Distance and proximity in nature reserve site selection with spatial spread risk heterogeneity

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Abstract

Reserve site selection research employs integer programming models that use the covering problem formats (set covering and maximal covering) to select sites to conserve species, sometimes reflecting 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 fire. This paper removes the classical assumption of homogeneous land sites and considers both contiguity in areas with a low risk of multi-parcel fires and distance between sites in areas with a high risk of large fires. 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

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 (Toregas et al., 1971; Church and ReVelle, 1974). 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 (Possingham et al., 1993 and Underhill, 1994) or the maximum number of species of the study area given a surface or site constraint (Church et al., 1996 and Camm et al., 1996).

Model refinements for reserve site selection include economic costs, redundant or "backup" coverage, probabilities of survival, dynamics, and spatial issues (e.g. ReVelle et al., 2002, for a survey). In location science, Hogan and ReVelle (1986) 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. Nature reserve site selection models have incorporated this backup concept by protecting species in two or more locations to improve their survival rate in case of external negative events (Malcolm and ReVelle, 2005). Probabilistic species presence (e.g. Arthur et al., 2004) and dynamic models (e.g. Costello and Polasky, 2004) have been considered in various papers even though most of the literature remains deterministic and static. Heterogeneity in land costs have been introduced by Ando et al. (1998) and Polasky et al. (2001) for promoting cost efficient site selection. Spatially explicit models have been introduced as part of the SLOSS (single large or several small) debate 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. Williams et al., 2005 and Moilanen et al., 2009, for surveys). Most spatial models consider agglomeration of selected sites to reduce edge effects, facilitate dispersal, allow recolonization (e.g. Cabeza et al., 2004; Araujo and Williams, 2000), and reduce management costs associated with the boundary length of a reserve network (McDonnell et al., 2002). 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 (Shafer, 2001; Busby et al., 2012).

This paper builds off of the deterministic and static strain of the literature but incorporates spatial constraints and land heterogeneity in a cost efficient setting. Because in some cases proximity amongst sites is an advantage but, in other cases, separation between sites is preferred (Williams, 2008), the spatial analysis in this paper considers both a separation distance and proximity requirements for the pattern of reserve sites chosen in a network. The landscape contains heterogeneity across land parcels in the risk posed to species on those parcels. On a particular landscape, fire risk heterogeneity arises, for example, if some parcels are located in areas where fires are more likely to be large and spread across multiple parcels while parcels in other areas are less likely to experience such large, spreading fires.

As mentioned by Shafer (2001), the geographic spread by a catastrophic agent is significant and creates risk for species. 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 (Haight et al., 2000, Camm et al., 2002, Arthur et al., 2004). Others incorporate uncertainties about species response to fragmentation (Moilanen and Wintle, 2006) or about extinction risk when making conservation

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decision (Nicholson and Possingham, 2007). Those risks are generally associated directly with species in a probabilistic setting whereas the risks analyzed in this paper arise from land characteristics that determine risk and heterogeneity of risk from large fires

In our context, fire kills species even when those species are within the reserve and, following the literature, this framework considers the need to protect species in more than one site in order to reduce the risk of species' disappearance. In addition, the risk of large fires (multiple parcels) varies across the landscape and our reserve site selection, unlike most other risk-based reserve site selection models, takes this land heterogeneity into account in establishing reserve networks. More precisely, the model described in the next section incorporates 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 "back-up 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.

The remainder of the paper is organized as follow. Section 2 presents the models and the next two sections apply the models to a stylized landscape (Section 3) and to an Oregon landscape (Section 4). The final section concludes.

2. **The models**

2.1. MODEL 1: SSCP

The Species Set Covering Problem (SSCP) enables the protection of all species – using the assumption that a species is preserved if it is located in at least one site that is part of the nature

reserve – at the lowest possible cost. The model is represented in equations (1) to (3) where there are n sites of land indexed j and represented by the set of sites J ($J=\{1,2,\ldots,n\}$) and m species indexed i and represented by the set of sites I ($I=\{1,2,\ldots,m\}$), where x_j is 1 if site j is selected for the reserve system and 0 otherwise, and where a_{ij} is equal to 1 or 0 depending on whether species i is present on site j or not.

$$\text{Min} \sum_{j \in J} c_j x_j \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in J} a_{ij} x_j \geq \beta \quad \forall i \in I \tag{2}$$

$$x_j = 0,1 \; ; \; a_{ij} = 0,1 \tag{3}$$

The objective (1) minimizes the cost of the reserve network, while requiring that, for each species i, at least one site x_j containing species i ($a_{ij}=1$) be selected ($x_j=1$); hence, $\beta=1$.

2.2. MODEL 2: SSCP WITH BACKUP COVERAGE

In this model, when a fire burns through a parcel, it is assumed that species in that parcel will not survive. Due to that risk, achieving the objective of conserving species post-fire is improved by requiring that each species be present in at least two sites. This backup coverage model is represented by the same equations as the SSCP but with parameter β in equation (2) taking the value of 2.

2.3. MODEL 3: SSCP WITH HETEROGENEOUS FIRE SPREAD RISK

Most reserve site selection papers consider land parcels as homogeneous, except for the cost of purchasing land for setting it aside as a reserve. However, in a large network, some geographic areas are more prone to fire hazards than others. Fire risk maps show the variability of the probability of fire across regions. Part of the probability of fire reflects the possibility that a fire

spreads beyond the parcel in which it ignites, which also varies across locations. Ignoring such spread risk heterogeneity in selecting reserves can lead to reserve networks with species in high spread risk areas being particularly vulnerable to disturbance. Acknowledging the importance of spatial heterogeneity in the spread of hazards, this paper divides the set of parcels into low, medium and high spread risk regions and imposes species backup conservation rules that reflect each location's spread risk.

