Optimal Wildlife Reserve Site Selection with Spatially Correlated Risk

Ying Xu

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
in
Forestry

Gwenlyn Busby, Chair
Gregory S. Amacher
Jay Sullivan

April 23th, 2012
Blacksburg, Virginia

Keywords: Wildlife, Spatially Correlated Risk, Reserve Site Selection, Optimization

Optimal Wildlife Reserve Site Selection with Spatially Correlated Risk

Ying Xu

ABSTRACT

As more emphasis is put on biodiversity conservation, how best to select a system of protected areas for wildlife conservation is an issue of great importance. There is a rich economics literature on the reserve site selection problem. However, most economic studies assume the independence of risks that affect wildlife species, leaving the issue of spatially correlated risk largely unexplored.

This study contributes to the literature in twoaspects. First, this study incorporates spatially correlated risk, into a reserve site selection model. And second, this study incorporates heterogeneous spatial risk, in the context of land development risk in Virginia, both with and without a budget constraint.

To evaluate the significance of spatially correlated risk in conservation design, I apply the reserve site selection model to a Virginia landscape. In a basic setting, a hazard is introduced which is allowed to spread to adjacent land parcels, where I investigate the impact of spatially correlated risk at three spatial scales: one-county, four-county, and state-level. Optimal reserve designs are characterized by similar spatial patterns indicating that spatially correlated risk plays an important role in the selection of parcels for reserve. Specifically, as spatially correlated risk increases, I find that, in general, reserve connectivity decreases. I also examine a setting with heterogeneous risk and observe similar patterns in the optimal reserve design. I find that the reserve becomes more dispersed in higher risk areas primarily. Finally, I explore the tradeoffs between species protection and budget constraints in the presence of heterogeneous spatial risk. All comparative statics indicate that spatial correlated risk plays an important role in conservation reserve design.

ACKNOWLEDGEMENTS

I would like to say thank you for all the people who helped me during my stay in the Department of Forest Resources and Environmental Conservation at Virginia Tech, from many professors to my families and friends. I owe them all my thanks.

I would especially like to thank my advisor Dr. Gwenlyn Busby for her guidance during this research, and for all the insights she shared with me and the great patience she had during all this time. I would also like to thank my committee members, Drs. Gregory Amacher and Jay Sullivan, for their valuable suggestions and comments about the improvement of my thesis.

My sincere thanks also go to my family for their love and support.

Table of Contents

List of Figures

List of Tables

1. Introduction

Biodiversity is declining at an unprecedented rate in many parts of the world. The United Nations estimates that, globally, between 150 and 200 species go extinct every 24 hours (United Nation Environment Programme). Land conservation is a major strategy to address biodiversity loss globally and nationally. The UNEP estimates that the U.S. has a total of 6,770 nationally designated (federal) protected areas, covering 27.08 percent of the nation’s total land area (UNEP). In spite of these land conservation efforts, extinction rates remain high. Risks such as land development, invasive species, and wildfire, for example, continue to threaten species survival in many areas.

In the Commonwealth of Virginia, forests cover 65% of the state, primarily with deciduous, broad leaf trees (Virginia Department of Environmental Quality, 2008), providing abundant areas as habitats for wildlife species, both plants and animals. However, because of human activity and other factors, many species become rare. How to best design nature reserves to protect these rare, threatened and endangered species (as defined by Virginia Department of Conservation and Recreation) effectively, is the central question of this thesis.

Because biodiversity conservation is an increasingly important topic, issues related to the design of protected area networks and the selection of individual sites for protection have received attention within the biological conservation and economics literature. Although a number of reserve site selection (RSS) studies have been formulated in recent years, few models incorporate the notion that risks to species survival may be spatially correlated. That is, when a natural or human hazard (land development, invasive species, wildfire, etc.) occurs on an individual parcel, the risk that nearby parcel are also affected is greater than the risk to more distant parcels.

This forms the basic idea, and is one major contribution of this study, given few existing investigations with spatially correlated risks properly considered. Specifically, the objectives of this thesis areto:

1. Apply a reserve site selection model to a Virginia landscape;

2. Incorporate spatial risk into the reserve site selection model and determine how reserve design changes as a result;

3. Vary the focal landscape and species types to investigate the extent to which observed changes in reserve design are generalizable,;

4. Incorporate heterogeneous spatial risk into the reserve site selection model and determine reserve design changes as a result.

We formulate a probabilistic model to demonstrate the impact of spatially correlated risks on reserve site selection, that is, we assume when a hazard occurs on one parcel, it will spread to its neighboring parcels. For example, this makes sense for land development risk, since urban sprawl always exhibits certain geographical patterns. Based on this notion, land development risk will spread to neighboring parcels with certain probabilities. Also, for wildfire risk, we know that when a fire ignites on an individual parcel, it is more likely to spread to its neighboring parcels and affect species there. Similarly, invasive species and pests that exist on an individual parcel are most likely to spread to neighboring parcels, in some cases depending on landscape characteristics, biological requirements, and human activities. Thus, incorporating spatially correlated risk into a RSS model is important to capture real world features.

In this study, we first consider a general risk factor, which can be of any type of disasters, including land development, fire, invasive species, pest, etc. To find the patterns of reserve sites distribution, we conduct analysis at three different levels: one county, four neighboring counties, and the whole state, based on homogeneous risk occurrences across parcels. Our model is based on three basic assumptions. First, we assume the probabilities of hazard spread decrease over space because such hazard spread is more likely to cause damage to neighboring areas. Second, and as in the literature, we assume species occurrence is spatially independent. And third, we assume that when a natural or human hazard occurs on an individual parcel, all species present in the parcel are lost. Building on these assumptions, we develop a RSS model that incorporates spatially correlated risk to solve for the optimal reserve design using a simulated annealing mathematical program. We then apply the model to a Virginia landscape.

Among many human activities that have accelerated the extinction of species, urban sprawl, or land development, is now considered as one major driving force of diversity loss which causes greatest extinction of species (Luniak, 1994, Kowarik, 1995, Savard et al., 2000, Stein et al., 2000, McKinney, 2002). With this in mind, we focus on land development as the risk and source of hazard in our modeling framework. In addition to the typical RSS model features, which seek to maximize the expected number of species, we introduce heterogeneous and spatially correlated land development risk. By characterizing the spatial pattern of the optimal reserve system design in the presence on spatially correlated risk, we are able to use results from this study to gain insight into tradeoffs between species protection, reserve connectivity, and land development thereby helping to answer important policy questions about biodiversity conservation.

2. Literature review

One way to deal with biodiversity loss associated with risk factors such as land development is the establishment of a system of protected areas, or a reserve system (Noss and Cooperrider, 1994, Pimm and Lawton, 1998). There is a rich literature on reserve system design exploring the spatial characteristics of the reserve system and the modeling choices for selecting land parcels to form such a system. This section provides an introduction of major studies in this area. Some previous studies on the impact of land development on biodiversity conservation are also reviewed.

2.1. Spatial characteristics of reserve system

Spatial characteristics have been a focus of researchers who formulate reserve design models to improve spatial coherence by controlling spatial attribution. Williams et al. (2005) provides an excellent review of the spatial attributes considered to be important in reserve design as well as site selection models that incorporate one or more of these attributes, including reserve connectivity, reserve shape, reserve proximity, as well as reserve size and number.

Tischendorf et al. (2000) discussed two types of connectivity of reserve parcels:

structural connectivity and functional connectivity. Wildlife corridors are often mentioned as a way to provide both structural and functional connections between disconnected reserves. The pros and cons of corridors have been discussed extensively in the conservation literature (Simberloff et al., 1987; Noss, 1987; Hobb, 1992; Simberloff, 1992; Hess, 1994; Earn et al., 2000).

The shape of reserves is also important to species survival within the reserves. A variety of shape measures or metrics have been developed in landscape ecology (Gustafson, 1998; Giles et al., 1999) and in other fields as well (Austin 1984; Medda et al., 1998). However, in real world cases the shape of reserves is so irregular that raises modeling difficulties which are neither solvable nor generalizable, and simple proxies are usually employed.

Reserve proximity studies center around the optimal distance between reserves, questioning whether it is better to be close or far from each other. Inter-reserve distance will influence the capability of species to migrate between reserves and to exist as a metapopulation. As pointed out by Diamond (1975), shorter distances make it easier for species to recolonize an area where it has become locally extinct and help prevent loss of genetic diversity due to inbreeding. On the contrary, longer distances can reduce the spread of diseases and intrusive species and keep away natural enemies of endangered species between reserves. Also, longer distances can increase the likelihood of species' survival from major disturbances (e.g., wildfire, hurricane), keep greater species diversity through greater habitat heterogeneity (Margules, 1982) and allow species to average over environmental fluctuations.

The reserve proximity is further formalized in literature as the reserve site selection problem (Kirkpatrick, 1983; Margules et al., 1988; Pressey et al., 1993). The primary question is how many parcels can best form a reserve network, or best protect species under the same conditions, which is supposed to protect wildlife most effectively.

2.2. The SLOSS debate

One school of thoughts suggests that a single large reserve is preferable to several smaller reserves with the same aggregate area (MacArthur and Wilson, 1967). Their argument is based on the reasoning that since species richness increases with habitat area, a larger block of habitat would support more species than any of the smaller blocks (Diamond, 1975). This idea has gained popularity in the 1960s and 1970s and was once standardized in many ecological textbooks (Williams et al., 2005).

However, as suggested by other researchers, there is no theoretical or empirical evidence for the proposed advantages a single large reserve, and if the smaller reserves had unshared species, it is possible that several smaller reserves could have protected more species than a single large reserve (Simberloff and Abele, 1982).

This is later referred to as the “SLOSS” debate (a single large or several small reserves), or more recently the “FLOMS” debate (a few large or many small reserves) (Williams et al., 2005). However, neither theory nor empirical evidence provide a clear answer to SLOSS or FLOMS, while more recent researcher focus more on “several small reserve” pattern because of the uneven distribution of species as well as a wide range of socioeconomic characters such as land price and land use pattern.

One consideration that favors several small reserves rather than a single large one is that, once certain hazards occur (e.g. wildfire, pests, land development, etc.) to some of the reserve sites, species may still be protected given their existence in other reserve sites located in other areas. We build up this analysis based on this notion.

2.3. Modeling choices: SSCP and MCSP

Location choice is always a major concern in establishing biological reserves. A large amount of literature addresses the reserve site selection problem, taking into consideration many kinds of restrictions under which the maximization of the likelihood of species’ survival is studied. Most reserve site selection models proposed in literature are based on the either species set covering problem (SSCP) and maximal covering species problem (MCSP). The SSCP model is to choose the least number of parcels in such a way that each species is protected, i.e. represented in at least one parcel. The MCSP model, in contrast, aims at maximizing the number of species for a given number of land sites to be selected or for a given number of parcels that can be selected, or a given amount of budget.

The SSCP model was first developed by Possingham et al. (1993). It selects the minimum number of land sites so that each species is covered (present in at least one chosen site that ensures its representation).

The basic SSCP model assumes there are *m* sites to select from and *n* species that occur in at least one site. Let A be an $m \times n$ matrix whose elements are:

$$a_{ij} = \begin{cases} 1, & \text{if species } j \text{ exists in site } i \\ 0, & \text{otherwise} \end{cases} \quad \text{, for } i=1,\ldots,m \text{ and } j=1,\ldots,n$$

The control variables that determine whether to choose a site or not, are:

$$x_i = \begin{cases} 1, & \text{if we reserve site } i \\ 0, & \text{otherwise} \end{cases}$$

and based on those assumptions above, the SSCP model tries to solve:

$$\begin{aligned} &\min \ \textstyle\sum_i x_i \\ &\text{s. t.} \left.\begin{aligned} \textstyle\sum_i a_{ij} x_i &\geq 1 \\ x_i &\in \{0,1\} \end{aligned}\right\} \text{ for } j = 1,\ldots,n \end{aligned}$$

This is an integer linear program and can be solved by many packages. Also, the authors suggest that this problem can be extended to include complexities such as sites with different costs (Possingham et al., 1993).

While the SSCP model present an ideal image of reserve system establishment given sufficient resources and no transaction costs such as land cost, many researchers argue that unfortunately, resources may limit what can actually be protected in a reserve system, which makes the SSCP model hardly useful to yield any feasible policy suggestions.

Rather than minimizing the necessary land parcels to protect all the endangered species, the MCSP model, first formulated by Church et al. (1996) and Camm et al. (1996), focuses on maximizing the protected number of species for a given number of land sites selected. More specifically, the MCSP model assumes the following:

$i =$ index of species to be protected
$j =$ index of areas that can be selected for the reserve system
$p =$ the number of areas that are to be selected for the reserve system
$N_i = \{ j \mid \text{where species } i \text{ is present in area } j \}$

$$Y_i = \begin{cases} 1, \text{ if species } i \text{ is covered by selected area} \\ 0, \text{ if not} \end{cases}$$

$$X_j = \begin{cases} 1, \text{ if area } j \text{ is selected for the reserve system} \\ 0, \text{ if not} \end{cases}$$

Under those technical assumptions the MCSP tries to solve:

$$\begin{aligned} &\max \ \textstyle\sum_i Y_i \\ &\text{s.t.} \ \sum_{j \in N_j} X_j \geq Y_i \\ &\qquad \sum_j X_j = p \\ &\qquad X_j = 0,1 \ \text{ for every j} \\ &\qquad Y_i = 0,1 \ \text{ for every i} \end{aligned}$$

In addition to designing a reserve network that seeks to maximize the likelihood of species' survival, many researchers have taken into consideration the cost minimizing objective. For example, Ando et al. (1998) further developed the model with budget constraints taking into consideration that most of the time government spending may not be able to protect all kinds of endangered species and that land prices of different parcels may vary a lot. They use the following notations: $J = \{ j \mid j = 1, \ldots, n \}$ is the index set of candidate reserve sites; $I = \{ i \mid i = 1, \ldots, m \}$ is the index set of species to be covered; N_j is the subset of J that contain species i; c_j is the loss associated with selecting site j and x_j =1 if site j is selected and 0 otherwise. Then, the problem is to solve the following:

$$\begin{aligned}&\max \ \textstyle\sum_{i \in I} y_i \\ &\text{s.t.} \ \sum_{j \in N_j} x_j \geq y_i \ \text{ for all } i \in I \ \text{ and } \sum_{j \in J} c_j x_j \leq b\end{aligned}$$

where y_j =1 if species i is contained in at least one of the selected sites and b is the maximum allowable loss (or government budget constraint). In the case that loss is measured by the number of selected sites, then c_j =1 for all j.

Using this MCSP model, Ando et al. (1998) have made comparative analysis of both site-minimizing problem and cost-minimizing problem, and shown how the results vary under different assumptions. For example, they found some sites in the Inner-Mountain West and the Midwest were included in cost-minimizing but not in site-minimizing solutions. Although they are not especially rich in species, but this deficiency is offset by their low cost. They concluded that the cost-optimal solution changes the optimal design of the reserve network, and achieves efficiency by avoiding costly sites and selecting nearby sites that have fewer species but are less costly.

Polasky et al. (2001) introduced a probability measure of species into the reserve site selection problem, in both site-constraint and budget-constraint specifications, and conducted empirical analysis employed data from Oregon, arguing that state level data would be more preferable since county-level data could not take into account the heterogeneity within counties which are comparatively large areas. They also reached the conclusion that budget-constrained specification that incorporates different land costs rather than site-constraint specification results in far more cost-effective conservation.

