

Climate change and optimal reserve selection in a dynamic world

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Abstract

In a recent paper (Strange et al 2006), we presented a novel expansion of the problem of optimal reserve site selection over time. In that paper we explored a case where areas with valuable biodiversity cannot all be protected immediately due to budget restrictions and where there is a probability of species going extinct on non-reserved as well as reserved sites. Non-reserved sites furthermore risk irreversible land-use conversion implying a loss of all species at that site. More importantly, we introduced a new type of control to the reserve selection literature – a swapping option: We provided the planner with the option to sell reserved sites in order to be able to buy another non-reserved site. This may be optimal if a reserved site has lost part of its conservation value. We formulated and solve this problem using stochastic dynamic integer-programming and showed that, due to the dynamic and stochastic nature of biodiversity evolution, the inclusion of a swapping option will increase overall efficiency – in particular for tight budgets. Finally, we tested a number of decision criteria (heuristics) to investigate alternatives to the computationally demanding task of determining the true optimum.

For the present draft paper we developed an additional expansion of the problem, which is made highly relevant by climate change: We introduced - in a small conceptual model - an important implication of climate change: That with climate change induced migration of (threatened) species, there is a probability that new species will immigrate into the sites of the potential reserve system. Such immigration may change optimal priorities. We showed that in this set-up, conservation goals will benefit from a new approach to conservation management, one which is in fact not conservative but dynamic. Again, the option to switch priorities becomes important for performance

Keywords: Biodiversity; Dynamic programming; Reserve network; Uncertainty, Climate Change

1. Introduction

This paper deals with forest and nature planning, and how to integrate uncertainty and the dynamics of climate change into conservation planning models. Even though intensive land use, nutrition loads, and invasive species are among the most severe threats against biodiversity climate change is believed to accelerate the change of species composition. Skov et al. (2006) use bioclimatic envelope models to evaluate the potential impacts of the A2 and B2 scenarios on 88 EU habitat plant species in Denmark (IPCC 2001). Using the more conserve B2 scenario they find that 67% of the species will be affected negatively, 12 % will benefit from climate change, and 21 % will remain unaffected. A recent study on 120 native terrestrial non-volant European mammals shows that the potential mammalian species richness is predicted to become dramatically reduced in the Mediterranean region but increase towards the northeast and for higher elevations (Levinsky et al. 2007). Hence, the Danish populations of mammals may potentially benefit from climate change. However, on a European level, assuming unlimited and no migration, respectively, their model predicts that 1% or 5–9% of European mammals risk extinction, while 32–46% or 70–78% may be severely threatened (lose > 30% of their current distribution) under the mild B1 and the severe A2 scenarios. Under the no migration assumption endemic species were predicted to be strongly negatively affected by future climatic changes, while widely distributed species are less severely affected. Even protected areas may then end up containing fewer species than they did when they were selected. It is evident that the lack of resources for protecting biodiversity makes it impossible to protect all conservation areas at once. Meanwhile, the risk of changing land uses, development of urban sprawl, intensified agricultural use etc., may cause that areas, which could not be protected previously turn out to contain less conservation value.

Climate change, and more broadly, environmental change may increase the future dynamics of species distributions. This even further stress that information on the current status of habitat quality and species viability as well as risk assessment are important elements when designing the future networks of conservation areas. In principle, in order to make an optimal decision (opposed to a sub-optimal one based on merely static information) the decision-maker must in each period then compare the current conservation status and possible future conservation value of a potential reserve, as well as the risk of the site being developed or degraded as compared to other sites. Computer modelling may assist the decision maker in handling such complex problems. One well-known approach to analyzing such a complex decision problem is stochastic dynamic programming (SDP), which determines the optimal sequence of decisions when the future status of the areas inside and outside the network is uncertain and depends on both previous decisions and stochastic influences. A few studies, such as Meir et al. (2002), Westphal et al. (2003), Costello and Polasky (2004), Meir et al. (2004) and Tenhumberg (2004), have applied this approach to deal with dynamics of the selection problem. Additionally, the SDP approach may provide the decision-makers with important answers to questions of timing. However, using SPD has the drawback that the computational burden increases exponentially in the number of sites considered. Costello and Polasky (2004) solve a conservation problem including maximum 10 sites and Meir et al. (2004) 12 sites. This has created a need for developing dynamic selection strategies that are almost as efficient as the optimal strategy identified by SPD, but with less computational burden (e.g., Costello and Polasky, 2004; Meir et al., 2004; Drechsler, 2005, Moilanen and Cabeza 2007).

