Optimal Corridor Design for Grizzly Bear in the U.S. Northern Rockies

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Abstract

In an attempt to address the negative ecological impacts of habitat fragmentation, wildlife corridors have been proposed as a way to connect areas of biological significance. In this paper, a model to maximize the amount of suitable wildlife habitat in a fully connected parcel network linking core habitat areas subject to a budget constraint is introduced. The standard economic framework of maximizing habitat benefits subject to a budget constraint that we employ in this paper is a divergence from other recently proposed models that focus only on minimizing the cost of a single parcel-wide corridor. While the budget constrained optimization model that we introduce is intuitively appealing, it presents substantial computational challenges above determining the cost-minimizing corridor. The optimization model is applied to the design of a wildlife corridor for grizzly bears in the U.S. Northern Rockies and is shown to drastically increase the aggregate habitat suitability of the corridor over parcel selection based on cost minimization alone. The relative tradeoffs between corridor cost and habitat suitability are illustrated through the construction of an efficiency frontier and, for cases where optimization is computationally impractical, a heuristic is suggested that closely approximates the optimally selected corridor.

1 Introduction

In many parts of the world, land development has resulted in a reduction and fragmentation of natural habitat, leading to increased rates of species decline and extinction. To combat the negative consequences of anthropogenic habitat fragmentation, the procurement of biologically valuable conservation land has been promoted by biologists as a way to ensure species viability. A large number of models for optimally selecting land parcels for conservation, formally referred to as the reserve site selection problem (RSSP), have been proposed in the conservation biology literature. These models select parcels to ensure that all targeted species in a given region are protected, as in the Set Covering Problem (SCP) (e.g., Margules, Nicholls and Pressey 1988; Underhill 1994), or they select a constrained number of parcels that maximize species richness, as in the Maximal Covering Problem (MCP) (e.g., Church, Stoms and Davis 1996; Camm et al. 1996).

A number of subsequent studies have added to the conservation biology literature by incorporating economic variables into the RSSP. These studies seek to procure conservation parcels, subject to a budget constraint, that maximize the number of species protected (e.g., Ando et al. 1998; Polasky et al. 2001; Costello and Polasky 2004) or maximize the environmental benefits of the sites selected (e.g., Ferraro 2003; Messer 2005; Newburn, Berck and Merenlender 2006). The results of these economic-based studies show that incorporating spatially heterogeneous financial costs into reserve site selection models leads to a substantially different set of priority parcels than standard SCP or MCP models that ignore parcel costs. Moreover, the parcels selected based on budget constrained optimization obtain considerably greater environmental benefits for the same conservation budget than traditional site selection models (Balmford, Gaston and Rodrigues 2000; Naidoo et al. 2006).

In recent years, biologists and economists have recognized that a parcel's spatial location relative to other protected parcels is also an essential attribute to consider in reserve site selection. Reflecting this, a variety of models that seek to increase the degree of spatial coherence among the set of parcels selected for conservation have been developed (Williams, ReVelle and Levin 2005 provide a thorough review). One primary way in which spatial attributes have been incorporated into site selection models is through the optimal selection of a connected reserve network, which is referred to here as a *wildlife corridor*.[1] The focus on developing models for the design of optimal wildlife corridors has come as biologists have highlighted the environmental imperative of connecting core areas of biological significance (Noss 1987).

[1] Wildlife corridors are also referred to more or less interchangeably as conservation, habitat, and movement corridors.

Beginning with the work of Sessions (1992), several models have been developed that attempt to optimally select a spatially connected set of parcels (e.g., Williams 1998, 2002; Williams and Snyder 2005; Cerdeira et al. 2005; Önal and Briers 2006; Fuller et al. 2006). The design of an optimal corridor is, in its essence, a standard economic problem where the conservation planner is attempting to select the most ecologically beneficial corridor given the conservation funding available. Previous models of optimal corridor design, however, have not considered the case of budget constrained optimization. In fact, with the exception of Sessions (1992) and Williams (1998), spatially heterogeneous parcel costs have been ignored altogether. We believe that the formulation of the corridor design problem presented here is the most relevant to a conservation planner, operating with limited funds with which to secure conservation land. The budget constrained optimization model, however, introduces some additional computational challenges and design elements into reserve selection over previous corridor selection models that have sought to minimize the number of sites required to ensure that a set of species are preserved (Önal and Briers 2006; Fuller 2006; and Cerdeira 2006) or minimize the amount of unsuitable habitat in the corridor (Williams 1998, 2002; Williams and Snyder 2005).

In this paper, a spatially explicit model that seeks the optimal construction of a wildlife corridor between multiple areas of biological significance is proposed. The model is then applied to the design of a wildlife corridor for grizzly bears connecting the Yellowstone, Salmon-Selway, and Northern Continental Divide Ecosystems in Idaho, Wyoming, and Montana. The results from the budget constrained optimization model are then used to define an efficiency frontier that highlights the tradeoffs between corridor cost and overall suitable habitat included in the corridor.

In the next section, the optimization model is motivated by highlighting the implementation of corridor projects in various parts of the world and reviewing the literature on optimal corridor design. In section 3, specific corridor design problem statements are introduced and the programming model is described. The design of a wildlife corridor for grizzly bears in the United States Northern Rocky Mountain region and the data sources used in the analysis are described in 4. Results of the corridor optimization in the Northern Rockies are provided in section 5. In section 6, a heuristic is suggested that is computationally more practical than optimization when a large number of parcels are available for selection. The concluding section describes implications for policy and future directions.

2 Review of Corridor Implementation and Literature

Properly implemented wildlife corridors provide numerous ecological benefits by returning the landscape to its natural connected state. By allowing species the ability to migrate between core areas of biological significance, corridors increase gene flow and reduce rates of inbreeding, thereby improving species fitness and survival (Schmitt and Seitz 2002). Corridors also allow for greater mobility (Andreassen et al. 1996), thus allowing the potential for species to escape predation and respond to stochastic events such as fire. Additionally, corridors allow species to respond more easily to long term climatic changes (McEuen 1993).