In regions with localized risk such as low-spread fires, ecologists often argue for agglomerated reserves. In response, connectivity requirements have been proposed in many papers as tools to create a spatially explicit reserve (e.g. Nalle et al., 2002; Önal and Briers, 2003, 2006; Hamaide and Sheerin, 2011). In our framework, in low spread risk areas, we impose such connectivity by requiring that backup coverage occur in adjacent parcels 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, Williams (2008) requires some amount of distance between primary and backup coverage sites to create a more dispersed pattern. Here, backup coverage of each species selected in a medium spread risk area cannot be located in an adjacent parcel –each species is shielded from an exogenous event such as a large fire by a surrounding ring. Similarly, if a parcel in a high spread risk area is selected to cover a particular species, secondary coverage for that species cannot be located in the first or second surrounding ring around the parcel to insure sufficient distance between selected sites to protect species from very large fires. Model 3 with heterogeneous fire spread risk can be formulated as follows:

$$\text{Min} \quad \sum_{j \in J} c_j x_j \tag{4}$$

$$\text{s.t.} \quad \sum_{j \in J} a_{ij} x_j \geq 2 \quad \forall i \in I \tag{5}$$

$$a_{ij}x_j + \sum_{h \in R_j} a_{ih}x_h \leq 1 \quad \forall i \in I, \forall j \in G \tag{6}$$

$$a_{ij}x_j + \sum_{l \in T_j} a_{il}x_l \leq 1 \quad \forall i \in I, \forall j \in V \tag{7}$$

$$a_{ij}x_j \leq \sum_{k \in H_j} f_{ik}x_k \quad \forall i \in I, \forall J \in L \tag{8}$$

$$x_j = 0,1 \; ; a_{ij}=0 \; ; f_{ij}=0 \tag{9}$$

where G, V and L are respectively the set of parcels with medium, high and low spread risks and therefore, $J = G \cup V \cup L$. f_{ik} is equal to 1 if species i is selected in a low spread risk area k and is 0 otherwise, R_j and H_j are defined as the sets of parcels around j in medium and low spread risk areas respectively and finally, T_j is the set of parcels composing the double surrounding ring around site j.

The first two equations represent the backup coverage model: the model minimizes the cost of the nature reserve (equation 4) with each species in the set present in at least two parcels of the reserve network (equation 5). Equation (6) stipulates that for medium spread risk areas $j \in G$, if species i is selected on site j ($a_{ij}=1$), none of the parcels surrounding j can be part of the reserve ($\sum_{h \in R_j} a_{ih}x_h = 0$). Similarly, equation (7) ensures that no parcel where species i is present can be located in the double surrounding ring of a selected high-risk site $j \in V$. On the contrary, when a low spread risk area $j \in L$ is selected for species i ($a_{ij}x_j = 1$), equation (8) requires that an adjacent site be selected to backup the species in question ($\sum_{k \in H_j} f_{ik}x_k \geq 1$).

2.4. MODEL 4: MAX. BACKUP COVERAGE WITH HETEROGENEOUS FIRE SPREAD RISK

For budgetary reasons (and/or because of some restrictive constraints), it may not be possible to protect each species in two different locations. Therefore, this model maximizes backup coverage, while requiring that all species have primary coverage, at various conservation budget levels, with the same distance and proximity requirements directed by the heterogeneous land sites. This model can be solved for different budgets based on the results obtained from the former model (Model 3) and the SSCP (Model 1). Model 4 is thus a maximal coverage model, with distance and proximity requirements due to a land risk heterogeneity and a budget constraint, and is formulated as follows:

$$\text{Max} \sum_{i \in I} u_i \tag{10}$$

$$\text{s.t.} \quad u_i \leq \sum_{j \in J} a_{ij} x_j - 1 \quad \forall i \in I \tag{11}$$

$$\sum_{j \in J} c_j x_j \leq B \tag{12}$$

$$a_{ij} x_j + \sum_{h \in R_j} a_{ih} x_h \leq 1 \quad \forall i \in I, \forall j \in G \tag{13}$$

$$a_{ij} x_j + \sum_{l \in T_j} a_{il} x_l \leq 1 \quad \forall i \in I, \forall j \in V \tag{14}$$

$$a_{ij} x_j \leq \sum_{k \in H_j} f_{ik} x_k \quad \forall i \in I, \forall J \in L \tag{15}$$

$$x_j = 0,1 \; ; \; u_i = 0,1 \; ; \; a_{ij} = 0 \; ; f_{ij} = 0 \tag{16}$$

where $u_i = 1$ if species i is located in two different parcels of the reserve network and where B represents the budget.

The purpose of this fourth model is to maximize the number of species that are back-covered (equation 10) with (equation 11) species i only having secondary coverage ($u_i = 1$) if at least two different land sites in which the species is present are selected ($\sum_{j \in J} a_{ij} x_j - 1 \geq 1$).

Because u_i is non-negative, the constraint also ensures that every species is covered at least once: $\sum_{j \in J} a_{ij} x_j - 1 \geq 0$. Equation (12) represents the budget constraint of the reserve network and

equations (13) to (15) are the same distance and proximity constraints related to spread risk heterogeneity in Model 3 (SSCP with heterogeneous fire spread risk).

All the models detailed in this section are solved on a stylized data set (Section 3) in order to compare how the optimal reserve varies if one takes into account heterogeneous land risks versus the standard procedure of homogeneous land risk sites. After that, in Section 4, a real data set is used to verify the impact of heterogeneity on site selection for some species inhabiting the U.S. state of Oregon.

