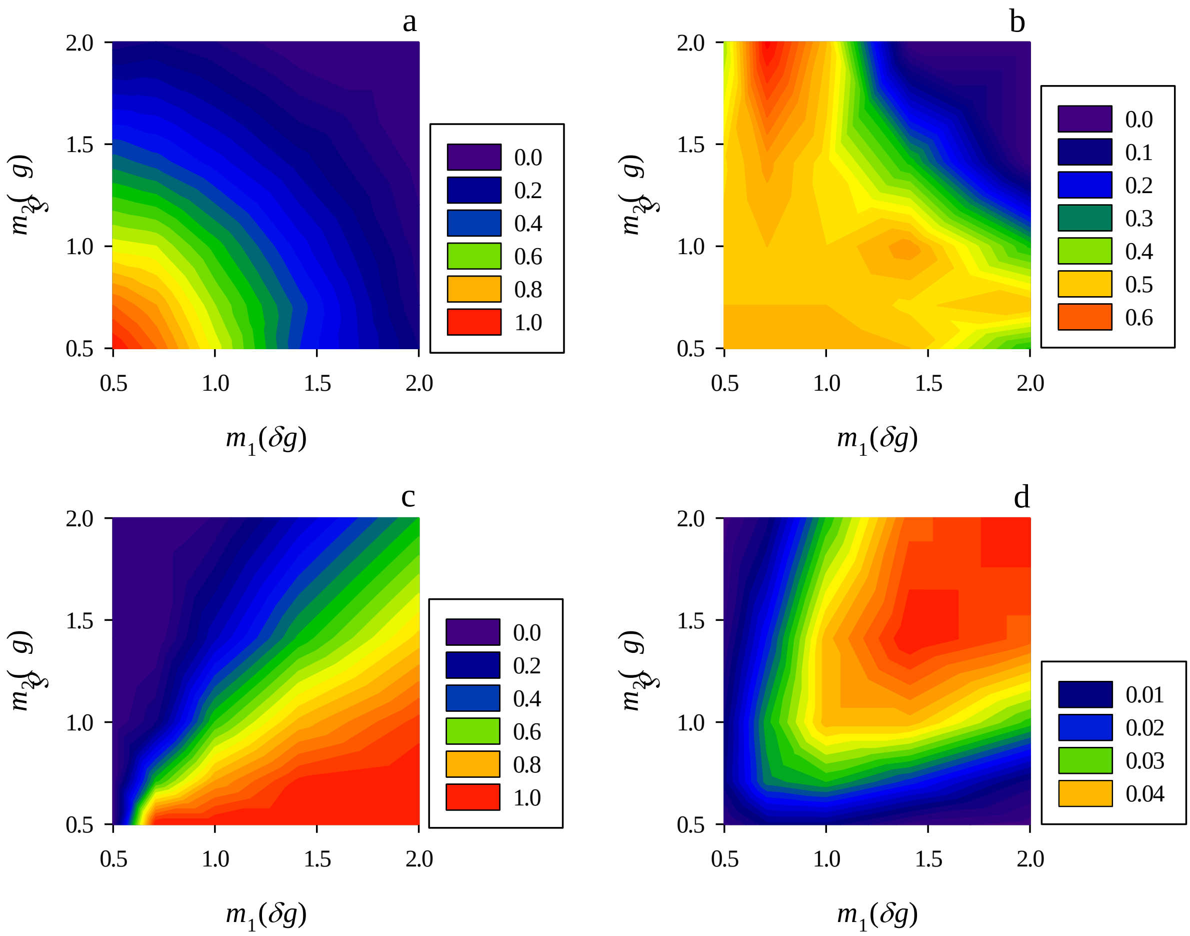


Figure A3: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter $\gamma_1(1)$ increased to 1.5 compared to the baseline scenario.

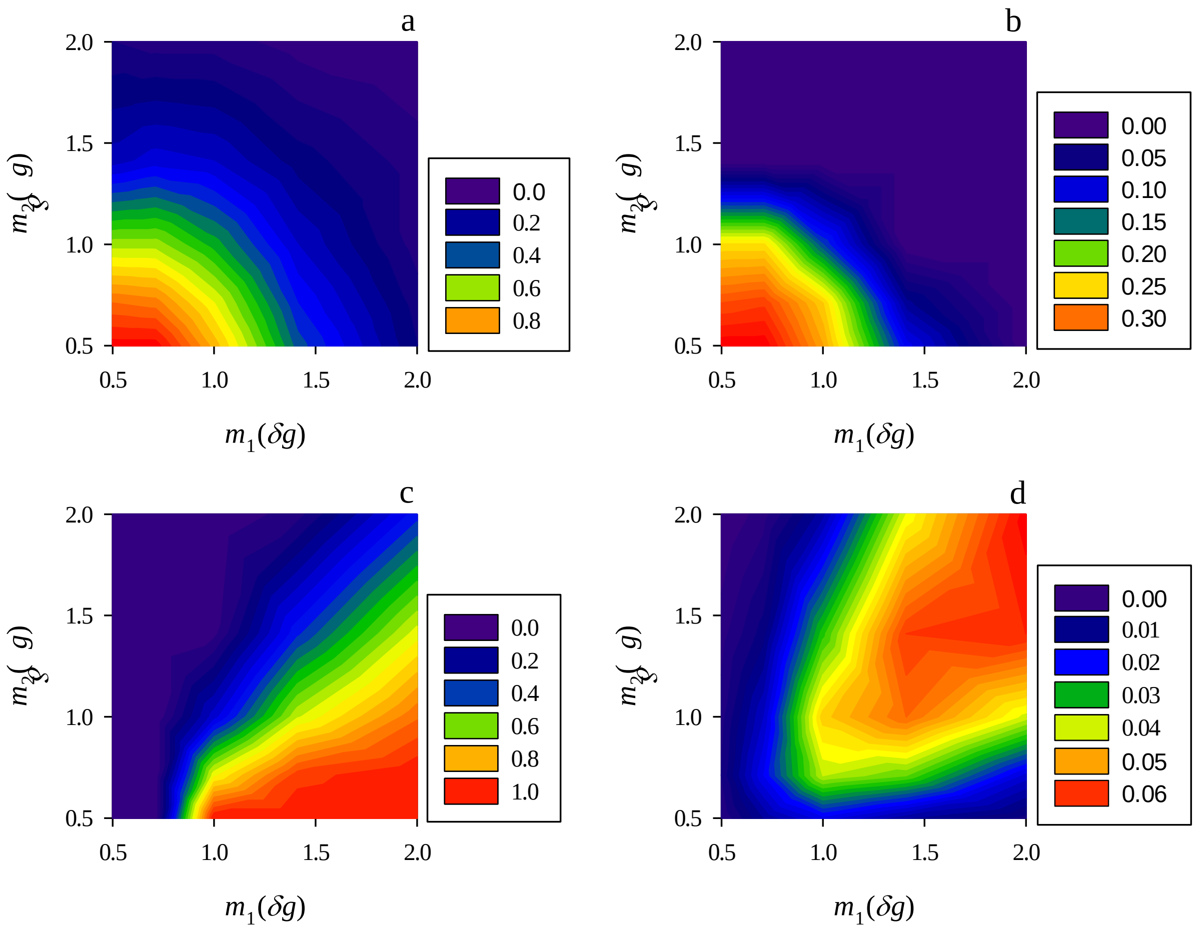


Figure A4: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter e increased to 0.05 compared to the baseline scenario.