Responding to the ecological benefits of connected ecosystems, a wide range of corridor projects have been proposed or are currently being implemented. The projects range from local scale projects, such as the Quimper Wildlife Corridor, which provides a 3.5 mile greenbelt in Jefferson County, WA, to much wider scale projects like the

‘Yellowstone to Yukon’ initiative, which seeks to implement a viable corridor stretching from Yellowstone National Park in northwestern Wyoming to the Yukon region of western Canada. Corridor projects are currently being planned or implemented by governments and private organizations across the world. In Europe, for example, numerous countries have initiated wildlife corridor projects, such as the National Ecological Network in the Netherlands. Near the India-Bangladesh border, the Siju-Rewak Corridor currently connects elephant populations in the Siju Wildlife Sanctuary and Rewak Reserve Forests. Similarly, the proposed Selous-Niassa Wildlife Protection Corridor Project in Africa would link game reserves in Tanzania and Mozambique to form Africa’s largest protected area. In northern Brazil, the Amapa Biodiversity Corridor connects 11 million hectares of some of the most pristine remaining areas of the Amazon Rainforest. In eastern Australia, a proposed 2,800 km corridor would link existing reserves in a corridor project dubbed the ‘Alps to Artherton’. This is by no means an exhaustive list of corridor projects currently being implemented around the world, but it is meant to illustrate the policy relevance of wildlife corridor design on several continents.

Despite the increasing number of corridors being implemented around the world, and several studies documenting the positive ecological benefits of existing corridors (e.g., Tewksbury et al. 2002; Haddad et al. 2003; Dixon et al. 2006), models for the optimal selection of corridor parcels have received comparatively little attention. The problem of optimal corridor design was first posed by Sessions (1992), who models the selection of a hypothetical corridor as a network Steiner tree (NST) problem. The hypothetical formulation employed by Sessions involves a landscape composed of a set of available parcels to connect a subset of critical parcels. The cost of each parcel is defined as the opportunity cost of not harvesting the parcel's timber and the objective is to connect the critical parcels with the least-cost set of available parcels. Noting that arriving at a solution may not be possible in polynomial time for a large set of parcels, Sessions uses a shortest path heuristic to select parcels that minimize the cost of connecting the critical parcels.

Williams (1998) also models the optimal selection of a hypothetical corridor as a NST problem, and addresses the dual objectives of minimizing corridor cost and minimizing the amount of unsuitable area included in the corridor. Using linear integer programming, Williams generates an efficiency frontier by varying the weights placed on each of the two objectives. In other words, he finds a set of points where one model objective (e.g., cost) cannot be made lower without increasing the other objective (e.g., unsuitable habitat). The efficiency frontier that is generated allows for a comparison of the tradeoffs between corridor cost and habitat unsuitability.

In subsequent work, Williams modifies his original model to consider cases where there are no predefined reserves and the planner is simply trying to form a connected reserve (Williams 2002; Williams and Snyder 2005). In Williams (2002) he considers a relaxation of the contiguity requirement by incorporating a separate contiguity parameter that can be adjusted to control the overall degree of connectivity in the parcels selected. In Williams and Snyder (2005), the authors take up the special case of percolating clusters, where the corridor is selected so as to connect one end of the landscape to the other (i.e., from north to south).

The studies by Sessions and Williams are groundbreaking in the formulations of the corridor problem that they introduce. Their models, however, only allow each parcel to be connected to two other parcels in the corridor and considering only a one parcel-wide corridor rules out the possibility of a corridor being “thicker” (i.e., multiple parcels wide) for at least some portion of the path. This would be beneficial, for example, if there is an agglomeration of high quality and low cost habitat in some portion of the corridor that could be cost-effectively incorporated into the reserve system. In addition, the authors do not extend their research to the study of an applied corridor instance, making it difficult to determine how the models perform in practice. Finally, although the problem Williams poses in his 1998 article is novel in that it incorporates both the financial and environmental attributes of each parcel, attempting to minimize unsuitable habitat could result in some perverse incentives. For example, suppose that two parcels have identical cost, cover the same linear distance between two reserves, and have the same percentage of suitable to unsuitable habitat. The only difference between the two parcels is that parcel A is wider, and therefore covers more area, than parcel B. The optimization model would tend to prefer parcel B over parcel A, all else being equal, since parcel A has more aggregate unsuitable area. By maximizing suitable area, our model avoids this potential shortcoming.

Recent articles by Cerdeira et al. (2005), Önal and Briers (2006) and Fuller et al. (2006) introduce models of optimal corridor design and apply them to specific study areas. Cerdeira et al. (2005) formulate a linear integer programming approach to solve a fully connected set covering problem and their model is applied to the case of 496 uniform and contiguous parcels in the county of Hertfordshire, UK. They find that a minimum of 22 contiguous sites are needed to optimally cover the 45 species of butterflies in the study area. A heuristic method that they develop in the paper selects 23 sites for conservation, which the authors take as evidence that their heuristic performs well in comparison to exact methods. Önal and Briers (2006) also formulate a fully connected set covering problem as a linear integer program. They apply their model to 121 bird species dispersed over 391 parcels in Berkshire County, UK and show that the model is too complex to be solved optimally. They then outline a procedure that involves solving the problem at a more aggregate scale and then selecting the minimum set of small disaggregate sites within the aggregate solution that cover all 121 species. This procedure is not guaranteed to find the optimal solution, since the minimum disaggregate number of sites could occur outside of the first stage, aggregate solution. The algorithm performs more favorably, however, than a heuristic procedure that is an extension of the greedy algorithm, where parcels are selected sequentially based on their contribution to the number of remaining unpreserved species. Finally, Fuller et al. (2006) apply a three stage algorithm to select a connected conservation network in central Mexico. They begin by selecting sites for conservation based on the habitat requirements of 99 species. They then define a set of paths that link the conservation areas with parcels containing suitable habitat. Finally, in the third stage, the paths that have the smallest area and impact on human populations are selected to form the connected reserve network.

The model presented in the next section diverges from previous corridor design studies in four important ways. First, the problem is modeled as one of finding the set of corridor parcels that maximizes habitat suitability, subject to a budget constraint. This is a change from previous studies that have modeled the problem as one of minimizing some aspect of parcel cost, either in terms of number of parcels, financial cost, or cost to wildlife traversing the corridor. This is the first corridor model to explicitly include a budget constraint; something that likely improves the relevance of the model for conservation planners, who generally operate in an environment with limited budgets. The second divergence from the studies reviewed above is that the model presented here does not limit the selected corridor to being only one parcel wide. This is important because it means that if the budget allotted for the corridor is higher than the minimum cost corridor, then the benefits of the corridor can be improved either by selecting a new route, or by making the corridor wider so that it cost-effectively includes adjacent parcels. The third contribution of this study is that it incorporates both estimated parcel costs and habitat suitability measures from a naturally occurring landscape. Williams (1998), the only other study to consider both parcel costs and habitat benefits relies on empirical results from a purely hypothetical instance. Finally, by changing the granularity of the parcels available for selection, a greater understanding of the relationship between computational complexity and the number of parcels in the landscape is gained.