Most of the studies assume that conservation status of the protected areas is unchanged within a long time horizon, even if time shows that the quality of some habitats turns out to disfavor target species. This irreversibility in decision making may prohibit any efficiency gains from adapting conservation strategies, i.e. swapping areas of low conservation value with more favorable ones in the future. In a recent paper (Strange et al 2006), we presented a novel expansion of the problem of optimal reserve site selection over time, allowing for adaptation. In that paper we explored a case where areas with valuable biodiversity cannot all be protected immediately due to budget restrictions and where there is a probability of species going extinct on non-reserved as well as reserved sites. Non-reserved

sites furthermore risk irreversible land-use conversion implying a loss of all species at that site. More importantly, we introduced a new type of control to the reserve selection literature – a swapping option: We provided the planner with the option to sell reserved sites in order to be able to buy another non-reserved site. This may be optimal if a reserved site has lost part of its conservation value. We formulated and solved this problem using SPD and showed that, due to the dynamic and stochastic nature of biodiversity evolution, the inclusion of a swapping option will increase overall efficiency – in particular for tight budgets. Finally, we tested a number of decision criteria (heuristics) to investigate alternatives to the computationally demanding task of determining the true optimum.

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2. Models

The models we use are expansions of a dynamic reserve site selection model in Costello and Polasky (2004). On the stochastic dynamics side, there is a risk of biodiversity losses (degradation) even on protected sites part of the reserve network as in Strange et al (2006). Protection of a site is rarely a guarantee against biodiversity losses. Protection strategies may fail and species disappear for several reasons, including ecological changes, exogenous effects or pressure not accounted for by the conservation efforts e.g. climate change. Also, as Kleijn et al. (2001) argue conservation agreements with land managers may not always be effective in protecting the species richness, e.g. due to lack of motivation and expertise. Furthermore, as a new development we allow for the *stochastic immigration* to occur at non-degraded sites, whether inside the reserve network or not. On the control side of the model, we include the option for the decision-maker to remove land from reserve status, e.g. by selling it or cancelling a subsidy contract between the authority and the landowners inside the reserve network. The decision-maker may take this action to increase budgets for protecting (buying or subsidizing owners of) new land, which is expected to improve biodiversity protection.

The number of sites j is J , i.e. $j = 1, 2, \dots, J$. Each site may host a currently native species i^n and potentially all I^n species in the network at $t = 0$, i.e. $i^n = 1, 2, \dots, I^n$. A additional set of immigration species I^f is defined, and a subset of the $i^f = 1, \dots, I^f$, species may immigrate into any non-degraded, non site in J . Letting $I = I^n + I^f$, we define a $J \times I$ matrix, A_t , where an element of the matrix $a_{ij} = 1$ if species i is present in area j , and equals 0 otherwise. For $t = 0$ this matrix represents the initial state of the sites and hence for the last I^f rows $a_{ij} = 0$ initially. As we allow for stochastic degradation, there is a site-specific probability $prob(d_j)$ that in any time step t a reserve or non-reserve site is for some reason degraded. In that event, the initial set of species present at the j 'th site, I_j , is reduced to a predefined smaller set $I_j^d \subset I_j$. Furthermore, for non-degraded sites there is a site and species specific probability, $prob(m_{ij})$, of immigration to site j of a subset of species $i^f \in I^f$. Thus, the matrix A_t is stochastic and evolve of the number of time steps T . At the start of each time period t , every site is in one of several possible states: converted, reserved and potentially degraded or containing new immigrated species, non-reserved and potentially degraded or containing new immigrated species. Non-reserve status implies that the area has neither been converted, nor selected as a reserve. In any time period t , non-reserve areas may be converted at the end of period t with the site-specific probability $prob(con_j)$. Once the area is converted, any suitable habitat within the area is destroyed and we assume that all species are removed from area j . Conversion as well as degradation is assumed to be irreversible, but immigration of new species does not exclude future risk of degradation nor conversion.

