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Backup coverage models in nature reserve site selection with spatial spread risk heterogeneity

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ABSTRACT

Set covering and maximal covering problems are well-known integer programming models in location analysis. Such models have also been used in reserve site selection modeling. They aim at selecting sites to conserve species, sometimes reflecting a desire to group protected sites together or to separate sites. This paper uses such models but considers the case of land heterogeneity in terms of the risk of large disturbances that threaten species even within a reserve, such as fires, diseases, pests or invasive species. It removes the classical assumption of homogeneous land sites and considers both adjacency in areas with a low risk of multi-parcel disturbance and distance between sites in areas with a high risk of a large destructive event. The models are explored in a stylized data set and applied to a portion of the state of Oregon with comparison between the standard covering models in homogeneous and heterogeneous risk settings.

1. Introduction

The setting aside of public and private land for the creation of nature reserves to preserve key habitat and species living within those reserves is a way to conserve biodiversity. For more than 20 years, researchers have formulated models that propose efficient methods for delineating sets of nature reserves to protect species. In many cases, reserve networks that contain a particular species in more than one reserve site increases the chances of species survival in the face of destructive events that could occur in, or spread to, a species' location. Much of the recent reserve site selection literature considers gains to species conservation from locating reserve sites in an agglomerated pattern. Less literature emphasizes that risks that spread across contiguous parcels such as invasive species, pests, or fire make agglomerated reserve sites less attractive and increase the benefits of establishing distance between reserve sites. The analysis here considers heterogeneity across a landscape in the types of risks that threaten species and, using a model derived from location science, requires either adjacency or distance between reserve sites depending on whether those risks tend to be localized or tend to spread, respectively.

Location science's set covering models and maximal covering models are aimed at locating the least number of facilities to cover all demand nodes and to cover as many demand nodes as possible with a given number of facilities, respectively [1,2]. The former model is generally termed the Location Set Covering Problem (LSCP) and the latter is referred to as the Maximal Covering Location Problem (MCLP). These models have been applied to nature reserve site selection as tools to protect – or "cover" – all of the species of a pre-determined area [3,4] or the maximum number of species of the study area given a restriction on the number or area of selected sites [5,6].

Model refinements for reserve site selection include economic costs, redundant or "backup" coverage, probabilities of survival, uncertainties, dynamic reserve site selection, habitat quality and spatial issues (e.g. Ref. [7] for a survey).

In location science [8], underlined the importance of "backup" (and hence, multiple) coverage, such as selecting an additional facility to cover each demand node in case a problem occurs in the first facility. This concept was refined over the years (e.g. Ref. [9]) and used to address a wide range of issues including reserve selection and reserve design. Among others [10], concentrated on a single species and determined the optimal number of reserves that should be established to maximize its persistence and [11] adapted Hogan and ReVelle's backup formulation to multiple species protection by maximizing the number of species covered more than

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once for a given reserve network. Within an SSCP format [12], imposed backup coverage for species present in multiple sites and single coverage for those present in one core site only, while [13] required additional protection for rare species by maximizing redundant coverage of these rare species.

Probabilistic species presence (e.g. Ref. [14]) and dynamic models (e.g. Ref. [15]) have been studied in various papers even though most of the literature remains deterministic and static. Several types of uncertainties or risks have been considered in the reserve selection literature. Uncertainty about species occurrence – the species' presence or absence on a site – implies that "covering" one parcel does not guarantee that that parcel's species are actually present in the reserve network [14,16,17]. Other articles incorporate uncertainties about species response to fragmentation [18] or about extinction risk when making conservation decision [19]. These risks generally impact species directly in a probabilistic setting.

Heterogeneity in land costs has been introduced by Refs. [20,21] for promoting cost efficient site selection and [22] introduced heterogeneity in terms of habitat quality into a reserve site selection.

Models with spatial considerations have been introduced as part of the SLOSS (single large or several small) debate [23] as many biologists suggest that spatially aggregated, contiguous or connected reserves increase the survival probabilities of many species. These models consider the delineation of core areas and buffer zones, proximity and compactness, connectivity, and boundary shape or convexity (e.g. Refs. [24,25] for surveys). Most spatial models consider agglomeration of selected sites to reduce edge effects, facilitate dispersal, allow recolonization (e.g. Refs. [26,27]), and reduce management costs associated with the boundary length of a reserve network [28]. The "several small" side of the SLOSS debate has received less attention even though such design features might lessen the risks associated with a catastrophe [29,30]. In particular, the spatial distribution of reserves into several small sites reduces the opportunity for risks that spread across a landscape, such as large fires, to impact multiple reserve parcels; hence, separation is sometimes preferred [31].