Based on Ando et al. (1998) and Polasky et al. (2001), Hamaide et al. (2009) developed a set covering model in which they differentiated “critical (e.g. threatened, endangered or rare species)” and “noncritical” species in Oregon. They imposed a spatial characteristic on selected sites. More specifically, selected sites to protect critical species are required to be “core” areas that have surrounding areas as “buffer”, which is intended to protect the core area from hazards from other areas. Hamaide et al. (2009) has a primary idea of preventing hazards by imposing the “core-buffer” spatial pattern, while it only helps in the case of on-site hazards.

2.4. Land development risk for wildlife species

In many parts of the world, population growth and economic expansion have caused significant change in land use pattern. A growing proportion of global land area is devoted to human uses such as agriculture, timber harvesting, farming and urban development. As the remaining area of undeveloped land becomes scarcer, the debate over economic development and resource conservation sharpens. There are scientific and public concerns that the loss of habitat has greatly increased the extinction rates of species. Among many human activities that have such negative impacts, urban sprawl, or land development, is now considered as one major driving force of diversity loss which causes greatest extinction of species (Luniak 1994, Kowarik 1995, Savard et al., 2000, Stein et al., 2000, McKinney 2002).

The literature has well recorded the changes in wildlife diversity along the urban to rural gradient, including plants (Kowarik 1995), birds and butterflies (Blair 2001), and insects (Denys and Schmidt 1998, McInyre 2000). In all these taxa, the number of species at the urban core drops dramatically, to less than half of the level found in rural areas (McKinney 2002). These studies suggest that land development presents serious threats to the species survival and indicate that the impact of development on many species is irreversible.

A few applications of the MCSP framework to the risk of land development have been recorded in the literature. One representative study is Snyder et al. (2004), which formulates a two-period site selection model that maximizes the expected number of species while accounting for uncertainty in site development between periods given constraints on the number of sites. This model is then solved using a linear-integer formulation. In spite of land development being one of the major threats to species survival, there is a growing disconnect between the impact of development and the amount of attention this issue receives in the RSS literature.

2.5. Summary

Spatial characteristics of wildlife reserve are widely investigated in literature, among which the size and number of reserves are a key topic. Most literature is based on either species set covering problem (SSCP) or maximal covering species problem (MCSP). However, few studies have investigated the optimal reserve site selection taking the spatial correlation of risks, in particular land development, into consideration. Similarly, the heterogeneity of risk across parcels is not well explored. This thesis contributes to the RSS literature by .

3. Model

In this section we introduce the modeling procedure of our analysis in detail. Section 3.1 describes the grid landscape that we use to delineate land parcels and upon which we specify the distribution of the species. Section 3.2 describes the basic assumptions of the model, with a graphical presentation of hazard spread. Finally, section 3.3 lays out the maximal covering species problem (MCSP) we use to model the RSS problem and section 3.4 introduces the simulated annealing algorithm we use to solve the model.

3.1. Species and landscape

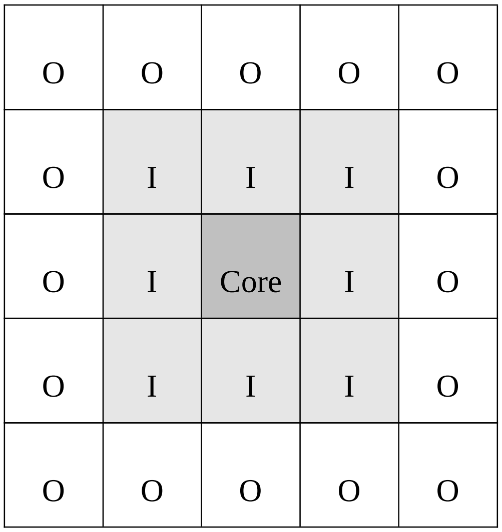
In our analysis, we include a total of 821 [threatened and endangered?] species across the Commonwealth of Virginia. Each individual species has a unique distribution across the state, with many species clustered in mountainous regions, including the Blue Ridge Mountains, and around the Tidewater coastal plain. Without a uniform species distribution, it is difficult to optimally design the reserve system that can best protect the largest number of species. Thus, we specify a grid landscape where each of the 821 is either present or absent within each parcel in the grid. The grid is defined using ArcView (CITE). The grid is composed of individual square land parcels, which are the smallest and most basic units in our analysis. We conduct analyses at three spatial scales: one-county, four-county, and statewide. At each scale, we apply the smallest square grid set that covers the focal landscape. By analyzing three different spatial scales, we can determine if characteristic reserve patterns emerge at multiple scales of analysis.

3.2. Basic assumptions

This sub-section describes several basic assumptions regarding spatially correlated risk in our model. These assumptions are important because they allow us to incorporate real-world aspects of the RSS problem into a modeling framework that is solvable. First, we assume that the occurrence of species is spatially independent, i.e. the occurrence of species in one parcel is not related to their occurrence in other parcels. Second, we assume that when the hazard occurs in the parcel, the existing endangered species will be wiped out. This assumption is necessary since it to a large extent represents the real world situation and simplifies our modeling of spatially correlated risk to a probability measure. For example, in the case of development risk, when the parcel is urbanized, threatened and endangered species habitat would be altered to such a degree that species survival on the parcel would no longer be possible. In Section 5we first assume homogeneous risk across parcels, where the probability of hazard occurrence is the same for each parcel. Then we examine the case of land development, where we incorporate heterogeneous land development risk across parcels into the model. .

To model hazard spread requires recognition of the fact that, in the real-world, a hazard, such as land development, wildfire, or disease, is more likely to affect nearby parcels than distant parcels. Thus, we assume that the probability of hazard spread decreases over space. Specifically, the hazard can spread to adjacent parcels and then onto one parcel further in each direction, that is, we assume double-level queen contiguity (Anselin and Rey, 2010). Figure 3.1 illustrates the possible range of spread when the hazard initiates on the core parcel. For simplicity, we assume that for an individual parcel (e.g. the core parcel in Figure 3.1), the probability of hazard spread to the outer-belt parcels is one-half of the probability of hazard spread to the inner-belt parcels. Thus, once we vary the probability of hazard spread from the core parcel to the inner-belt parcels at 0, 0.5 and 1, as seen in Fig 3.1 and illustrated again in the following empirical analysis, the probability of spread from the core parcel to the outer-belt parcels will be 0, 0.25 and 0.5, respectively.

Fig.3-1 A Graphical Illustration of Inner-Belt (I) and Outer-Belt Parcels (O)



O	O	O	O	O
O	I	I	I	O
O	I	Core	I	O
O	I	I	I	O
O	O	O	O	O

3.3. Maximal covering species problem (MCSP)

The basic problem faced by the land manager, or government planner, is how best to design a system of protected areas to maximize the number of species under protection. To address this problem, we specify a nonlinear mixed integer optimization model to select a group of land parcels that maximizes the expected number of species, subject to the site-constraint and a total risk constraint. In this section we describe the formal mathematical setup of our MCSP model with spatially correlated risk.

In our optimization model, there are n parcels indexed by j ($J = \{1,2,\ldots,n\}$) and m species indexed i ($I = \{1,2,\ldots,m\}$). On each parcel j, species i is not present with probability q_{ij}. The calculation of q_{ij} depends on the initial presence or absence of species and on the probability of hazard on the parcel, p_j.

$$q_{ij}^{x_j} = \begin{cases} p_j a_{ij} & \text{for all } N_i \\ 1 & \text{otherwise} \end{cases}$$

where

$N_i =$ set of parcels containing species i

$p_j =$ probability of on-site hazard on parcel j

$$a_{ij} = \begin{cases} 0 & \text{when species } i \text{ is not present on parcel } j \\ 1 & \text{when species } i \text{ is present on parcel } j \end{cases}$$

Then the model is specified as follows:

$$\text{Max} \sum_{i \in I} (1 - \prod_{j \in J} q_{ij}^{x_j}) \qquad [1]$$

Subject to

$$\sum_{j \in J} c_j x_j \leq B \qquad [2]$$

$$p_j x_j + \sum_{k \in H_j} p_k f_k x_k + \sum_{l \in O_j} p_l t_l x_l \leq \alpha \quad \text{for all j} \qquad [3]$$

where

H_j = set of inner-belt parcels of parcel j
O_j = set of outer-belt parcels of parcel j
p_k = probability of hazard occurence on inner-belt parcel k
p_l = probability of hazard occurence on outer-belt parcel l
f_k = probability hazard spread from inner-belt parcel $k \in H_j$ to parcel j
t_l = probability hazard spread from outer-belt parcel $l \in O_j$ to parcel j
α = maximum allowable risk

in which x_j the decision variable is equal to 1 if parcel j is selected for the reserve system; or x_i = 0. In this setting, the hazard spread to the inner-belt and outer-belt parcels are specifed in Equation [3].

The model includes two constraints, equations [2] and [3]. Equation [2] is the budget constraint where c_j is the individual cost of each land parcel and B is the given budget in monetary terms. In cases where we do not specify a monetary budget constraint, but constrain the number of parcels that can be selected, we set c_j =1 for all j and let B equal the maximum number of parcels allowed in the reserve.

Equation [3] differentiates risk components: the probability that the hazard occurs on the individual parcel (the first term on the left-hand-side of the inequality) and the risk that the hazard spreads onto the individual parcel from nearby parcels (either on the inner-belt, the second term on the left-hand-side or the outer-belt, the last term on the left-hand-side). Then the total risk that threatens the habitat on each parcel is the sum of all the three types of probabilities above. Equation [3] says that the joint probabilities of hazard, i.e. the total risk, should be no greater than a maximum allowable risk, α. Intuitively, the maximum allowable risk, α, can be interpreted as the threshold above which the parcel shall not be selected as a reserve. In practice, this risk threshold may come from past conservation studies and planning experiences, and we may expect α to decrease as the size of a single parcel increases or the total number of parcels in the reserve decreases. In thisanalysis, however, we set α equal to 20. In all cases described in the results section, the constraint is non-binding and does not influence the optimal reserve design. Thus, in our case α is mainly for illustration purposes and Equation [3] serves as mechanism to differentiate these 3 different risk types (on-site, spread from inner-belt neighboring parcels, and spread from outer-belt parcels). Admittedly, sensitivity analysis with respect to α may be of importance when the constraint is binding, we leave that for future work. We solve the optimization model by deciding if x_j (the decision variable) equal to 0 or 1 for each j such that the reserve includes a group of parcels that maximizes the expected number of species, subject to equations [2] and [3].

3.4. Simulated annealing algorithm

The MCSP presented in section 3.3 cannot be solved using traditional optimization techniques. Specifically, because of the model's nonlinearities and size of the problem it is not possible to determine the optimal value of x_j for each j, where x_j is a binary decision variable that determines if parcel j is selected for reserve. Thus, we employ a heuristic which seeks to identify a good, though not necessarily optimal solution to the problem by iteratively identifying candidate solutions (the set of J where $x_j = 1$) that increase the value of the objective function.

We employ a simulated annealing heuristic to identify a good approximation to the global optimum of a given function. The name comes from annealing in metallurgy, which is a technique to reduce the defects of a material by heating and controlled cooling. The heating process causes the atoms to change their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy. The controlled cooling, however, gives them more chances to find configurations with lower internal energy than the amount in the initial state.

Analogically, the basic idea of the simulated annealing algorithm is to approximate the global optimum via iteration (the "cooling"). In each step of the algorithm, the current solution is replaced by a random solution in the neighborhood of the current solution. The new solution may then be accepted with a probability that depends on both its location in the neighborhood and a global parameter T (the "temperature"), that is slowly decreased during the process. The dependency is such that the choice between the previous and current solution is almost random when T is large, but increasingly selects the better solution as T goes to zero.

Simulated annealing is suitable for situations where the search space is large and discrete. For many problems that are impossible to be solved by exhaustive enumeration and approximation with a small error is accepted, simulated annealing may be more efficient in calculation, which significantly lowers the requirement of computer hardware and shortens the computing time. Here we need to note that the results from simulated annealing are "close" approximates rather than the global maximum. Thus, we term the solution as "best available" ones since they are not necessarily exactly the optimum. The algorithm applied to the RSS begins with the choice of an initial temperature t_0. At the original temperature t_0, we repeat for L (the length of Markov chain) times of the algorithm described below:

1. Choose parcel *a* randomly. If parcel *a* does not belong to the parcels which are already selected for reserves, we select it and see whether it is feasible or not. If all the reserves we select right now after we select parcel *a* satisfy the constraints both [2] and [3] in our model which are defined as budget (or parcel number) constraint and total risk constraint, respectively, , it is feasible to select parcel *a* and we set x_a = 1. If not, we replace another parcel *b* which is already chosen to be a reserve candidate with parcel *a*. If it is acceptable (defined below) after substitution, we accept the substitution of *b* by *a*, which means we choose parcel *a* to be a reserve candidate instead of parcel *b* with parcel *b* replaced. The acceptability condition is that the set of selected parcels satisfy: 1) all the constraints after substitution, and (2)the difference value *df* (defined below) is great than 0. If not, the absolute value of (-*df / t*) is less than the random number from 0-1, which is also acceptable. Here $f = \sum_{i \in I} (1 - \prod_{j \in J} q_{ij}^{xi})$, (*I* is set of species and x_i is the decision variable), this function is the objective value of our model. *df* is defined as f_a - f_b (fa is the optimum when parcel *a* is chosen but parcel *b* is not , which means $a \in I$ but $b \notin I$. f_b is defined in a similar way.

2. If parcel *a* has already been chosen as a reserve candidate, that is $a \in I$, replace parcel *a* with parcel *b* which has not been selected before, i.e. $b \notin I$. If it is acceptable after substitution, we accept the substitution.

We reduce the temperature to (t_0 x t_f, in which t_f is cooling parameter). Continue to reduce the temperature, and repeat the iterations for L=100 times as before. When the temperature reaches the stopping temperature, the search terminates. The limited temperature is (t_0 *(cooling parameter^loop)) where the cooling parameter is also called the weakening coefficient, and loop is annealing (cooling) times.

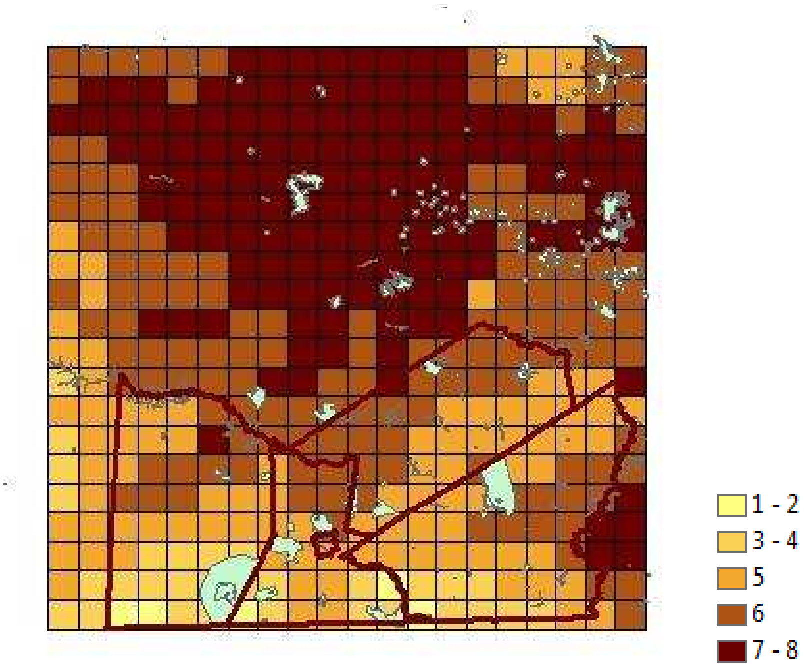
4. Data

The species data, in terms of habitat distribution, comes from the Natural Heritage GIS data from Virginia Department of Conservation and Recreation. In this thesis, we consider species that are documented as rare, threatened or endangered. These data are retrieved in the form of GIS layer files and we assess the distribution of the species in a GIS environment. We include 821 total rare, threatened or endangered species. For simplicity, we collectively term the 821 species as "rare" in the remainder of the thesis.

