Fires and Outbreaks and Pests, Oh My!

Spatially-correlated Risk in Reserve Site Selection

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Abstract

Establishing nature reserves protects species from land cover conversion and lost habitat. Even when a species is contained in a reserve, however, many factors still threaten their survival. To address the risk of survival after reserve establishment, reserve networks can be created that allow some redundancy of species coverage and maximize the expected number of species that survive. In some regions, however, the threats to species within a reserve may be spatially correlated. As examples, fires, diseases, and infestations all spread from a starting point and threaten neighboring parcels in addition to the initial location. This paper develops a reserve site selection optimization framework that compares the reserve networks from cases in which risks do and do not reflect spatial correlation. In addition to demonstrating the role of spatially-correlated risk in creating incentives to design more dispersed reserve networks, we also identify differences between the optimal networks to achieve various objectives such as maximizing the expected number of species versus minimizing the chance that no species survive. Finding differences in the optimal distribution of reserves across a stylized landscape, the paper then considers an Oregon landscape.

Keywords: reserve site selection; biodiversity conservation; nature reserve design; natural hazards; wildfire

1. Introduction

Networks of nature reserves offer protection to biodiversity and individual species. Because constraints limit the amount of area allocated to biodiversity conservation, the reserve site selection (RSS) and related literatures examine the issue of selecting parcels to be conserved across a landscape with species distributed across that landscape. In the simplest maximal covering problem, the objective is to choose parcels for preservation to "cover" or represent the greatest number of species in the reserve system, with no additional value for protecting a species twice. Building from that foundation, this literature solves the maximal species coverage problem for a variety of settings including addressing uncertainty about species occurrence through probabilistic approaches and issues of contiguity of reserves through connectivity and border length constraints.

The probabilistic RSS models typically address uncertainty about species presence/absence at a particular location in a landscape [1] with an objective of maximizing the expected number of species covered by a reserve network. Because the probability of a species being present on a parcel is less than one, it can be optimal to conserve two or more plots with the same species to increase the expected value of the species conserved. Our framework addresses a different kind of uncertainty: whether or not the species will survive on a parcel within the reserve. Here, we assume that the presence/absence data are perfect but we model risks to the species that may cause them to be unprotected despite being located on a parcel within the reserve. Species within the reserve are protected from lost habitat, assuming that the reserve is large enough to provide sufficient habitat, but these species can still be killed by natural causes like disease or fire and by human-based causes like pollution or hunting. Converting the standard coverage model to one that maximizes the expected number of species in the network based on the probability of their survival addresses some of the issues surrounding risks to species even though they are in reserves, and leads to similar redundancies in species types across reserves within the network as are found in the probabilistic presence/absence data case.

In many cases, the probability that a species survives within the reserve network may not be independent across space. As part of the SLOSS (single large or several small) debate, many biologists suggest that spatially aggregated, contiguous or connected reserves increase the survival probabilities of many species [2-5]. With that biological information, many studies within the RSS literature extend the modeling framework to include constraints on the length of borders or the amount of connectivity in a reserve system (see [6] for a review).

The "several small" side of the SLOSS debate has received less attention, but argues that wildlife corridors may also create corridors for the dispersal of disease and pests and that spreading reserves apart may decrease some risks to species within reserve systems. Because disease, pests, invasive species, and fires all spread spatially from a starting point, they pose risks to parcels that are connected to each other in a way that permits or encourages that spread. Although the risk associated with the starting point, such as the location of the lightning strike that ignites a fire, may be independent across a landscape, once that threat to species has begun, the risk it poses on the landscape is spatially-correlated to the initial location. In the case of spatially-correlated risk, the probability of species survival on any one parcel is no longer independent of the risks facing neighboring parcels.

In the biological literature, while most studies treat risks to species survival as randomly distributed across space, metapopulation models of individual species have been used to explore the impact of spatially-correlated risk on extinction risk. When spatially-correlated risk is incorporated into the metapopulation modeling framework, spatially aggregated habitat is not found to improve species survival and, in fact, may even increase the risk of extinction [7-9]. Within the RSS and spatial economics literature, however, to our knowledge, there has not been a study that incorporates spatially-correlated risk. On a landscape with many species (when the management objective is to choose a reserve design that maximizes biodiversity, for instance), the single-species findings from the biological literature may not hold unambiguously. Our contribution to the RSS literature is our careful examination of the impact of spatially-correlated risk on optimal reserve site selection.