3 Connection Subgraph Problem

The corridor model that is presented here assumes a landscape that is divided up into a set of contiguous, non-overlapping parcels. Utilizing terminology from graph theory, the landscape is represented by a graph (G) made up of vertices (parcels) and edges (parcel adjacencies) so that $G = G(V,E)$. A subset of the vertices in the graph are predefined as terminal vertices (reserves), $T \subseteq V$. Next, it is assumed that associated with each vertex is a nonnegative cost, c, representing the amount necessary to secure the vertex for inclusion in the corridor, and a nonnegative utility, u, which represents the environmental benefit (i.e., habitat suitability) of the vertex. Finally, it is assumed that the conservation planner has a finite budget constraint, B, and a desired level of aggregate utility, U. The Connection Subgraph Problem requires finding a subgraph H of G such that (1) H is fully connected (2) $T \subseteq V(H)$, i.e., the subgraph includes all terminal vertices (3) $\sum_{v \in V(H)} c(v) \leq B$,

i.e., the subgraph has aggregate cost no greater then the available budget and

(4) $\sum_{v \in V(H)} u(v) \geq U$, i.e., the subgraph has aggregate utility of at least the desired level.

The last two conditions can then be relaxed to obtain three separate optimization problems[2] of interest to the conservation planner.

(1) Budget Constrained Utility Optimization

(2) Utility Constrained Cost Minimization

(3) Unconstrained Cost Minimization

By comparing the connection subgraph problem to the network Steiner tree problem, it can be shown that the connection subgraph problem is NP-complete (Conrad et al. 2007). NP-completeness is a term used in computational complexity theory to define a problem where it is “easy” to verify that a particular solution satisfies the constraints[3] (i.e., the reserves are connected and the utility and/or budget constraint is met), but it is potentially not possible to prove that a particular feasible solution is an optimum. Proving optimality may not be possible, because the computational time necessary to show that no other solution has a higher utility increases exponentially as the number of vertices increase.

The differences in terms of parcel selection and computational complexity of cost constrained utility optimization, as opposed to the unconstrained cost minimization, are illustrated in the hypothetical 3x3 parcel map presented in Figure 1, where parcels C and G

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[2] The unconstrained utility optimization could also be added to the set of problems above, but since it is assumed that each vertex has nonnegative utility this would simply entail a subgraph that is identical to the graph itself, i.e., every parcel in the landscape is acquired.

[3] Computationally speaking, the term “easy” in this case refers to a feasibility condition that can be checked in polynomial time.

are to be connected with a contiguous corridor. In this simple example, corridor costs are minimized with the selection of parcels B, E, and H as shown in panel I. With this selection, the cost is 7 units and the utility of the parcels selected is 5. Now suppose that the conservation planner has available a budget of 10 units. Rather than simply selecting the least cost path, the planner would now be interested in finding the corridor that yields the highest utility, with a cost of no more than 10 units. Panel II, shows that for a budget of 10 units, the planner maximizes utility by selecting E, F, H, and I for a total utility of 9. If the conservation planner's budget is further increased to 11 units, as in panel III, the optimal selection of parcels is A, B, D, with a corresponding aggregate utility of 10. It is not surprising that considering only parcel costs in panel I results in a very different set of selected parcels from that in panels II and III, where both parcel cost and utility are considered. What is unique about the constrained corridor optimization problem is that a marginal change in the available budget can result in the selection of mutually exclusive sets of parcels, as illustrated in panels II and III. Given the constraint that all of the selected parcels must be connected, the model outcomes can change drastically as budget levels are varied, which is different from typical reserve site selection models where marginal changes in budget levels generally only influence the selection of a small subset of the available parcels.

Figure 1 also illustrates the computational challenges of the budget constrained utility maximization problem. If the objective is to find a least cost path, as has been done in all previous studies, only six possible paths in the 3x3 parcel grid need to be considered. The optimal selection will never include paths that are more than one parcel wide, as this can only add to the cost of the corridor. For the case of constrained utility maximization, however, the set of potentially optimal corridors jumps from six to thirty. Thus, even in this small hypothetical case, the challenge of maximizing utility given a budget constraint is considerably greater than simply finding the single-parcel-wide least cost path. The computation complexity of the problem is analyzed more rigorously in Conrad et al. (2007) and the challenges of reaching an optimal solution for the Northern Rockies corridor are dealt with later in the paper.

3.1 Mixed Integer Linear Programming Model

To solve the connection subgraph problem, a Mixed Integer Linear Programming Model is formulated where the binary variable x_i represents each vertex $i \in V$ and indicates whether i is included in the connected subgraph. The budget constrained utility maximization problem can be written

$$Max \sum_{i \in V} u_i x_i \tag{1}$$

$$s.t. \sum_{i \in V} c_i x_i \leq B \tag{2}$$

$$x_i \in \{0,1\} \quad \forall \; i \in V \, . \tag{3}$$

To ensure that connectivity is achieved, four additional constraints are included by applying a particular network flow model. In the model, each edge is represented by a nonnegative variable y_{ij}, which reflects the amount of flow from vertex i to vertex j. Flow that is identical in volume to the n vertices in the graph is "injected" from an external vertex x_0 into one of the terminal vertices. This constraint is formalized in equation (4) below. Further, the constraint provided in equation (5) ensures that only flow that is injected into the terminal parcel is utilized by the network.

$$x_0 + y_{0t} = n \tag{4}$$

$$y_{0t} = \sum x_i \tag{5}$$

Next, each of the vertices that are included in the subgraph retains one unit of flow. This implies that the flow from vertex *i* to vertex *j* must be less than the total amount of flow injected into the system,

$$y_{ij} < nx_j \,,\ \forall \{i, j\} \in E \,. \tag{6}$$

The conservation of flow in the network requires that the sum of all flow entering a vertex must be identical to the amount remaining at the vertex plus the amount of flow that leaves the vertex. This constraint is formalized as

$$\sum_{i:\{i,j\} \in E} y_{ij} = x_j + \sum_{i:\{i,j\} \in E} y_{ij} \,,\ \forall\ j \in V. \tag{7}$$

Finally, to ensure that all of the terminal vertices are included in the subgraph, each of the terminal vertices is forced to retain one unit of flow,

$$x_t = 1,\ \forall\ t \in T. \tag{8}$$

The constrained utility optimization problem above can be transformed into its dual, utility constrained cost minimization problem by essentially swapping (1) and (2). The utility constrained cost minimization problem is written as

$$Min \sum_{i \in V} c_i x_i \tag{9}$$

$$s.t. \sum_{i \in V} u_i x_i \geq U \,, \tag{10}$$

with the four connectivity constraints remaining the same. The unconstrained cost minimization problem, the so called “least-cost path”, can be obtained by eliminating constraint (10).