For the budget constrained case with heterogeneous spatial risk, we approximate land value, using farm land value data from the National Agricultural Statistical Service, United States Department of Agriculture (USDA, 2007). Using the Quick Stats web tool, we retrieve the county-level average farm real estate value from the electronic tables. These county-level values are then assigned to individual parcels within the four-county focal area. The land values assigned to parcels located across counties are averaged by the proportion of the parcels area in each county.

In the case of land development analysis, every parcel has different development risk based on Virginia Conservation Lands Needs Assessment (VCLNA)'s specification. In this dataset, obtained by the Virginia Department of Conservation and Recreation's Natural Heritage Program, land development risk in every Virginia county is evaluated on a 1-8 scale, in which counties with a score 1 are the least likely to be developed and those with score 8 are the most likely to be developed. In our analysis, we convert these scores by dividing them by 100, which generates probabilities of land development ranging from 0.01 to 0.08. A graph that shows the heterogeneous land development risks is as follows (measured in original scale 1-8):

Fig 4-1 Risk Distribution in the Study Region



5. Results

In this section, we first apply the MCSP model to a RSS problem on a Virginia landscape with homogenous risk. Initially, in section 5.1, we do not specify the type of spatial risk, but the hazard threatening habitat can be thought of as any such risk, including land development, wildfire, or invasive species. Then, in section 5.2, we apply heterogeneous land development risk data to a Virginia landscape. For each case we describe the results in terms of the expected number of species present in the optimal reserve and the connectivity of the parcels included in the optimal reserve. In all cases, the risk parameter, α, is set equal to 20 and is non-binding in each case.

5.1. Homogeneous spatial risk in a Virginia landscape

To begin, we evaluate the impact of homogeneous spatial risk on reserve design at three geographic scales within Virginia: one-county, four-counties and statewide. These three scales provide insight into reserve planning at different scales and allow us to look for common features in reserve design results via cross-level comparison. At each scale, we apply spatial data from the Virginia Department of Conservation and Recreation on species presence-absence (a_{ij}) and solve for the best available reserve design (i.e. decide if x_j equals 0 or 1 for all j), subject to the model's constraints.

This section is organized as follows. In sections 5.1.1, 5.1.2, and 5.1.3, we apply the MCSP model to three geographic scales, respectively. Each section includes modeling results when all rare species are included, when only rare plant species are included, and when only rare animal species are included. Part 5.2 introduces heterogeneous spatial risk into the modeling framework, both with and without budget constraint.

5.1.1. One-county analysis

In this section we present modeling results for three cases: all rare species, rare plant species only, and rare animal species only. We analyze the spatial pattern of the best reserve design across these three cases in search of similarities as well as possible differences. For each case, the same simulated annealing solution method is employed; we set the initial temperature t_0=300, the length of Markov chain (L) at 300, cooling parameter at 0.95 and cooling times at 1000.

All species

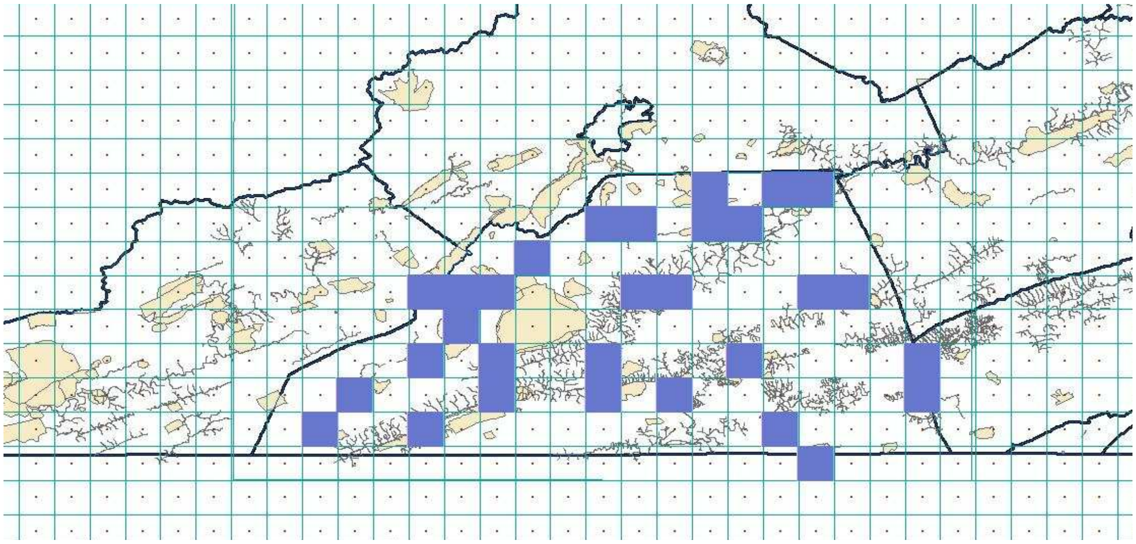
This section includes all rare species within the one-county area, including both plants and animals. We focus on Scott County, which provides habitat for more species than most other counties across the state. In the one-county setting we define a 21 x 21 (441 parcel) grid landscape. There are 85 individual rare species present in the county.

On each individual parcel the probability of hazard from on-site occurrence and spread from neighbors. For simplicity in this section we focus on hazard spread from adjacent neighbors (inner-belt) only. To maximize the expected number of species protected, we select B=30 (6.8% of total area) reserves from the 441 total parcels within the grid landscape.

We use simulated annealing algorithm described before to solve RSS problem. What we want to see is the distribution of reserves and how it changes as probability of hazard spread changes in the presence of a fixed probability of hazard occurrence. To do this, we set the probability of hazard occurrence p_j0.05 and look for the maximum number of surviving species and their distribution pattern under three different probabilities of hazard spread, $f_k=0$, $f_k=0.5$ and $f_k=1$. We develop and employ a simple connectivity index (*CI*) to quantify the spatial patterns of the best reserves. For each reserve, we count the number of inner-belt reserves and assign them a weight of 1, and count the number of outer-belt reserves and assign them a weight of 0.5. Then the connectivity index is a weighted sum of the nearby parcels of each reserve. For example, if a certain selected reserve *j* has *k* inner-belt reserves and *l* outer-belt reserves nearby, then $CI_j = k + 0.5l$, and then $CI = \Sigma_j CI_j$. Reserves that are highly connected will have higher CI values than reserves that are more dispersed.

Figure 5.1 below illustrates the distribution of reserves when we set the probability of hazard spread f_k=0. In this case, there is no spread from the parcel where the hazard initiates to adjacent parcels and hazard risk is not spatial correlated. In this case we observe that the selected reserves are close to each other. Additionally, we find that the reserves selected are parcels that contain the greatest number of species. We also find that most of the reserves we choose are close to rivers. For example, Copper Creek, one of the major watersheds in the county, provides habitat for many rare aquatic plants and animals, and 20 of the 30 parcels included in the best available reserve are located along this river. Others selected reserves are distributed along smaller rivers, including Hilton Creek, Big Maccasin Creek, North Fork Clinch River, Stony Creek. The connectivity index (*CI*) of the best available reserve is 43 when the probability of hazard spread f_k=0.

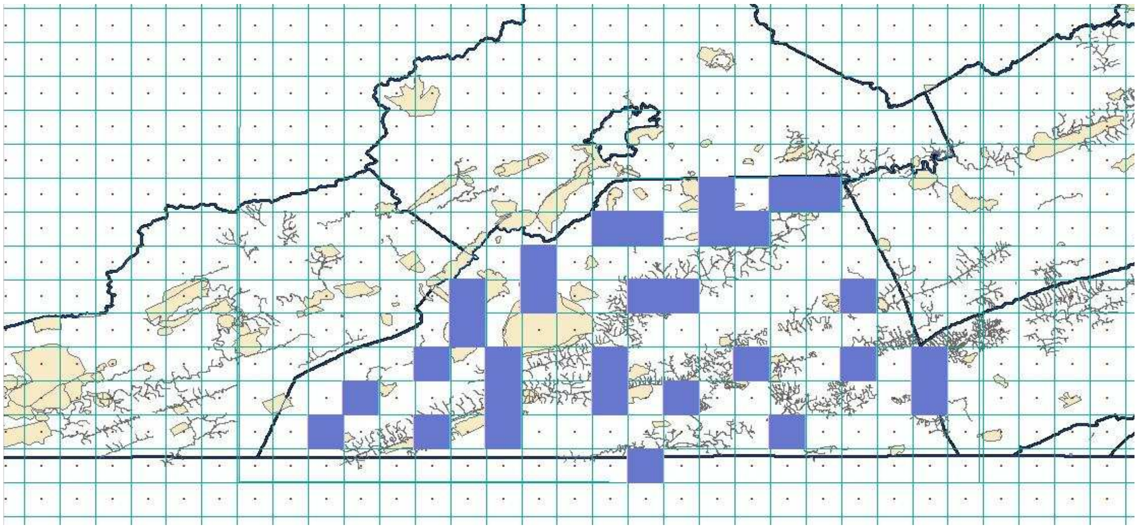
Fig 5-1 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– All rare species



Next we increase the probability of hazard spread (f_k) from an individual parcel to an inner-belt parcel from f_k=0 to f_k=0.5. With a positive probability of hazard spread between adjacent parcels, the land manager must now weigh the tradeoffs between selecting parcels with the greatest number of species and designing a reserve system that includes adjacent parcels.

In Figure 5.2 we see again that most parcels selected for reserve coincide with rivers and many adjacencies exist among selected parcels. That is, even though there is a positive risk of hazard spread, adjacencies remain in the best available reserve design. Most parcels selected are those with the greatest number of species, often regardless of whether or not those parcels are adjacent to other parcels selected for protection. However, in this case, the connectivity index (*CI*) decreases to 36 as the selected reserves are slightly more dispersed than in the case without spatially correlated risk.

Fig 5-2 Reserve Design when the Probability of Hazard Spread (**f_k**) is equal to 0.5– All rare species



Finally, when the probability of hazard spread to the inner belt parcels f_k=1, indicating that once the hazard occurs on an individual parcel, it always spreads to the eight adjacent parcels. In this case, the connectivity index (*CI*) of the best reserve decreases to 26. Figure 5.3 shows that most of the selected reserves are along rivers, as in previous cases, but in many cases the reserves are separated by at least one parcel. Again, there are still adjacencies in the best available reserve with spatially correlated risk taken into consideration.

We see that the distribution pattern of selected reserves is very similar to previous cases. Table 5.1 displays the comparative statics of connectivity index and optimum as the probability of hazard spread changes, showing that as the probability of hazard spread increases, the connectivity of the reserve decreases.

Fig 5-3 Reserve Design when the Probability of Hazard Spread (***f_k***) is equal to 1– All rare species

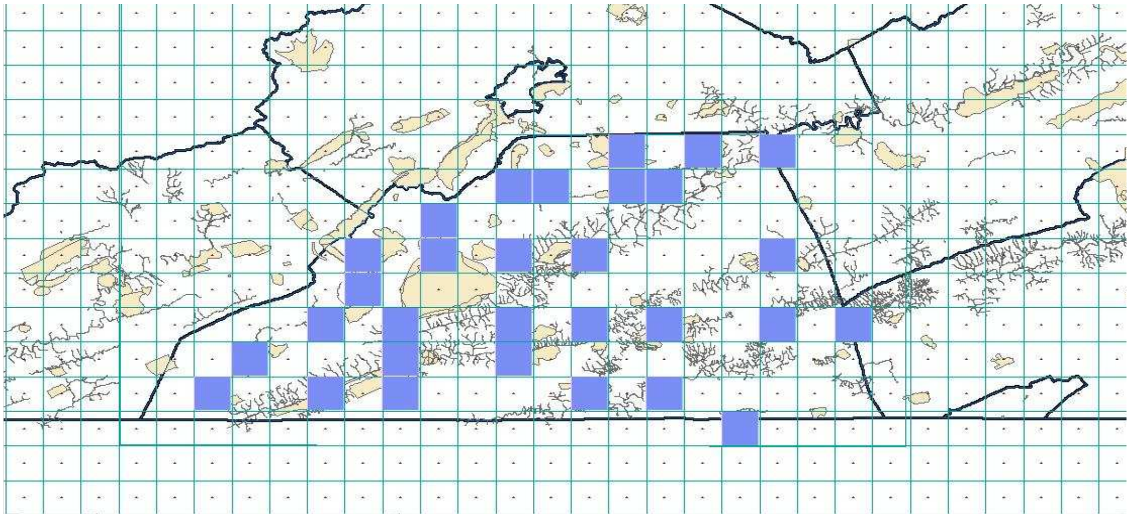


Table 5-1 Connectivity Index and Expected Number of Species ($p_j = 0.05$)

Probability of Hazard Spread (f_k)	Reserve Connectivity	Expected No. of Species
0	43	70
0.5	36	68
1	26	66

As the probability of hazard spread (f_k) becomes larger, the connectivity gets smaller and the expected number of species protected in reserves gets smaller (Table5-1). It makes sense because if reserves are selected to be close to each other, when the probability of hazard spread increases, the species in nearby regions are more likely to be wiped out. Thus, the reserves are further from each other when the probability of hazard spread increases. When adjacent parcels are included in the reserve, in some cases a greater number of parcels is affected given the spread of hazards. Therefore, the expected number of surviving species becomes smaller.

Rare Plants

When solving the RSS problem to maximized the expected number of all species, we found that the reserves tend to be located along rivers. However, we also want to see whether the reserves are likely to be close to rivers if we consider plants and animals separately. As in the case for all species, we fix the probability of hazard occurrence, and vary the probability of hazard spread (fk and tl) to see how the connectivity of the best reserve and the expected number of species change.

Again, focusing on Scott County, we solve the model on a 21 x 21 grid landscape.

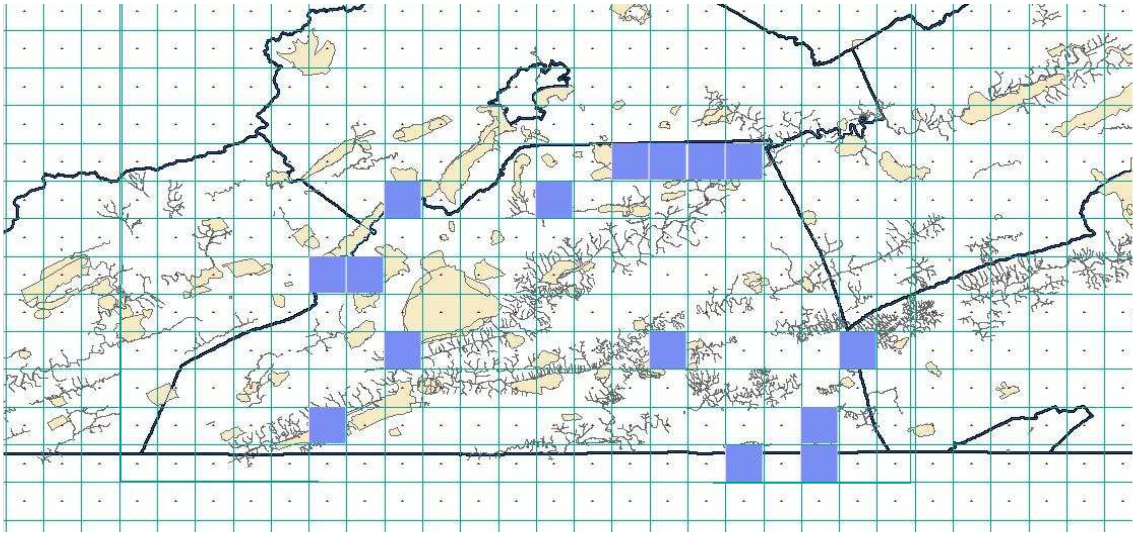
Twenty species of rare plants are present in Scott County. Because we are considering plants only, we select B=15 parcels from the 441 total square parcels to maximize the expected number of species.

