Selecting A Land Conservation Reserve for Local or Regional Ecosystem Health with Development: Amphibian Metapopulation and Residential Development

(draft in progress)

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Abstract

Establishing habitat corridors has been an important strategy in many conservation practices. Nonetheless, the existing literature has ignored the role habitat corridors could play in reserve network design. Based on modern ecological theory, the effectiveness of a reserve system largely depends on its connectivity, but it is less clear how recent spatial modeling of reserve network design improves the connectivity of the reserve system as required by population persistence in a highly fragmented, heterogeneous landscape. This study explicitly incorporates the idea of habitat corridor into optimal reserve design, an approach which might significantly reduce the uncertainty brought by land use change or a source-sink habitat matrix. More importantly, by formulating this conservation issue into an integer programming problem, this study demonstrates a general, systematic, and flexible way to design a well-connected reserve network, and develops standard modeling methods readily applicable to many conservation practices.

Keywords: nature reserve, ecosystem, spatial configuration, amphibian

Introduction

Establishing biological reserves has long been one of the most important and commonly used strategies for biodiversity conservation (Soule 1991; Margules & Pressey 2000; Pressey & Cowling 2001). However, the effectiveness of a reserve system largely depends on the degree to which it satisfies the biological or ecological requirements of targeted species. According to modern ecological theories including island biogeography theory and metapopulation dynamics, the connectivity within the reserve system is critical to maintaining viable biological populations, which implicitly imposes spatial requirements on reserve network design. One tactic for establishing a well-connected reserve network is to link isolated protected areas into one large system through the use of habitat corridors: strips of land parcels running between the reserves (Simberloff et al. 1992; Hill 1995; Primack 1998). Since habitat loss and fragmentation has been commonly recognized as the leading cause of the loss of biodiversity, a well-connected reserve system can be reasonably expected to maintain long-term survival of endangered species by allowing movement, and thus recolonization, among high-quality habitats. This recognition has driven the application of habitat corridor theory in quite a few conservation practices (Mann & Plummer 1995; Spackman & Hughes 1995; Machtans et al. 1996; Wilcove & May 1986; Mwalyosi 1991; Gosselink et al. 1990).

Despite its ecological importance, incorporating the habitat corridor approach into reserve network design has been generally ignored in the literature. Many reserve design studies model reserve site selection as a representiveness problem, leaving the design of effective reserve systems an open question. Recently, spatial aspects of reserve networks have been the focus of reserve design studies. Most of these studies pursue a compact reserve network by focusing on the spatial geometry of the reserve system including minimal distance and low edge/area ratio rather than by examining explicitly the role of the habitat corridor in reserve network design (Nicholls & Margules 1993; Williams & ReVelle 1998; Nalle et al. 2001; Briers 2002; McDonnell et al. 2002; Onal & Briers 2002, 2003). No doubt these spatial geometry-based algorithms to some extent reduce fragmentation of the designed reserve system compared to those without spatial consideration. They may, however, still be insufficient to achieve the connectivity requirements of endangered species without accounting for the heterogeneous, disturbing habitat matrix and development-driven landscape uncertainty where the strategy of habitat corridor is valued.

This study attempts to integrate connectivity into optimal reserve design through explicitly modeling the selection of habitat corridor among protected areas in a heterogeneous landscape. More importantly, by using a standard optimization method — integer programming (IP), this study demonstrates how to formulate and solve the issue of conservation planning with habitat corridors, which is readily applicable to most conservation practices involving corridor connection. The remaining sections of this paper are organized as follows. Section 2 describes the IP formulation as applied to the design of breeding habitat conservation for amphibian species. Section 3 demonstrates the use of our model through an empirical example. We discuss our model and conclude the paper in section 4.