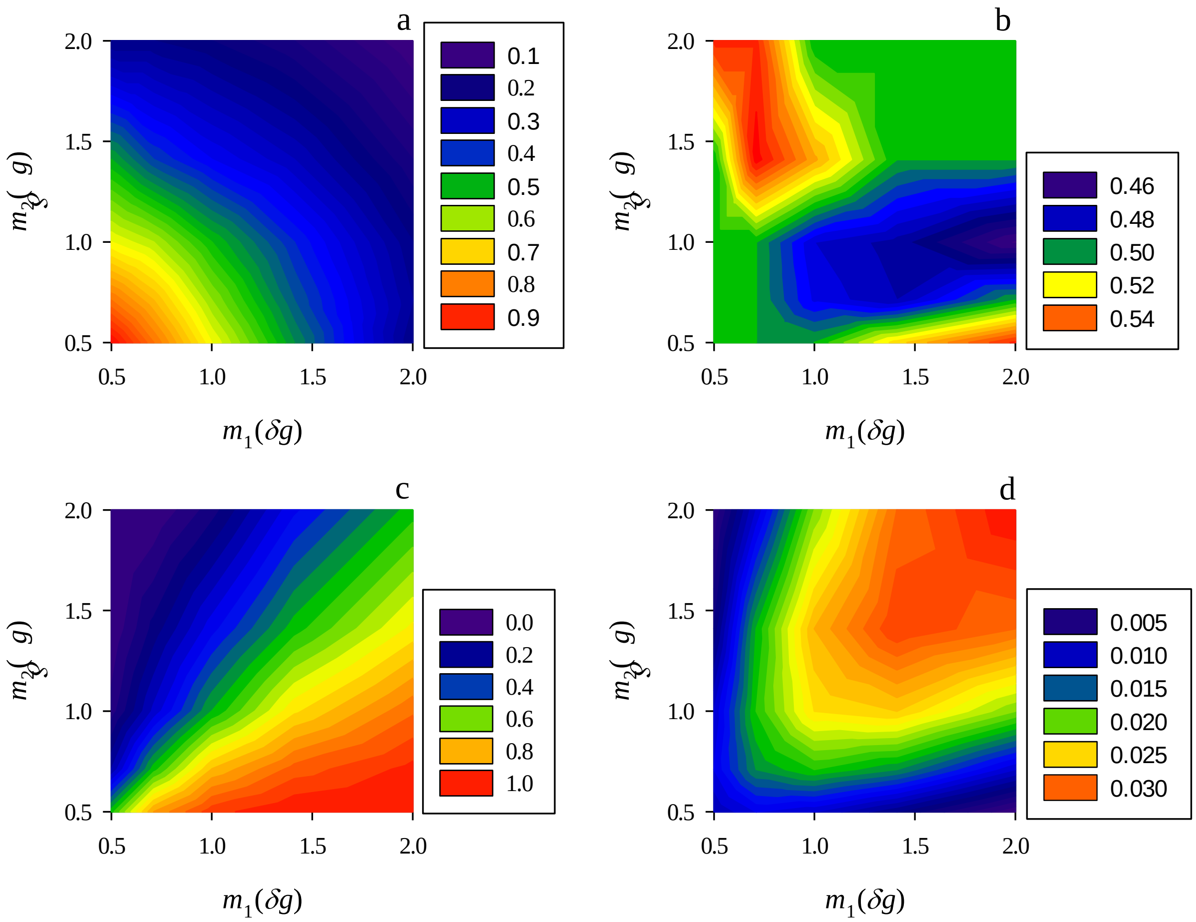


Figure A5: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter $g_1(1)$ increased to 1.5 compared to the baseline scenario.

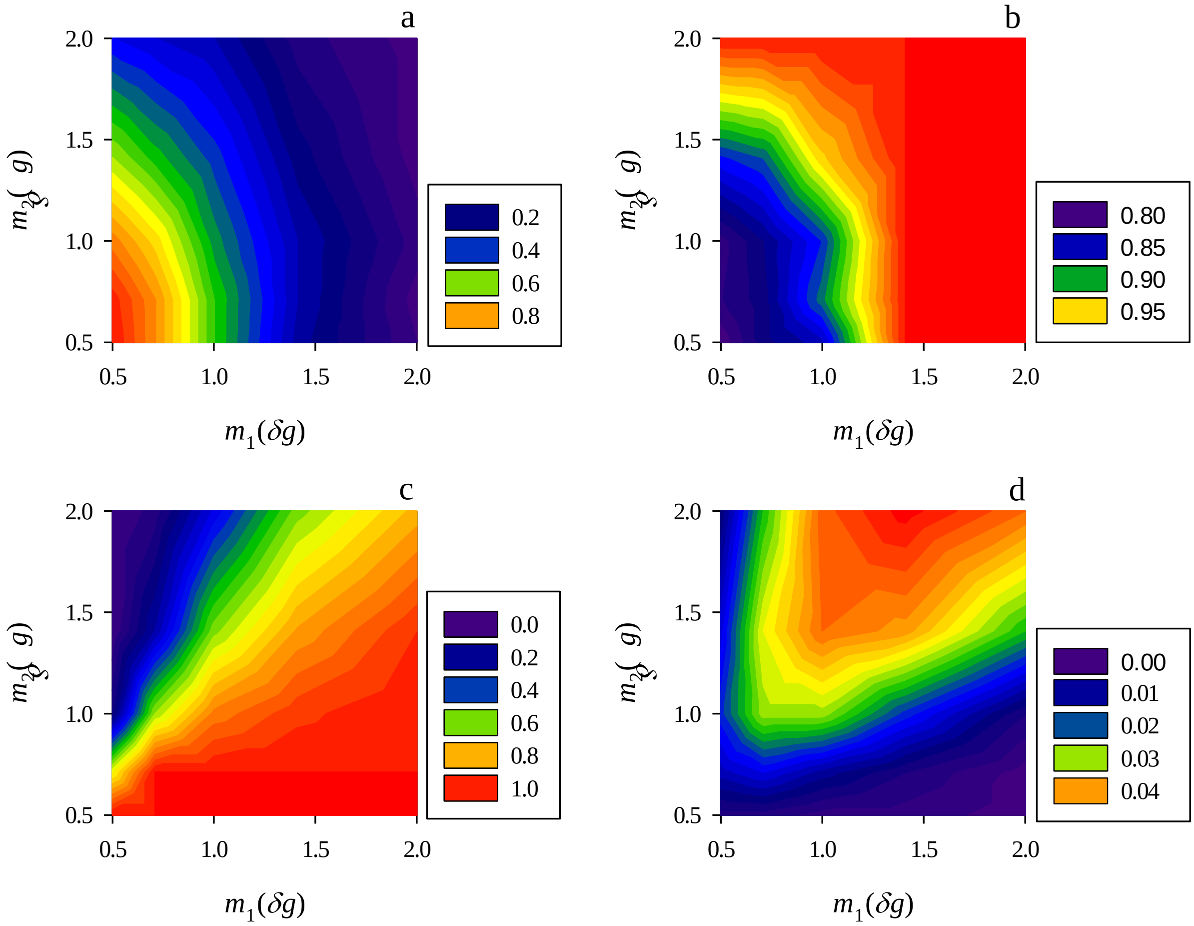


Figure A6: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter z reduced to 0.5 compared to the baseline scenario.