The formulation presented here allows for the possibility that the corridor can be more than one parcel wide. This is favorable, given that the overall utility of the parcels selected can be increased by widening the corridor or by incorporating paths to areas of high quality habitat. It may be, however, that the conservation planner wishes to eliminate the possibility of having peninsulas in the network, which could represent dead ends to wildlife in the corridor. While this option is not explored empirically in this paper, in practice peninsulas could be reduced[4] through the institution of an additional constraint, which requires that every vertex receiving flow must output flow to at least one other vertex that is different from the input vertex. Formally, the constraint is

$$y_{ji} > x_i + y_{ij}, \ \forall\, i, j \in H \neq T. \qquad (11)$$

4 Wildlife Corridor Application

The U.S. Northern Rocky Mountain Region is unparalleled in the continental U.S. in terms of indigenous species richness. The region is home to significant populations of grizzly bears, mountain lions, gray wolves, bighorn sheep, elk, moose and bison. In addition, the region contains three of the largest wild, undeveloped areas in the continental U.S; The Greater Yellowstone, Salmon-Selway[5] and Northern Continental Divide Ecosystems together comprise a land area of approximately 80,000 square miles, larger than the combined size of the states of New York, Massachusetts, New Hampshire and Vermont. The 25% population growth rate of the mountain West, however, was the highest of any region of the United States in the 1990's. Moreover, many rural counties in the region gained population at higher rates than the urban counties (Hansen et al. 2002). While many people are attracted to the region because of the abundant natural amenities,

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[4] It is still possible with this constraint for there to exist a multiple parcel wide peninsula, however one parcel wide peninsulas would be eliminated.

[5] The Salmon-Selway Ecosystem is also referred to as the Bitterroot Ecosystem.

the sprawling development that has resulted is leading to an increasingly fragmented landscape for wildlife.

Development and habitat fragmentation in the Northern Rockies has led to a situation where populations of grizzly bears, which were once abundant across the region, now live almost exclusively in the Yellowstone and Northern Continental Divide Ecosystems. While the number of grizzlies in the Yellowstone Ecosystem, estimated between 400-600, has been stable enough to warrant their recent removal from the endangered species list (US FWS 2007), grizzly populations outside of Yellowstone remain federally protected under the Endangered Species Act (ESA). A wildlife corridor would have the potential to allow populations of grizzlies to return to the Salmon-Selway Ecosystem and improve the general viability of grizzly populations across the Northern Rockies. Further, the grizzly bear is referred to as an "umbrella species", meaning that its survival improves the persistence of a wide range of other species living in the region (Walker and Craighead 1997).

The overall viability of a proposed corridor will undoubtedly be determined by the nature of the sites that are selected to connect the landscape. Given the limited conservation funding available, a corridor that is overly expensive will make the project a budgetary impossibility. Moreover, a corridor that incorporates sites with limited habitat quality will fail to provide an environment conducive to the free movement of wildlife populations.

4.1 Description of Data Sources

The study area for this analysis is comprised of 64 counties in Idaho and western Montana, located in the U.S. Northern Rockies region. At the aggregate level, the parcels that are considered for inclusion in the corridor are the 64 counties themselves. While securing an entire county to be included in the reserve may seem infeasible, the county-level analysis provides an illustrative example of a case where the optimization problem is relatively simple from a computational perspective. The county level model allows us to identify general corridor areas that contain low cost, suitable habitat, similar to Ando et al. (1998). The county model also provides a means of comparing the results of an aggregate model with relatively few sites, to more granular models with greater numbers of parcels. A map of the study area is included below as Figure 2.

To investigate the impact of increasing the granularity of the available parcels, the study area is further segmented into continuous sets of square grid cells. The largest grid cells are 60km on each side and segment the study area into 118 parcels. The parcel size is then incrementally reduced to square grids with sides of 50km, 40km, 25km, 10km and 5km. With the most granular grid size of 5km, the study area is segmented into 12,788 cells. Given the relatively large range of an adult grizzly (the home range of an adult female grizzly bear is approximately 125 square km), grid sizes smaller than 5km are unlikely to be suitable for grizzly bear movement (Mace and Waller 1997). Increasing the granularity of the grid cells allows for much more precision in defining parcel habitat suitability and acquisition costs and it also increases the number of parcels in the landscape. Given the greater number of parcels available for the corridor, increasing the granularity also increases the complexity of the optimization problem. Thus, comparing results across the continuum of cell sizes allows for an investigation into the tradeoffs inherent in the granularity of the model that allows for increased specificity at the cost of greater computational complexity. In addition, increasing the granularity of the parcels is equivalent to increasing the scope of a study area with fixed parcel sizes. Therefore increasing the parcel granularity provides insight into the scales at which corridor optimization is possible.

Grizzly bear habitat suitability data, developed and provided by the Craighead Environmental Research Institute (CERI), is used to measure the utility of each parcel. These data spatially define habitat that is considered to be suitable for grizzlies. The suitable habitat is measured on a 30 meter grid and each grid cell is given a score from 2 to 4, with 4 being the highest quality habitat. The habitat suitability data are then aggregated to the larger grid and county levels used in the analysis by summing the habitat scores within each parcel boundary. This method of aggregation implicitly assumes, for example, that a cell with a habitat suitability value of 4 is twice as beneficial as a habitat suitability value of 2.