3. <u>Applications on a stylized data set</u>

The purpose of this section is to solve the models described in the previous section and to infer the impact of heterogeneous risk on optimal reserve selection. We generate a 10 x 10 grid landscape with 10 species. The grid landscape contains biodiversity hotspots of 5 or more species, species-rich cells of 2 species, and parcels with either one or no species. We assume homogenous land value where the cost of protecting each site is normalized to 1; in other words, we do not consider costs in the stylized example but costs are considered in the OR data set (Section 4). Presence and absence data are generated randomly. The random data produces a landscape that contains 5 biodiversity hotspots, 17 species-rich parcels, 58 sites with 1 species, no species in the remaining 20 sites, and each species is present on between 5 and 20 parcels.

The models in this and the next section are coded with Mosel language and run with Xpress-MP (2012).

3.1. RESULTS FOR MODELS 1 AND 2

Figure 1 shows the optimal reserve selection of Models 1 and 2, that is, the set covering and the backup covering models.

Figure 1

Model 1 (SSCP) requires 4 sites, all of which are biodiversity hotspots, to protect all species of interest (black cells). Model 2 (the backup coverage model) selects 8 sites, including the 4 biodiversity hotspots of the SSCP, 2 species rich sites and 2 sites with one species. These 4 extra sites are the striped cells in Figure 1[i].

3.2. RESULTS FOR MODEL 3: SSCP WITH HETEROGENEOUS FIRE SPREAD RISK

In order to test the impact of land risk heterogeneity on the backup coverage formulation, three different fire spread risk maps are considered that represent a range of real-world settings. The first landscape, named Western High Spread Risk, places high spread risk areas on the western edge of the grid landscape with fire spread risk decreasing eastward. The second landscape, named Central High Spread Risk, considers that the center of the region – from north to south – is of high fire spread risk and the risk decreases towards the west while the eastern half of the grid landscape is a low spread risk area. The last layout, named Southeastern High Spread Risk, displays a high spread risk area agglomerated towards the southeast of the region while the northwest bears a medium spread risk and the other sites are at low fire risk. These three heterogeneous land risk landscape examples are displayed in Figures 2 to 6 where darker sites mean higher risks. For each of the three risk patterns, there are 20 high spread risk parcels, 30 medium spread risk parcels and 50 low spread risk parcels. The large number of low spread risk

parcels reflects the predominance of low spread risk sites observed even in the fire-prone western U.S.

To demonstrate the impact of each characteristics of these models, we sequentially add high spread risk area distance requirements (equations 4, 5 and 7), then the medium spread risk area distance requirements (equation 6), and finally the low spread risk areas proximity constraints (equation 8). In all cases, the complete set covering model with heterogeneous land risks (equations 4 to 9) cannot be solved on these randomly generated landscapes due to the low spread risk connectivity restrictions. Because quite a few sites contain no species, it is not possible to backup cover each species in selected low spread risk areas with another contiguous parcel where the same species is present. In that circumstance, the maximal covering problem (Model 4) is then used to provide primary and secondary coverage – meeting the distance and proximity constraints – for the largest number of species in the set.

For the Western High Spread Risk landscape, beginning with its only high risk area distance requirements, the model selects 9 sites: two-thirds of the sites are located towards the east (far from the high spread risk zone) and the only site located on the high spread risk zone is a biodiversity hotspot (Figure 2a). Compared to Model 2 (homogeneous backup cover case in Figure 1), only 3 sites (3 out of 9 sites, or 33%) instead of 5 (5 out of 8 sites, or 63%) are located on the west part of the region. Adding medium spread risk area distance constraints reinforces that pattern (Figure 2b). The model now selects 9 sites, 7 of which are located towards the east. The only two sites selected among the medium or high spread risk areas are two biodiversity hotspots containing 5 species each. Fire spread risk heterogeneity dramatically modifies the optimal reserve selection: more sites are needed to backup cover all species (9 instead of 8), but more importantly, the selection is driven away from high and medium spread risk fire areas, providing protection to those species located in less risky sites.

Figure 2

For the Central High Spread Risk landscape (high spread risk parcels in dark grey cells of Figure 3a), the model selects 8 sites towards the west or the east, without choosing a high spread risk area parcel, which does not differ much from the output of Model 2 (homogeneous backup model). Adding medium spread risk distance constraints to account for a larger land risk heterogeneity (medium grey cells of Figure 3b) does not increase the number of sites selected; one eastern site replaces a western site closer to the medium spread risk zone, but the model nevertheless selects 4 medium spread risk areas, 2 of which are biodiversity hotspots. More importantly, the addition of the medium spread risk distance requirements (Figure 3b) imposes a larger separation between selected patches of land compared to the high spread risk case only (Figure 3a). This example shows that heterogeneous land risk sites modifies the optimal reserve selection in two ways – although the changes are less pronounced than in the previous example – with the introduction of medium spread risk distance constraints : i) an additional site is selected in the non-risky eastern geographical area (for the same total number of parcels chosen) and ii) the selection of (riskier) sites is dispersed on its surface.

Figure 3

For the Southeastern High Spread Risk landscape (Figure 4a), while the total number of sites does not change compared to Model 2 (SSCP with backup coverage), the model chooses sites located far from risky areas, except for 1 biodiversity hotspot. Adding medium spread risk constraints (Figure 4b) leads to much more scattered reserve sites, which results in reducing the

northwestern reserves (3 versus 5 in the previous case) and replacing them by one additional high spread risk and one additional low-risk zone parcels. Here again, the optimal reserve selection varies with land risk heterogeneity and the associated site location rules, leading to more dispersed reserve sites.

Figure 4

3.3. RESULTS FOR MODEL 4: MAX. COVERING WITH HETEROGENEOUS FIRE SPREAD RISK

The above examples demonstrate that accounting for heterogeneous fire spread risks on the landscape modifies optimal site selection. Still, these results do not include connectivity requirements for species in low spread risk areas because those set covering models are not solvable. The maximal covering formulation of equations (10) to (16) can help determine how the reserve locations are influenced when trying to promote secondary coverage for the largest number of species – while keeping a representation of each species in the network – with the imposition of distance and proximity requirements based on land risks.