In this paper, we develop a simple static model of the expected maximum species coverage problem where each parcel in the landscape, and therefore the species on that parcel, faces risk of habitat destruction even if the parcel is in the reserve. We develop a stylized landscape and, using Monte Carlo simulations, generate a large sample of species distributions on that landscape. For each species distribution, we solve for the optimal parcels to preserve, given an area constraint, in the case of spatially-independent risks and the case of spatially-correlated risks. We describe the differences in the resulting reserve networks and discuss how the choice of objective functions that reflect some desire to avoid bad events, such as minimizing the chance that no species survive in the reserve influences the optimal reserve design. Finally, we apply the optimization to an eco-region in Oregon that has several endangered species and significant threat of habitat destruction from large fires.

2. Modeling Spatially-correlated Risk in a Stylized Landscape

In species covering models where species presence/absence data is known with certainty, the reserve site selection problem is non-stochastic and the objective is simply to maximize the number of species represented in the reserve. Although we assume perfect presence/absence data here, we consider the probability that some hazard, such as fire, disease, or pests, threatens species in the reserve and the problem becomes stochastic and species survival is probabilistic. ReVelle and others [10] describe, in general terms, a probabilistic maximal covering problem (or expected covering problem) where there is uncertainty in the objective. Although many types of hazards are spatially-correlated, for ease of exposition in what follows, we will develop the examples with a risk of fire. In this section we develop a modeling framework that considers spatially-independent and spatially-correlated risk in the choice of parcels to conserve in a reserve network.

We begin with a landscape with n parcels indexed j = (1,2,…,n) and m species of which i= (0,1,2,…,m) survive a period of disturbance, here fire. On each parcel j, the presence (or absence) of each species is known with certainty. Our objective is to design a reserve system made up of a set of parcels described by the vector ***r*** that maximizes the expected number of species present in the reserve after a period of fire. The set of reserve systems R includes all possible combinations of parcels that satisfy the constraint:

$$\sum_{j \in J} x_{jr} \leq \bar{R} \text{ for all } \mathrm{r} \in \mathrm{R} \qquad [1]$$

$$x_{jr} = 1 \text{ if parcel } j \text{ is included in reserve } r\text{, 0 otherwise}$$

$$\bar{R} = \text{ maximum number of parcels in reserve system}$$

Determining the optimal reserve design requires establishing the probability, p_{ir}, that the post-fire reserve system contains i species, where i = (0,1,2,…,m) with $m+1$ possible number of surviving species (including i=0). Based on ignition probabilities and fire spread characteristics, K (indexed k= {1,2,…,K}) "burn patterns" can occur during the fire period. Each burn pattern occurs with a known probability and corresponds to a number of post-fire species (i) remaining in the reserve (r). For ease of exposition, we assume that no species survive fire if their parcel burns.

For each reserve design, we calculate the probability that *i* species survive by summing the probabilities of each burn pattern in the set of burn patterns for which *i* total species survive (equation 2). Weighting each of the possible *m* number of species surviving by the probability of that number of species surviving, p_{ir}, determines the expected number of species for that reserve system. Our problem, then, is to choose the reserve *r* that satisfies:

$$\text{Max} \sum_{i=0}^{m} i p_{ir} \qquad [2]$$

Subject to equation [1] above and

$$p_{ir} = \sum_{k} b_{kir} \qquad [3]$$

Where

p_{ir} = probability *i* total species in reserve *r* survive fire

b_{kir} = probability of burn pattern k where i species survive in reserve r

In all expected covering problems, expected species presence in the same parcel and across parcels is assumed to be independent [1, 11-13]. In our spatially-correlated risk case, however, we relax the assumption of independence across parcels. Our contribution to the existing reserve site selection literature is our effort to include the risk of fire spread in the model. If there is a fire on parcel *j*, not only will species on parcel *j* be affected, but there is also the possibility that the fire will spread to adjacent parcels, thereby reducing expected species presence on all surrounding parcels.