The cost of each parcel is calculated in three steps. First, spatial data on land stewardship, available for the states of Montana and Idaho from the GAP Analysis project (USGS 1999), are used to classify privately and publicly owned land in the study area. Next, the amount of private land acreage within each parcel is calculated. The private land acreage is then multiplied by the county specific average value of farm real estate per acre, available from the USDA's Census of Agriculture (2002). For grid cells with land acreage in multiple counties, the county specific real estate value per acre is multiplied by the amount of private acreage in each county and then summed. Using the value of farm real estate is a proxy for the cost of all private land, as it is reflects the opportunity costs faced by private land owners. Ando et al. (1998) similarly use county-level average farm real estate value in their reserve selection model.

In delineating the cost of each parcel, we assume that land already in the public domain is freely available for inclusion in the corridor. Incorporating the opportunity cost of lost timber or mining contracts could be included as proxies for the cost of acquiring public land as in Polasky et al. (2001) and Sessions (1992). The costs of incorporating public land in the corridor are not included in the present analysis, however, as there are insufficient data with which to capture the heterogeneity in lost resource profitability associated with each parcel. In addition, it is possible that some limited resource extraction could occur on land included in the corridor. A depiction of the spatial distribution of parcel costs and parcel utilities at the 10km grid level is included as Figure 3.

By calculating the cost of each parcel based on the real estate value of the privately owned acreage, the assumption is that the parcels included in the corridor will be acquired with fee-simple purchases. For large projects, such as a corridor connecting the three large ecosystems in the Northern Rockies, the funds necessary to purchase a viable corridor outright will be large. Yet the cost estimates should be put into perspective by comparison to the significant amount of both public and private funding currently being spent on land conservation. In 2006, 133 separate ballot initiatives across the U.S. approved $6.7 billion in public funds for the procurement of conservation land (LTA 2007). This funding is in addition to the efforts of private land trusts at the local, state and national levels, who conserved 37 million acres in 2005 (LTA 2005) and other federal conservation programs such as the Conservation Reserve Program (CRP), which had annual expenditures exceeding $1.8 billion in 2006 (USDA 2006).

It should also be noted that parcels may not necessary need to be purchased outright in order to be included in the corridor, as easements and other voluntary agreements may be sufficient to maintain habitat. This voluntary type of arrangement is being used, for example, in the ‘Alps to Artherton’ project in Australia, where the Australian government is seeking agreements with private land owners to abstain from certain land use practices in exchange for annual payments.

While securing voluntary agreements for habitat protection may be a more viable strategy for cost-effectively targeting parcels to include in the corridor, there is insufficient data on the incentives necessary to secure such voluntary arrangements. The real estate value can therefore be thought of more as an upper-bound on a parcel’s cost[6], noting that the potential for voluntary habitat protection could significantly reduce the funds necessary to acquire the corridor.

One additional consideration in terms of the cost of the corridor is the transaction and management costs associated with securing property rights and maintaining the selected parcels (e.g., Groeneveld 2005; Naidoo et al. 2006; Newburn, Berck and Merenlender 2006). In the present analysis, the influence of transaction costs on corridor design for the 5km grid parcels is investigated by finding the cost minimizing corridor both with and without a $5,000 transaction cost per parcel acquired. Transaction costs are likely to play a more significant role when the cell granularity is small, as the transaction cost represents a greater proportion of the overall cost of the parcel and the number of potential paths is large.

Beyond defining the costs and utilities of parcel acquisition, it is also necessary to define the parcel adjacencies for all of the parcels in the study area. The adjacencies for both the aggregate-county and square grid parcels are defined based on shared

[6] This of course assumes that landowners are willing to sell land for inclusion in the corridor, which is likely not be valid in many circumstances.

borders/edges. For the grid parcels this implies that interior parcels are adjacent to exactly four other parcels.

Finally, it should be noted that there are regions within the study area that may represent either natural or man-made barriers to grizzly bear movement. For example, grizzlies may not be able to cross the Mission Mountain Range in Northwestern Montana or parts of the Clark Fork of the Columbia and other large rivers that flow through the study area. Man-made obstructions such as Interstate 90 or highly urbanized areas near major cities may also be impenetrable. As such, the land use planner is advised to ground truth the optimization results to ensure that these barrier areas are not included in a proposed corridor.

5 Model Results

This section reports the optimization results of the connection subgraph problem described in section 3 for the county-level parcels and the separate grid parcel granularities. First, the results from the unconstrained cost minimization model are reported along with an explanation of the algorithm that is employed. Second, the results and algorithms used for the budget constrained utility maximization model are described. The unconstrained minimum cost corridor problem corresponds to the minimum Steiner tree problem. In the case where the number of reserves is bounded, the minimum Steiner tree problem can be computed in polynomial time (Promel and Steger 2002). For the case considered here with three reserves, the algorithm that is implemented runs in time roughly equivalent to n^3, where n is the number of parcels. The algorithm first computes the shortest path between each parcel and all other parcels in the study area, which generates what is referred to as an all-pairs shortest path (APSP) matrix (Corman et al. 2001). In this case, the path length is measured strictly in terms of parcel cost. Next, the algorithm determines the parcel that minimizes the distance between that parcel and the three reserves, which is referred to as the center point.[7] The minimum cost corridor is then determined based on the shortest path between the chosen center point and the three reserves. The minimum cost corridor results for each granularity are reported in Table 1.

After computing the unconstrained minimum cost corridor, the budget constrained utility maximization corridor is determined for budgets greater than the minimum cost. For parcel granularities down to 50km, the optimal budget constrained corridor can be computed using standard, off-the-shelf CPLEX optimization software using the MIP formulation described in section 3. For parcel granularities smaller than 50km, a preprocessing step is executed using the all-pairs shortest path matrix generated in the minimum cost solution. Specifically, if the minimum cost of connecting a given parcel to its two closest reserves exceeds the budget, then that parcel is "pruned" from the set of available parcels. This preprocessing step allows for the calculation of the optimal corridor for the 40km parcel granularities. Unfortunately, for parcels granularities smaller than 40km, optimal corridors cannot be determined even with this preprocessing step. For the smaller parcel granularities, a heuristic method, explained in greater detail in the next section, can be implemented based on the minimum cost corridor.

For the county, 60km, 50km and 40km parcel granularities, the utility maximizing corridor for a budget that is 10% greater than the cost minimum is provided in Table 2. For the 50km and 40km grids, the effect of varying the size of the budget on the parcels

[7] In the case of three reserves, it is guaranteed that there will be exactly one center point. When there are more than three reserves, the algorithm finds all k-2 centerpoints through a Dreyfus-Wagner algorithm (Corman et al. 2001)

selected is evaluated in greater detail. To this end an efficiency frontier is generated illustrating the tradeoffs between parcel cost and the suitable habitat in the corridor.