The output of the maximal covering models is given in Figures 5 and 6 for the Western High Spread Risk landscape and the Southeastern High Spread Risk landscape, respectively. Results are very similar for the Central risks but they are not detailed here as they do not bring any additional insight. Because costs are normalized to 1 in the stylized data set (they are not normalized in the Oregon data set), the budget equation (equation 12) simply becomes a site constraint.

Figure 5

Figure 6

In the Western High Spread Risk landscape, if the site limit is set at 5 (budget proxy), only 4 species benefit from secondary coverage. Gradually relaxing the constraint enables backup coverage to a maximum of 7 species on 8 or more sites, as shown in Figure 5[ii]. Only 3 of these selected sites are identical to the backup coverage model with homogeneous land sites (Model 2, Figure 1). Interestingly, no low spread risk area is selected, even though reserves located towards the east are selected in Model 3 with the same landscape (Figure 2b)[iii].

Figure 6 depicts the case of agglomerated low, medium and high spread risk areas in the various quadrants of the region. Five sites offer secondary coverage to 4 species and, all together, 9 species are protected in 11 sites. This pattern chooses 2 parcels, including one biodiversity hotspot, in the high spread risk zone, 5 sites in medium spread risk areas and 4 located in low spread risk areas. Here again, heterogeneity in land risk sites brings about a different optimal reserve: only 4 of the original 8 optimal sites of the SSCP with backup coverage (Model 2, Figure 1) are part of the 11 sites selected[iv].

Even though a precise outcome is specific to each data set, in general, fire spread risk heterogeneity alters the optimal reserve network in two expected ways: first, parcels selected for reserve move from higher spread risk to lower spread risk areas and second, the network becomes generally more scattered, except in low spread risk areas. The stylized examples offer primary and secondary coverage to each species when high and medium spread risk distance constraints are imposed but not when the low spread risk connectivity requirements are added. When all proximity and distance constraints are added in a maximal covering formulation, the optimal reserve again changes in a similar way as with the set covering model. The particular data set for the stylized landscapes finds that, the majority of land sites selected changes when land spread

risk heterogeneity is accounted for, and, because there are few species-rich sites, it is difficult to select connected low spread risk areas containing the same species, but these results depend on the specific setting.

4. **Applications with the Oregon data set**

Here, Oregon is divided into identical 635 square kilometers hexagonal sites. Data mapping terrestrial vertebrates to each hexagon have been developed for the Biodiversity Research Consortium and are obtained from Master et al. (1995). We use the subset of data contained in Polasky et al. (2001) that comprises 289 sites in Oregon, containing 415 species as well as cost data for each of the sites (expressed in average per acre land value).

This study concentrates on the impact of fire risk spread heterogeneity on the optimal selection of nature reserves. To emphasize that type of heterogeneity, we rule out heterogeneity in species distributions[v]. The Oregon data set's species frequency distribution follows a bimodal distribution with many rare species and many common species. Because that type of distribution constrains the ability to find solutions and adds heterogeneity that masks the impact of land risk spread heterogeneity on the optimal selection of a reserve, we do not consider the rarest species in this analysis. Based on definitions of "rare" in the literature (e.g. Cofre and Marquet, 1999; Storch and Sizling, 2002; Hamaide et al., 2006), we define rare species as those present in fewer than 10% of the parcels (here, fewer than 30 sites). Excluding rare species from the Oregon data set produces a unimodal distribution with 328 species in 289 sites.

Unlike the stylized landscape, the set covering formulation with all constraints (equations 4 to 9), that is Model 3, is solvable for the Oregon landscape, which obviates the need for the

maximal covering formulation of Model 4. Because many species-rich sites exist in the Oregon landscape, it is possible to find connected sites in low spread risk areas where the same species can be covered twice.

Similar to the stylized landscape described in the previous section, low spread risk areas predominate in Oregon. We divide the subset of the state into low, medium or high spread risk depending on the site's fire probability, originally computed by Finney (2007). Fire probabilities represent an estimate of the probability of burning from large, spreading fires. Small fires contained by the "initial attack" of suppression effort contribute little to the burn probability and are therefore not included in the probability measure used here. Parcels with a fire probability lower than 1% (0 to 0.9%) are considered low spread risk areas. Those with a fire probability ranging from 1 to 2% are defined as medium spread risk areas and parcels with a probability of fire between 3 and 8% (maximum probability assigned) are defined as high spread risk areas[vi]. As shown in Figure 9, there are 44 high spread risk areas, agglomerated towards the East of the data set (dark grey cells), 41 medium spread risk areas agglomerated on the northwest of the high spread risk areas (medium grey cells) and the remaining 204 parcels are low spread risk areas (light grey cells). As in the stylized examples, low spread risk areas dominate and the same risk parcels are essentially clustered geographically.

4.1. RESULTS FOR MODELS 1 AND 2

Starting from the SSCP model and initially treating land risk as homogeneous, the solution to Model 1 is that all species are protected at the minimum cost of $3,234[vii] in 6 sites. Backup coverage, or Model 2, illustrated in Figure 7, necessitates the selection of 12 sites for a cost of $6,425; in other words, the cost and the number of sites selected double when species are represented at least twice in the network. Five of the 6 SSCP sites are also selected for the

backup model because they are the cheapest sites containing the largest number of complementary species.

Figure 7

4.2. RESULTS FOR MODEL 3 (SSCP WITH HETEROGENEOUS FIRE SPREAD RISK)

For purposes of comparison with the output of Model 3 in the stylized example (Figures 2 to 4), Figure 8 displays the optimal reserve selection if high spread risk areas only (dark grey cells) are taken into account, with the other sites being considered homogeneous in fire spread risk.