In this case, the hazard may spread to adjacent parcels (inner-belt) *and* one parcel further in each direction (outer-belt). In this case, changes in reserve connectivity and expected number of plant species as the probability of hazard spread changes should be more significant because spatial correlated risks now plays a larger role in reserve design.

As described in the modeling section, we also assume that, to a certain parcel, the probability of hazard spread from the outer-belt parcels is half of the probability of hazard spread from the inner-belt parcels. Thus, we set the probability of hazard spread from the inner-belt parcels f_k= 0, f_k=0.5 and f_k=1, and the relevant probability from the outer-belt parcels t_l=0, t_l=0.25 and t_l=0.5, respectively. Again, we fix the probability of on-site hazard occurrence equal to 0.05 (p_j).

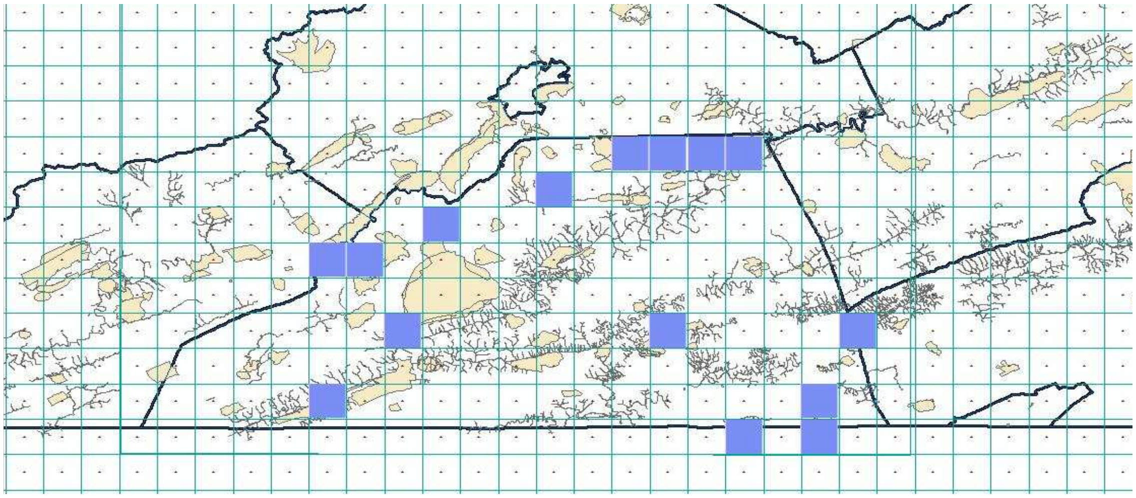
Figure 5.4 below shows the distribution of reserves when there is no spatially correlated risk and we set the probability of hazard spread (f_k) from the inner-belt parcels and outer-belt parcels initially at 0. When there is no hazard spread (f_k) from nearby parcels and the probability of hazard occurrence (p_j) for every parcel is the same, maximizing the expected plant is equal to selecting a group of parcels with most kinds of plants. From Figure 5.4 we see that the parcels selected for plants are also close to rivers (including smaller rivers like Stony Creek). In this case, the connectivity index (*CI*) of the best available reserve is 21.

Fig 5-4 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– Rare Plants



Next, we increase the probabilities of hazard spread to 0.5 and 0.25, for the inner-belt parcels (f_k) and outer-belt (t_l) respectively. The connectivity index (*CI*) of the best available reserve for rare plants decreases to 20, meaning that parcels include in the reserve are now further from each other. As shown in Figure 5.5, a number of parcels within the best available reserve are along rivers.

Fig 5-5 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0.5– Rare Plants



Finally, we increase the probabilities of hazard spread to $f_k = 1$ and $t_l = 0.5$, respectively. It becomes more obvious that the reserves are further from each other, and the connectivity index (*CI*) of reserves falls to 15. The distribution of reserves is shown in Figure 5.6. It makes sense because the spatial correlated risk becomes bigger and plays a more important role in the process of selecting reserves for plants. Like the result of the analysis of all species, when spatial correlated risk increases, the parcels in the optimal reserve become more dispersed.

Fig 5-6 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0.5– Rare Plants

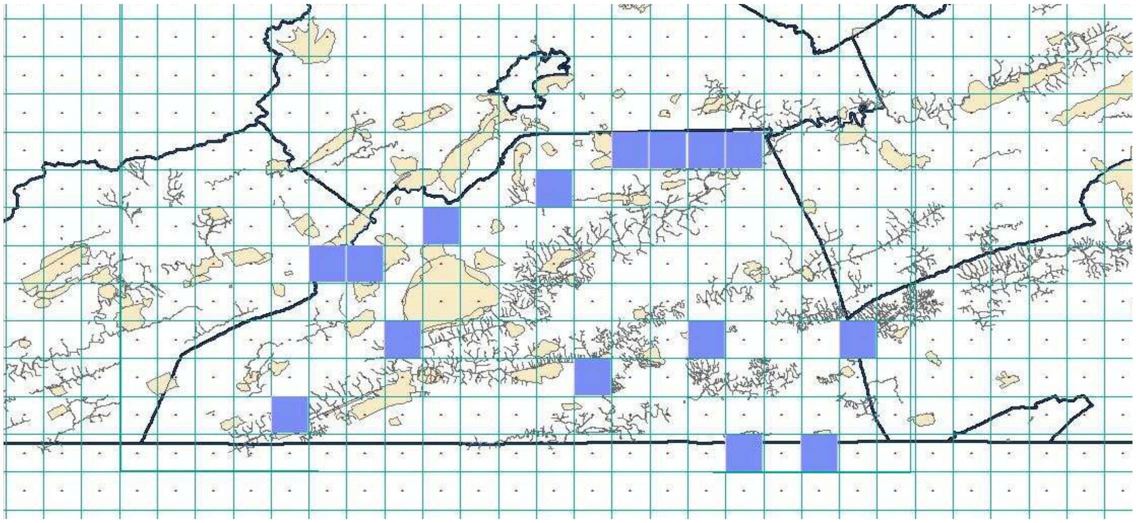


Table 5-2 Connectivity Index and Expected Number of Species ($p_j = 0.05$)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	21	19.3
0.5	0.25	20	18.8
1	0.5	15	18.3

In the study of rare plants, the optimal reserve design changes significantly as the probability of hazard spread increases. From Table 5-2 we can see that both the connectivity index (*CI*) and the expected number of rare plant species decreases as the probability of hazard spread becomes larger and a larger area is now affected.

Rare Animals

In this section we apply the RSS model to solve for the best available reserve design when only rare animals in Scott County are considered. There are 28 individual species of rare animals in Scott County.

First, we set the probability of inner-belt hazard spread (f_k) at 0, and thus the probability of hazard spread to the outer-belt (t_l)s also 0. The reserve distribution for animals is shown in Figure 5.7. Compared to the optimal reserve for rare plant species, the optimal reserve for rare animal species is even more closely coincides with rivers. This result is likely due to the fact that many of the rare species in Scott County are aquatic. Therefore, rivers there are the best places to be reserved. In this case, the connectivity index (*CI*) is 22.

Fig 5-7 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– Rare Animals

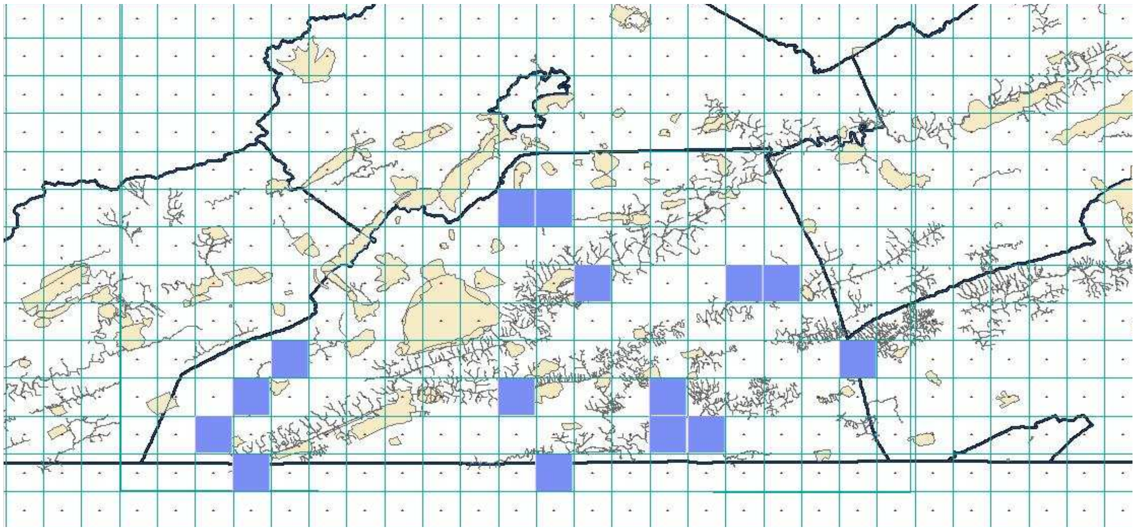
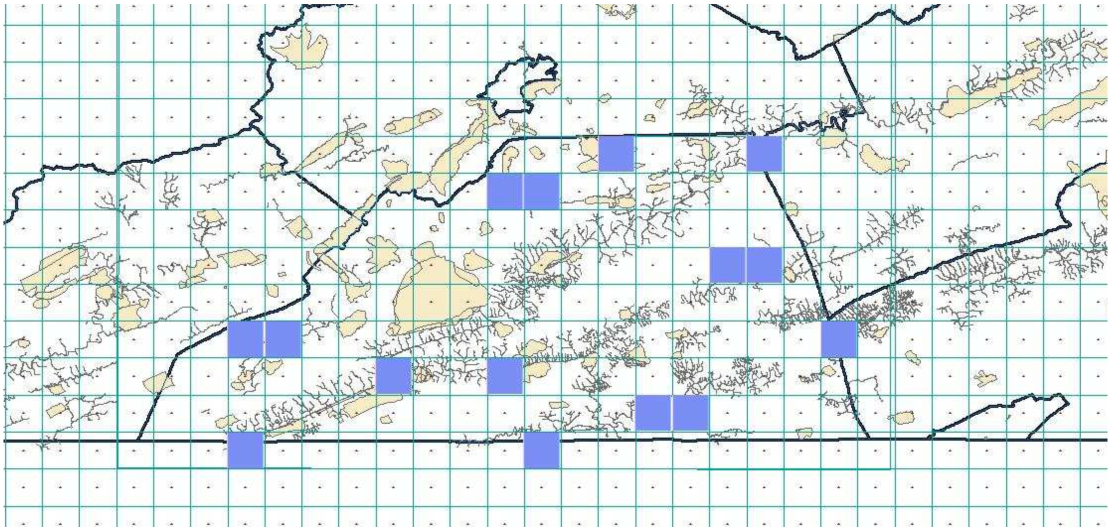


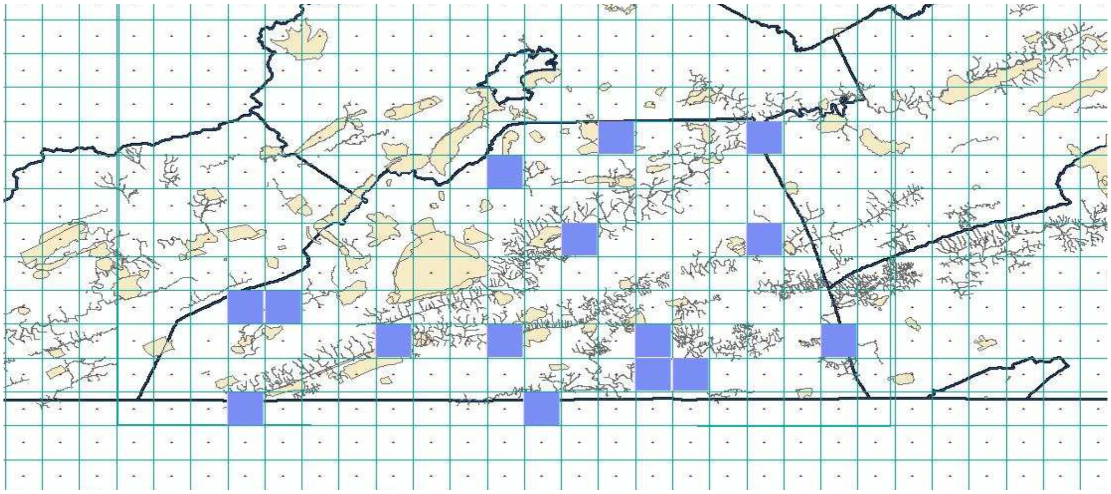
Figure 5.8 shows the case in which the probabilities of hazard spread increase to f_k = 0.5 and t_l = 0.25, respectively. In this case, we observe an notable change in reserve pattern and the connectivity index (*CI*) decreases to 11. Although reserve connectivity decreases, reserves parcels remain located along rivers. This is because rivers provide habitat for the rare aquatic animal species in Scott County and the number of species existing in individual parcels affects reserve design.

Fig 5-8 Reserve Design when the Probability of Hazard Spread (**f_k**) is equal to 0.5– Rare Animals



When the probabilities of hazard spread increase to f_k = 1 and t_l = 0.5, respectively, the connectivity index (*CI*) decreases to 10, and selected reserves are very far from each other. However, the reserves are also distributed along rivers. Results are shown in Figure 5-9.

Fig 5-9 Reserve Design when the Probability of Hazard Spread (***f*$_k$**) is equal to 1– Rare Animals



To conclude, the pattern of animal reserves is similar as before (Table 5.3). Both the connectivity and optimum decrease as the probability of hazard spread increases.

Table 5-3 Connectivity Index and Expected Number of Species (p_j = 0.05)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	22	26.0
0.5	0.25	11	25.6
1	0.5	10	25.0

5.1.2. Four-county analysis

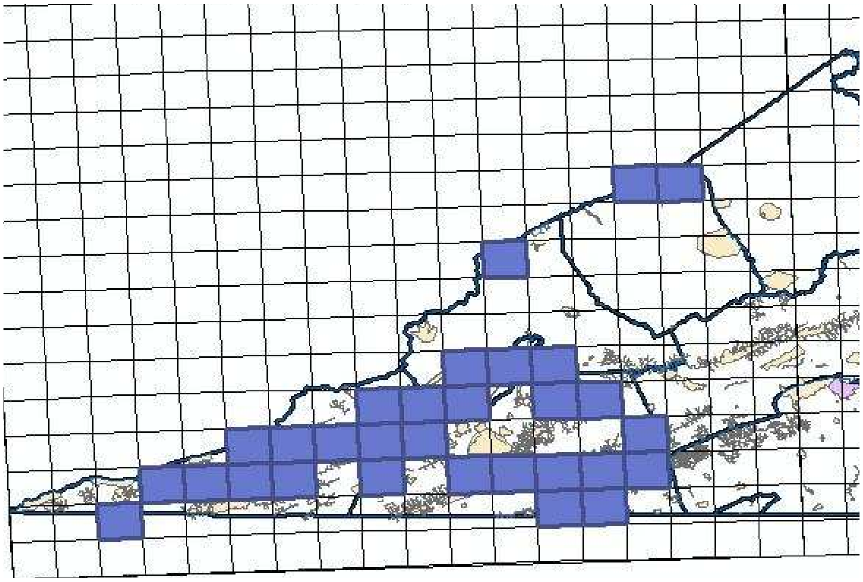
All species

In the real-world of conservation planning, decision-makers might be interested in looking beyond a one-county area for larger scale planning purposes. For example, when designing a reserve, conservation planners might want to include an entire ecosystem type or species range, which could easily extend beyond the political boundaries of a single county. Thus, in order to apply our model to such broader context, next we expand our focal landscape to include four counties in Southwest Virginia: Scott County, Lee County, Wise County and Dickenson County. Using GIS, we overlay the four-county area with an 18 x 18 grid. There are 137 total species present within the four-county area. We set B equal to 30 and solve the model to maximize the expected number of species in the presence of spatially correlated risk. In this setting, hazard spread from both inner-belt (f_k) and outer-belt (t_l)are considered.