The cost of selecting area j at time t as a reserve could involve time and site specific variations in costs, but in our simplified case here we take the costs as constant across time and site, i.e. the same cost, c , for any site, at any time. Following the notation of Costello & Polasky (2004) we let R_t be a $J \times 1$ vector where R_{jt} equals 1 if site j is part of the reserve network at the beginning of period t , and 0 otherwise. Let X_t be a $J \times 1$ vector where X_{jt} equals 1 if site j is selected as a reserve in period t , and 0 otherwise. Let L_t be a $J \times 1$ vector where L_{jt} equals 1 if the protected area j is sold (swapped) in period t , and 0 otherwise. Therefore, the total set of reserve areas R_{t+1} in period $t+1$ equals the set of reserve areas at the beginning of period t plus the selected reserve areas in period t minus the sold reserve areas in period t . That is, $R_{t+1} = R_t + X_t - L_t$. We also define N_t as a $J \times 1$ vector where N_{jt} equals 1 if area j is non-reserve at the beginning of period t , and 0 otherwise. S_t is defined as a $J \times 1$ random vector where element S_{jt} equals 1 if stand j is converted in period t (following the allocation decision in that period), and 0 otherwise. Hence, the equation of motion of non-reserve areas between period t and $t + 1$ is $N_{t+1} = N_t - X_t - S_t + L_t$.

In each period, the authority faces a budget constraint, which consists of the funds supplied, b_t , plus the amount achieved by selling – if optimal - and swapping protected areas from the existing reserve network. To keep the budget dynamics simple, we assume that protected areas are sold at identical market prices, m , equalling the cost c . We also let $m = c = b_t$, i.e. the new budget available in each period allows for buying exactly one site. This simple structure is similar to that of Costello and Polasky (2004). Of course, it would be more realistic to assume variations in selling-prices and acquisition costs for sites, and hence a dynamic budget constraint (in the absence of borrowing) could be suggested. This, however, would increase the computational complexity of the problem beyond reason for the purpose of this paper. For convenience we define two vectors C and M of size $J \times 1$, with each element equaling c and m , respectively.

Thus, altogether, there are two J period t state variables in this model, N_t and R_t , and two J period t control variables, X_t and L_t . At the beginning of period t , the planning authority observes N_t and R_t . The planner receives a budget payment b_t sufficient for buying one site and then chooses $X_t \leq 1 + L_t \leq N_t$ and $L_t \leq R_t$. Elements of N_t that have not been selected as reserve sites are then subject to possible conversion, and all elements not yet converted are subject to possible degradation according to $prob(d_j)$.

In many static reserve selection studies, the maximization problem investigated corresponds to the maximum coverage problem, i.e. maximizing the number of species covered within the selected reserves at the end of the planning horizon (i.e. the beginning of period $T + 1$). This, however, is a poor objective in a dynamic and stochastic world. To demonstrate that, our aim is to investigate two models with differing objectives: Model (i) maximizes the expected number of species of the whole system as of period $T + 1$, and Model (ii) maximizes the expected number of species within the reserve network as of period $T+1$. This corresponds to maximizing over $N_t + R_t$ and R_t , respectively. The dynamic selection problem is as follows:

$$V(N_t, R_t) = \max_{\substack{X_t \leq N_t \\ L_t \leq R_t}} E(V(N_{t+1}, R_{t+1}))$$

s.t.

$$X_t' C \leq b_t + L_t' M$$

$$N_{t+1} = N_t - X_t - S_t + L_t$$

$$R_{t+1} = R_t + X_t - L_t$$

(1)

$$E(V(N_{T+1}, R_{T+1})) = \min_{\substack{\in \mathbb{1}^J, (N_{T+1} + R_{T+1})' E(A_{T+1}) \in \mathbb{1}^J}} \quad \text{(Model i)}$$

$$E(V(N_{T+1}, R_{T+1})) = \min_{\substack{\in \mathbb{1}^J, R_{T+1}' E(A_{T+1}) \in \mathbb{1}^J}} \quad \text{(Model ii)}$$