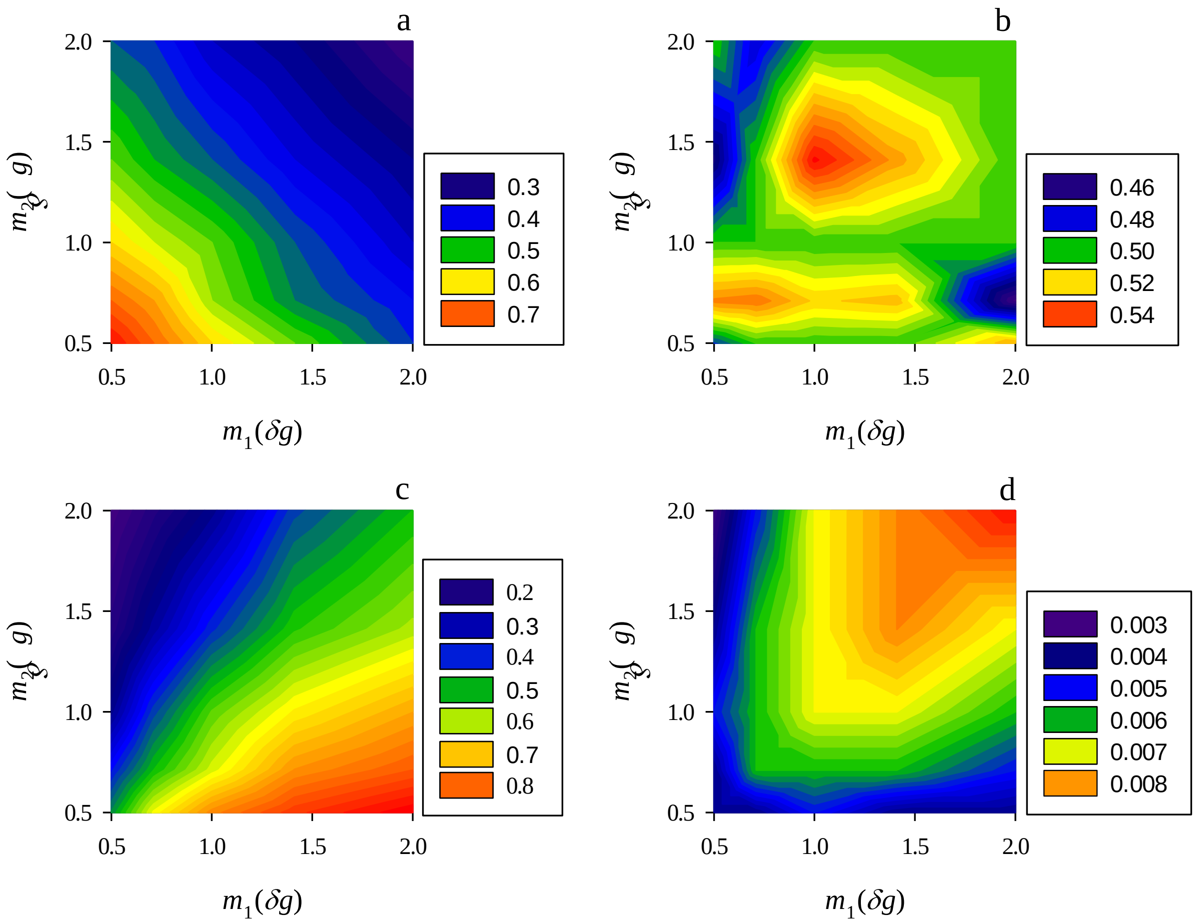


Figure A7: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter z increased to 2.0 compared to the baseline scenario.

