Comment

Applying a Decision-Theory Framework to Landscape Planning for Biodiversity: Follow-Up to Watson et al.

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Habitat reconstruction and landscape planning have become important topics in conservation because we recognize that in many landscapes the quantity and quality of habitat is inadequate to meet biodiversity conservation goals. One method for prioritizing habitat reconstruction is the focal-species approach (Lambeck 1997), in which a suite of sensitive species is identified in order to define the landscape configuration and habitat composition needed to conserve the whole biota. These surrogate species typically include the species most sensitive to habitat area, isolation, certain critical resources, and disturbances such as fire. As with other surrogacy approaches, it is hoped that the needs of other species in the biota will fall under the umbrella of these focal species (but see Lindemayer et al. 2002). Watson et al. (2001) use this focal-species approach to develop guidelines for the size and placement of eucalypt woodland remnants for conserving birds in a region of southeastern Australia. They identify the Easter Yellow Robin (*Eopsaltria australis*) as a focal species for isolation and the Hooded Robin (*Melanodryas cucullata*) as the species most sensitive to habitat area and complexity. The method has the considerable advantage of being easy to communicate and is apparently straightforward to implement because the habitat needs of only a few critical benchmark surrogate species are considered. We believe this approach is only a partial solution, and here we show how it can be formulated explicitly in the broader context of optimal landscape design.

The focal-species approach helps define an easily understood goal, but it does not address the issue of how to most efficaciously reconstruct habitat given a fixed amount of available resources. Moreover, the species in

a community may have conflicting needs in terms of habitat variables and spatial configuration, and the focal-species approach is incapable of effectively "adjudicating" when these species' requirements are at variance. The landscape-design problem has been only partially formulated, and we believe it is necessary to look at habitat reconstruction within a decision-theory framework (Possingham et al. 2001).

To illustrate how to formulate habitat reconstruction in a decision-theory context, we must first define an objective function. Let us assume that our goal is to maximize the occurrence of a number of species in the landscape and that we are interested in determining which areas of the landscape to restore. First, we divide the landscape into a set of sites (often a grid, but could be planning units), where the size of a site is the unit of restoration, a function of sociopolitical concerns as well as the scale of organisms of interest. Let $\mathbf{x}$ be a vector of sites in the landscape, where each element, x_i, is either 0 or 1. If the site is vegetated, then $x_i = 1$, otherwise $x_i = 0$. A possible objective function is

$$\text{maximize } V(\mathbf{x}) = \sum_{j \in \{\text{species}\}} \alpha_j \left[\sum_{i \in \{\text{sites}\}} p_{ij}(\mathbf{x}) \right]$$

$$\text{subject to } \sum_{i \in \{\text{sites}\}} x_i c_i \leq q$$

The probability that focal species j is present in site i, p_{ij}, is a function of the other vegetated sites in the landscape. The probabilities would be derived from logistic-regression analyses of species distribution and would be a function of the site vegetation, biophysical characteristics, the size and shape of the patch in which the site is embedded, and the spatial configuration of other patches in the landscape. It could also be a simple rule that if a patch in which the site is embedded is so large or has so much interior, core habitat, the probability of occurrence would be 1.0. Our control variables are which sites we choose to restore. The weighting factor, α_j, allows us to give priority to certain species. The de-

fault would be to set $\alpha_j = 1$ for all j. The financial cost associated with restoring site i, c_i, which may include costs of revegetation, maintenance, leasing, easements, or acquisition, depends on the socioeconomic issues of the region. The available budget over a planning period (e.g., 20 years) is q.

Restated, the goal is to maximize the function $V(\mathbf{x})$, which is the weighted sum of the probabilities of occurrence of all j focal species over all i vegetated sites in the landscape for restoration, given that the restoration cost is less than or equal to the budget size, q. We can think of this formulation as the "landscape restoration problem."

In a sense, the focal-species approach as first employed is a qualitative expression of the landscape-restoration problem. By formulating the problem with a clear objective and an economic constraint, we are able to use optimization tools to find good solutions to the problem. In the absence of a well-defined problem, we cannot use standard algorithms to solve the problem and would need to operationalize the focal-species approach with ad hoc actions. Indeed, if the focal species have conflicting habitat needs, then it is doubtful that any robust qualitative rules could be developed.