To determine all the burn patterns with fire spread, we consider the ignition occurring in any of the *n* parcels with fires spreading from that point to adjacent parcels. Although the probability of ignition itself is independent across space, when the fire spreads beyond the ignited parcel, it spreads to each of the neighboring 8 contiguous parcels in a grid-landscape, but not beyond those closest neighbors, or first-order, queen contiguity [14]. (A more general model could include other spatial spread patterns based on the characteristics of the landscape and the disturbance.) This spatial spread links the probability of species survival across space. Fires can also ignite outside the focal landscape and spread into the focal grid landscape. To determine the burn patterns with spatially-independent fire, again we consider all *n* possible ignition points, but fires do not spread from that point. To focus on the impact of spatial versus non-spatial risk, we insure that the same amount of the landscape burns in the spatial spread and non-spatial fire cases, but with non-spatial fire risk the burned parcels are randomly distributed (reflecting multiple ignitions).

To explore the impact of spatially-correlated risk on optimal reserve site selection, we examine a range of initial species distributions, generated via Monte Carlo simulations. For each species distribution, we identify the optimal reserve design for the case where fires spread from a single ignition point and where fire ignitions are randomly distributed. Solving this optimal reserve site selection model requires a numerical approach to fully depict the resulting landscapes. We develop a Matlab mathematical program to solve the optimization using complete enumeration over our stylized landscape. For the case of one species on the landscape, the basic algorithm is described in table 1.

Table 1. Reserve-site selection algorithm on a stylized landscape

Step 1	Enumerate distribution of the two species on the stylized landscape for the optimization.
Step 2	Calculate all possible reserve designs with the maximum parcel constraint.
Step 3	Calculate all possible burn patterns and the probability of each, using the probability of ignition and of spread.
Step 4	For each possible reserve design, calculate the probability of zero, one, and two species being present in the reserve following fire.
Step 5	For each reserve design, calculate the expected number of species.
Step 6	Select the reserve design with the maximum number of expected species.

3. Results

The optimal reserve design depends first on whether or not fires spread and second on the distribution of species across the landscape. For consistency in comparisons and to highlight the impact of spatially correlated risk, we constrain the expected number of burned parcels to be equal for the fire spread and no-spread cases. Whereas in the fire spread case, fire ignites and spreads to adjacent parcels, in the no-spread case, single fire ignitions are randomly distributed across the landscape. In section 3.1, we describe the results from the stylized landscape and in section 3.2 we describe the results from the Oregon landscape.

3.1 Stylized landscape. Our stylized landscape consists of a 5-by-5 grid of parcels (n=25) (Figure 1) where species presence is known with certainty. There are two individual species (m=2; A and B) each present on 5 randomly distributed parcels, 20% of total area. Within the grid, each parcel contains zero species, a single species, or two species, which we refer to as a "hotspot." Monte Carlo simulations randomly generate one-hundred individual species distributions. For both the spatial spread and non-spatial fire spread cases, the problem is to choose the two-parcel reserve ($\bar{R}$ =2)that maximizes the expected number of species given the randomly generated species distributions. Because there are multiple solutions, optimal reserve designs are characterized and grouped according to species distribution in tables 2 and 3. Any parcel containing both species constitutes a biodiversity hotspot for this simple analysis.

Figure 1: Five-by-five grid landscape

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Table 2: Optimal reserve design with spatially-independent risk

Biodiversity hotspots	No. of optimal reserves designs	Expected number of species	Optimal reserve design includes…
Zero hotspots	25	1.6767	Any 1 parcel with species A and any 1 parcel with species B
One hotspot	8	1.8123	Hotspot parcel and parcel with either species A or B
Two hotspots	1	1.9479	Both hotspot parcels

Table 3: Optimal reserve design with spatially-correlated risk

Biodiversity Hotspots	Optimal reserve design includes…
Zero hotspots	Any 1 parcel with species A and any 1 parcel with species B
One hotspot	Hotspot parcel and a second parcel with species A or B, as far from the hotspot parcel as possible (for all solutions where the second reserve parcel is 5 or more parcels from the hotspot, the number of expected species is the same).
Two adjacent hotspots	One hotspot parcel and a second parcel with species A or B as far from the reserve hotspot as possible (for all solutions where the second reserve parcel is 5 or more parcels from the hotspot give, the number of expected species is the same).
Two non-adjacent hotspots	Both hotspots (even in the case where the two hotspots share a vertex)