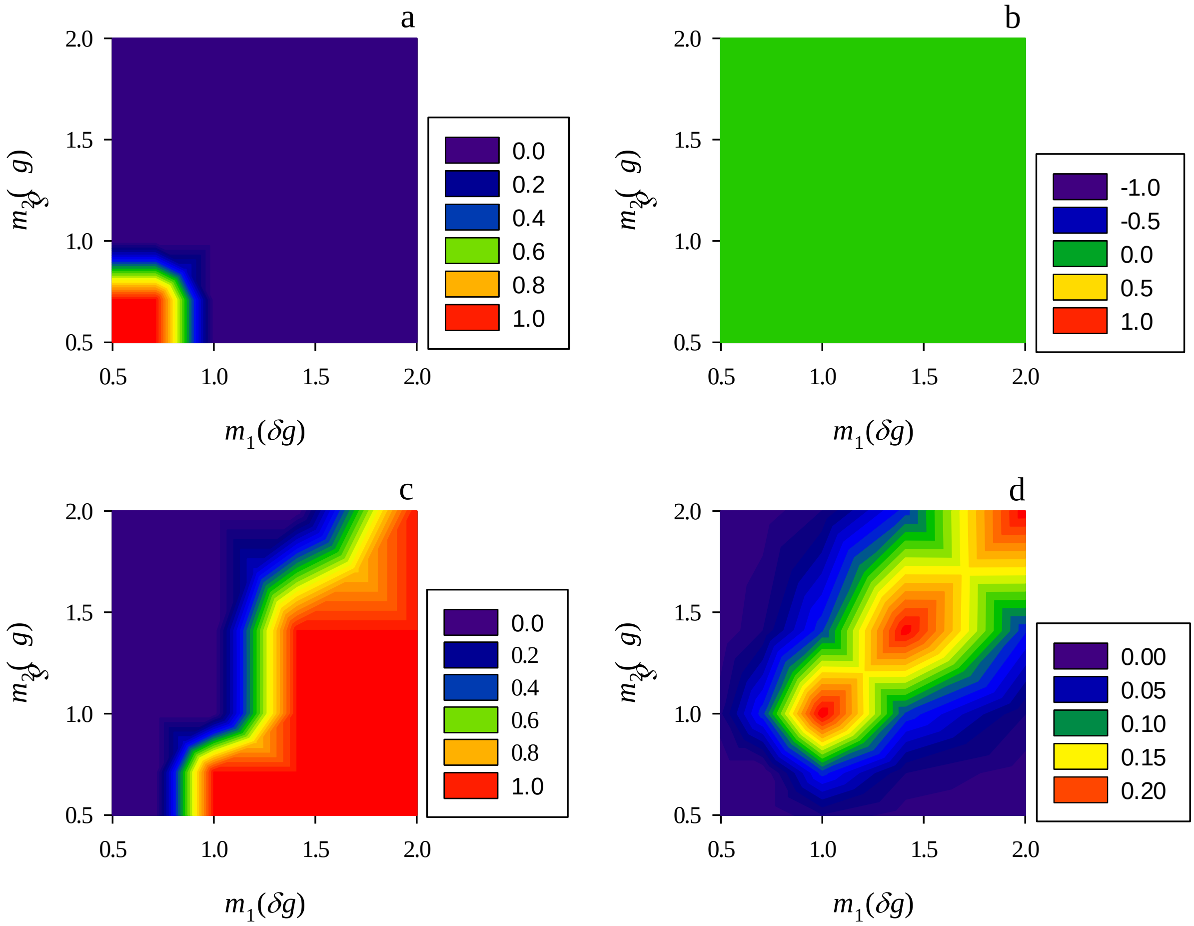


Figure A8: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameters $\sigma_1(\delta\gamma)$ and $\sigma_2(\delta\gamma)$ reduced to 0.2 compared to the baseline scenario.

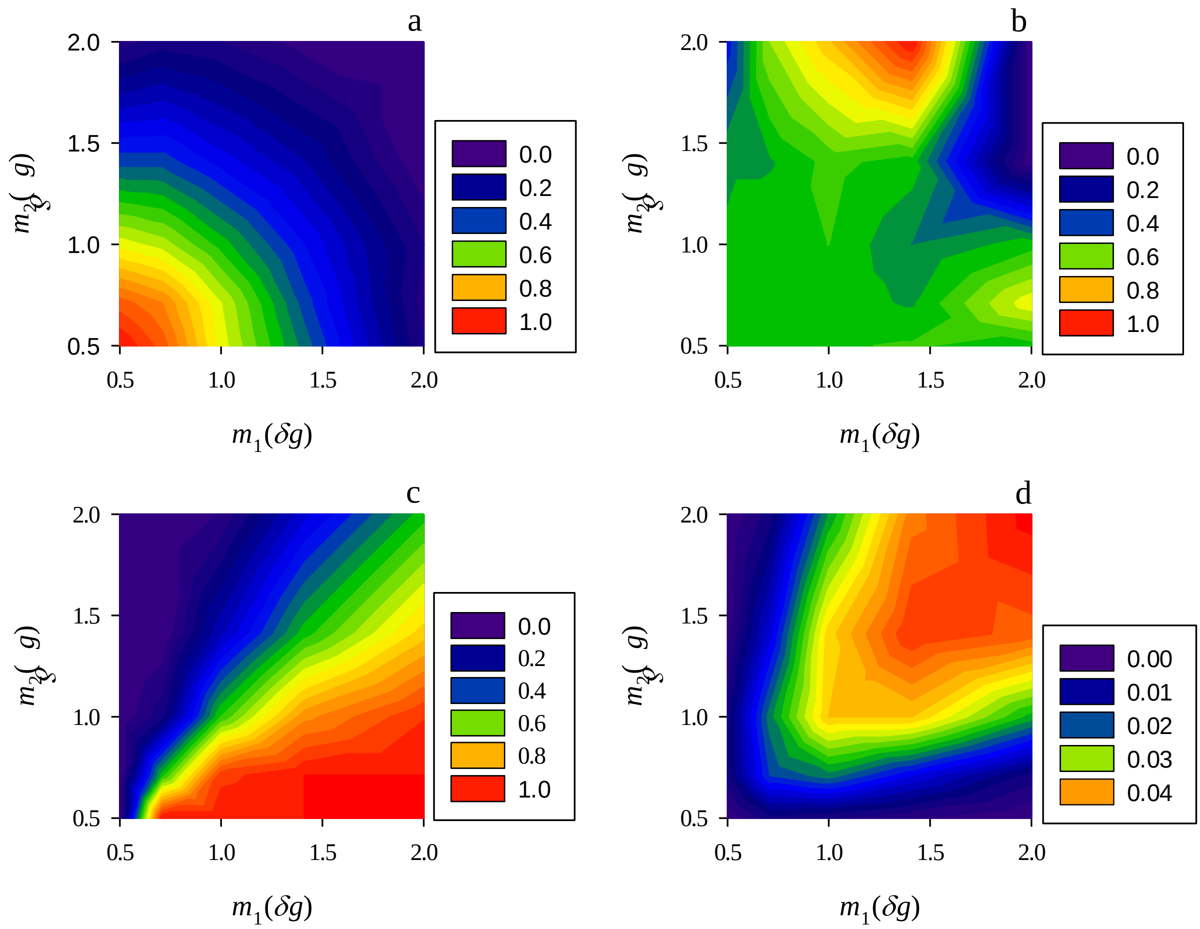


Figure A9: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameters $\sigma_1(\delta g)$ and $\sigma_2(\delta g)$ reduced to 0.2 compared to the baseline scenario.