5.1 Cost Minimizing Corridor

The number of parcels available for acquisition ranges from 64, in the case of the county-level grid, to 12,788, for the 5km grid. When the parcels available for acquisition are the counties themselves, the minimum cost corridor has a price tag of over $1.9 billion. As expected, as the size of the available parcels is reduced, the corresponding cost of the cheapest corridor diminishes. At the 5km granularity, the cost of the corridor is slightly less than $11 million. A portion of the decrease in cost is a result of the fact that less overall land area is being purchased; the 5km cost minimizing corridor covers over 1.6 million acres, while the county-level minimum cost corridor covers nearly 10 million acres. However, the difference in cost between the county corridor and 5km corridor cannot be explained by differences in preserved acreage alone. Increasing the parcel granularity allows for greater specificity and the corridor is better able to incorporate low cost areas composed primarily, and in some cases exclusively, of zero cost national forest land. As evidence of this, the cost per acre in the county grid is $197, while the cost per acre of the 5km grid is only $6. It should be noted that higher percentages of public land also tends to increase the amount of suitable habitat per acre as national forest land generally has high habitat suitability.

Changing the parcel granularity not only influences the cost of the parcels selected and the complexity of the problem, but it also influences the general path that the corridor follows. For the county level, 60km and 50km parcel maps, the minimum cost corridor essentially forms the shape of an upside-down T, where the parcels selected are concentrated in the region in the middle of the three ecosystems. When the parcel size is reduced to 40km and below, the minimum cost corridor traces a path connecting the three reserves that resembles the shape of a C, with the Salmon-Selway Ecosystem connecting directly to the Northern Continental Divide Ecosystem via a parcel path in the northwestern portion of the study area. By increasing the parcel granularity, the model avoids higher priced areas in southwestern Montana and instead chooses a slightly longer corridor that incorporates more national forest land. Thus, influencing the parcel granularity not only influences the estimated cost of the cheapest corridor, but it also has a significant influence on the general path that the corridor follows across the landscape. Maps of the optimally selected minimum cost corridors for each of the parcel sizes are included as Figure 4.

The addition a $5,000 transaction cost per parcel at the 5km level reduces the number of parcels selected from 265 to 196. When transaction costs are considered, each parcel adds incrementally to the overall cost of the corridor. Thus, the minimum cost corridor tends to select parcels that provide more of a direct link between the reserve sites, rather than following a slightly longer path that includes more zero cost, national forest parcels.

5.2 Cost Constrained Utility Maximizing Corridor

While determining the minimum cost corridor connecting core areas of biological significance is important for land use planners in determining the financial feasibility of a wildlife corridor, selecting a corridor based on cost alone is likely to yield outcomes that leave out relatively low cost parcels with high quality habitat. If a land use planner has a budget that is larger than the minimum cost corridor, she would ideally determine the corridor that maximizes the amount of suitable habitat given the budget that is available. After determining the minimum cost corridor, we find the corridor that maximizes the amount of suitable habitat for a budget that is 10% greater than the minimum cost corridor. Unfortunately, at parcel granularities smaller than 40km it is not possible to prove the optimality of the cost constrained utility maximizing corridor. In other words, the program can find a feasible solution that connects the reserves and meets the budget constraint, but proving that a particular feasible solution is the optimal solution requires excessive computational time.

A summary of the parcels selected for the utility maximizing corridors, given a budget that is 10% higher than the cost minimum, is provided in Table 2 for the county-level, 60km, 50km and 40km grids. At the county level, increasing the budget by 10% does not change the parcels selected in the optimal corridor. For this coarse parcel size, the budget increase is not enough to motivate the selection of a different set of counties. At the 60km level, increasing the budget by 10% results in the optimal selection of 20 parcels as opposed to the 11 parcels selected in the cost minimization model. When the grid size is further reduced to 50km, the number of selected parcels jumps from 12 to 22, while at the 40km level the number of selected parcels goes from 15 to 23. In each case, budget constrained optimization results in a significant increase in aggregate habitat suitability, for example at the 50km level, suitable habitat increases from 5,902,000 units in the cost minimization model to 12,187,572. It should be noted that the minimum cost 50km grid obtains the maximum habitat suitability possible for a budget equal to the minimum cost. Therefore the increase in aggregate habitat suitability at the higher budget level is strictly a result of the increase in budget.

A visual depiction of the optimal corridors for the 50km parcels under varying budgets is presented in Figure 5. The shape of the 50km corridor changes considerably under budget constrained maximization. Rather than forming the upside-down T as in the cost minimization solution, the budget constrained optimization solution looks more like a C, with the inclusion of a number of buffer parcels around the Salmon-Selway Ecosystem that are both low cost and contain a high degree of suitable habitat.

5.3 Efficiency Frontier

The results of the cost minimizing corridor and the utility maximizing corridor with a10% greater budget allude to the tradeoffs that exist between corridor cost and overall habitat suitability measures. The conservation planner is likely to be interested both in reducing the overall cost of the corridor and in incorporating as much suitable habitat as possible, but may not have an exact idea of the relative tradeoffs between these two objectives. The efficiency frontier that we estimate represents the locus of non-inferior parcel combinations, where in order to improve one of the objectives, the other objective must be made worse off. In this case to increase the amount of suitable habitat in the corridor for a point on the efficiency frontier, the cost of the corridor must increase.

To delineate the efficiency frontier, we utilize the constraint method (Willis and Perlack 1980), which involves first solving for the minimum cost corridor and then solving the cost constrained utility maximization problem for various budget levels greater than the minimum cost corridor.[8] The constraint method differs slightly from the weighting method, such as that used in Williams (1988), which involves incrementally changing the weights on the cost and habitat objectives. The constraint method is preferable in this case

[8] The identical efficiency frontier could also be generated by minimizing the cost of the corridor and systematically changing the constraint on the overall level of suitable habitat.

because it is able to determine all of the noninferior solutions. In contrast, when the objective space is nonconvex (e.g., when the decision variable is zero-one), the weighting method is not able to find all noninferior solutions (Willis and Perlack 1980). Since it is minimizing a linear combination of the two objectives, the weighting method finds only the convex hull of noninferior solutions and ignores solutions in the interior of the hull (a problem referred to as the “duality gap”).