Model Formulation

Suppose conservation managers are facing a reserve design problem involving the efficient selection of land parcels to protect pond-breeding amphibian species in a watershed. Each breeding pond represents one local population which experiences stochastic population turnover as determined by the processes of extinction and recolonization. If the watershed is highly fragmented such that the amphibian of the source ponds cannot succeed in recolonizing extinct ponds through population migration, the metapopulation in the watershed will go extinct in the long term. To maintain long-term persistence of the amphibian requires a system with high connectivity for which we construct habitat corridors by selecting land parcels as reserves to connect breeding ponds. The rationale underlying this conservation practice is to protect amphibian species by protecting their dispersal process from disturbances, especially human-induced land use changes, that might permanently destroy those habitats critical for species survival. We formulate this conservation issue into the set covering problem (SCP) and the maximal coverage problem (MCP) as appeared originally in the literature of operation research, which corresponds to varying conservation situations. The variables involved in the model are defined as follows:

i, j = pond identification

N_i = the neighbor set of pond i

z_{ij} = the status of connection between pond i and j, with 1 indicating connection, and 0 otherwise

c_{ij} = the cost of habitat corridor z_{ij} determined by component land parcels

w_i = the cost of pond i

x_i = the status of pond i, with 1 indicating being selected, and 0 otherwise

B = budget

A = the specified number of connections

MCP formulation

The MCP describes a conservation situation with limited budget, where the available budget typically is not enough to acquire land parcels for corridor connection between all breeding ponds in the watershed. Given heterogeneous land costs, conservation managers have to choose habitat corridors between breeding ponds strategically to maximize the connectivity of the reserve network. The mathematical model is as follows:

$$\text{Max} \quad \sum_i \sum_j z_{ij}$$

$$\text{s. t.} \qquad \sum_i \sum_{j>i} c_{ij} z_{ij} + \sum_i w_i x_i \le B \qquad (1)$$

$$z_{ij} = z_{ji} \qquad (2)$$

$$z_{ij} = 0 \qquad \forall\, j \notin N_i \qquad (3)$$

$$\sum_j z_{ij} \le 3 \qquad \forall\, i \qquad (4)$$

$$x_i \ge z_{ij} \qquad (5)$$

$$z_{ij}, x_i \in (0, 1) \qquad (6)$$

The objective function maximizes the connection of the designed reserve network through habitat corridors. Constraint (1) is a budget constraint that the cost of land acquisition to construct habitat corridor plus the cost of ponds involved should not be greater than the budget available. Note that setting j > i in this constraint precludes double counting the connection cost. Constraint (2) is a symmetry restriction, that is, whenever pond i is connected/not connected to pond j, pond j is also connected/not connected to pond i. By constraint (3), the model only allows corridor connections between a focal pond and neighboring ponds which are defined as all ponds within a biologically specified radius of the focal pond. This constraint implicitly assumes the dispersal process of amphibians is only possible between direct neighboring ponds within a limited distance because migration is energy-depleting and subject to a variety of risks. Since habitat corridors may be clustered on some ponds because of cost advantage when these ponds have been selected already, constraint (4) limits the maximum number of connections of one pond with other ponds to 2, which helps evenly distribute habitat corridors within the reserve system. This constraint assigns no value on the extra connection if the focal pond has already been connected to two other ponds. Constraint (5) means the pair of ponds has to be selected whenever there is a corridor connection between them.

SCP formulation

The SCP describes a conservation situation where conservation biologists have prescribed minimum connection requirements, and conservation managers seek to minimize the cost of achieving these requirements. Given heterogeneous land costs, an optimal model of corridor selection could make a difference in terms of total expense. The mathematical model is as follows:

$$\text{Min} \quad \sum_i \sum_{j>i} c_{ij} z_{ij} + \sum_i w_i x_i$$

s. t. $$\sum_{i}\sum_{j>i} z_{ij} \geq A \qquad (1')$$

$$z_{ij} = z_{ji} \qquad (2')$$

$$z_{ij} = 0 \quad \forall\, j \notin N_i \qquad (3')$$

$$\sum_{j} z_{ij} \leq 3 \quad \forall\, i \qquad (4')$$

$$x_i \geq z_{ij} \qquad (5')$$

$$z_{ij}, x_i \in (0, 1) \qquad (6')$$

The objective function minimizes the cost of a well-connected reserve network while achieving the minimum connection requirement specified by constraint (1'). The remaining constraints are the same as their counterparts in the MCP formulation.

An Empirical Example

We apply our optimization models to the conservation issue of amphibian species of the Pawcatuck Watershed in southern Rhode Island. For the purpose of clarity and demonstration, we focus on a subarea at the northeast corner of the watershed, which includes 39 temporal breeding ponds (Figure 1).