As expected, when risk is spatially-independent and there is no fire spread, the location of parcels included in the optimal reserve does not change the expected number of species conserved by the reserve system. A reserve design that includes two adjacent parcels produces the same number of expected species as a reserve design that includes two distant parcels. However, when risk is spatially-correlated, for species distributions with one or more biodiversity hotspots, decisions about optimal reserve design that ignore the relative location of reserve parcels result in inefficient choices. Specifically, fire spread creates an incentive to spread out reserve parcels, even if that means including a parcel with a single species in the reserve instead of another hotspot. We do not report number of optimal reserve designs and the expected number of species in table 3 because it varies with the distribution of species (for example, when two parcels each with both species present are included in the reserve, the expected number of species will be greater than if there were only one species present on each parcel) .

Surprisingly, we find that with fire spread and zero hotspots, location does not matter in the selection of the optimal reserve design. Whether reserve parcels are adjacent or separated by 5 parcels, as long as species 1 is present on one parcel and species 2 is present on the other parcel within the reserve, the number of expected species is the same. Although the expected number of species is the same, there are tradeoffs between the probabilities of species survival, illustrated in table 4.

Table 4. Expected number of species with spatially-correlated risk and zero hotspots

	Adjacent parcels	Parcels separated by one	Parcels separated by more than one
Probability **zero** species survive fire	6/49 (0.122)	3/49 (0.061)	0/49 (0.000)
Probability only **one** species survives fire	6/49 (0.122)	12/49 (0.245)	18/49 (0.367)
Probability **both** species survive fire	37/49 (0.756)	34/49 (0.694)	31/49 (0.633)
Expected Number of Species	**1.632**	**1.632**	**1.632**

Despite the spatial spread of fire, a pattern with adjacent reserve parcels creates the largest probability that both species survive (i.e., neither parcel in the reserve burns). This result derives from the low number of burn patterns that affect both clustered parcels in the reserve. When reserve parcels are further from each other, more burn patterns affect at least one reserve parcel, making it less likely that both species will survive fire. However, reserve systems with adjacent parcels also create the largest probability that both parcels burn. A single large fire can eliminate both species in the reserve when reserve parcels are separated by one, but the probability of this burn pattern occurring is small. When reserve parcels are separated by more than one parcel, however, a single large fire cannot eliminate both species in the reserve, which minimizes the probability of zero species surviving.

3.2 Oregon landscape. On the stylized landscape it is possible to numerically solve the reserve site selection problem with spatially-correlated risk, but solving a similar real-world problem is not possible when the number of species and parcels is large. Heuristics are often used to solve large problems that cannot be solved by traditional mathematical programming techniques. In particular, in the field of natural resource management, heuristics have been applied to many spatial forest planning and harvest scheduling problems [15, 16](e.g., Murray and Church, 1999 and Bettinger et al., 2002). We use a simulated annealing algorithm to find solutions to the reserve site selection problem on an Oregon landscape. In forest planning problems, simulated annealing algorithms have been found to perform well relative to other heuristics, such as genetic and tabu search algorithms [17, 18]. Because simulated annealing is a heuristic, it does not guarantee the optimal solution, or even the same solution, every time. However, by thoroughly searching the solution space we can be certain of a "good" solution.

The mathematical programming model is applied to species presence data for terrestrial vertebrate species in Oregon. The landscape is partitioned into 289 hexagon-shaped parcels, each approximately 157,000 acres (635 km^2). Though this spatial scale seems relatively coarse, it is consistent with the scale of fires in Oregon, which can reach nearly 500,000 acres in size (e.g., the 2002 Biscuit Fire). The complete or partial data set has been widely used in the reserve site selection literature [12, 13, 19, 20]. For each parcel, we have species presence-absence data for 424 terrestrial vertebrate species. The average number of species on a single parcel is 204.11 and the minimum and maximum number of species is 165 and 264, respectively. Because the range of species present on each parcel is not extreme, there are no clear "hotspots" as in the stylized landscape example.

The problem is to choose the optimal thirty-parcel ($\bar{R}$) reserve—approximately 10% of total area—to to maximize the expected number of species. Again, we assume that fire eliminates all species on burned parcels. Rather than solving the problem numerically, as done for the stylized landscape, we conduct simulations to evaluate the impact of fire on species presence in the reserve. Our simulated annealing algorithm is outlined in table 5.

