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A modeling framework for life history-based conservation planning

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ABSTRACT

Reserve site selection models can be enhanced by including habitat conditions that populations need for food, shelter, and reproduction. We present a new population protection function that determines whether minimum areas of land with desired habitat features are present within the desired spatial conditions in the protected sites. Embedding the protection function as a constraint in reserve site selection models provides a way to select sets of sites that satisfy these habitat requirements. We illustrate the mechanics and the flexibility of the protection function by embedding it in two linear-integer programming models for reserve site selection and applying the models to a case study of *Myotis* bat conservation on Lopez Island, United States. The models capture high-resolution, species-specific habitat requirements that are critical for *Myotis* persistence. The models help quantify the increasing marginal costs of protecting *Myotis* habitat and show that optimal site selection strategies are sensitive to the relative importance of habitat requirements.

1. Introduction

Conservation planners make land use and management decisions to ensure the long term viability of species and ecosystems (Margules and Pressey, 2000). One facet of conservation planning is the decision about which parcels of land to purchase or restore given budget limits (Moilanen, 2005). Many types of quantitative tools have been developed to address this reserve site selection problem (see Sarkar et al., 2006 or Moilanen et al., 2009 for reviews). Integer programming formulations typically use number of species represented, number of times species are represented, reserve area, and measures of connectedness and fragmentation as criteria for site selection (e.g., ReVelle et al., 2002; Williams et al., 2004). Most experts agree that these criteria are limited because they do not account for all the factors that affect the long-term viability of populations, including the amount, quality, and spatial arrangement of habitat features that species need to persist (e.g., Church et al., 2000; Sarkar et al., 2006).

To address this limitation, we present a population protection function that can be used to represent habitat requirements in linear-integer formulations of reserve site selection models. The protection function is based on the assumption that every species has specific habitat requirements for food, shelter, and reproduction. Further, these requirements can be expressed using measures of land cover and vegetation structure at the patch and landscape scales. The protection function determines whether minimum areas of land with desired habitat features are present within desired spatial conditions in the protected sites. We demonstrate how the protection function can be embedded as a constraint in two types of reserve site selection models. In both cases, a set of sites that meets all of the habitat requirements for a given species must be contained in the reserve system for that species to be considered adequately protected.

The population protection function is akin to a habitat suitability index (HSI) model, a tool developed in the 1980s to evaluate wildlife habitat (U.S. Fish and Wildlife Service, 1980, 1981). HSI models express habitat quality on a suitability index scaled from zero to one based on functional relationships between species presence and habitat variables. HSI models are widely used in forest planning simulation to evaluate trends in indicators of biodiversity (Marzluff et al., 2002; Larson et al., 2004; Edenius and Mikusiński, 2006; Spies et al., 2007). They are also embedded in timber harvest scheduling models to determine the optimal timing and location of harvest areas while providing desired levels of landscape structure and composition associated with suitable wildlife habitat (Öhman et al., 2011).

A few reserve site selection models include persistence-limiting factors based on habitat quality and location. For example, Church et al. (2000) classify sites by habitat quality and assign weights to protecting species based on the levels of habitat quality that are available in the protected sites. The objective of the model is to maximize the weighted sum of species present. Malcolm and ReVelle (2002) and Williams et al. (2003) develop flyway models

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for migrating birds that identify sets of sites that are within a maximum distance of each other to facilitate migration. Miller et al. (2009) select parcels to restore and protect wetland habitat in agricultural landscapes surrounding core butterfly reserves. Our population protection function provides a general framework for including habitat features and spatial conditions at the individual site and landscape scale in reserve site selection models. This framework is useful at a time when the accumulation of knowledge about the needs and life history of sensitive species has reached unprecedented resolutions due to technological advances in remote sensing, wildlife tracking and statistical analyses (e.g., Barclay and Kurta, 2007; Tomkiewicz et al., 2010; Cagnacci et al., 2010).

A few reserve site selection models directly optimize the likelihood of species presence or persistence as functions of habitat features of the candidate sites. For example, Moilanen (2005) estimates the probability of species presence in each site as a nonlinear function of habitat quality in and around the site. The reserve selection model minimizes the cost of protecting sites subject to a lower bound on the expected number of sites containing each species. Polasky et al. (2008) predict species persistence in a landscape as a nonlinear function of habitat preferences, area requirements, and dispersal abilities in a given land use pattern. They choose land uses to maximize the expected number of species sustained on the landscape subject to economic constraints. While these models contain detailed relationships for the likelihood of species presence or persistence, they are nonlinear-integer formulations that require heuristic algorithms and custom software for solution. Further, the solutions have no guarantee of optimality. In contrast, our population protection function can be embedded in linear-integer programming formulations, for which exact solutions can be found using off-the-shelf commercial software such as ILOG CPLEX (IBM, 2011).