Here $V(\cdot)$ is the maximized objective function, which equals the maximized expected number of species covered within the entire system (Model *i*) or the reserve network (Model *ii*). E is the expectation operator with respect to the stochastic evolution of A_{t+1} . The first constraint represents the budget, whereas the second and third include the equations of motion for the state variables between periods. The problem is solved recursively, so as to maximize the diversity at $T + 1$. For all possible states of the world at T , we estimate the value of the optimal program at the end of the planning period in two ways, as described by the two last lines in (1). $\epsilon_{1 \times 1}$ and $\epsilon_{1 \times 1}$ are matrices of ones sorting out the relevant sets of species from the matrix between them; the minimum operator ensures against double-counting of species. This is a SPD problem, and using Bellman's equation and Principle of optimality (Bellman, 1957), we set up a procedure of backward recursion to determine the best decision strategy at the current time, given the premise that each future decision is also optimally taken. Working through the problem gives us the optimal decisions in any state of the world and the associated expected value of the optimal program from there.

3. Simple illustrations

In Strange et al (2006) we presented the simple illustration reproduced in Table 1 and Figure 1 below. It shows the benefits of the swapping option and hence a flexible reserve strategy, when environmental degradation may also take place on sites in the reserve network. In the initial state, both A and B are non-degraded and one of them is chosen for protection. Following that an environmental change as well as conversion may take place, and the decision maker reviews his initial decision. Swapping degraded sites in the network for non-degraded sites outside the network of course unambiguously increases the expected coverage of species at the end of the period considered. The relative and absolute gain is of course the largest, when the initial choice is not optimal, here choice B. Nevertheless, swapping will still be strictly optimal with 13.5% probability even when A is chosen first.

Table 1. Configuration as well as probabilities of conversion and environmental degradation.

	Area A	Area B
Species present without degradation	1,2,3,4	5,6,7
Species present with degradation	4	7
Probability of conversion	0.4	0.5
Probability of degradation	0.3	0.1

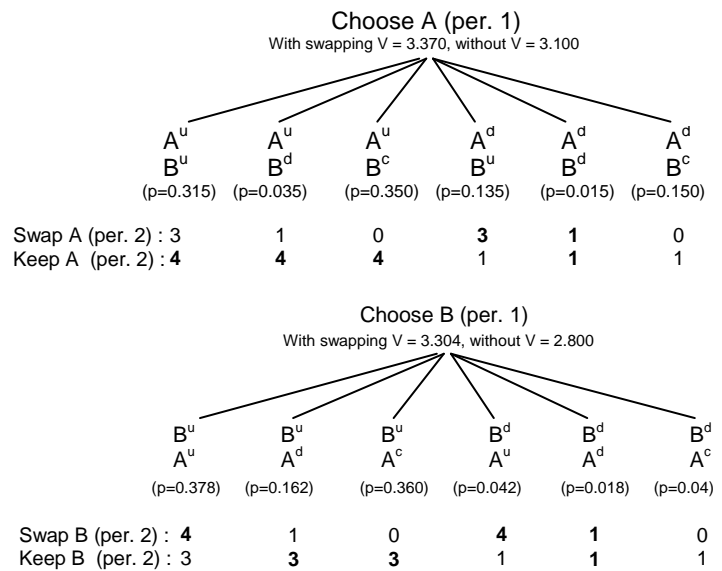


Figure 1 A two sites-two periods example, where the decision maker can secure one site as a reserve. Converted sites are labeled 'c', degraded 'd' and non-degraded 'u'.