Figure 8

The minimum cost amounts to $6,487 for the selection of 12 sites, which is nearly the same as in Model 2 (backup model). This shows that the double ring distance constraint for backup species coverage selected in high spread risk area has little effect on cost and, therefore, on the design of the optimal reserve compared to the backup coverage Model 2. In fact, Model 3 with high spread risk constraints selects only 12 different sites, among which 10 are similar to Model 2: a high and a low-risk site are replaced by two low-risk sites. In other words, the reserve network includes only 1 high spread risk area instead of 2 for Model 2, hence, as expected, the heterogeneous fire spread risk drives the nature reserve selection away from high spread risk areas.

Including all spread risk heterogeneity constraints in Model 3 gives an optimal reserve selection displayed in Figure 9 (3 different shades of grey over the data set). It confirms that the

highest number of sites are selected in low spread risk areas, or, said differently, most species are present in such low spread risk places. This finding implies that the site connectivity requirements for providing a second coverage to each species necessitate selection of many additional sites, which results in a large cost increase. The minimum cost to solve the complete model reaches $78,050 and the model selects 38 sites with 3 in the high spread risk zone, 2 in the medium spread risk zone, and 33 in low fire risk areas.

Figure 9

The very large cost increase is due solely to the low spread risk connectivity requirements. As a matter of fact, if only low spread risk constraints were added to Model 2 (which means that no distance requirements would be imposed for riskier sites), the cost amounts to $76,996 with the selection of 36 sites, which is much higher than if high spread risk constraints only were included ($6,487 for 12 sites).

The general conclusion found in the stylized landscape cases remains valid. First, taking land risk heterogeneity into account drives selected sites away from higher spread risk zones: only 3 high spread risk parcels are chosen when spatial spread risk heterogeneity is considered (Model 3, Figure 9).   Second, selection of low spread risk parcels shows some clustering in the reserve design. The stylized model's conclusion that higher spread risk sites tend to be more scattered, cannot be seen with these data, which is logical because very few such sites are selected here[viii].

5. Conclusion

The application of coverage problems on nature reserve selection aims at preserving species diversity by protecting all species in a network or as many species as possible. Models have been refined over the years to enhance species protection, by adding spatial requirements. These models nevertheless use the assumption that land sites are homogeneous.

This paper considers heterogeneity in the risk of large fire disturbances in determining the optimal reserve network. Each site is assigned to either a low, medium or high fire spread risk category, based on the probability of burning from a large fire. For promoting species survival, the models in this paper also impose that either each species (set covering problem) or as many species as possible (maximal covering problem) be covered at two different locations. The location of the secondary coverage is a function of land risk heterogeneity: connectivity between sites is required if a species is selected in a low spread risk zone and distance between sites (one or two surrounding rings for medium and high spread risk locations respectively) is applied if a species is selected in a higher risk area. Because this paper concentrates on land risk heterogeneity, other types of heterogeneities that may complicate interpretation of results (except land costs) are removed.

The results of these models show that fire spread risk heterogeneity – and other types of hazards that can vary in their degree of agglomeration such as invasive species and habitat disease – modify the design and locations of the optimal reserve network: i) larger budgets are needed and more sites are selected with the distance and proximity requirements than with a standard backup coverage model, ii) fewer sites are selected in higher risk zones, iii) those sites selected in such zones are generally more scattered, and iv) sites selected in lower risk areas are generally more clustered. Hence, nature reserve selection not accounting for land risk heterogeneity may mistakenly locate reserves in potentially hazardous areas, without adequate secondary coverage of species, which may threaten species survival.

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[i] Note that some species are protected more than twice because some may be contained in more than 2 biodiversity hotspots, as made possible by of the inequality in equation 2.

[ii] Figures 5 and 6 depict the outcome of the maximal covering problem that protects the largest number of species in the smallest number of sites.

[iii] This is due to the specific species distribution of this random data set where very few species are located in contiguous low spread risk areas

[iv] Even though the two networks compared are different, on one side, the reserve covers all species twice and on the other side, 1 primary covered species cannot benefit from secondary coverage.

[v] The heterogeneity in land costs can still be considered if the purpose is to create a cost efficient reserve network considering land risk heterogeneity.

[vi] Due to the range of fire probabilities within each hexagon, the largest probability is used for determining the risk of each hexagon.

[vii] As mentioned in Ando et al. (1998) and done in Polasky et al. (2001), "because the size of the unit area serves only to scale cost, for convenience, we took it to 1 acre". Thus, we normalize the size of the reserve in each parcel to one acre and use the average per acre land cost to determine the cost per site.

[viii] These riskier sites are scattered but not more so than if high spread risk only is included in Model 3.