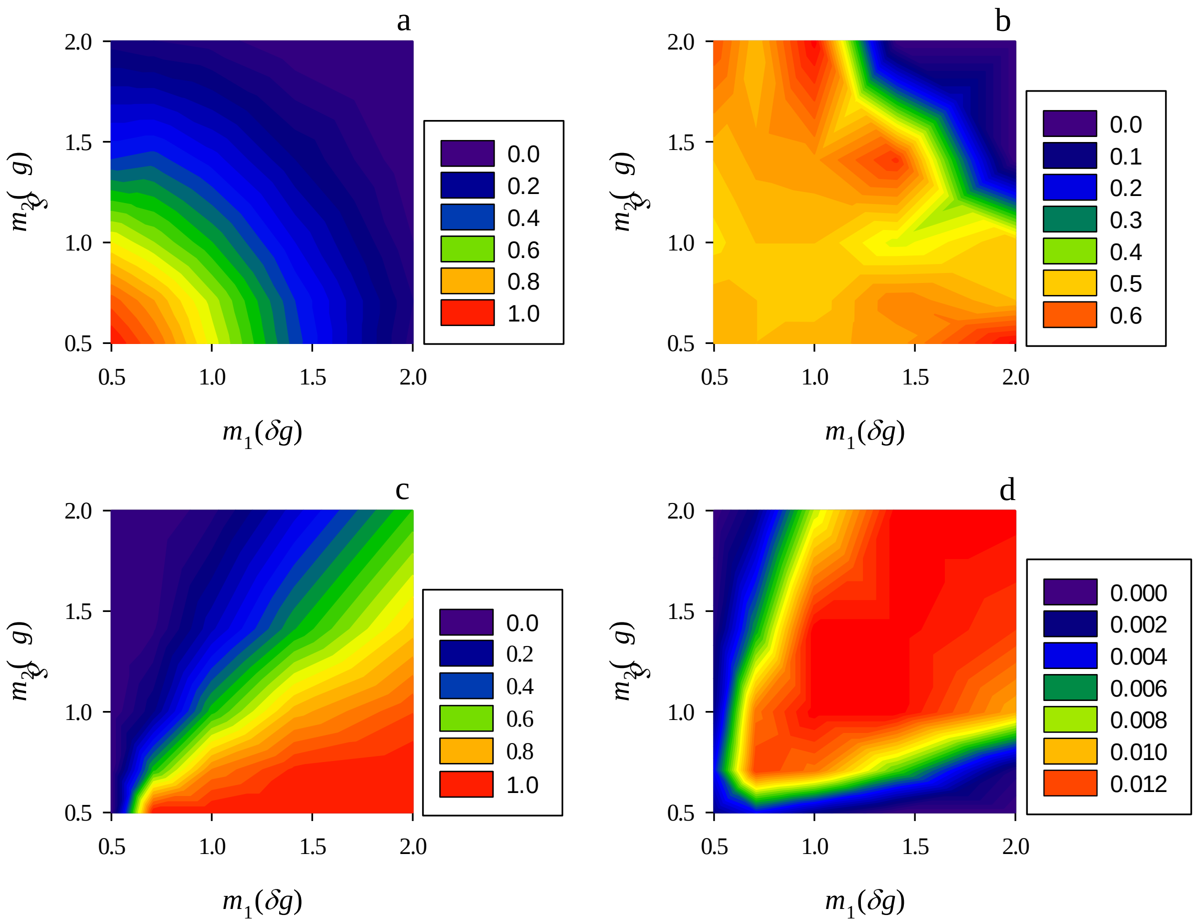


Figure A10: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter r_γ reduced to –0.8 compared to the baseline scenario.

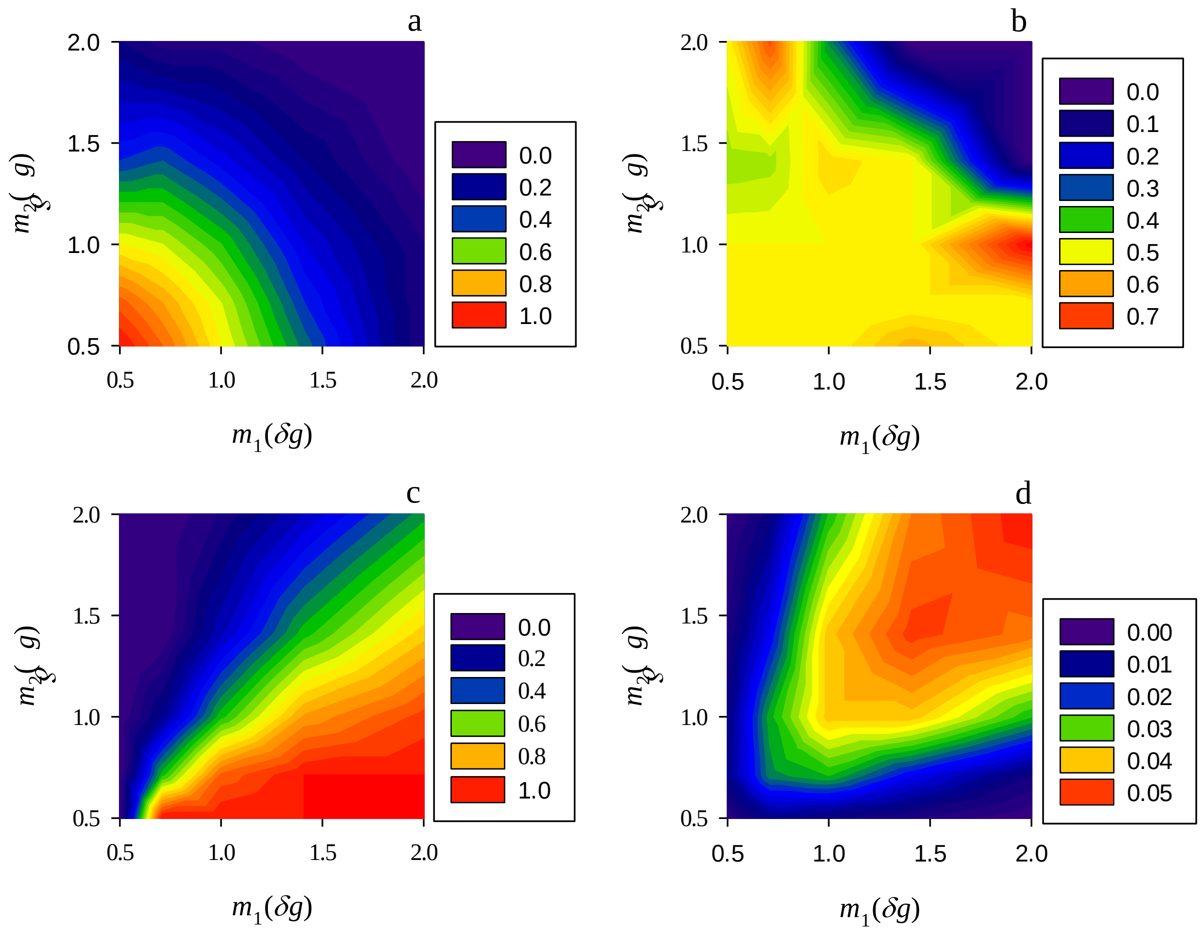


Figure A11: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter r_γ increased to +0.8 compared to the baseline scenario.