The targeted amphibian species is wood frog (*Rana sylvatica*), representing spring-breeding species considered obligate breeders in vernal pools (dependent on temporary wetlands for breeding habitat), marbled salamander (*A. opacum*), a fall breeding species, and grey tree frog (*Hylaversicolor*), an arboreal species considered uniquely sensitive to development. Parcel-level property value data was obtained from all towns falling within this subarea. A simple Kriging method using ArcGIS

8.3 Spatial Analyst produces 1-ha land cost grids. Skidds (2004) provides details on the above information.

We use the algebraic programming language GAMS 20.7 to solve our optimization models. Because the SCP and the MCP can be regarded as the dual approach of each other, they would generate the same result if we set the budget in the MCP equal to the minimum cost for the specified connection goal. Therefore, we only present the modeling output from the MCP formulation (Figure 2).

Discussion

The habitat corridor approach has been embraced with enthusiasm by many conservation managers as a strategy for managing wide-ranging species (Primack 1998). Nonetheless, the existing literature of reserve design largely ignores the role it could play in designing a reserve network with high connectivity. To some extent, using habitat corridors demonstrates certain advantages over the application of spatial geometry for conservation planning. For example, in a highly fragmented landscape or a landscape facing heavy development pressures from competitive land uses, say, in densely populated Europe, establishing habitat corridors may be the only way to protect critical habitats or endangered species effectively within a hostile environment. On the other hand, how the spatial structure of landscape relates to landscape connectivity consequences is still a case-specific question without a commonly agreed upon, effective measure of connectivity in spatial ecology (see Moilanen & Nieminen 2002), while the habitat corridor approach at least reduces some of the uncertainty involved in the above issues.

This study addresses the strategy of incorporating habitat corridor into optimal reserve design, methodologically contributing to the existing literature. This modeling approach may be of interest to conservation managers who intend to establish habitat corridors and to conservation biologists examining the potential of habitat corridors for contributing to a well-connected reserve network. By formulating this conservation issue as an integer programming problem, this study creates a general, systematic, and flexible way to model reserve design with habitat corridor. Sessions (1992) has modeled habitat connections as a Steiner network problem which can only be solved by heuristic methods. One major drawback associated with this method is the suboptimality of solutions, that is, the reserve network designed may not be optimal even if it does exist. Moreover, the development of heuristic algorithms to solve a Steiner network is very complicated, demanding highly sophisticated programming and professional skills which may dramatically increase the management cost of conservation planning. In contrast, our modeling method, similarly, seeks an optimal solution if it exists, yet is quite general, straightforward, and easy to apply. Also, our modeling method demonstrates some flexibility to address varying policy situations such as budget-constrained decision-making, which might be a challenge for a direct application of the Steiner tree approach.

Similar to most spatial modeling studies on reserve network design, this study is also subject to the issue of being *ad hoc* on reserve site selection. That is, it is not clear how the selection of reserve sites is related to their conservation effects by following some prescribed spatial surrogates such as “being compact” or “being connected." Nonetheless, this study, assuming the validity of those spatial surrogates, is intended to propose a standard optimization method that (1) could flexibly incorporate the extensively used and powerful conservation strategy — habitat corridors — into optimal reserve design, and (2) can be easily used to help corridor-relevant conservation decisions. Future extensions might focus on: exploring how the selection of habitat corridors improves the probability of species survival, and thus affects the designed reserve network; the tradeoff between conservation strategies in relation to their conservation effects with and without corridor connection, and determining how reserve design algorithms could help conservation managers identify the condition of applying habitat corridors approach in a heterogeneous landscape. However, these research initiatives will depend on a clear delineation and measure of connectivity, on clearly understanding how the spatial configuration of the reserve network is related to the connectivity measure, and on the development of ecological theory that could quantitatively describe how the spatial configuration of a reserve network in a heterogeneous landscape affects the survival of biological populations.