Turning to the case where we allow for immigration of species to take place, we introduce now a probability of immigration into this simple example. In states where the sites A and B are non-degraded and non-converted we allow for the stochastic immigration of a species no. 8. The probability of immigration is site specific and we set $\text{prob}(m_{8A}) = 0.2$ and $\text{prob}(m_{8B}) = 0.6$. The

inclusion of the immigration probability implies an expansion in the number of possible states from 9 (3^2) to 16 (4^2). The results are summarized in Figure 2, where we show only part of the possible states, but include all those where a switch may be optimal. In Figure 2, we see that it is now marginally better to pick site B as the first site protected, and only switch to site A, when favorable. As we see in Table 1, site A already inhabits four species. Only with immigration, site B may hold four species. Site B, however, has a much lower probability of degradation than site A, but a higher risk of conversion. This together with the higher probability of immigration has the overall effect of making site B a better first choice than site A. Still, the swapping option will be in use frequently as seen in Figure 2. Even when choosing the B-site first, swapping for site A once the environmental state has been revealed will happen with a probability of 23.9% and the absolute expected gain from swapping has increased from 0.270 (when choosing optimally site A in Figure 1) to 0.331 in the presence of stochastic immigration.

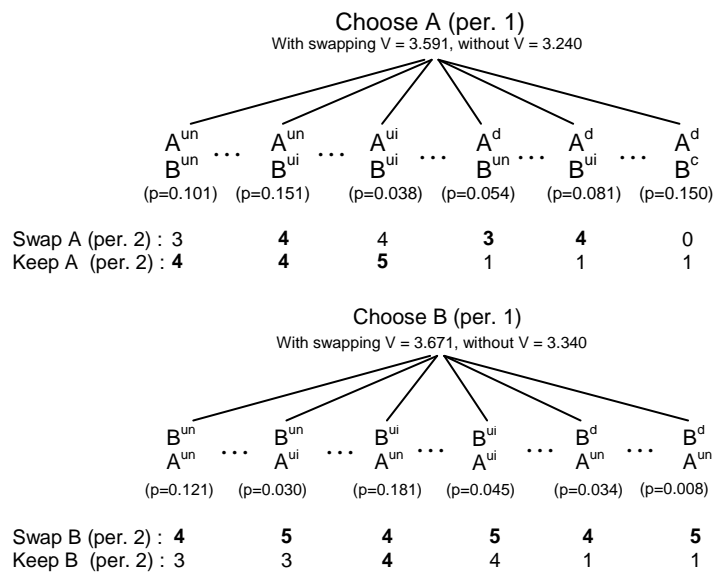


Figure 2 A two sites-two periods example, where the decision maker can secure one site as a reserve. Converted sites are labeled ‘c’, degraded ‘d’, non-degraded with immigration ‘ui’ and non-degraded without immigration ‘un’.

4. Concluding discussion

In this short working paper, we have developed the first initial drafts of a modelling approach designed to improve the coverage of species in a conservation network facing climate change induced stochastic changes in population distributions. We build on work we have undertaken (Strange et al 2006), but in fact the general approach here resembles flexible management designs presented in the theory of real options (Dixit and Pindyck 1994). The capability of repeatedly switching from one configuration of the reserve network to a new one is strongly inspired by the repeated real options concept as first coined by Malchow-Møller and Thorsen (2005).

Clearly, the first challenge to solve here is the computational one. As we have seen, the inclusion of stochastic immigration to non-degraded sites implies an increase in the state space, which further adds to the computational burden often found in SPD problems. Thus, the search for quicker and still almost as efficient decision algorithms is just as relevant as it was in Strange et al (2006).

A second tremendous challenge is of course to enable the models to analyse real world problem sizes using empirical information on species and probabilities of degradation, conversion and immigration. This requires a strong macro-ecological competence.

Can we say anything about likely policy implications at this level? Well, the concept of conservation programmes has since its very beginning been conservative in nature by definition, and this has in

practice translated into a high degree of static and incremental planning. The approach taken here and the indicative results illustrated suggests there is a need for more dynamic and flexible approaches to maintain efficiency (a high species protection) of conservation networks, in particular facing effects of climate change.

The implications of swapping could be useful for in a more general discussion of state intervention and investments. Hence, on a more practical level, the results could be used to e.g. raise the question if state ownership of large areas of spruce forests with low contents of environmental values is the best possible allocation of state capital? Perhaps it would be wiser to sell the land to private investors and use the funds to buy up private land believed to be environmentally more important in the future. Likewise, one may review the current conservation practice and evaluate if some conservation investments are likely to be entirely in vane due to climate change. Again, one may reconsider if the investments could be better used elsewhere.

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