Because the landscape-restoration problem is highly nonlinear and "computationally hard" (a so-called "NP-hard problem") (Cormen et al. 1990), it cannot be solved in a reasonable time for problems with many sites, but fortunately there are many approximate heuristic algorithms that can be used to generate good solutions (Sait & Youssef 1999). Simulated annealing (Metropolis et al. 1953; Kirkpatrick et al. 1983) has been used effectively in reserve design (Possingham et al. 2000; McDonnell et al. 2002). A straightforward "greedy" algorithm may also produce useful answers (Pressey et al. 1997), but it has the drawback of producing only one solution, and in landscape planning we often need many good alternatives.

For various budget sizes, we can derive sets of optimal solutions and distill the spatial characteristics of the landscapes—the size, shape, and isolation of patches, the distribution of various habitat types, and the frequency that certain sites are selected ("summed irreplaceability"). Moreover, we can find the solutions at a smaller budget size that are the best subset of solutions reached at larger budget sizes, which allows us to incorporate dynamics and plan for future restoration.

We are currently using simulated annealing algorithms to find a set of solutions for optimal habitat reconstruction for birds in the Mount Lofty Ranges of South Australia. Figure 1 shows one solution for 22 woodland bird species in a section of the region, where the total region-wide budget size is 20,000 ha. For this scenario, the landscape is considered binary (native vegetation or matrix, which is primarily pasture/cropland), and the objective function is to maximize the probability of occurrence over all species and all newly revegetated sites. All
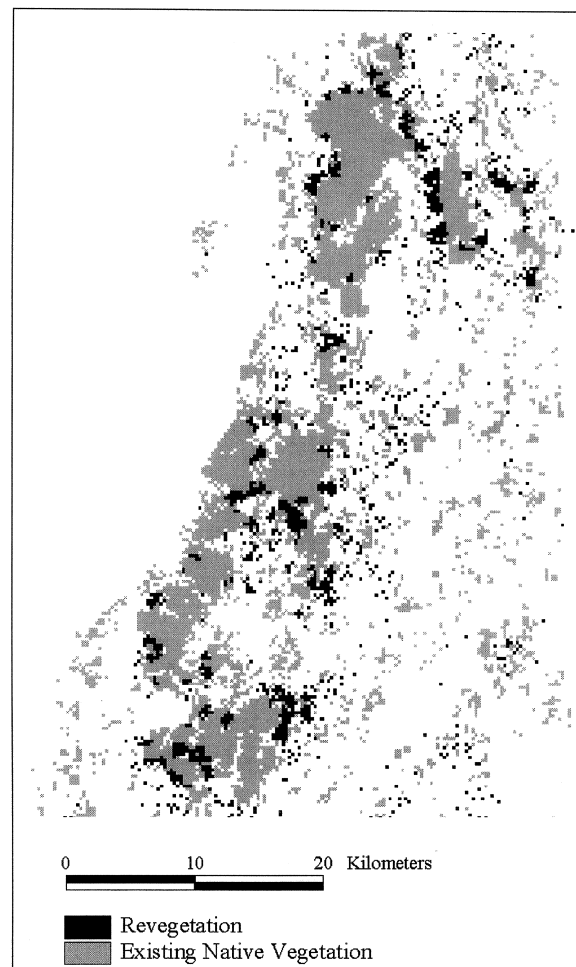

Figure 1. A habitat restoration scenario for 22 species of euclaypt woodland birds in an area of the Mount Lofty Ranges, South Australia. The map is a section of the 500,000-ha region, where the budget size for revegetation is 20,000 ha and the grain-cell size is 6.25 ha.

sites have equal costs. The probability functions are derived from logistic-regression analyses of the effects of the spatial pattern of native vegetation around survey points (e.g., total area of native vegetation, number of patches, patch isolation), based on bird-atlas data. The responses of the species are variable with regard to the spatial pattern, but this one run of the optimization algorithm shows that, for many species in the community, accreting habitat to large contiguous blocks of vegetation is a good strategy. Other species are less sensitive to patch area and respond more positively to the number of patches in the landscape. With the incorporation of more site-specific variables and costs and the inclusion of finer habitat types, the results may differ greatly. The optimal solutions may not easily be intuited from a qualitative understanding of the species biology, given the complexity of the constraints.

Because socioeconomic factors drive conservation planning, we believe that to be relevant to on-the-ground projects, conservation science should be focused more on formulating problems explicitly and showing how the broad variety of decision-making tools can be used to deliver solutions. Conservation biology cannot operate outside the reality of financial limitations.

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