Table 5. Simulated annealing reserve site selection algorithm

Step 1	Define the initial thirty-hexagon reserve.
Step 2	Apply fire to landscape and allow to burn through repeated randomized experiments. Calculate the average number of species remaining in thirty-hexagon reserve after fire.
Step 3	Randomly select a hexagon to leave reserve.
Step 4	Randomly select a hexagon to input into the reserve.
Step 5	Apply fire to landscape and allow to burn through repeated randomized experiments. Calculate the average number of species remaining in thirty-hexagon reserve after fire.
Step 6	If solution is better than best so far, save as best and current. If not, calculate Boltzman constant – there is some positive probability of accepting a non-improving addition to the thirty-hexagon reserve.
Step 7	Increase counter and return to Step 3.

We compare the results of the optimization for the case with spatially-correlated risk to the optimal reserve where risk is spatially-independent. In the presence of spatially-correlated risk, fires spread and each fire simulation consists of an ignition on a randomly selected parcel and spread to the six adjacent parcels. In contrast, when fires do not spread, there are 7 ignitions randomly distributed across the landscape. Optimal reserve designs for these two cases are illustrated in figures 2 and 3.

Figure 2. Optimal reserve design with spatially-independent risk

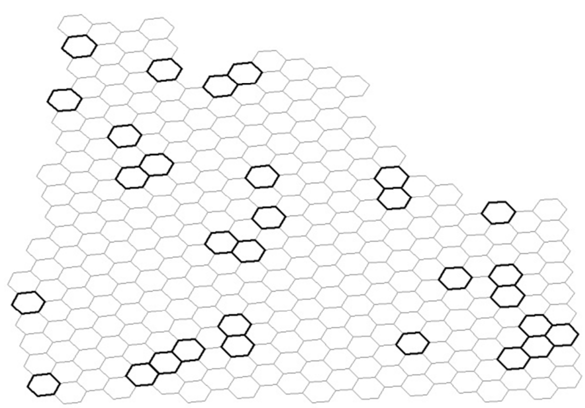
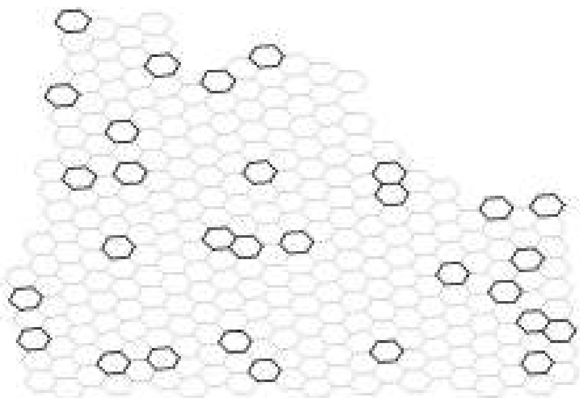


Figure 3. Optimal reserve design with spatially-correlated risk



The influence of spatially-correlated risk on the number of expected species can be seen by comparing optimal reserve designs in figures 2 and 3. When risk is spatially-independent, the optimal reserve includes 12 shared borders – five pairs of adjacent hexagons, one group of three adjacent hexagons, and one group of four clustered hexagons. Within the optimal reserve, the average number of species is 211.9 and the minimum and maximum number of species in a single hexagon is 182 and 264, respectively. The expected number of species for the optimal reserve pattern and fire regime is 413.15. With spatially-correlated risk, however, the optimal reserve contains only three shared borders – three pairs of adjacent hexagons. In the presence of spatially-correlated risk, the benefit from reduced hazard risk makes the dispersed reserve pattern the preferred choice. Within the optimal reserve, the average number of species is 210.23 and the minimum and maximum number of species in a single hexagon is 175 and 264, respectively. The average number of species per-parcel in the optimal reserve is slightly lower than when risk is spatially independent indicating a tradeoff between spatial risk and including species within the reserve. Included within the three pairs of adjacent reserve parcels are three of the five rarest species, present on only one parcel in the entire landscape. The expected number of species for this reserve pattern and fire regime is 413.30, slightly greater than in the case with spatially-independent risk. If the reserve site selection managers ignore the spatially-correlated risk and impose the non-spatially reserve network on this large-fire-prone landscape, they protect an expected 413.06 species, or 0.06% fewer species than if they recognized the spatial aspects of risk in establishing the reserve network. The difference in the number of expected species is relatively small in the Oregon example because there are many hexagons with a large number of species. However, in landscapes where there are few parcels with many species, the failure to account for spatially-correlated risk may be more costly.