As before, we use simulated annealing algorithm to solve the RSS problem. Again, we consider the case in which the probability of hazard occurrence (pj) on an individual parcel is 0.05, and study the comparative statics when the probability of hazard spread to inner-belt parcels (f_k) changes from 0, to 0.5, and to 1. Spread to core parcel from outer-belt parcels (t_l) changes from_0, 0.25 to 0.5, respectively. For all cases in the four-county analysis, we set the initial temperature at 300, the length of Markov chain at 300, weaken coefficient at 0.95 and annealing times at 1000.

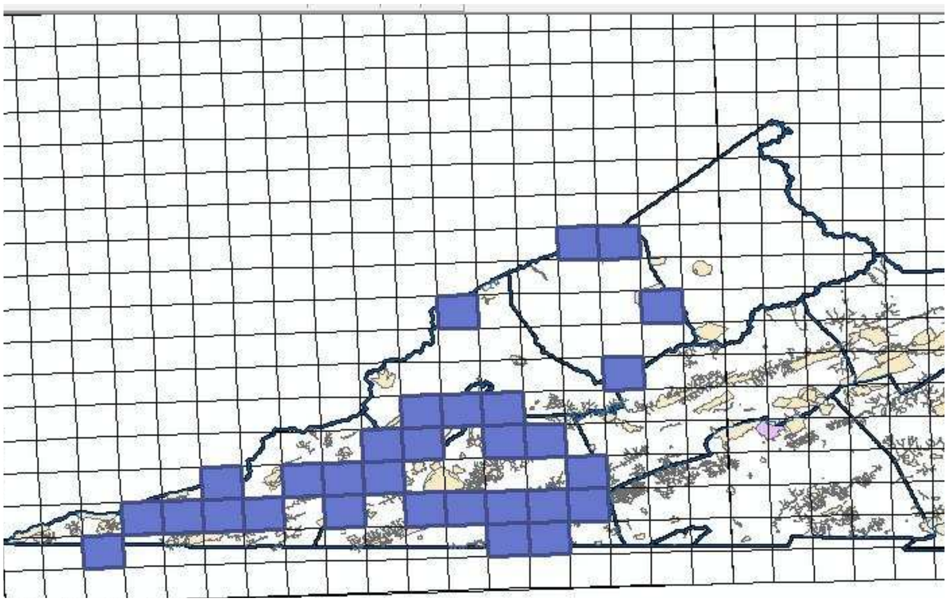
Figure 5.10 shows the distribution of parcels selected for reserve when we set the probability of hazard spread from both of inner-belt (f_k) and outer-belt (t_l) both at 0. In this case, there is no spatially correlated risk and, as a result, the reserve parcels are close to each other. Also, most of the reserves are located near rivers, as observed in the one-county analysis. The connectivity index (*CI*) of the reserve is 152.

Fig 5-10 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– All Rare Species



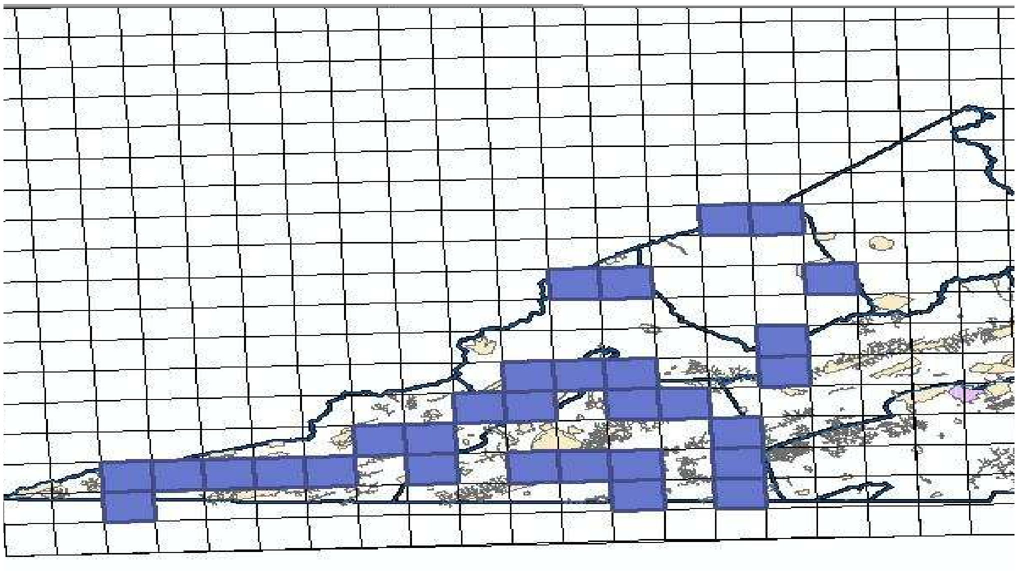
Next we set the probability of hazard spread from inner-belt (f_k) and outer-belt (t_l) at 0.5 and 0.25, and reach the selected reserves shown in Figure 5.11 below. The connectivity index (*CI*) of the reserve decreases to 137.5. From Figure 5.11 we can also see that the reserves tend to be located in areas with rivers.

Fig 5-11 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0.5– All Rare Species



Finally, we set the probability of hazard spread at ($f_k = 1$ and $t_l = 0.5$ respectively, which, as before, means that once a hazard occurs, it will certainly spread to adjacent parcels. In this case, the connectivity index (*CI*) of the reserve decreases to 108.5, which verifies the negative correlation between the probability of hazard spread and distributional connectivity. Figure 5.12 below depicts the parcels selected for reserve.

Fig 5-12 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 1– All Rare Species



In the analysis above we see that the distribution pattern of parcels selected for reserve is similar prior results. That is, as the probability of hazard spread increases, the connectivity index (*CI*) decreases. Table 5.4 below shows the comparative statics of connectivity index and expected number of species) as the probability of hazard spread changes.

Table 5-4 Connectivity Index and Expected Number of Species ($p_j = 0.05$)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	152	115.0
0.5	0.25	137.5	104.4
1	0.5	108.5	94.0

Rare plants

In the following study, we seek to select the reserves for plants in these four counties (Scott, Lee, Wise and Dickenson). There are 43 kinds of rare plants existing in 324 parcels within the four-county area. To maximize the expected number of rare plants, we select $B = 15$ parcels for reserve. In this setting, as before, hazard spread to both inner-belt (f_k) and outer-belt (t_l) are considered.

First we examine the case where there is no spatially correlated risk andthe probability of hazard spread from the individual parcel to the inner-belt is 0. In this case, the reserve design is as shown in Figure 5.13. Here we observe the reserves clustered in watersheds; connectivity index (*CI*) is 45.

Fig 5-13 Reserve Design when the Probability of Hazard Spread (**f_k**) is equal to 0 – Rare Plants

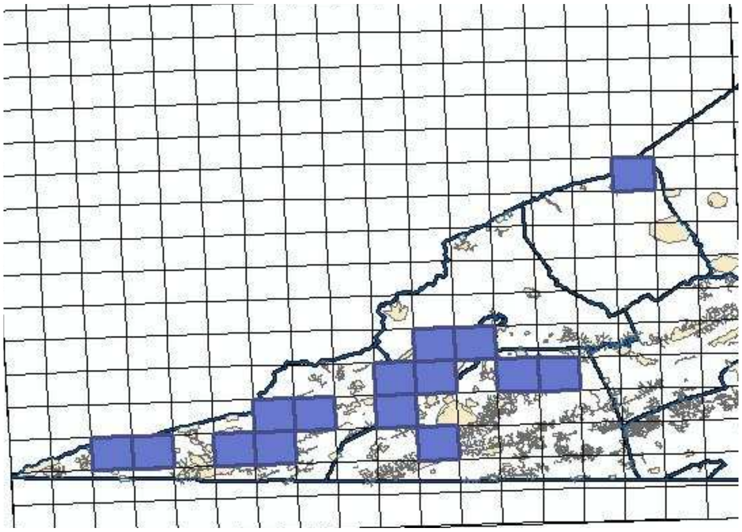
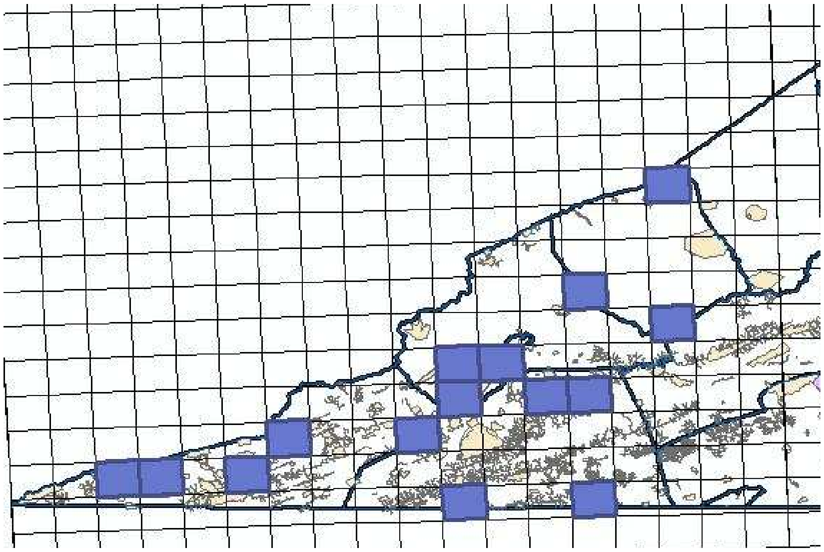


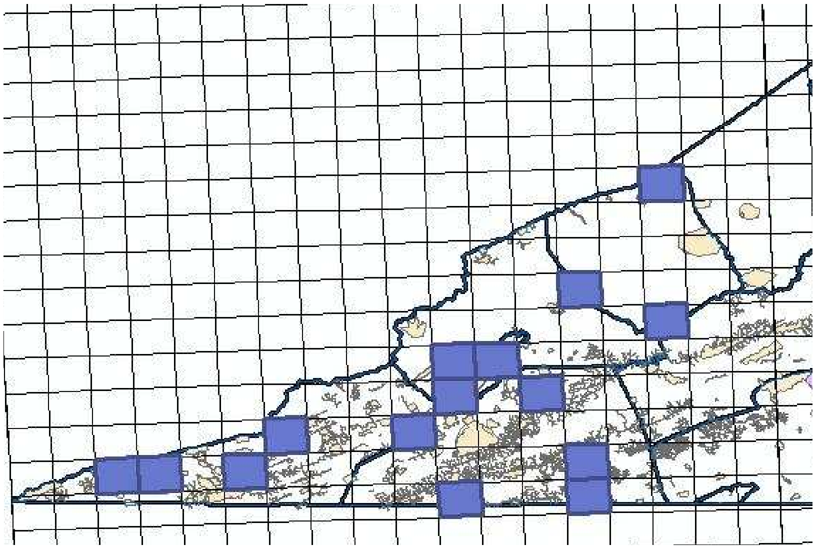
Figure 5.14 shows the reserves design when_f_k =0.5 for the inner-belt and t_l =0.25 for the outer-belt. In this situation, parcels selected for reserve are more dispersed. The connectivity index (*CI*) of reserves decreases to 26 in this case. There are is a small number of parcels selected for reserve in Dickenson County because only a small number of rare plants are present within the county.

Fig 5-14 Reserve Design when the Probability of Hazard Spread (***f***$_k$) is equal to 0.5 – Rare Plants



When the probability of inner-belt hazard spread (f_k) increases to 1, the reserve distribution shifts to a pattern shown in Figure 5.15, the connectivity (*CI*) decrease further to 24. Obviously, the reserves selected are also located in watersheds.

Fig 5-15 Reserve Design when the Probability of Hazard Spread (***f_k***) is equal to 1 – Rare Plants



Similar to former analysis, Table 5.5 verifies the pattern of reserves distribution again. The connectivity index and expected number of plants become smaller when the spatial correlated risk becomes larger.

Table 5-5 Connectivity Index and Expected Number of Species (***p_j*** = 0.05)

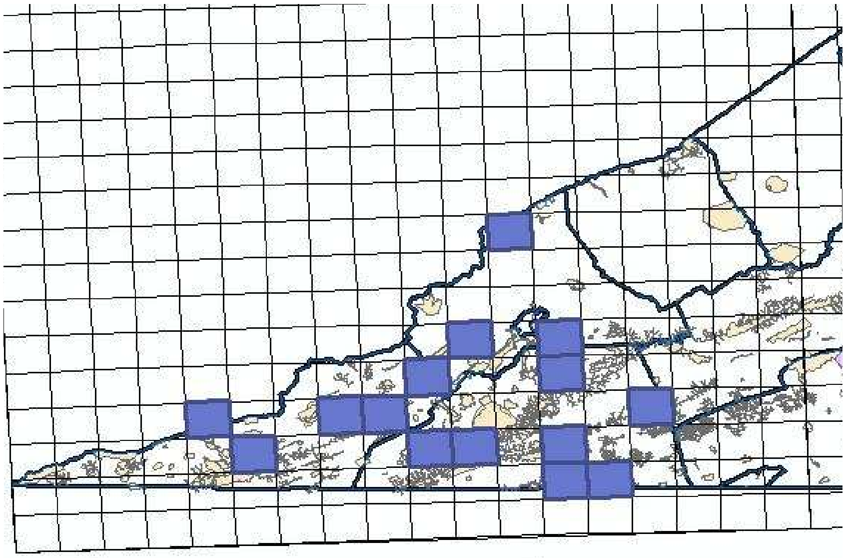
Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	45	34.6
0.5	0.25	26	33.0
1	0.5	24	31.5

Rare animals

We continue to study the reserves for rare animals on this four county scale. There are 42 kinds of animals in these four counties, which are represented by the same grid system. In this study, we aim at selecting 15 parcels for reserves and find the pattern of reserves distribution. The parameters do not change in this study.

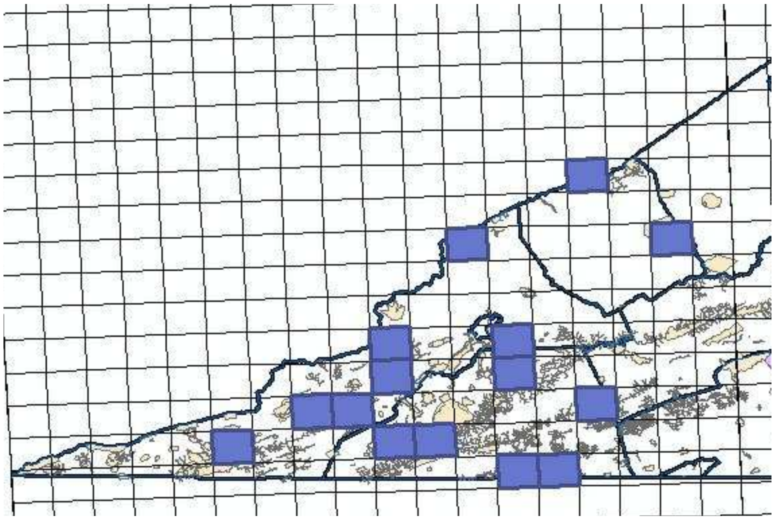
Firstly, we set the probability of hazard spread from inner-belt at 0. The reserves for animals are clustered in Lee County and Scott County. The connectivity index is 38, which is comparatively large. The reserves for animals are closer to rivers than reserves for plants because most rare animals there are aquatic and inhabit by the river.