Figures
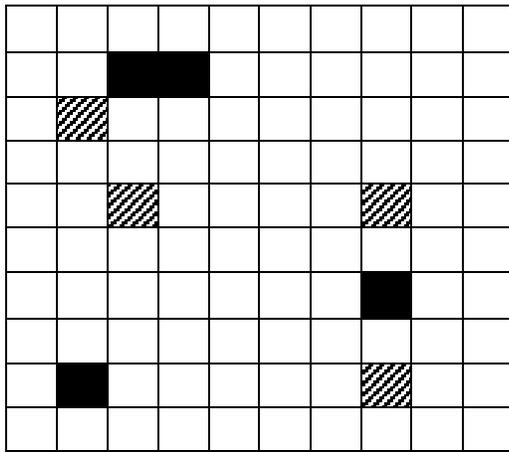
<u>Figure 1:</u> SSCP (back cells) - Model 1 - and backup coverage (black and striped cells) - Model 2
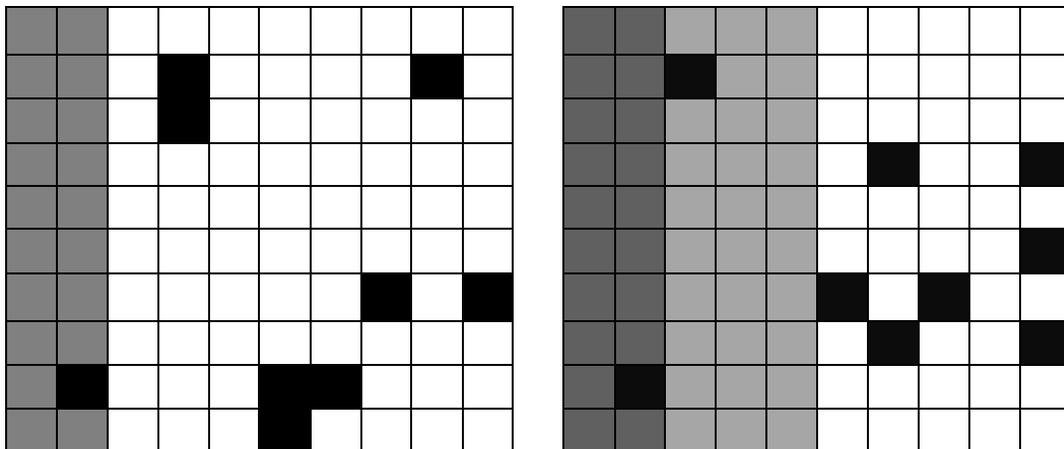

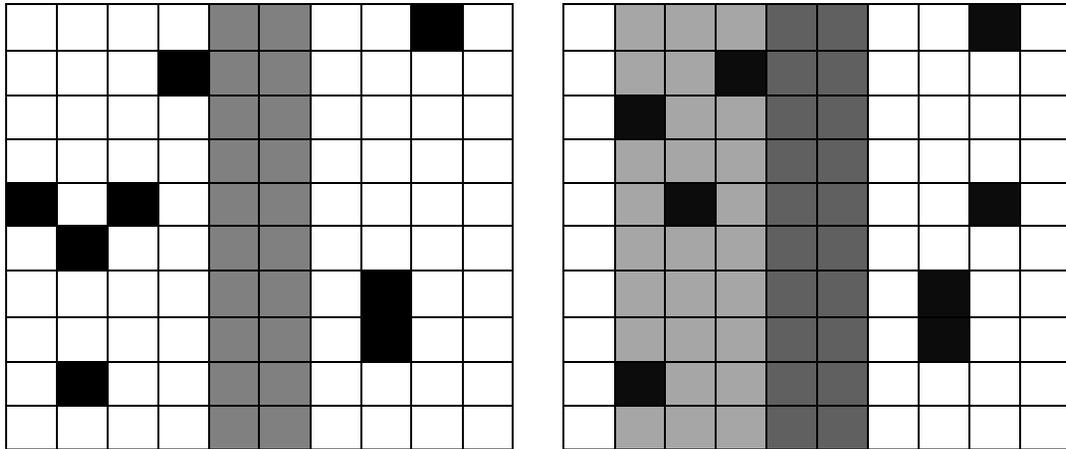<u>Figure 2:</u> Model 3 output with Western high spread risk (2a) and when adding medium spread risk (2b)

Figure 3: Model 3 output with Central high spread risk (3a) and when adding medium spread risk (3b)
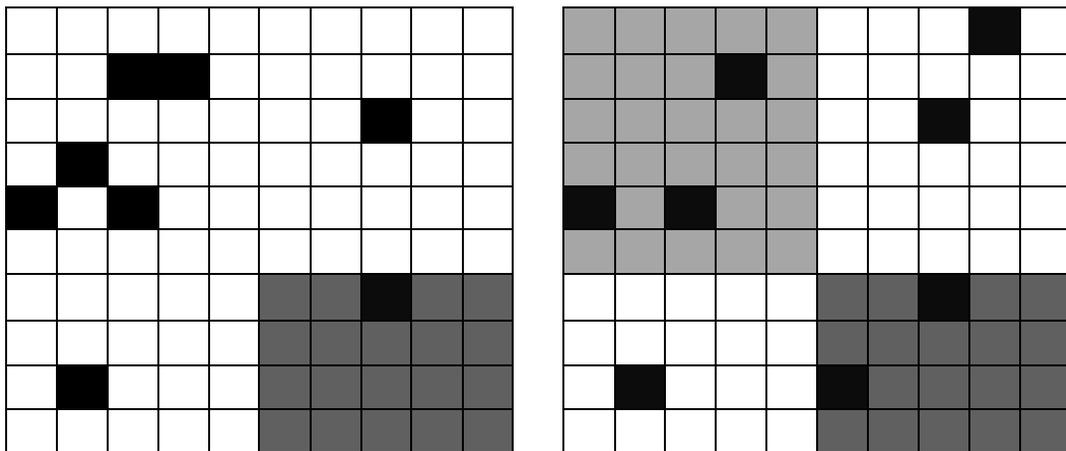

