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Innovative Applications of O.R.

Optimal design of compact and functionally contiguous conservation management areas

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ABSTRACT

Compactness and landscape connectivity are essential properties for effective functioning of conservation reserves. In this article we introduce a linear integer programming model to determine optimal configuration of a conservation reserve with such properties. Connectivity can be defined either as structural (physical) connectivity or functional connectivity; the model developed here addresses both properties. We apply the model to identify the optimal conservation management areas for protection of Gopher Tortoise (GT) in a military installation, Ft. Benning, Georgia, which serves as a safe refuge for this 'at risk' species. The recent expansion in the military mission of the installation increases the pressure on scarce GT habitat areas, which requires moving some of the existent populations in those areas to suitably chosen new conservation management areas within the boundaries of the installation. Using the model, we find the most suitable and spatially coherent management areas outside the heavily used training areas.

1. Introduction

In many parts of the world conservation reserves are established to protect critical habitat areas from agricultural/urban development and managed to maintain or enhance species survival chances. Due to the scarcity of financial resources, determination of the optimal amount and location of those areas is an important issue. Typically, this is done by dividing the landscape into discrete land units (sites) and selecting an optimal subset of them assuming that each site provides measurable habitat services to the targeted species. This problem is often stated as minimization of the cost of selected sites while meeting the conservation goals (e.g., minimum occurrence of each species in selected sites), or maximization of a conservation objective (e.g. number of species protected) subject to the available resource constraints (Moilanen, Wilson, and Possingham 2009). These problems were addressed initially by using heuristic approaches (e.g., Pressey, Humphries, Margules, Vane-Wright, & Williams, 1993, 1997). Later, they were formulated as linear mixed-integer programs (MIP) in the framework of the set covering problem (SCP) and maximal covering problem (MCP) (Camm, Polasky, Solow, & Csuti, 1996; Church & ReVelle, 1974; Church et al. 1996; Cocks & Baird, 1989; Kirkpatrick, 1983; Polasky, Camm, & Garber-Yonts, 2001; Possingham, Ball, & Andelman, 2000; Toregas & ReVelle, 1973; Underhill, 1994; Williams & ReVelle, 1997). Although the optimal solutions of these MIP formulations are economically efficient, they usually lack spatial coherence. This may limit the chances of inter-site dispersal and long-term survival of species within the conservation reserve areas. Also, managing a spatially coherent reserve network is more convenient and efficient than managing many sites scattered over a large area. Therefore, additional mechanisms need to be introduced in the SCP and MCP formulations to take spatial properties into account when determining the optimal site selection.

Spatial criteria in reserve site selection may take a variety of forms (Haight & Snyder, 2009; Williams, ReVelle, & Levin, 2005). Most commonly used criteria include compactness (Fischer & Church, 2003; Jafari & Hearne, 2013; Önal and Briers, 2003; Tóth & McDill 2008; Wright, ReVelle, & Cohon, 1983), proximity of selected sites (Briers 2002; Dissanayake, Önal, Westervelt, & Balbach, 2012; Miller, Snyder, Skibbe, & Haight, 2009; Nalle, Arthur, Montgomery, & Sessions, 2002; Önal and Briers, 2002; Rothley, 1999; Snyder, Miller, Skibbe, & Haight, 2007; Williams, 2008), habitat fragmentation (Önal & Briers, 2005; Önal & Wang, 2008), contiguity (Cerdeira & Pinto, 2005; Cerdeira et al., 2005, 2010; Cova & Church, 2000; Duque

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et al., 2011; Jafari & Hearne, 2013; Marianov, ReVelle, & Snyder, 2008; Önal & Briers, 2006; Tóth et al., 2009; Wang & Önal, 2011, 2013; Williams, 2001; Carvajal et al., 2013), existence of buffers and corridors (Conrad, Gomes, van Hoeve, Sabharwal, & Suter, 2012; Williams, 1998; Williams & ReVelle, 1996, 1998; Williams & Snyder, 2005), and accessibility (Önal & Yanprechaset, 2007; Ruliffson, Haight, Gobster, & Homans, 2003). Incorporating these criteria in optimum site selection requires more sophisticated and computationally complex mathematical models than the SCP and MCP formulations. Consideration of multiple attributes together increases this challenge further. This article presents a linear integer programming model to incorporate compactness and connectivity criteria simultaneously.

