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Achieving full connectivity of sites in the multiperiod reserve network design problem

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ABSTRACT

The conservation reserve design problem is a challenge to solve because of the spatial and temporal nature of the problem, uncertainties in the decision process, and the possibility of alternative conservation actions for any given land parcel. Conservation agencies tasked with reserve design may benefit from a dynamic decision system that provides tactical guidance for short-term decision opportunities while maintaining focus on a long-term objective of assembling the best set of protected areas possible. To plan cost-effective conservation over time under time-varying action costs and budget, we propose a multi-period mixed integer programming model for the budget-constrained selection of fully connected sites. The objective is to maximize a summed conservation value over all network parcels at the end of the planning horizon. The originality of this work is in achieving full spatial connectivity of the selected sites during the schedule of conservation actions.

1. Introduction

Reserve network design is the problem of selecting parcels of land such that the assembled set maximizes some criterion pertaining to the conservation of species or natural communities with consideration of spatial constraints [47]. The problem is characterized by some common features that make its solution computationally challenging. First, the problem is spatially defined, where the decision criterion may be just as sensitive to where parcels occur on the landscape and their positions relative to one another as to how much land area is selected. Second, sources of uncertainty—for example, variability in land prices or acquisition budgets, errors in assessing land quality, and uncertainty about urbanization trends, market dynamics, and habitat requirements of a focal species or community—are always present and expose the decision maker to the risk of ineffective selections or missed opportunities. Third, selections are almost always carried out over time, implying that an optimal sequence of actions cannot be made without consideration of the dynamics of land availability and budget resources, and these processes are often unknown. Fourth, the decision maker may have alternatives other than land purchase (e.g., conservation easements, incentives for landowner behavior) that induce tradeoffs in costs and benefits.

The general reserve site selection problem concerns which sites to select from a pool of candidates to maximize biological benefits within a given budget. Absent any constraints regarding the spatial configuration of sites and assuming all sites have identical conservation value and cost, maximization involves a combinatorial problem of selecting p sites from n candidates, where the number of possible solutions is $\binom{n}{p}$.

The reserve site selection problem has been studied extensively, particularly in the context of a one-time decision, i.e., as a static formulation; Williams et al. [47] and Billionnet [4] provide comprehensive reviews. In practice, conservation actions are taken over time in the face of stochastic land availability, habitat loss, and budgets. Recognizing this, a few studies have addressed reserve site selection as a dynamic problem. Dynamic approaches formally acknowledge the fact that future optimal trajectories of conservation actions depend on today's action and its

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outcome; thus, evaluating the best action today requires taking into account all future actions and consequences that may occur over some specified time horizon. For this reason, such approaches explicitly account for random events related to land availability status [17,38,41], land market feedbacks [1,15,20,41], land costs [45], habitat suitability, and budget availability, among others. Others account for uncertainty in key estimated parameters, such as survival or persistence probabilities [5,27]. Stochastic dynamic programming [13,23,32,35,39], heuristic algorithms [6,18,24] and integer programming models [15,17,36,38,41] have been applied to solve these dynamic decision problems. Approximate dynamic programming [33] may be particularly useful in reserve site selection applications as exact methods quickly succumb to problem size.

Our interest is in a special subclass of this problem, the reserve network design problem (RNDP), in which a constraint of parcel connectivity is imposed. The constraints involved in finding admissible solutions of contiguous regions introduce greater complexity to the problem, compared with the reserve site selection problem.

In selecting sites for reserve design purposes connectivity of habitat is important for allowing species to move freely within a protected area. The aim of this work is to formulate an improved algorithm for the design of a network of sites for conservation purposes which maximizes some utility subject to various constraints. These constraints include a budget limitation and spatial attributes such as connectivity.

Allocating least cost Hamiltonian circuits or paths in a graph encompass various applications of real-life problems including transportation scheduling problems, delivery problems, forest planning, telecommunication and social networks, reserve network design, and political and school districting [7–9,11,12,16,21,22,34,37,44]. Each of these problems, known as a variation of the travelling salesman problem, require particular objectives and constraints to be satisfied.