Fig 5-16 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0 – Rare Animals



Secondly, we increase the probability of inner-belt and out-belt hazard probability to 0.5 and 0.25 respectively. The reserves disperse significantly and the connectivity index (*CI*) decrease from 38 to 29. The pattern is shown in Figure 5.17

Fig 5-17 Reserve Design when the Probability of Hazard Spread (***f***$_k$) is equal to 0.5 – Rare Animals



Finally, we reset the probability of hazard spread to 1 and 0.5 respectively. The connectivity index (*CI*) then decreases to 25, while reserves are mainly distributed along rivers as before.

Fig 5-18 Reserve Design when the Probability of Hazard Spread ($\boldsymbol{f_k}$) is equal to 1 – Rare Animals

Table 5.6 shows the pattern of reserves distribution, from which we see that the connectivity index and optimum change exactly the same way.

Table 5-6 Connectivity Index and Expected Number of Species ($\boldsymbol{p_j}$ = 0.05)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	38	36.5
0.5	0.25	29	34.8
1	0.5	25	33.3

5.1.3. State-wide analysis

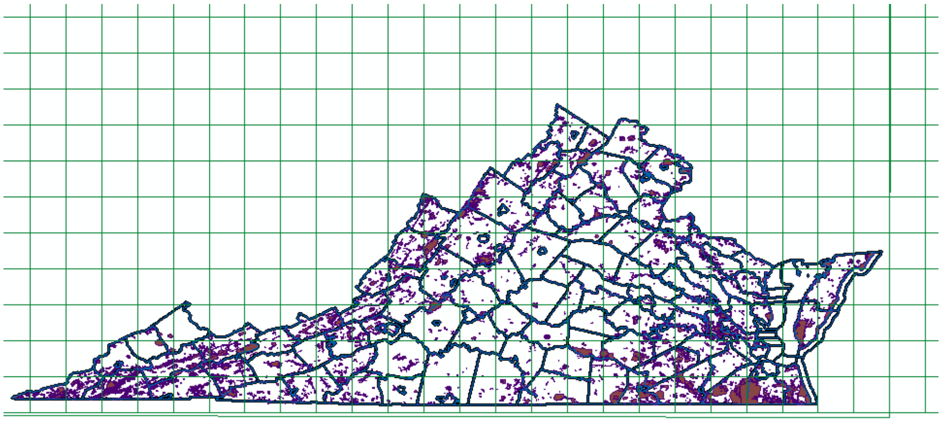
In the United States, many states have developed specific conservation planning guidelines. In practice, it is important for the state-level planners to design a comprehensive strategic plan for wildlife conservation, which is later to be implemented at different administrative levels. Thus, to provide state-level decision makers with information on the optimality of reserve design is of great importance.

This section conducts analyses at the state level. Modeling at this level is of greater difficulty because the numbers of both species and parcels grow dramatically and the run time of the simulated annealing program increases exponentially.

All Species

In order to find whether this model can be applied to larger scale, we choose the Commonwealth of Virginia and attempt to select an optimal reserve for the whole state. Using ArcMap, the Commonwealth is included within an 25 x 25 grid landscape. There are 821 species present in the state. Figure 5-19 below shows the distribution of habitats of those species.

Fig 5-19 Distribution of Rare Species of the Whole State

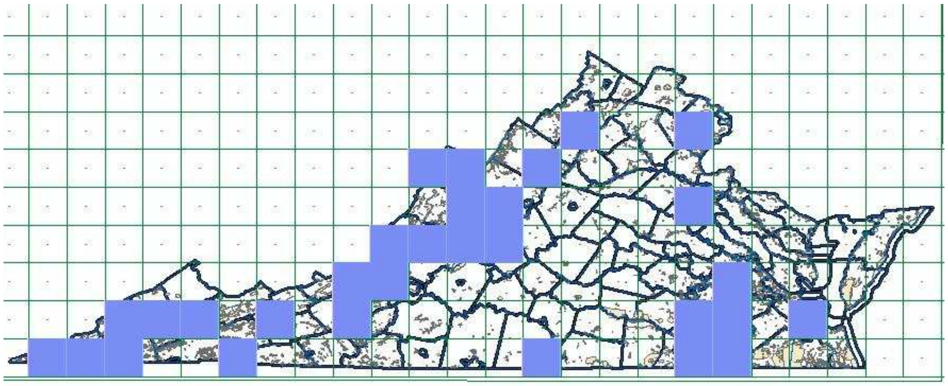


Data source: Natural Heritage GIS data, Virginia Dept of Conservation and Recreation

To maximize the expected number of species, we to select 30 parcels (4.8% of the total area) for reserve from those 625 square parcels. Again, we use simulated annealing algorithm to solve problem with the same parameters. For computational ease, we consider hazard spread to the inner-belt neighbors only.

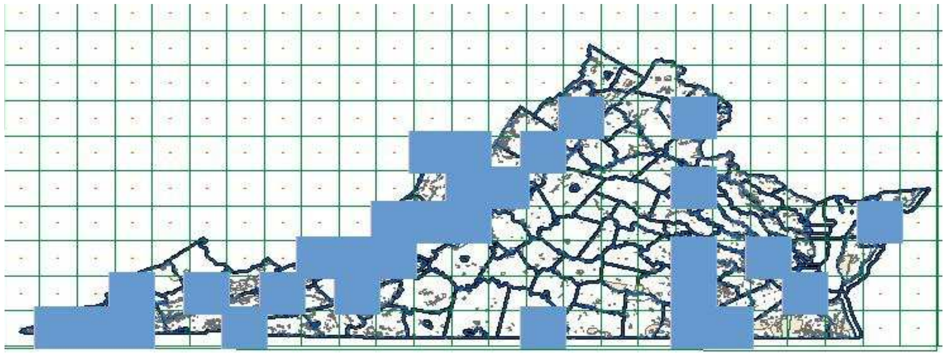
We first set the probability of hazard spread f_k=0 and selected the reserves, which are shown in Figure 5.20 We see that most of the reserves we choose are settled on the western and eastern parts of Virginia, with only a few located in the central part of the state. This pattern is consistent with the species distribution (see Figure 5.19). In this situation, the most reserves are distributed along the Appalachian Mountain ranges and the Tidewater region. In this case the connectivity index (*CI*) of reserves is 75.

Fig 5-20 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– All Rare Species



When we increase the probability of hazard spread (f_k) to 0.5, the reserve design (Figure 5.21) changes slightly, but reserve parcels remain concentrated in the western and eastern parts of Virginia. The connectivity index (*CI*) decreases to 65.

Fig 5-21 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0.5– All Rare Species



Finally, we increase the probability of hazard spread to 1. The connectivity index falls to 53, indicating that the parcels selected for reserve are more dispersed.. But because there are fewer species in parcels located in central Virginia, again few parcels are chosen for reserve in this area.

Fig 5-22 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 1– All Rare Species

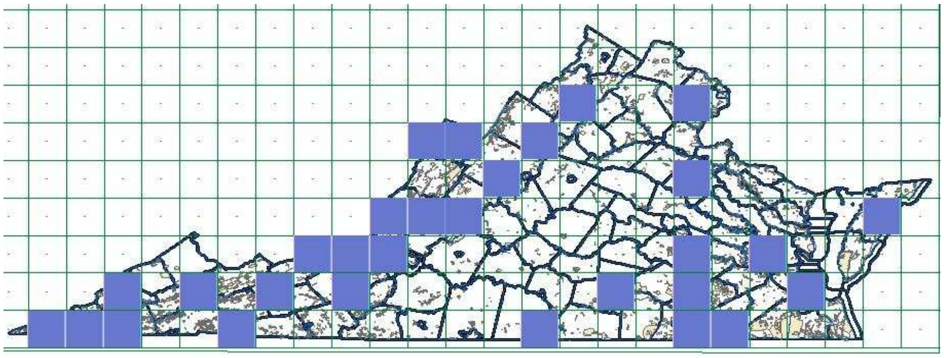


Table 5.7 shows the expected number of species and connectivity index. We verified that our model can be applied to the whole state to select reserves.

Table 5-7 Connectivity Index and Expected Number of Species (p_j = 0.05)

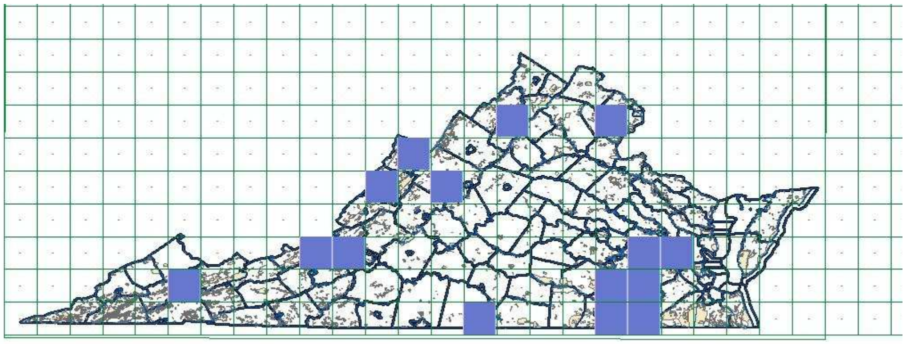
Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	75	565
0.5	0.25	65	538
1	0.5	53	514

Rare plants

In this subsection, we select the optimal reserve design to maximize the expected number of rare plants. Statewide, there are 425 species of rare plants. To maximize the expected number of rare plants, we select 15 parcels for reserve. In this case, hazard spread may occur from the individual parcel to the inner-belt and the outer-belt. All other parameters are unchanged.

Figure 5.23 shows the distribution of reserves around the whole state when there is no hazard spread between parcels. Here we see that the parcels selected for reserve are concentrated in the far western and eastern parts of Virginia. In contrast to the result from the onecounty and four-county analysess, not all of the reserves are near rivers. The connectivity index (*CI*) is 34.5.

Fig 5-23 Reserve Design when the Probability of Hazard Spread (***f_k***) is equal to 0– Rare Plants



When we reset the probability of hazard spread from inner-belt and outer-belt at 0.5 and 0.25, the connectivity index decreases to 28 as the parcels selected for reserve become more dispersed. Again we see a concentration of reserve parcels located in the far western and south eastern parts of the state.

Fig 5-24 Plant Reserves Distribution with Inner-Belt Hazard Spread Probability= 0.5– Rare Plants

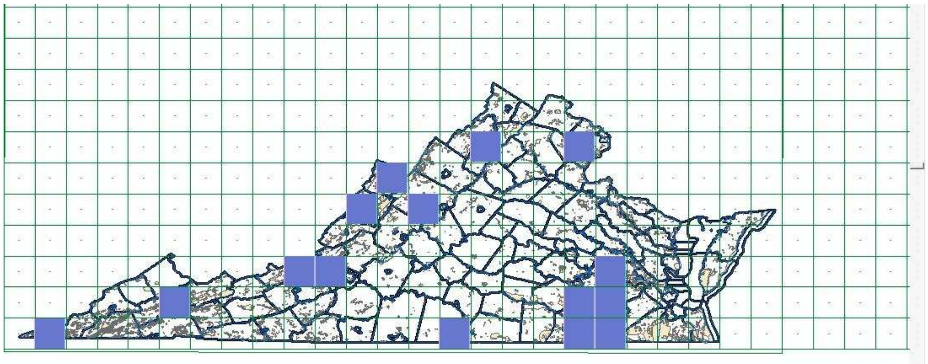


Figure 5.25 shows the reserves distribution when the probability of hazard spread is 1. In this case, the connectivity (*CI*) decreases to 22. However, adjacencies exist among parcels in both the far western and south eastern parts of the state.

Fig 5-25 Reserve Design when the Probability of Hazard Spread (***f**$_k$*) is equal to 1– Rare Plants

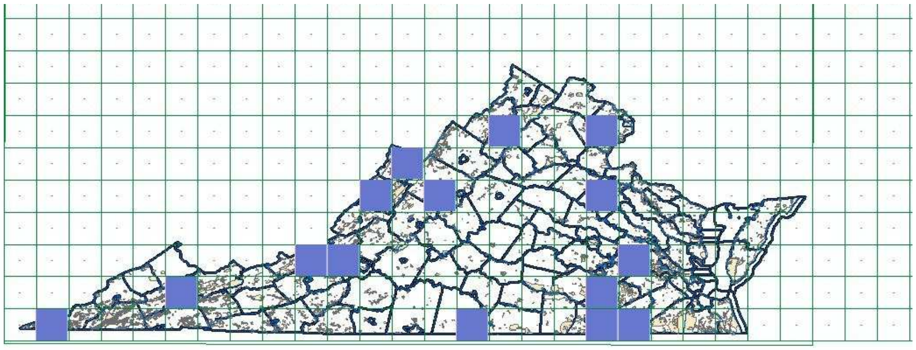


Table 5.8 below describes a similar as we discuss before.

Table 5-8 Connectivity Index and Expected Number of Species ($p_j = 0.05$)

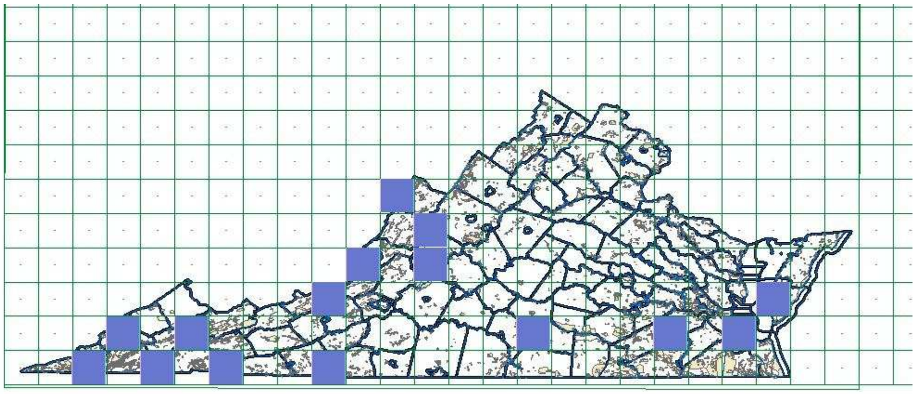
Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	34.5	320
0.5	0.25	28	308
1	0.5	22	297

Rare animals

Finally, we apply our model to solve the reserve selection problem for rare animals statewide. There are 212 rare animal species present in the state of Virginia. We maintain the same parameters as in previosu cases and allow for hazard spread from the individual parcel to the inner-belt and outer-belt parcels.

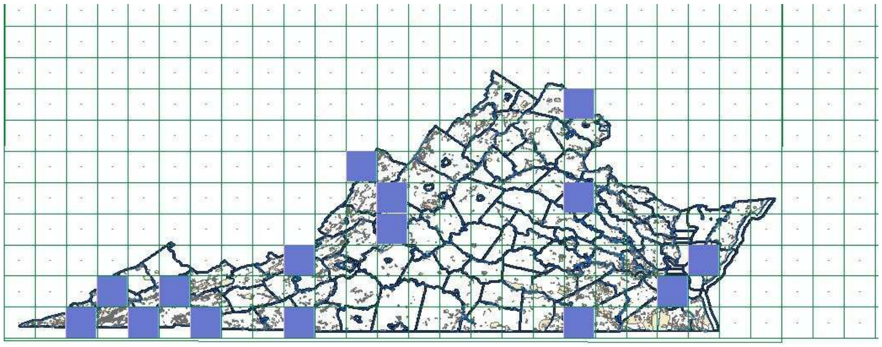
First we examine the case when there is no spatially correlated risk and the probability of hazard spread to the inner- and outer-belts is set equal to zero. For this case, the distribution of parcels selected for reserve is shown in Figure 5.26, below. The connectivity index of the optimal reserve design is 25 and adjacencies among parcels selected for reserve are present primarily in the western part of the state.