Lastly, we mention that in the facility location literature, problems with compound coverage requirements similar to that of the general species protection function depicted in this paper have been documented. Schilling et al. (1979) considered a fire protection system for the City of Baltimore, United States, where demand nodes were covered only if both primary and certain specialty fire fighting equipment were available. While the logical structure of Schilling et al.'s (1979) model was similar, the model proposed here is more general in that the coverage requirements are not restricted to be binary in nature.

We first present our generalized population protection function and then demonstrate how it can be embedded in two types of reserve site selection models. We illustrate how the model and the generalized protection function work in practice with a case study of protecting habitat for *Myotis* bats on Lopez Island, United States. The models capture high-resolution, species-specific habitat requirements that are critical for species persistence. We show how sensitive the set of optimal reserves might be to the relative importance of various habitat requirements. We conclude by discussing the flexibility and limitations of the proposed approach, and illustrate its compatibility with other spatial models.

2. Methods

2.1. A generalized concept of protection

In the following, we provide a general definition of our concept of protection to motivate the proposed mathematical programming models. The principles of representativeness and persistence advocated by Margules and Pressey (2000) imply that a species may be considered effectively protected only if at least one sustainable population is protected, indicating that a population is the unit of conservation concern. Accordingly, we define a population as a group of conspecific individuals occupying a particular place for a particular time. To distinguish one population from another, we assume that each population retains exclusive use of some resource, defining its particular place as distinct from other populations.

Using terminology defined in Williams et al. (2005), a site refers to a single decision unit that can be selected or not, a reserve is a spatially cohesive (e.g., connected) set of sites selected together, and a reserve system is a set of reserves that makes up the solution to a reserve design problem. Let K_j be the set of distinct survival requirements for population j of a given species, and let k index set K_j. Set K_j may vary between species, but will be the same for each population j of a given species. For simplicity, we refer to K_j as habitat requirements, although it does not need to be restricted in practice since survival requirements other than habitat may include such factors as the availability of prey or the presence of reproductive males and females. Index k appears as a superscript throughout the mathematical notation in this paper to distinguish it from other indices. Lastly, I denotes the set of sites where conservation action may be taken as part of creating a reserve system, and J denotes the set of populations that need and can receive protection. Let i index set I and j index set J. The proposed species specific population protection function, $y_j(\vec{x})$ is a continuous function that determines the amount of protection afforded to population j in the reserve system:

$$y_j(\vec{x}) = \min_{k \in K_j} \left(\frac{1}{m_j^k} \sum_{i \in S_j^k} a_{ij}^k x_i \right) \tag{1}$$

Decision variable x_i is binary: $x_i = 1$ if site i is selected for protection, 0otherwise. Parameters m_j^k and a_{ij}^k, respectively, are the minimum amount of habitat k required by population j, and the amount of habitat k available to population j in location i. We note that this specification assumes that multiple populations (or species) can share commonly accessible resources without any foregone benefits. A discussion about the relaxation of this assumption is presented in the Conclusions. Set S_j^k denotes the resource locations that population j can use to satisfy its habitat requirement k. The summation term is thus the total amount of habitat k available to population j. Dividing by the minimum amount that is required scales the sum so that values below one indicate under-protection, and values above one indicate that requirement k is met. The function $y_j(\vec{x})$, therefore, takes a value greater than one only if all habitat requirements (K_j) are satisfied for population j. The value of the function is strictly less than one if any one of the habitat requirements in K_j is unsatisfied, indicating inadequate protection. In the next section, we show how this population protection function can be embedded in a linear-integer reserve site selection model.

2.2. Model formulation

Mathematical programming is a useful tool to design conservation reserves because of its flexibility to incorporate various conservation goals and because efficient, off-the shelf software is available to formulate and identify optimal solutions. Efficiency in optimization is particularly important when the number of possible conservation actions is high, and the constraints on these actions are complex. Mathematical programs comprise objective functions that represent quantitative goals, such as maximizing conservation benefits or minimizing costs, and inequalities that represent resource limitations or conservation requirements. An example of the latter in our context is the requirement for a population to be considered protected. Multi-objective mathematical