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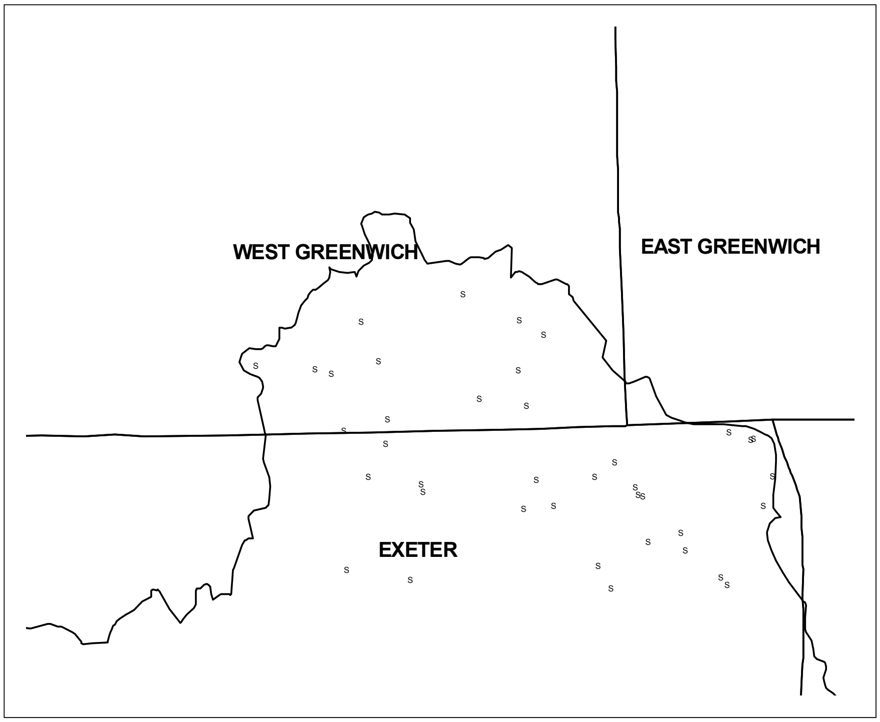

Figure 1. Sample Area at the Northwestern Corner of the Pawcatuck Watershed

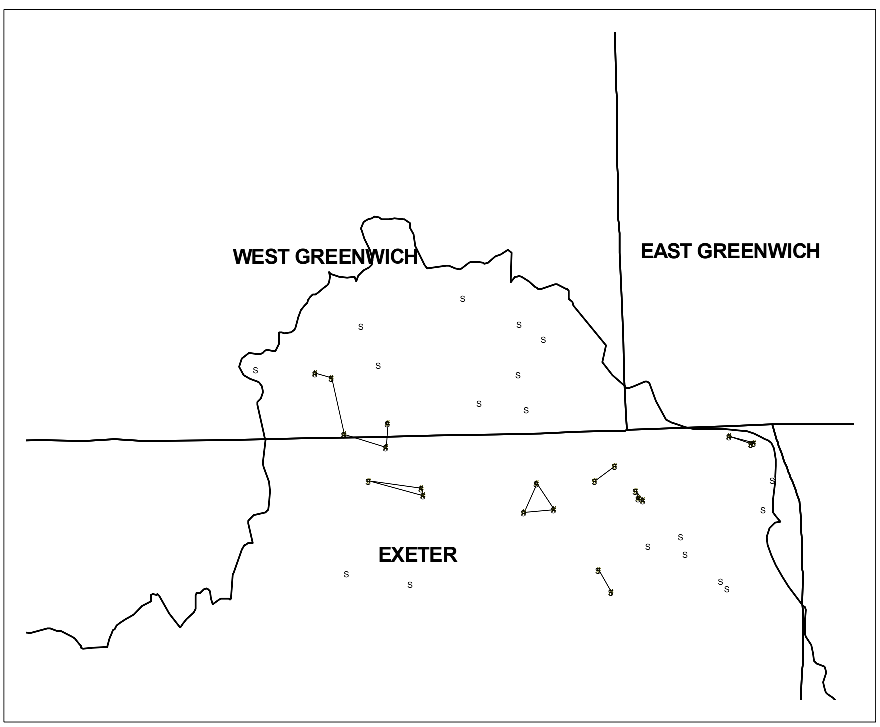

Figure 2. Modeling Result of Optimal Reserve Network with Habitat Corridor