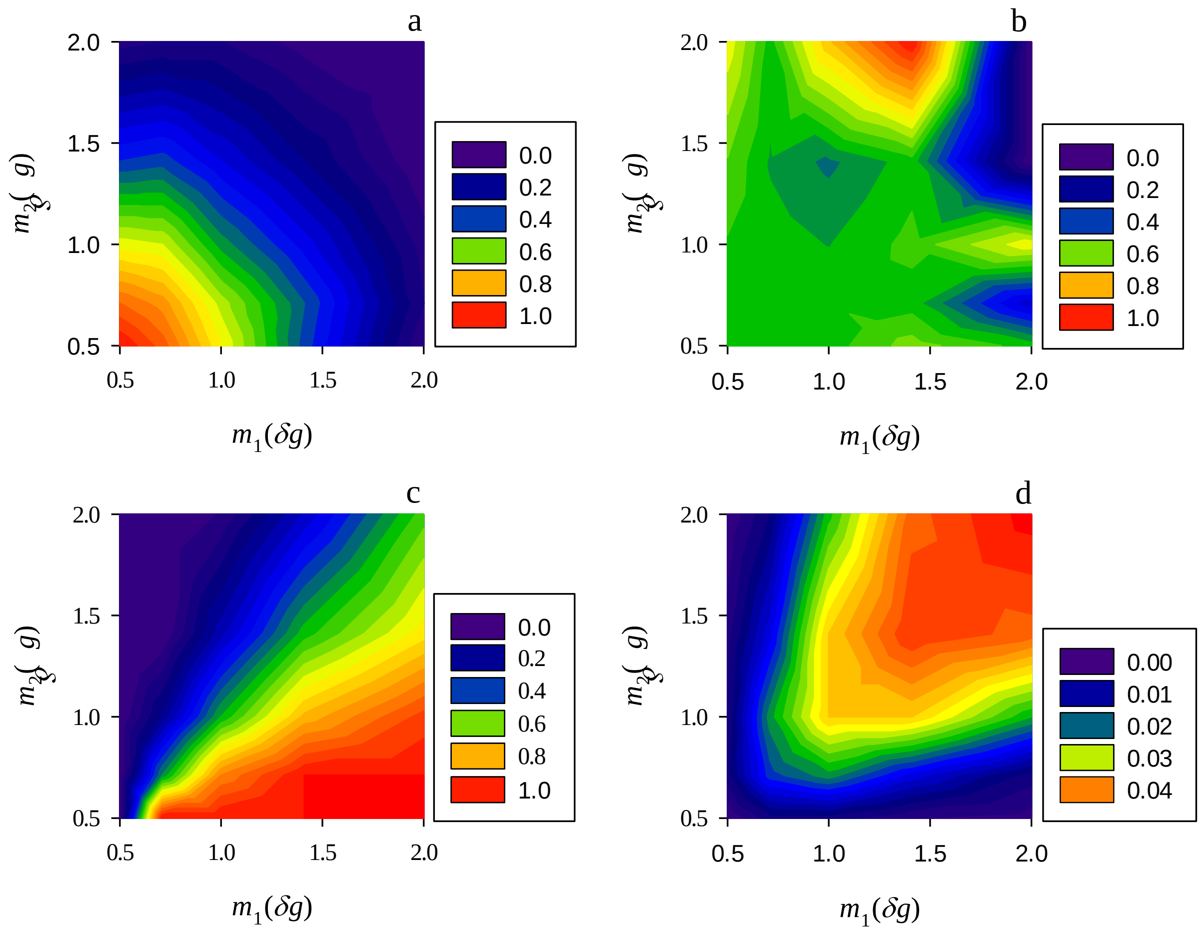


Figure A12: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter r_g reduced to –0.8 compared to the baseline scenario.

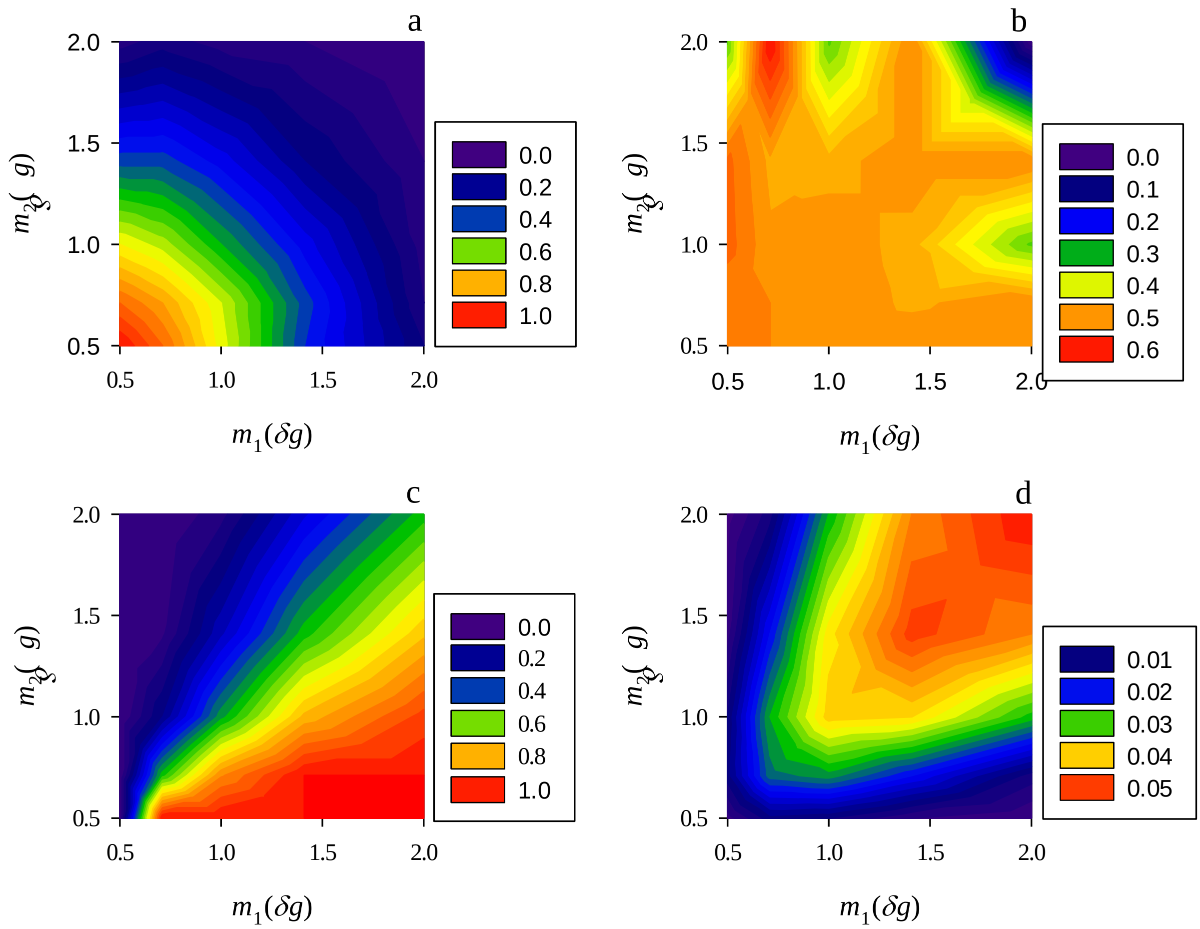


Figure A13: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter r_g increased to +0.8 compared to the baseline scenario.