4. Discussion and concluding remarks

In this paper, we develop a reserve site selection framework that addresses the issue of risks to species within the reserve and that recognizes that those risks can be correlated across space. We focus on an example of fires that spread from an ignition point, but outbreaks of diseases, pest infestations, and invasive species also produce risks that are correlated across space. Some of the reserve site selection literature incorporates spatial considerations such as the desire to have connectivity between reserve sites, but spatially-correlated risk works in the opposite direction. Which consideration dominates will depend on the particular setting, but large fires, pests, diseases, and invasive species are increasingly threatening species conservation in the western U.S.

In the probabilistic maximum coverage models, as here, the typical objective function is to maximize the expected number of species in the reserve. In the case of conserving species in the face of risk, such as fire, conservation actors may consider other objective functions. For example, a conservation land manager may conserve land to minimize the chance of extreme negative events such as losing all species to the natural hazard. In our model, that objective function equates to designing a reserve that minimizes the probability of zero species surviving the fire period. For the case with fire spread and zero hotspots, the reserve network that minimizes the chance of losing both species is a reserve network with parcels that are spread far enough apart that the hazard cannot spread from any one reserve parcel to the other (table 4), while the expected value objective is indifferent between that and other distributions of the reserve sites. In contrast, if the manager's objective function is to maximize the chance that both species survive, rather than the expected number of species, under some parameter values including those used in our stylized model, the optimal reserve contains adjacent parcels whenever there are spatially-correlated risks on the landscape. While our model does not explicitly consider the benefits of reserve contiguity, we find that, depending on the objective function, adjacencies within a reserve may be optimal. Ongoing research further explores the impact of different objective functions on reserve networks, especially when the objective function reflects some desire to avoid negative outcomes.

Other avenues for future research include an exploration of other types of spatially correlated risk, such as disease whose spread depends on species presence and contact between species on adjacent parcels. When spread requires species presence, barriers might be viable conservation strategies, just as fire breaks might augment conservation by limiting fire spread. But, creating such barriers might also have negative ecological effects, creating additional tradeoffs worthy of more study. A second line of research includes expanding the framework to consider the probability of species survival as a function of connectivity of reserves and the benefits of spatial aggregation, and thereby incorporating concepts from the biology literature, allowing us to test whether connectivity or spatially-correlated risk dominates reserve site selection in a particular setting.

The Oregon example illustrates that including spatially-correlated risk in a real-world setting can influence optimal reserve design. We find that even in the presence of spatially-correlated risk and when the objective is to maximize the number of expected species, it may be optimal to maintain adjacencies within the reserve. This result is a function of the tradeoff between risk and presence of biodiversity hotspots. In the Oregon example, the benefit of including adjacent parcels, many with a large number of species and the presence of rare species, outweighed the risk of both parcels burning in a single fire for three sets of parcels. For several other areas of this ecoregion, however, the spatially-correlated risk leads to locating reserve parcels at a distance from each other.

Our central result here is that spatially-correlated risk creates incentives to spread reserve sites apart from each other, but the objective function and competing forces determine whether that incentive dominates in the reserve pattern. Locating reserve sites at a distance from each other minimizes the probability that no species will survive because no single large, spreading fire can destroy species in two distant sites. Working in the opposite direction, however, locating reserve sites near each other maximizes the probability that all species survive when the probability of a large fire in any particular location is relatively small. These forces interact with the objective function to determine the optimal reserve pattern. We find cases in which maximizing the expected number of species leads to indifference between agglomerated versus disaggregated reserves while a more risk-sensitive objective that minimizes the chance of losing half or all species produces a spatially disaggregated reserve network. We also find that when species are distributed in a manner that creates “hotspots” with a high number of species, spatially-correlated fire risk can change the pattern of conservation with the hotspots becoming less desirable due to their susceptibility to risk. The popular decision framework that simply prioritizes conservation of hotspots does not consider risks and can lead to a socially undesirable reserve network. Similarly, the current reserve site selection literature's emphasis on maximizing the expected number of species conserved may not adequately address concerns and goals of some conservation managers in the face of risk.

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