The spatial analysis in this paper considers both a separation distance and proximity requirements for the pattern of reserve sites chosen in a network. In portions of the landscape that face low risk of hazards that spread from one parcel to another, proximity requirements lead to agglomeration of reserve sites. In portions of the landscape that face habitat-disrupting processes that spread from one parcel to another such as fire, separation requirements lead to more dispersed reserve sites. At a regional scale, a landscape contains both such types of risk to habitat and to species. For example, within one landscape, small fires might be likely in moist forests while large, spreading fires threaten broader areas of dry forests.

Various destructive forces create risks to species through the hazard's impact on habitat even within a reserve network. When a hazard such as pests, invasive species, or fire destroys a parcel's habitat, the species in those parcels may no longer be protected by the reserve system. The risk of large disturbances (multiple parcels) varies across the landscape and our reserve site selection, unlike most other risk-based reserve site selection models, takes this land risk heterogeneity into account in establishing reserve networks. In regions with large, spreading hazard risks, separating reserve sites reduces the chance that one hazard event will destroy all of a particular species' habitat.

Spreading hazard risks have rarely been incorporated in reserve site selection despite their increasing importance in many settings, including the western United States. For example, the spreading disease Swiss Needle Cast killed trees on more than 300,000 acres in Oregon in 2010 and the pest Mountain Pine Beetle damaged over 450,000 acres of forest habitat in 2009 and 2010 [32].

Here, we use the example of large spreading wildfires as a spatially spreading hazard due to the pedagogical ease of envisioning fires spreading rapidly across many parcels and to represent one of the most significant threats to habitat in the western United States and beyond. The increase in the number and extent of wildfires in the western United States is well documented [33,34]. Since 1987, wildfire frequency is nearly four times the average of 1970–1986 and the total area burned by fires is more than six and a half times its previous level [33]. The National Interagency Fire Center (NIFC) reports that between 2000 and 2013, there were 151 "large fires" (exceeding 100,000 acres) in the U.S. Oregon is well represented in this group, with 11 "large fires" over the same period, the most expansive of which occurred in 2012 and burned over 550,000 acres [35]. Given the widespread impact of fire throughout the western United States and predicted increases future large fire occurrence [36], the focus on this spatially spreading hazard is timely and offers insight into a current challenge to reserve design.

A fire risk map for Oregon [37] provides the basis for describing the risk of large fires across the state. Although fuel treatments and fire suppression activities can alter or limit the spread of fires, large spreading fires still present a major concern. In addition, agencies tasked with habitat management to protect species often have limited means to address the fire hazard directly. Indeed, in the western United States, public land managers are unable to complete widespread fuel treatments to mitigate wildfire risk. First, budget constraints for land management activities limit the total number of acres that can be treated, with a 37% reduction in federal budgets during the past year [38]. Second, Collins et al. [39] outline additional constraints on fuel treatment on public land, including restrictions on risk-mitigating activities that disrupt habitat, policies that limit the use of prescribed fires to specific areas and times, and legal processes that delay or prevent fuel treatment projects. Last, even when land managers can undertake such fire damage mitigation, public distrust, and lawsuits often block such projects [40,41]. Thus, large, spreading fires pose a considerable threat to habitat but species protection agencies cannot control or manage that risk directly, which increases the need for other tools such as reserve site location choices that reflect the spatial characteristics of the risks facing species within reserves.

The models described in the next section incorporate a landscape with heterogeneous risk by dividing parcels into low, medium or high spread risk areas. In low spread risk areas, spatial contiguity is promoted by requiring "backup coverage" for each species in two adjacent parcels; however, distance constraints are imposed for preserving the species in medium and high spread risk areas to avoid a spreading fire affecting a species protected in two locations. More precisely, connectivity or adjacency requirements have been proposed in many reserve site selection and design articles as tools to create agglomerated reserve networks (e.g. Refs. [42–45]). Adjacency constraints and clique constraints are also used in timber harvest and scheduling literature (e.g. Refs. [46,47]) and are relevant to spatially constructed reserve site selection (proximity requirements). Indeed, in low fire spread risk areas, we impose proximity by requiring that backup coverage occur in parcels adjacent to primary coverage. Less well addressed are situations in which managers desire reserve sites to be spread at some distance, as they might in the case of spreading or large contiguous threats to species. For example, Ref. [31], requires some amount of distance between primary and backup coverage sites to create a more dispersed pattern and in location science, and Ref. [48] imposes minimum distance between undesirable facilities.

The remainder of the paper is organized as follows. Section 2 presents the models and the next two sections apply the models