Figure 4: Model 3 output with SE high spread risk (3a) and when adding NW medium spread risk (3b)
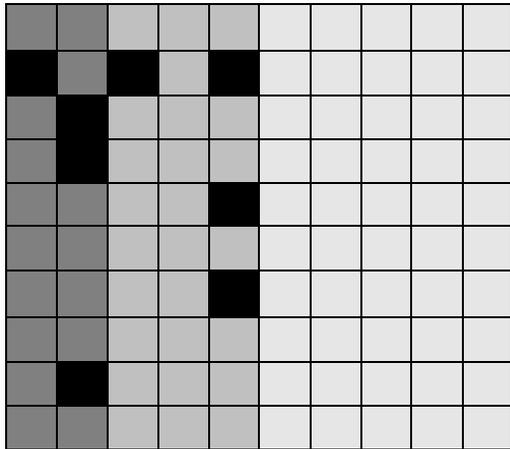
Figure 5: Model 4: Max coverage model with heterogeneous land risk site and Western high spread risk
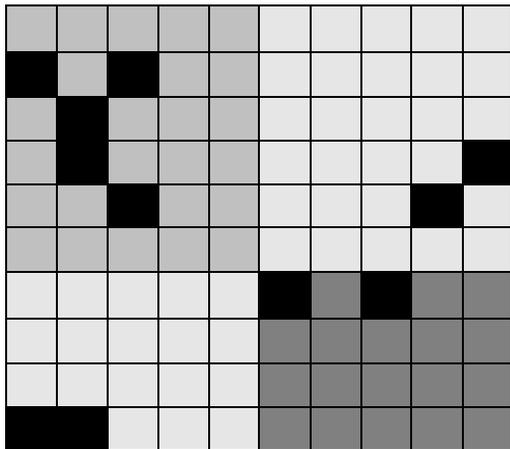
Figure 6: Model 4: Max coverage model with heterogeneous land risk site and SE high spread risk
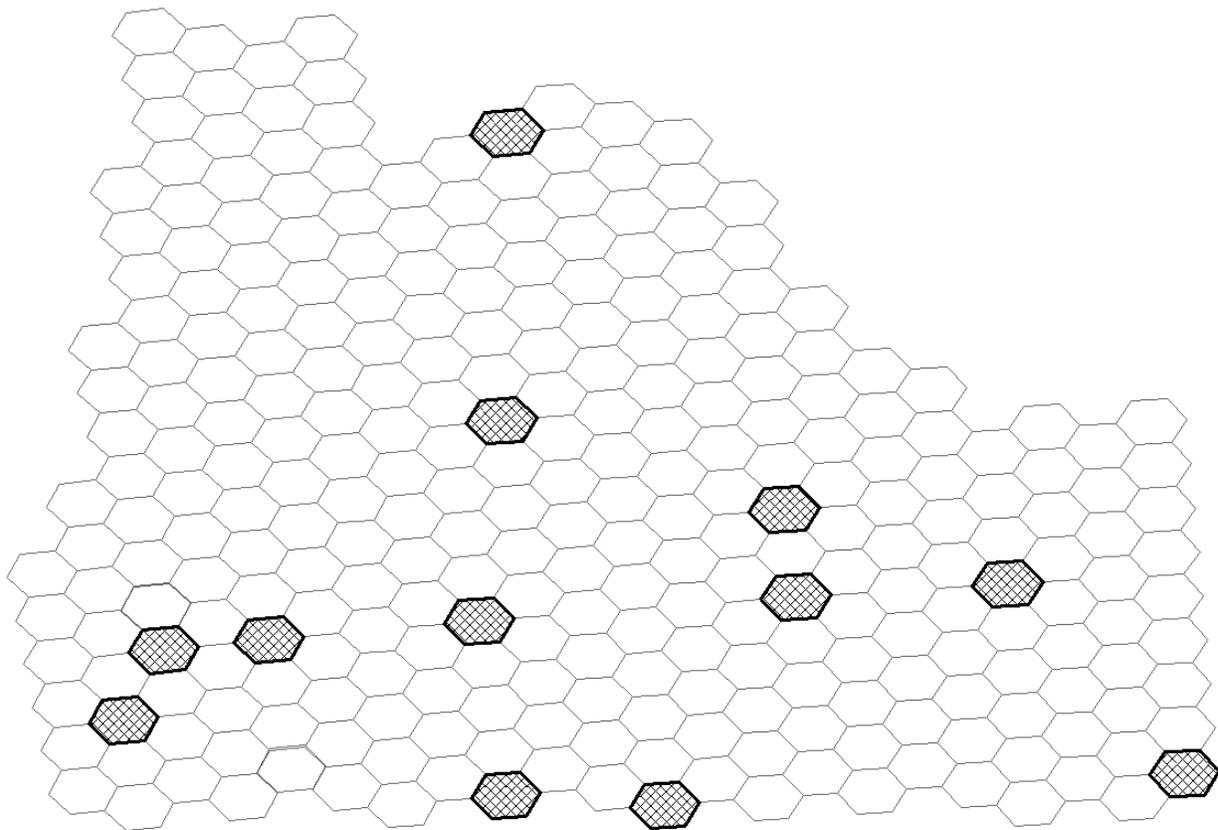
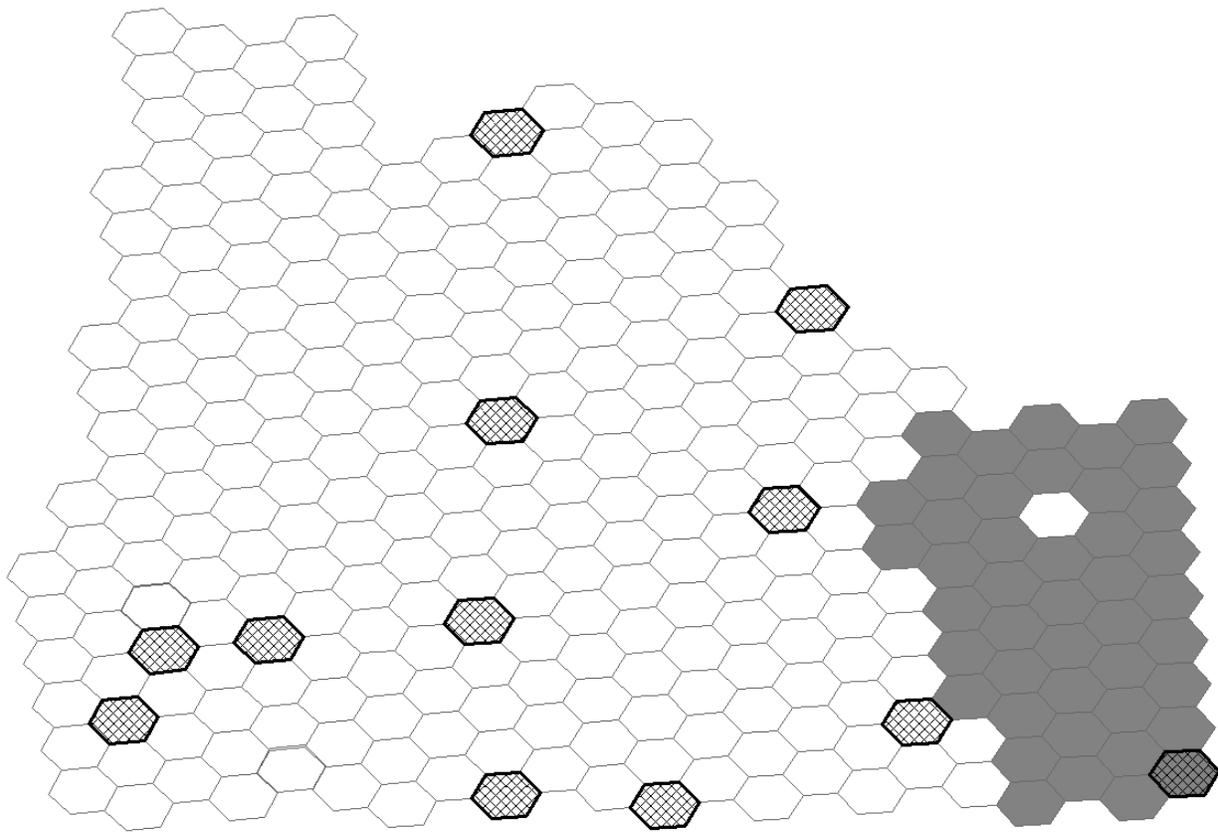Figure 7: Model 2: OR Backup coverage problem