Connectivity is an important factor for efficient functioning of conservation reserves. A well-connected reserve network[1] allows the species to utilize all the resources available in the reserve and increases the likelihood of species survival and ability to colonize suitable habitat areas. This depends not only on the habitat characteristics of an individual reserve site, but also on the characteristics of the neighboring reserve sites (Van Teeffelen et al., 2006). Connectivity is approached in different ways. *Metapopulation connectivity* deals with spatially separated but interacting local populations in the reserve network (Hanski, 1999; Moilanen & Hanski, 1998; Moilanen & Hanski 2001). *Landscape connectivity*, on the other hand, deals with the degree to which the landscape facilitates movement of species within reserves. Landscape connectivity can be achieved either by *structural connectivity* (or physical contiguity) that allows species to dwell in the reserve without having to get out of the protected area, or *functional connectivity* which deals with the degree to which a reserve facilitates species' capability to move within the reserve (Bunn, Urban, & Keitt, 2000; Taylor, Fahrig, & With, 2006; Taylor, Fahrig, Henein, & Merriam, 1993; Tischendorf & Fahrig, 2000; Urban & Keitt 2001). A structurally connected reserve may not necessarily be functionally connected if physical characteristics of some sites impede movement within or between the reserved areas (e.g. presence of steep rocky terrains or water bodies, lack of sufficient vegetation or forest cover). Although the importance of functional connectivity has been widely acknowledged, a generally agreed upon operational definition of the concept is not yet available (Bélisle, 2005; Kadoya, 2009). Incorporating these two connectivity criteria in site selection may lead to dramatically different configurations. For instance, minimization of the reserve size along with the physical contiguity requirement may lead to an elongated, narrow and winding reserve configuration containing the best available but spatially dispersed sites (see, for instance, Cerdeira, Gaston, & Pinto, 2005; Önal & Briers, 2006; Williams & Snyder, 2005). This would increase the likelihood of species' exposure to unfavorable conditions within and outside the reserve area and may not work effectively if the individuals tend to roam around or move in random directions. A contiguous reserve configuration may include poor quality sites just to obtain physical connections (bridges) between good habitats. Such a reserve would not be *functionally* connected if the targeted species do not have the capability to cross those bridging sites. Therefore, in essence the reserve would consist of multiple 'functionally detached' sub-reserves some of which may not be large enough to provide adequate habitat services for a minimum viable population of the target species. On the other hand, a functionally connected reserve may not be structurally connected if the species (e.g. birds, butterflies) can crossover between closest, but not necessarily adjacent areas in the reserve. In many cases a network of multiple connected reserves is a preferred configuration than a single large connected reserve to safeguard against catastrophic events such as fire, diseases, etc.[2] In this article we address these issues and present a linear integer programming model to determine an optimal *compact* and *connected* reserve network configuration where connectivity can be enforced in the form of *structural connectivity* and/or *functional connectivity*. We apply this approach to the protection of a ground-bound species where compactness, structural connectivity, and functional connectivity must be enforced together.

2. Problem description

Many rare, threatened, and endangered species in the U.S. are found within the boundaries or in the vicinity of military installations (Flather, Joyce, & Bloomgarden, 1994; Flather, Knowles, & Kendall, 1998; Stein, Scott, & Benton, 2008).[3] The Department of Defense (DoD) allocates a significant amount of capital, human resources and land for conservation efforts toward protecting and managing wildlife habitat in and around military installations.[4] Ft. Benning, Georgia, is one of those installations where several endangered, threatened, and at-risk species are under protection. In this article we consider a particular keystone species, Gopher Tortoise (*Gopherus polyphemus*), which has an 'at risk' status and currently has an extensive population in Ft. Benning. The installation is currently undergoing an expansion of its military mission that requires converting more lands into military training areas. Therefore, managing those lands in the best possible way as an alternative to costly arrangements, such as purchasing additional land or acquisition of property rights for lands around the installation, is an important issue. The land managers plan to identify lands outside of the current and future military training areas for maintaining sustainable GT populations (including the relocated populations and populations that might be brought from outside the installation). These areas, called 'Conservation Management Areas' (CMA), will be used less for military training purposes or assigned to appropriate training exercises to the extent possible. Since GT is a ground-bound species, a selected CMA should be as compact as possible and connected both structurally and functionally in order to facilitate movement of GTs in those areas. In addition, if multiple CMAs are to be configured, each CMA must be large enough to sustain a minimum viable GT population in it. We note that interaction of the protected GT populations in different CMAs is not an issue, which means that two CMAs can be located at distant parts of the installation. Thus, connectivity (both structural and functional) is required at local (landscape) level, not at the entire CMA network level.

3. The model

To address the issues described above we first partition the area considered for development of a conservation reserve[5] into disjoint spatial units (e.g., a uniform square grid cover[6]). Each spatial unit (site) is either selected and becomes part of a reserve in the network or is left out. When selecting sites the spatial locations of indi-

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[1] Throughout the paper we use the term 'reserve' for a collection of sites that work together to serve a viable population of one or more targeted species. A 'reserve network' consists of multiple reserves that collectively serve a sufficiently large total population of each targeted species.

[2] For the merits of establishing multiple reserves see Zhou and Wang (2006).

[3] Although the total amount of land controlled by the DoD is only 3.4 percent of the federally administered lands, 26 percent of the threatened and endangered species occurs on the military lands (Flather et al., 1994).

[4] In 2006, for instance, the DoD spent $4.1 billion on environment related expenses of which $1.4 billion was for environment restoration and $204.1 million was for conservation (Benton et al., 2008). The DoD also implements various management policies on military lands including protection of endangered, threatened and at-risk species (Diersing et al., 1992; DoD (2011, p.12).

[5] Here we use the term 'reserve' to refer to the protected areas in general. In the empirical application we use the term CMA instead of 'reserve' because the military does not really view these areas as 'reserves'; the conservation objectives are always secondary and subject to the military objectives.

[6] The cover may consist of triangles, rectangles, polygons, or irregular shapes. Thus, the square grid assumption is not restrictive. Throughout the paper we will use the terms 'cell' and 'site' interchangeably.