The efficiency frontier for the Northern Rockies corridor is illustrated by using the constraint method on the 50km parcels. Beginning with the minimum cost corridor, the budget constraint is systematically increased and the results are presented in Table 3. In addition, the graphical efficiency frontier is provided for the 50km grid in Figure 6.

The results show that aggregate habitat suitability measures increase nonlinearly with increases in the conservation budget. For the case of the 50km grid, increases in the budget up to 10% above the minimum cost corridor increase overall habitat suitability at an approximate rate of 48 units for every $1 increase in the budget. At budget levels between 50% and 150% greater than the minimum cost corridor, however, the rate of increase in habitat suitability associated with increases in the budget is less than 6 units for every 1 dollar increase in the budget.

Table 3 reveals several noteworthy trends as the conservation budget is increased. First, similar to the overall HSI, the number of acres preserved increases at a decreasing rate with changes in the budget. For budget increases above the cost minimum between 0 and 10%, approximately 0.033 additional acres are preserved for each additional dollar in the case of the 50km grid. For budget increases between 50 and 150%, the number of additional acres preserved per dollar falls to 0.005. In addition, the percentage of private land that is included in the corridor follows a U shaped trajectory as the budget is increased. For marginal increases in the budget above the cost minimum, the optimal corridor incorporates higher quantities of public land. As parcels with high percentages of public land are exhausted at higher budget levels, the optimal corridor adds additional parcels with greater percentages of private land. The overall percentages of private land are reflected in the cost per acre, which also decreases for initial budgetary increases and then grows as the low cost parcels are exhausted.

The HSI per acre preserved increases dramatically for initial budgetary increases, but then plateaus and finally decreases slightly for the higher budget levels. The plateau in the case of the 50km grid occurs at approximately 1.10 units per acre. This again illustrates the fact that greater granularity allows for the targeting of low cost, high benefit parcels. Taken together, the results indicate significant marginal benefits in terms of greater numbers of acres preserved, higher habitat suitability per acre and lower costs per acre for marginal in increases in the conservation budget above the cost minimum. These marginal benefits are reduced at higher budget levels, as the number of low cost and high benefit parcels becomes scarce.

While the marginal benefits of budget increases are high in close proximity to the cost minimum, the marginal cost in terms of computational complexity is great. As the budget is increased above the cost minimum, the time necessary to prove utility maximization, in this example, decreases. Thus it may be possible to prove an optimal solution when the allotted budget is high, but as the budget becomes increasingly constrained, proving optimality may not be possible. The optimization results therefore illustrate the significant tradeoffs between computational complexity and the amount of suitable habitat in the corridor. Given that land use planners are likely to have budgetary constraints that restrict their spending to levels that approximate the cost-minimizing corridor, these tradeoffs represent a significant policy dilemma. At low budget levels the overall utility of the corridor can be drastically increased by selecting parcels optimally, yet proving optimality becomes considerably more difficult

5.4 Minimum Cost Extension Heuristic

Proving that a particular corridor is optimal given a budget constraint is not possible in a reasonable amount of time for the case of parcel granularities smaller than 40km. Conservation planners, however, need not be completely without guidance for selecting corridor parcels when the number of available parcels is large. This section describes a heuristic that generates a feasible corridor that approximates, and in some cases is equivalent to, the optimal corridor. Results from the application of the heuristic to the 40km parcels are illustrated in detail to show the degree to which the heuristic results approximate the optimal results.

The heuristic procedure is performed using the minimum cost corridor as a baseline. The parcels selected for the minimum cost corridor are then treated as if they themselves are reserves, guaranteeing an initial connected path. Next, the optimal extension of the minimum cost corridor is calculated using the optimization procedure described above, where parcels that are not feasible given the budget constraint are pruned and the additional parcels are optimally selected from the remaining set using CPLEX.

The comparative results depicted in Figure 7 reveal that the minimum cost extension heuristic closely approximates the optimal corridor for the 40km parcels. Indeed, for budgets up to approximately 25% more than the cost minimizing corridor, the minimum cost extension heuristic selects the identical set of parcels as the optimization algorithm. At higher budget levels the correspondence between the heuristic and the optimum is not exact, but the difference is relatively minor. For budget levels up to 70% more than the minimum cost corridor, the difference in habitat suitability between the optimally selected and heuristically selected corridor is never more than seven percent. The results suggest that in cases where optimization is not possible, the minimum cost extension heuristic allows conservation planners to capture the majority of the habitat benefits for a given budget, especially for budget levels that are close to the cost minimum. Importantly, the minimum cost extension heuristic is significantly less computationally intensive and provides feasible solutions for granularities at least as small as the 5km grid, in a reasonable timeframe.

6 Conclusion

The design of a wildlife corridor that connects key areas of biological significance is a classic economic problem that involves selecting the most suitable corridor habitat given a particular conservation budget. The case of an optimal design for a wildlife corridor connecting the Northern Continental Divide, Salmon-Selway and Yellowstone Ecosystems in the U.S. Northern Rockies is considered in this paper using both heterogeneous parcel costs and utilities. Optimization is conducted over a range of parcel granularities and the results indicate that as the granularity of the parcels change, the cost minimizing corridor is likely to follow considerably different paths, reflecting the tradeoff between parcel cost and benefit as well as the parcel’s location in the landscape. The results also provide evidence that determining the connected set of parcels that minimize corridor cost is computationally easier than proving that a particular set of parcels maximize the amount of suitable corridor habitat for a given budget level. In the study area evaluated in this paper it is not possible to prove optimality for budget levels near the cost minimum, when the number of parcels is greater than 240.

For small scale problems, budget constrained maximization allows conservation planners to optimally utilize the funds allotted for corridor acquisition and the efficiency frontier illustrates the tradeoffs that exist between corridor cost and overall habitat suitability. Budgets in excess of the cost minimum corridor have the potential to provide considerably higher levels of habitat suitability, though the marginal benefit of budgetary increases is concave. This implies that the greatest potential benefit of optimization occurs for budget levels that are close to the cost minimum. Unfortunately, this budget range is also the most challenging in terms of computational complexity. In cases where optimization is not practical, evidence is provided that a heuristic, which finds the optimal extension of the minimum cost corridor, closely approximates the optimal solution. Future corridor research comparing the cost effectiveness of heuristics over a variety of parcel costs and utilities will be useful to land use planners as corridor projects are proposed for increasingly large landscapes.