Fig 5-26 Reserve Design when the Probability of Hazard Spread (***f**$_k$*) is equal to 0– Rare Animals



For the case where the probabilities of hazard spread are set at 0.5 and 0.25, respectively, the distribution of parcels selected for reserve is as shown in Figure 5.27. Here the connectivity index (*CI*) falls only slightly, to 19. The reserve design remains very similar to the case where there was no spatially correlated risk.

Fig 5-27 Reserve Design when the Probability of Hazard Spread (***f**$_k$*) is equal to 0.5– Rare Animals



In the case where the hazard spreads with certainty, the distribution of parcels selected for reserve is as shown in Figure 5.28. which is identical to the reserve design depicted in

Figure 5.27, and the connectivity index (*CI*) remains unchanged at 19. In spite of an increase in probability of hazard spread, the adjacencies present in the reserve remain.

Fig 5-28 Reserve Design when the Probability of Hazard Spread ($\boldsymbol{f_k}$) is equal to 1– Rare Animals

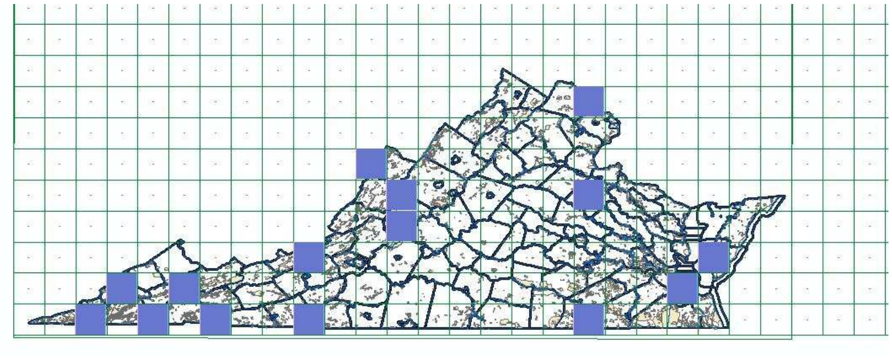


Table 5.9 summarizes results from the statewide analysis of rare animals, which exhibits a similar pattern as seen before. However, in this specific case the connectivity index does not decrease when the risk of hazard spread increases above f_k=0.5 and t_l=0.25.

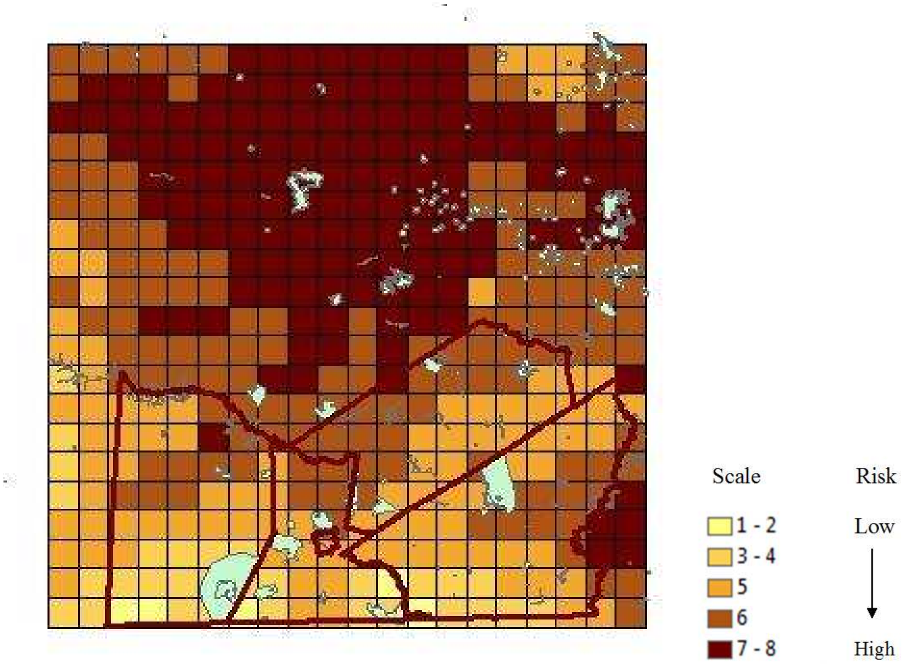
Table 5-9 Connectivity Index and Expected Number of Species ($\boldsymbol{p_j}$ = 0.05)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	25	168
0.5	0.25	19	162
1	0.5	19	156

5.2. Heterogeneous spatial risk in a Virginia landscape

This section contributes to the literature of land development risk and reserve design in two aspects. First, by modifying the MCSP framework outlined in section 3, we incorporate heterogeneous spatial risk. Specifically, we apply observed values for land development risk in a four-county area in southern Virginia. Within the focal area, development risk values range from 1 to 8. As show in Figure 5.29, development risk increases from rural areas to the urban center of Sussex County, Brunswick County, South Hampton County, Greensville County and Emporia City. Given these assumptions, we solve for the reserve design that maximizes the expected number of species.

Fig 5-29 Risk Distribution in the 4-County Focal Area



The four-county focal area includes: Sussex County, Brunswick County, South Hampton County, Greensville County and Emporia City. This area contains 20 rare species. Because land development is one of the most significant threats to conservation in Virginia, results from the model will provide insight into tradeoffs between habitat conservation and continued land development.

We illustrate the modeling procedure and conduct analysis first both without and with budget constraint (*B*), which is a monetary budget from the government. Before we introduce the budget constraint, *B* firstly (in the without budget case) take the form of the number of parcels that we may select, as we did in previous sections. We then interpret the results from a comparative static point of view as the probability of hazard spread varies.

5.2.1. Unconstrained optimization

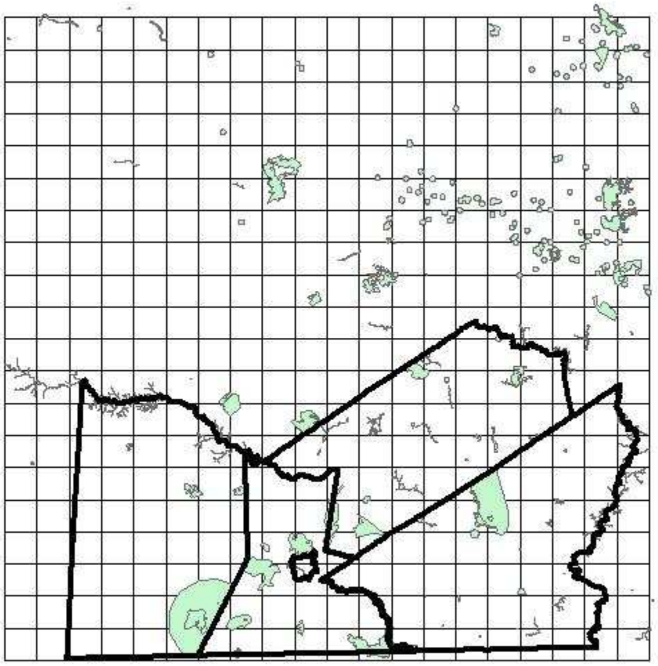
To begin our analysis, we select 20 rare species which are widely observed in these counties[1] and illustrated in Figure 5.30. The green regions in the graph is the distribution

---

[1] The species included are Atlantic pigtoe, Bachman's Sparrow, Bald eagle, Barking treefrog, Blackbanded sunfish, Dwarf wedgemussel, Green floater, Henslow's sparrow, Loggerhead shrike, Mabee's salamander,

of endangered species, and the focal area outlined in black, including Sussex County, Brunswick County, South Hampton County, Greensville County and Emporia City,_constitute the study region. From the graph we can see that these species are widely present in the focal area and the habitats of them in the study region are of a much greater area than neighboring counties.

Fig 5-30 Distribution of Selected Species in the Study Region



Dwarf Crabgrass, Easter big-eared Bat, Eastern Lampmussel, Golden Colicroot, Lined Topminnow, Virginia Thistle, Round-leaved Goldenrod, Southern Bladderwort, Oak Toad and Reniform Sedge..

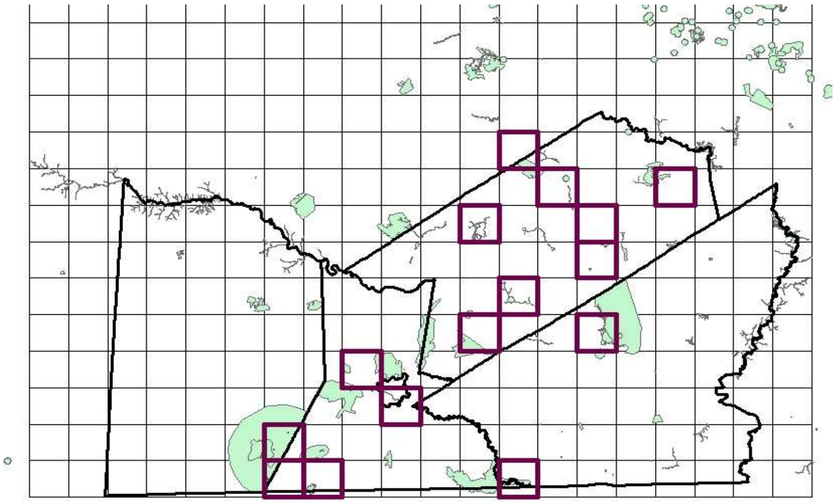
In this analysis, we draw grid in an GIS environment, and choose a square area that covers the whole analyzed places, which is divided into 20 x 20 small square parcels. Every parcel has different development risk based on Virginia Conservation Lands Needs Assessment (VCLNA)'s specification. In the whole state of Virginia, the development risk observed in each parcel is ranked from 1 to 8, in which 1 denotes the lowest development risk and 8 means the highest. To apply the development risk data to our model, we converted ranked development risk to probability of hazard. For simplicity reasons, we set 1 to be 0.01 and set 8 to be 0.08 by defining $p_j=s/100$ where s is the scale of 1-8, which represents the probability of on-site hazard occurrence (which is p_j in the model). The distribution of those risks is shown in Figure 5-30.

Figure 5-30 illustrates the significant variance of on-site development risk (p_j) in our study region, ranging from 0.03 to 0.08. Also, we find that many rare species are present in parcels with relatively high risk of development As in the standard setting, every parcel has a total development risk that includes both the individual parcel risk (p_j) and the spread risk from neighboring parcels (f_k and t_l).

To maximize the expected number of species protected, we set B=15. We solve the problem with heterogeneous spatial risk using the simulated annealing algorithm described above. We vary the probability of development spread (f_k) from the individual parcel to inner-belt parcels from 0, 0.5 to 1. The probability of development spread from the individual parcel to outer-belt parcels (t_l) is then equal to 0, 0.25, and 0.5, respectively.. To solve for the optimal reserve design, we set the initial temperature (t_0) at 300, the length of Markov chain (L) at 300, weakening coefficient at 0.95 and annealing times at 1000.

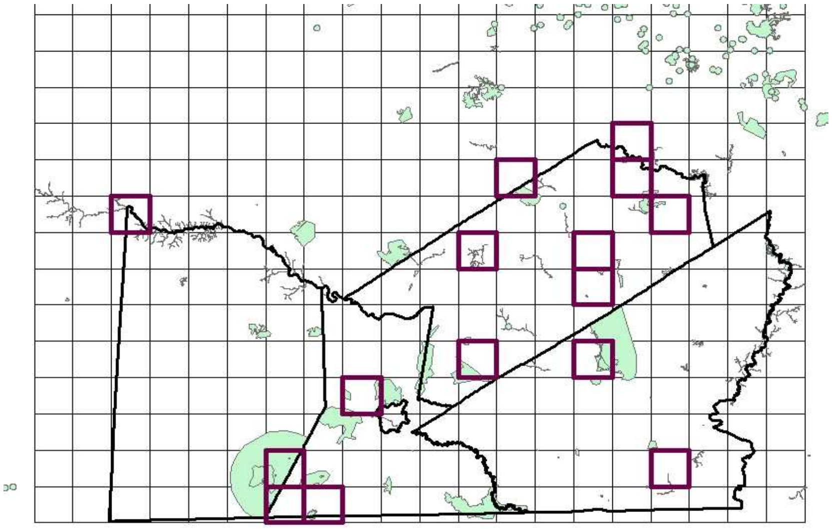
Figure 5.31 shows the distribution of reserves when the probability of development spread to both inner-belt and outer-belt parcels (f_k) initially at 0. When development does not spread between parcels, there is no spatially correlated risk and many of the parcels selected for reserve are near each other. We find that the reserves selected are parcels with the greatest number of species. In this case, the connectivity index (CI) of the optimal reserve is 25.

Fig 5-31 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0– All Rare Species



To examine the impact of spatially correlated risk on optimal reserve design, we reset the probability of hazard spread to inner belt nearby parcels (f_k) at 0.5 and out-belt parcels at 0.25. In this case, the connectivity index decreases to 18.5 and the parcels selected for reserve are more dispersed.

Fig 5-32 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 0.5– All Rare Species



Finally, we set the probability of hazard spread at $f_k = 1$ and $t_l = 0.5$, respectively, i.e. when one parcel is developed, the adjacent, inner-belt parcels will certainly be developed as well, wiping out the species there. In this case, parcels selected for reserve are more dispersed and the connectivity index decreases to 16.

Fig 5-33 Reserve Design when the Probability of Hazard Spread (f_k) is equal to 1– All Rare Species

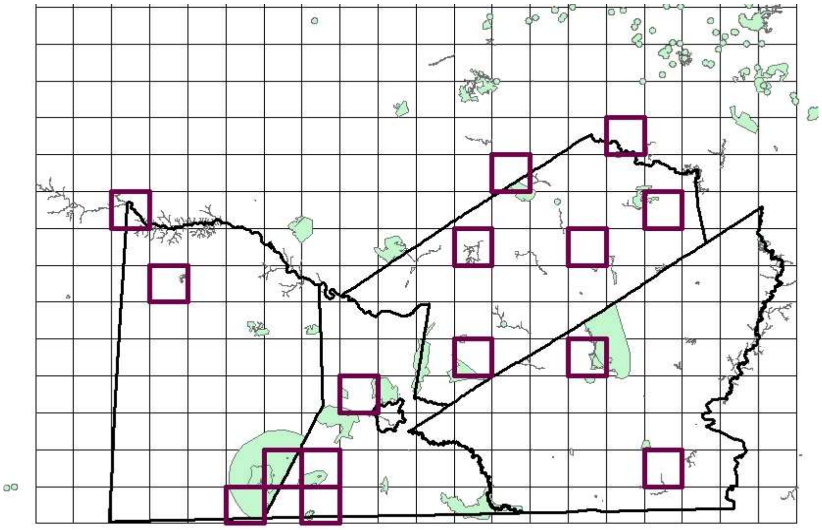


Table 5-10 Connectivity Index and Expected Number of Species ($\boldsymbol{p_j} = 0.05$)

Probability of Hazard Spread from Inner-Belt (f_k)	Probability of Hazard Spread from Outer-Belt (t_l)	Reserve Connectivity	Expected No. of Species
0	0	25	19.69
0.5	0.25	18.5	19.53
1	0.5	16	19.33

In the analysis above we see that in general the clusters of parcels selected for reserve are primarily located in areas with lower probabilities of development. Some parcels in areas characterized by higher levels of development risk are included in the optimal reserve, but there are no adjacencies among these selected parcels. Again, we observe that as the probability of development spread increases, the connectivity index (*CI*) of the optimal reserve decreases since more areas are affected.