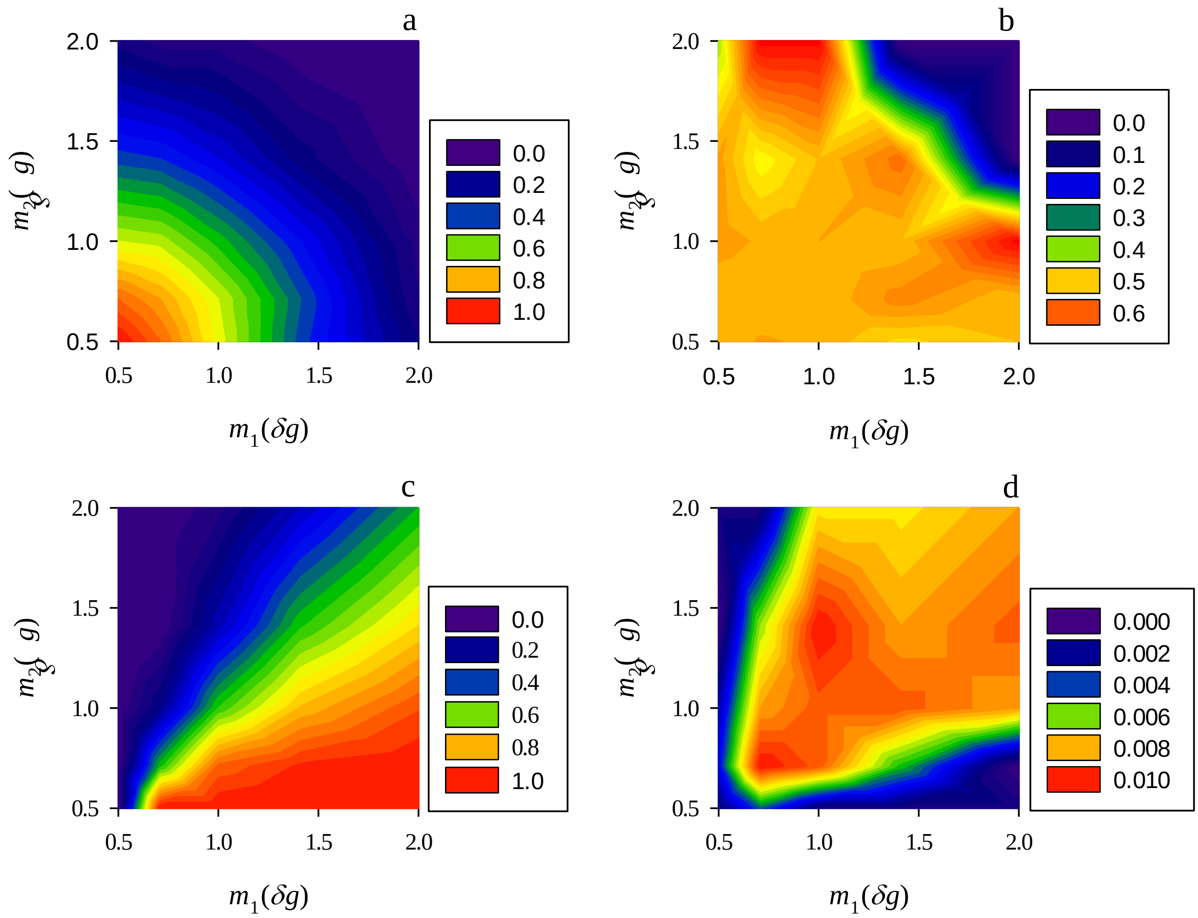


Figure A14: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter ρ_B reduced to 0.2 compared to the baseline scenario.

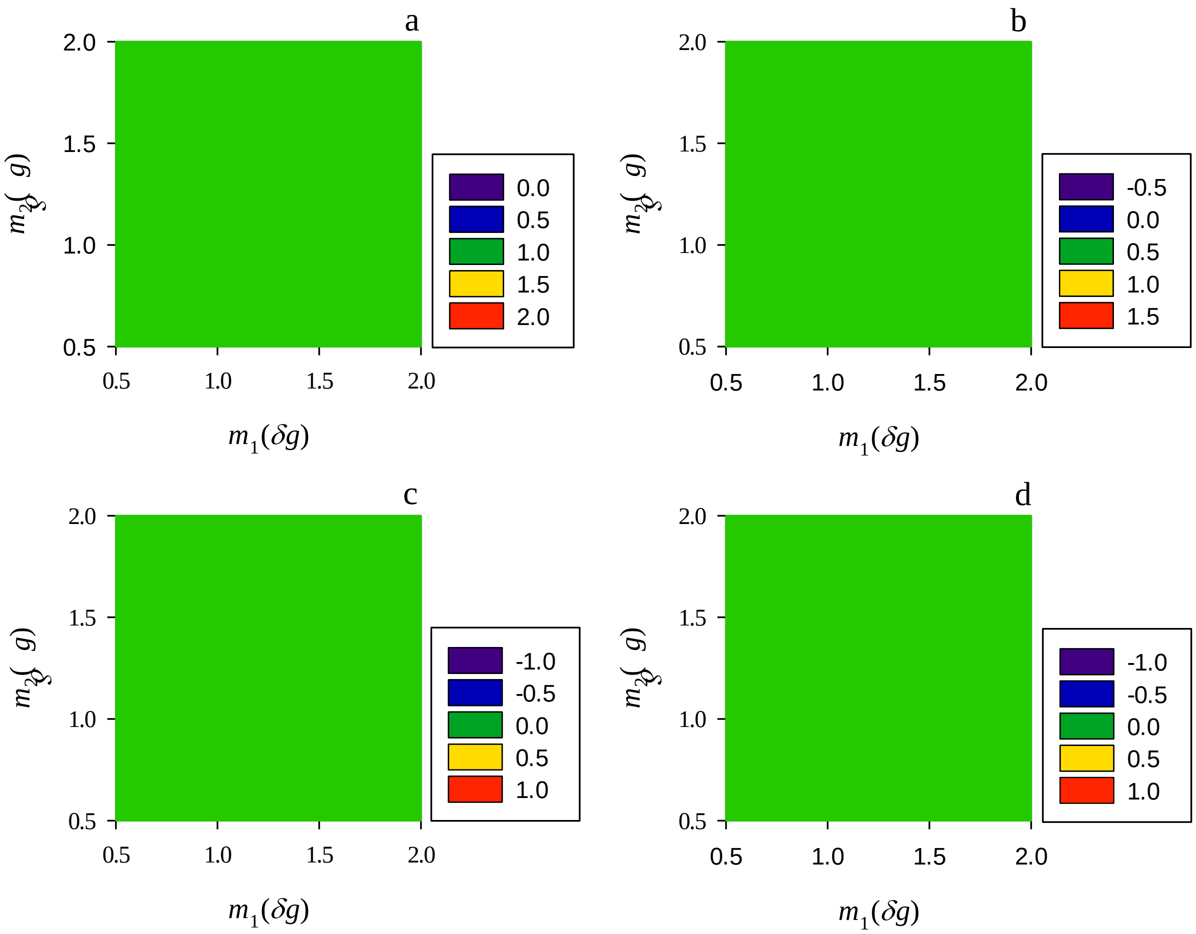


Figure A15: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter ρ_C increased to 5 compared to the baseline scenario.