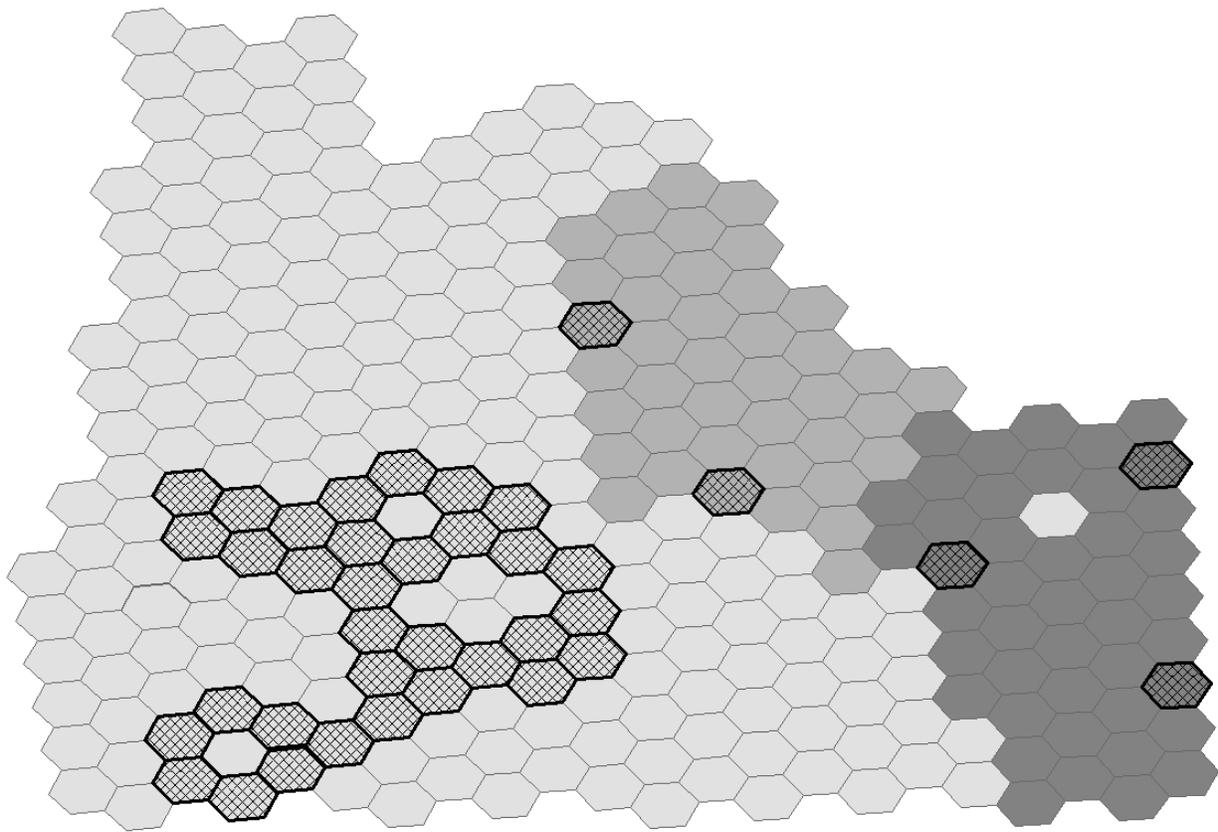Figure 8: Model 3: OR model output with high spread risk areas only (dark grey cells)

Figure 9: Model 3: OR model output with heterogeneous land risk