5.2.2. Budget constrained optimization

In recent years, conservation has become a political priority in Virginia. For example, Governor McDonnell pledged to protect 400,000 acres during his four-year term. Governor Kaine, who proceeded McDonnell, was successful in a similar pledge and successfully protected 400,000 acres during his tenure. In an eight-year period, this could mean the protection of 800,000 acres, or 3% of the total area in Commonwealth of Virginia. The potential benefits of this landscape-scale conservation effort are great, and in this section we examine the tradeoffs between habitat conservation and the cost of land protection. We aim to use optimization to solve this problem, and draw useful policy suggestion for the selection of reserves to maximize the number of endangered species, with proper consideration of spatially correlated development risk and budget constraint.

As described in section 4, land cost values represent average per acre cost of farmland by county. Table 5.11 presents the results from the budget constrained MCSP applied to the four-county focal area over a range of budget levels. The parcel size is about 9,600 acres (15 square miles). The cost per species included in Table 5.11 is a measure of the conservation efficiency.

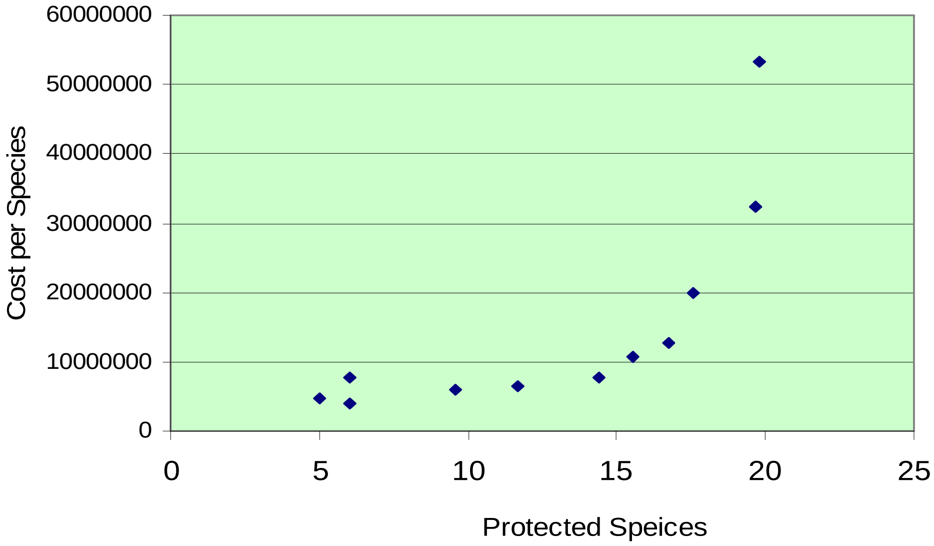
Table 5-11 Expected Number of Species and Cost per Species with Heterogeneous Risk

Budget Constraint	Expected Number of Species	Cost per Species	Number of Parcels in Reserve
$1,056,000,000.00	19.79	$53,360,282.97	46
$633,600,000.00	19.65	$32244274.81	34
$352,000,000.00	17.6	$20,000,000.00	19
$211,200,000.00	16.74	$12,616,487.46	11
$168,192,000.00	15.55	$10,816,205.79	7
$112,128,000.00	14.43	$7,770,478.17	4
$74,752,000.00	11.66	$6,410,977.70	3
$56,064,000.00	9.55	$5,870,575.92	2
$46,720,000.00	6	$7,786,666.67	1
$24,294,400.00	6	$4,049,066.67	1
$23,360,000.00	5	$4,672,000.00	1
$23,360,000.00	0	∞	0

From Table 5.11, we can see that when the conservation budget tightens, both the number of protected species and the number of parcels selected for reserve decrease as well. Over the range of budget levels included, the total number of acres conserved ranges from 9,600 to 441,600 acres. When the budget constraint drops below $23.36 million, the selected reserves and the expected number of species decreases to 0.

We find that when there are 4 selected parcel, the number of protected species is 14.43. When it decreases to 3, 11.66 species are protected, and even when the number of reserves further decreases to 1, there are still 5 species under protection. These results indicate that the species are clustered in the focal area, the information of which is helpful for conservation practitioners since this simulation gives them a priority rank of choosing reserve parcels in a certain order when their budget constraint is limited, which is easily seen in real world cases. Also, notice that when the expected number of protected species approaches the total number of species in this 4 county area (which is 20), there are steep jumps in the average cost of protecting species, since there are significant increases in the number of parcels that need to be protected, which drives the average cost up rapidly.

Fig 5-34 The Distribution of Cost per Species



The cost per species, i.e. how the cost per species varies as the total number of protected species increases, is illustrated in figure 5.34. In this graph, we see that the cost per species increases exponentially as the total number of protected species increases. However, we find that when budget constraint is set at about $24.29 million dollars, the average cost per species cost is the lowest, and the protected number of species is 6.

6. Discussion and concluding remarks

This analysis aims to find a means for the optimal biodiversity conservation strategy in the presence of spatially correlated risk. We first introduce homogenous spatial risk in a MCSP framework and solve the RSS problem at three different geographical scales: one-county, four-county and statewide. Next we examine the case of heterogeneous spatial risk—land development risk—in a MCSP framework and solve the RSS problem for a four-county area in Virginia. We contribute to the literature by introducing spatially correlated risk in the context of the RSS problem, which is investigated intensively in several cases with different geographical areas, species types, risk types, and both without and with budget constraint. Incorporating spatial risk into the MCSP framework makes the programming process much more complicated and computationally intensive, but also allow for a more realistic analysis.

The major findings of our study include:

1. Spatial risk matters. Given the comparative statics provided in each section, we see that in the presence of spatially correlated risk, the optimal reserve is different than when hazard risk is uncorrelated. With spatially correlated risk, parcels selected for

reserve are more dispersed. Also, the maximum expected number of species declines when spatially correlated risk increases.

2. Even with spatially correlated risk, however, over a range of settings, adjacencies among parcels in the optimal reserve remain. This is because of the high concentration of rare species in some areas. In spite of the spatial risk, including adjacent parcels with large numbers of species in the reserve maximizes the expected number of species.

3. In Virginia, we observe tradeoffs between species protection and spatially correlated risk most clearly in areas with high concentrations of habitat, such as river systems in the southwestern part of the state. In the presence of ‘biodiversity hotspots’ the optimal reserve design is characterized by adjacencies in areas where a large number of species present, in spite of the spatial risk. In landscapes where biodiversity hotspots are present and spatial risk is present, conservation planners must be keenly aware of the tradeoffs involved. For example, further study into risk probabilities associated with hazards that spread along rivers and in riparian areas may be of value when designing a system of conservation reserves in southwestern Virginia.

4. In the case of heterogeneous spatially correlated risk, as such risk increases, reserve connectivity decreases particularly in areas where spatially correlated risk is greater. Adjacencies among parcels within the optimal reserve are present, but limited to lower risk areas.

Results from the budget constrained setting allow decisions-making based on both the costs and benefits of conservation. There is the opportunity for future work to address the dynamics of RSS problem given periodic budget constraints, which would provide additional insights into conservation planning.

From all the analyses above, we see that spatially correlated risk is an important factor that should not be ignored in both wildlife analyses and conservation practices. Indeed, conservation planning that fails to consider the spatial correlation of risks will lead to incorrect results and thus the optimality of reserve design would suffer. This study has the potential to improve reserve site selection decisions and provide conservation planners with more quantitative analysis to assist decision-making at many different administrative levels.

Overall, our results emphasize the significance of spatially correlated risk for conservation planning in Virginia. This notion stays valid across all the variations of focal areas in which the grid size also changes. In the statewide analysis, for example, failing to consider spatially correlated risk will result in an overestimation of the maximum number of protected species of more than 50 species, or nearly 10% of the total, for our chosen parameters. In practice, failing to incorporated spatial risk into a conservation decision-making framework may result in inefficient reserve design and the failure to meet conservation goals.

This thesis is a first-step in the exploration of spatially correlated in a Virginia context and there are many opportunities for future study on policy issues in this area. Specifically, conservation policies can be designed in a way that best offsets the negative impacts of the spatial correlation of risks. For example, county or state tax incentives may be designed to encourage conservation of parcels located away from currently reserved parcels, and land use taxes may be revised accordingly to help form a better reserve system. For example, for parcels that are rich in species and located away from currently reserved ones, the tax may be set lower for land uses that promote conservation and higher for other uses, thereby providing incentive for conservation. Further, area-specific conservation easements might be designed based on ex-ante reserve design, which would likely reduce the cost of conservation. Also, fiscal conditions need to be considered when a reserve system is under design, and the cost structure, based on the budget constrained optimization, may be of importance.

This research serves as a platform for a number of possible extensions. . First, , we may include both parcel number and monetary budget as constraints into the model, as seen in some real world cases, and see how the best available set of reserve parcels change as adjustments occur to certain parameters. Third, different weights of species can be used to differentiate the value of these species. This is of importance when the primary goal of reserve design is to protect an individual “high-value” species rather than a large group that includes all rare species. All of the above require more advanced computation tools, with which a finer grid system (with smaller parcels) may also be used.

Reference:

1. Ando A, Camm J, Polasky S and Solow A (1998) ,Species Distributions, Land Values, and Efficient Conservation, Science 27 : 279 , 2126-2128

2. Anselin L and Rey SJ eds. (2010), Perspectives on Spatial Data Analysis. Springer Verlag, Berlin
3. Austin RF, Measuring and comparing two-dimensional shapes, in: Spatial Statistics and Models, eds. G.L. Gaile and C.J. Willmott D. Reidel Publishing Co., Dordrecht, 1984

4. Blair RB (2001), Birds and butterflies along urban gradients in two ecoregions of the U.S. Pages 33–56 in Lockwood JL,McKinney ML, eds. Biotic Homogenization. Norwell (MA): Kluwer

5. Camm J, Polasky S, Slow A and Csuti B (1996), A Note on Optimal Algorithms for Reserve Site Selection, Biological Conservation 78, pp. 353-355

6. Chruch R, Stoms D and Davis F (1996), Reserve Selection as Maximal Covering Location Problem, Biological Conservation, 76, pp. 105-112

7. Denys C, Schmidt H (1998), Insect communities on experimental mugwort plots along an urban gradient. Oecologia 113: 269–277

8. Diamond JM (1975), The island dilemma: lessons of modern biogeographic studies for the design of nature reserves, Biological Conservation, 7 pp. 129–146

9. Earn DJD, Levin SA and Rohani, P (2000), Coherence and Conservation, Science 290, 1360-1364

10. Giles RH and Trani MG (1999), Key elements of landscape pattern measures, Environ. Manag. 23(4)

11. Hamaide B, Williams JC, ReVelle CS (2009), Cost-efficient Reserve Site Selection Favoring Persistence of Threatened and Endangered Species. Geographical Analysis. Volume 41, Issue 1, pages 66–84

12. Hess GR (1994), Conservation corridors and contagious disease: a cautionary note, Conserv. Biol. 8(1)

13. Hobbs RJ (1992), The role of corridors in conservation: solution or bandwagon?, Trends Ecol. Evol. 7(11)

14. Kirkpatrick J (1983), An iterative method for establishing priorities for the selection

of nature reserves: an example from Tasmania. Biological Conservation 25, 127–134

15. Kowarik I (1995), On the role of alien species in urban flora and vegetation. Pages 85–103 in Pysek P, Prach K,Rejmánek M,Wade PM, eds. Plant Invasions—General Aspects and Special Problems. Amsterdam (Netherlands): SPB Academic

16. Luniak M (1994), The development of bird communities in new housing estates in Warsaw.Memorabilia Zoologica 49: 257–267

17. Macarthur.RH and Wilson EO (1967), The theory of island biogeography. Princeton, N.J.,Princeton University Press.

18. Margules C, Nicholls A and Pressey R, (1988), Selecting networks of reserves to maximize biological diversity.Biological Conservation 43, 63–76

19. Margules CR, Higgs AJ and Rafe RW (1982), Modern biogeographic theory: are there any lessons for nature reserve design?, Biol. Conserv. 24

20. McIntyre NE (2000), Ecology of urban arthropods: A review and a call to action. Annals of the Entomological Society of America 93: 825–835

21. McKinney ML, (2002), Urbanization, biodiversity and conservation. Bioscience 52,

883–890

22. Medda F, Nijkamp P and Rietveld P (1998), Recognition and classification of urban shapes, Geogr. Anal. 30(3)

23. Noss RF and Cooperrider AY (1994), Saving Nature's Legacy, Island Press, Washington, DC

24. Noss RF, (1987) Corridors in real landscapes: a reply to Simberloff and Cox, Conserv. Biol. 1(2)

25. Polasky S, Camm JD and Garber-Yonts B (2001), Selecting Biological Reserves Cost-Effectively: An Application to Terrestrial Vertebrate Conservation in Oregon. Land Economics 77:68-78

26. Pimm SL and Lawton JH (1998), Planning for biodiversity, Science 279, 2068–2069

27. Possingham HJ, Day J, Goldfinch M and Salzborn F (1993), The Mathematics of Designing a Network of Protected Areas for Conservation, in Decision Sciences, Tools for Today, Proceedings of the ASOR Conference, Adelaide, Australia, edited by D. Sutton, E. Cousins and C, Pierce, University of Adelaide Publications

28. Pressey R, Humphries C, Margules C, Vane-Wright R and Williams P (1993), Beyond opportunism: key principles for systematic reserve selection. Trends in Ecology and Evolution 8, 124–128

29. Savard JL, Clergau P and Mennechez G (2000), Biodiversity conceptsand urban ecosystems. Landscape and Urban Planning 48,131–142

30. Snyder S, ReVelle C, Haight R, (2004) One- and two-objective approaches to an area-constrained habitat reserve site selection problem, Biological Conservation, 119(4), 565-574

31. Stein BA, Kutner L, Adams J. (2000), Precious Heritage. Oxford (United Kingdom): Oxford University Press

32. Simberloff DS and Abele LG (1982), Refuge design and island biogeographic theory: effects of fragmentation. American Naturalist, 120: pp. 41-56

33. Simberloff D and Cox J (1987), Consequences and costs of conservation corridors, Conserv. Biol. 1(1)

34. Simberloff D, Farr JA, Cox J and Mehlman DW (1992), Movement corridors: conservation bargains or poor investments?, Conserv. Biol. 6(4)

35. Tischendorf L and Fahrig L (2000), On the usage and measurement of landscape connectivity. Oikos, 90: 7–19

36. United Nations Environment Programme, http://www.unep.org/wed/2010/english/biodiversity.asp

37. United Nations Environment Programme, Summary of protection by Country and Territory on the 31st January 2008" (XLS). World Database on Protected Areas

38. USDA (2007), Census of Agriculture, Quick Stats web tool, at: http://quickstats.nass.usda.gov/?long_desc__LIKE=farm+real+estate+county&x=6&y=14

39. Virginia Department of Environmental Quality (2008), Virginia's Forest Resources. Natural Resource Education Guide. January 21, 2008

40. Virginia Department of Conservation and Recreation, http://www.dcr.virginia.gov/natural_heritage/infoservices.shtml#lists

41. U.S. Fish and Wildlife Service, http://ecos.fws.gov/tess_public/StateListingAndOccurrence.do?state=VA

42. Williams JC, Revelle CS and Levin SA (1982), Spatial Attributes and Reserve Design Models: A Review, Environmental Modeling and Assessment, 10 (3), 163-81