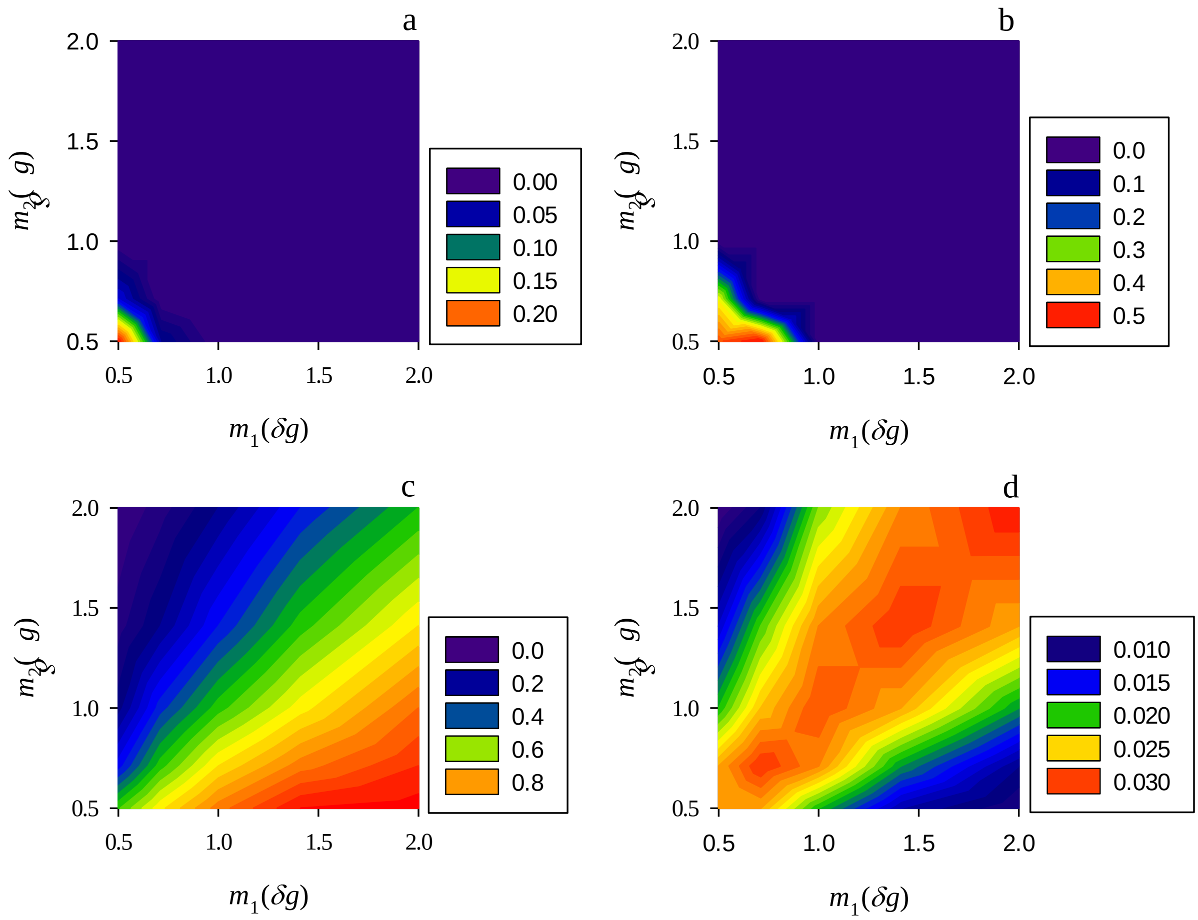


Figure A16: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter C increased to 400 compared to the baseline scenario.

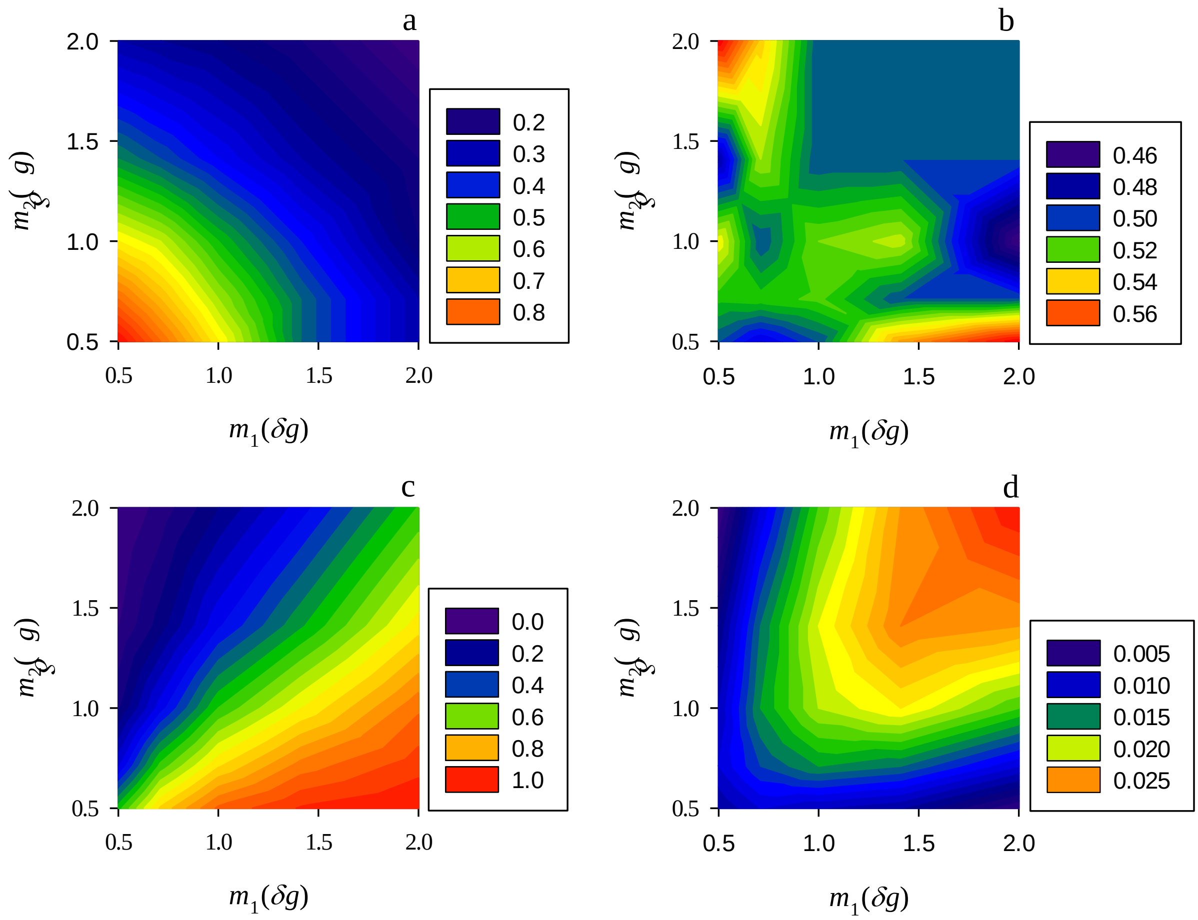


Figure A17: Cost-effective share of the budget in period 1 (panel a), cost-effective share of the period-1 budget in region 1 (panel b), cost-effective share of the period-2 budget in region 1 (panel c) and efficiency gain of the flexible strategy compared to the fixed strategy (panel d) as functions of the climate change factors $m_1(\delta g)$ and $m_2(\delta g)$. Parameter s increased to 2 compared to the baseline scenario.