ELSEVIER

BIOLOGICAL CONSERVATION

Optimal reserve selection in a dynamic world

Niels Strange[a,*], Bo Jellesmark Thorsen[b,1], Jesper Bladt[c,2]

[a]*The Royal Veterinary and Agricultural University, Department of Economics, Politics and Management Planning, Rolighedsvej 23, DK-1958 Frederiksberg, Denmark*
[b]*The Royal Veterinary and Agricultural University, Department of Economics, Politics and Management Planning, Department of Forestry and Forest Products, Hørsholm Kongevej 11, DK-2970 Hoersholm, Denmark*
[c]*University of Aarhus, Institute of Biological Science, Department of Systematic Botany, Ny Munkegade, Building 1540, DK-8000 Aarhus C, Denmark*

A R T I C L E   I N F O

A B S T R A C T

In this paper we present a novel expansion of the problem of optimal reserve site selection over time. We explore a case where areas with valuable biodiversity cannot all be protected immediately due to budget restrictions and there is a probability of species extinction on reserved as well as non-reserved sites. Add to this the risk of land-use conversion facing all non-reserved areas. We furthermore introduce a new type of control by making the planning authorities have the option to sell reserved land on which biodiversity value has decreased. We formulate and solve this problem through stochastic dynamic integer-programming. The current study shows that, due to the dynamic and stochastic nature of biodiversity evolution, the inclusion of a swapping option may increase overall efficiency. Finally, we test a number of decision criteria (heuristics) to investigate alternatives to the cumbersome task of determining the true optimum.

1. Introduction

Human activities are rapidly increasing the number of species threatened with extinction, increasing the conservation needs globally. Yet, resources available for protection are strongly limited. This increases the interest in identifying which areas of habitat are the most important to protect in order to preserve biodiversity for the future. However, the condition of land areas may change in the future, thereby influencing the biodiversity they contain. Conservation authorities are thus facing the problem of how to target their actions so that they accomplish the most with limited budgets, while acknowledging the uncertainty of the future states of areas and of the environment globally. This issue is at the very forefront of conservation planning and this article adds new findings.

Political prioritizing requires that the reserve network design relies on sound biological information, not only information on species occurrence but also viability measures. Uncertain species occurrence data may dramatically affect the network. Two methods have been proposed in the literature for solving the reserve site selection problem with probabilistic presence–absence species information. One is the 'expected coverage' approach, which maximizes the expected number of species covered (Polasky et al., 2000). The other method is the 'threshold approach', which maximizes the

* *Corresponding author:* Tel.: +45 35 28 17 53; fax: +45 35 28 15 08.
  E-mail addresses: nst@kvl.dk (N. Strange), bjt@kvl.dk (B.J. Thorsen), bladt@biology.au.dk (J. Bladt).
[1] Tel.: +45 35 28 1700; fax: +45 35 28 15 08.
[2] Tel.: +45 89 42 47 22.

number of species covered, where a species counts as covered only if the probability of coverage reaches a specified threshold (e.g., Arthur et al., 2002; Margules and Stein, 1989; Haight et al., 2000). Both selection approaches find that reserve network sites differ significantly when using probabilistic data to maximize the expected number of species represented versus using non-stochastic approaches.

These results stress that information on habitat quality and species viability is important when designing the network. However, in the long run such 'single point in time' decisions may be suboptimal, because complete reserve networks usually cannot all be protected at once and some selected areas may therefore have changed before they are protected. These areas will typically turn out to contain less conservation value than originally assumed, e.g. host fewer species and/or less complementary species. Such dependence of the future conservation value of a reserve on the presence and status of other reserves has proved technically demanding, as the decision-makers do not know the future environmental state of the areas. Therefore, in order to make an optimal choice the decision-makers must in each period 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. One 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 et al. (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).

Reserves should be protected and subsidized accordingly, and this status is usually assumed 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 swapping such areas with more favorable ones in the future. For the strategy to be successful we find it crucial to pay direct attention to the dynamics of habitat development and to reformulate the conservation strategies in accordance with a changing environment.

This study has the following intentions. Like in the aforementioned dynamic selection problems, we show the importance of including uncertainty and time in the priority setting. Secondly, we extend the decision problem of previous studies such as Costello and Polasky (2004) by including the probability of environmental degradation. Additionally to Meir et al. (2004) we include the possibility of degradation not only in

non-reserved areas but also inside reserves. Thirdly, we evaluate conservation strategies including the possibility of swapping previously selected reserves with remaining and more favorable sites. Fourthly, we evaluate alternative heuristics to the optimal sequential approach. Moreover, most dynamic procedures for reserve selection aim at maximizing the number (or the expected number) of species covered by a reserve network. The reasoning behind this is that only reserves can be controlled and that reserves should form the basis for long-term persistence of biodiversity. In contrast, the recent studies using SDP aim at maximizing the number of species in the whole system, assuming that species vulnerability can be assessed both in reserves and non-reserve areas. This makes it possible to consider which species are likely to persist outside reserves and to take this into account in the planning process. We evaluate the consequences of conservation strategies focusing on maximizing the expected number of species within the reserve network as well as in the whole system of reserves and non-reserve areas.

2. Materials and methods

2.1. The stochastic dynamic model

In the following we expand the model of dynamic reserve site selection in Costello and Polasky (2004) by including control variables that allow the decision-maker to remove land from reserve status, e.g. by selling it or canceling a subsidy contract between the authority and the landowners inside the reserve network. The decision-maker may do this to increase budgets for protecting (buying or subsidizing owners of) new land, which is expected to improve biodiversity protection. One major reason for selling reserve land could be that the protection strategies may fail and species disappear because of climate change or environmental degradation. Kleijn et al. (2001) argue that management agreements may not always be effective in protecting the species richness and that the motivation and expertise of the landowners may play a crucial role. For such reasons we introduce a probability of extinction even on protected land.

Any site in the model is denoted j, and the total number of habitat areas is J, i.e. $j = 1, 2, \ldots, J$. Each area may host a species i and potentially all I species, i.e. $i = 1, 2, \ldots, I$. We define a $J \times I$ matrix, A, where an element of the matrix a_{ij} equals 1 if species i is present in area j, and equals 0 otherwise. This matrix represents the initial state of the sites. Since, however, we allow for stochastic negative environmental effects, there is a site-specific probability $Prob(d_j)$ that in any time period a reserve or non-reserved 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 $I_j^d \subset I_j$. We are dealing with a finite discrete time problem and the total number of periods is T. At the start of each time period t, every site is in one of three possible states: converted, reserve, or non-reserve – in the latter two states the site may also be degraded or not. 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