Several methods have been presented for the reserve network design problem with consideration of contiguity requirements. Williams [46] formulated the first general, practical integer programming method for land acquisition that enforced full contiguity of the selected sites. The method required the specification of the number of sites to be selected. Others have also used graph theory and network optimisation [10,14,29–31] to solve the RNDP. Where budget resources were sufficient, Önal and Wang [31] considered minimizing the sum of gaps between neighboring sites to encourage a fully connected reserve. Conrad et al. [10] proposed a hybrid approach that combines graph algorithms with mixed integer programming (MIP)-based optimization for finding corridors connecting multiple protected areas together. Finding corridors required preselecting sites in the landscape to act as a source and a sink. Jafari and Hearne [19] proposed a mixed integer programming formulation of the RNDP using the concept of flow in a network. The method ensures full contiguity of both regularly (grid-based) and irregularly shaped candidate sites. The model also accommodates other forms of spatial constraint such as compactness, which is often an important property of a solution.

To our knowledge, the reserve network design problem in which a constraint of parcel contiguity is imposed has not been investigated in the context of a multi-period decision problem. That is, the making of optimal decisions with respect to which parcels to choose and the order in which to acquire and connect them may be informed by the length of the planning time horizon and assumptions about the time trajectory of budgets, parcel costs, and parcel values.

We present a model to solve the multi-period reserve network design problem where extrinsic factors (budgets, land prices, conservation values) may vary over the length of a fixed planning horizon. We demonstrate application of our model to a real reserve network design problem regarding conservation of the gopher tortoise (*Gopherus polyphemus*) in Georgia, USA. Our model provides an optimal solution that describes where to purchase parcels and in what order to acquire them for the goal of making the largest contiguous reserve possible constrained by budget. Although our solution is not stochastic, we extend the static one-shot RNDP [19] with multiple time steps, time-varying parameters, and dynamic carry-over of budget, which is a significant step toward fully dynamic representation of the problem.

Our work herein focuses on the multi-period mixed integer programming model for budget-constrained selection of fully connected sites for cost-effective conservation. The objective is to maximize a summed conservation value over all network parcels at the end of the planning horizon under time-varying conservation costs and budget. An overview of the proposed model is presented in Section 2 and the formulation and extension of the model accompanied by an example in Section 3. The study area and the focal species, as well as the design and results of applying the model to the case study, are described in Section 4. We discuss opportunities and limitations of the model, as well as areas of future research in Section 5.

2. Materials and method

2.1. Landscape representation

Consider a landscape as a graph (network) that consists of N nodes (sites) and set of arcs that link them. Each node has its own attributes such as cost and utility values. The utility value associated with each node may be a weighted average of multiple attributes that are of importance to conservation planners. The arcs define links between two nodes, representing two adjacent sites with a common boundary. In this work we will frequently refer to the flow in the network. To construct our flow network, we add a dummy node as the supply node containing the total capital available to the network. In our application, capital is represented by the total budget available. Capital can only flow along arcs, in other words, from a node to one or more of its neighbouring nodes (see Fig. 1).

2.2. Description

In our approach, we use mathematical programming techniques to build a network in a periodwise process, considering for selection at each period those parcels connected to those already chosen in previous periods. Thus, we achieve a fully connected reserve network over the planning time horizon. However, the combinatorial nature of the problem poses difficult challenges. The selection of a parcel is not based merely on the intrinsic value that it adds to the network, but also on its role as a connection to potential parts of the network yet to be acquired.

The most challenging part of the proposed method is to obtain a fully connected solution at time $t = 0$. To do so we call the flow-based model that provides the optimal “one-shot” (non periodwise) solution [19]. A brief description of that model is presented in Model 1. All the nodes of the network are involved in the solution in this static model (the constraints have been defined for every node in the network).

In this model, the decision variables and parameters are as follows: F_{ij} is a variable that indicates the flow of capital from node i (including the supply node, node 0) to node j; x_{ij} is a binary variable indicating whether or not capital flows along the arc (i, j); N_i is the set of nodes connected to node i (the adjacency set); c_i is the price value and u_i is the utility value of node i; B is the to-