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Table 1. Cost Minimization Results

Parcel size	Number of parcels	Parcels selected	Corridor Cost (thousand)	Total HSI (thousand)	Acres Preserved (thousand)	% Private	Cost per acre ($)
County	64	5	1,904,355	7,038	9,649	27.2%	197.4
60km	118	11	1,657,740	7,188	8,234	27.1%	201.3
50km	167	12	1,329,090	5,902	6,777	30.7%	196.1
40km	239	16	891,052	5,807	5,409	13.6%	164.7
25km	570	23	449,430	3,743	3,408	12.5%	131.9
10km	3,296	120	99,341	3,679	4,096	1.9%	24.3
5km	12,788	265	10,865	2,147	1,637	0.5%	6.6
5km†	12,788	196	11,824	1,576	1,210	0.7%	9.8

† Includes a $5,000 transaction cost per parcel selected.

Table 2. Budget Constrained Utility Maximization Results

Parcel size	Number of parcels	Parcels selected	Corridor Cost (million)	Total HSI (thousand)	Acres Preserved (thousand)	% Private	Cost per acre
County	64	5	1,904	7,038	9,649	27.2%	197.3
60km	118	20	1,821	14,240	14,209	32.1%	128.2
50km	167	22	1,461	12,188	11,303	19.4%	129.3
40km	239	23	999	11,832	9,932	8.4%	100.6
25km	570	-	-	-	-	-	-
10km	3,296	-	-	-	-	-	-
5km	12,788	-	-	-	-	-	-

Note: Budget is set 10% higher than the cost minimum solution.

Table 3. Budget Constrained Utility Maximization for 50km Parcels

Budget (million)	Cost (million)	Total HSI (thousand)	Acres Preserved (thousand)	Percent Private	Cost per Acre ($)	HSI per Acre
-	1,329	5,902	6,777	30.7%	196.1	0.87
1,396	1,394	9,842	9,608	22.2%	145.1	1.02
1,462	1,461	12,188	11,303	19.4%	129.3	1.08
1,528	1,526	13,220	12,176	18.5%	125.3	1.09
1,595	1,594	14,145	12,874	15.5%	123.8	1.10
1,728	1,727	15,533	14,131	15.7%	122.2	1.10
1,861	1,857	16,777	15,119	15.2%	122.8	1.11
1,994	1,992	17,811	16,239	16.1%	122.7	1.10
2,658	2,658	22,151	20,105	16.2%	132.2	1.10
3,323	3,321	25,500	23,298	16.5%	142.5	1.09

Figure 1. Hypothetical Corridor Optimization

I. Minimum Cost Corridor
Cost = 7, Habitat = 5

5 **A** 4	2 **B** 2	**C**
3 **D** 5	2 **E** 2	3 **F** 3
G	1 **H** 3	3 **I** 2

II. Optimal Corridor *B*=10
Cost = 10, Habitat = 9

5 **A** 4	2 **B** 2	**C**
3 **D** 5	2 **E** 2	3 **F** 3
G	1 **H** 3	3 **I** 2

III. Optimal Corridor *B*=11
Cost = 11, Habitat = 10

5 **A** 4	2 **B** 2	**C**
3 **D** 5	2 **E** 2	3 **F** 3
G	1 **H** 3	3 **I** 2

Note: Parcel labels are provided in the lower left, costs are in the lower right and utilities are in the upper left.

Figure 2. U.S. Northern Rockies Study Area

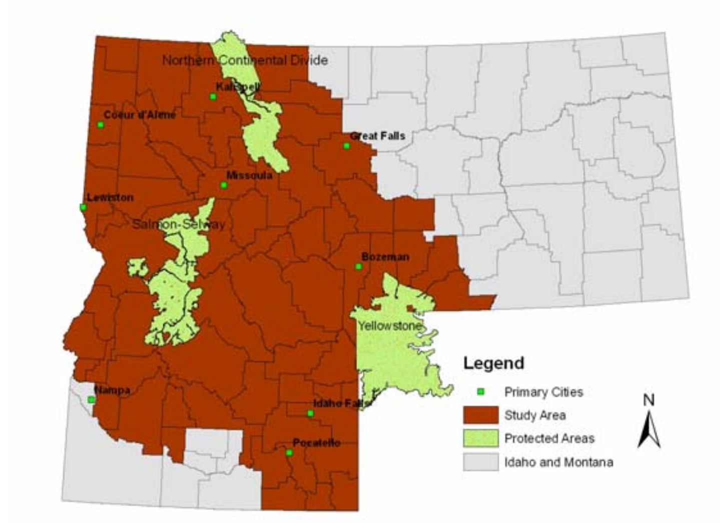


Figure 3. Habitat Suitability and Parcel Cost for 10km Grid Parcels

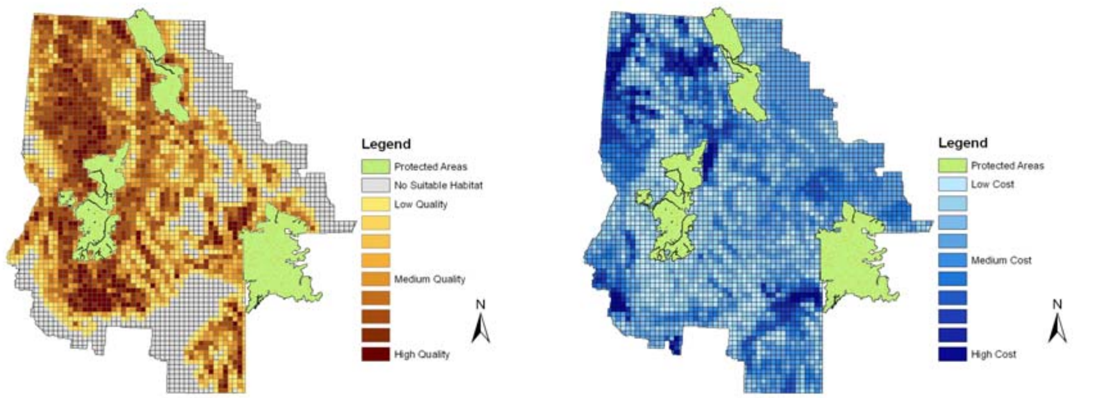


Figure 4. Unconstrained Cost Minimum Corridor for Each Granularity

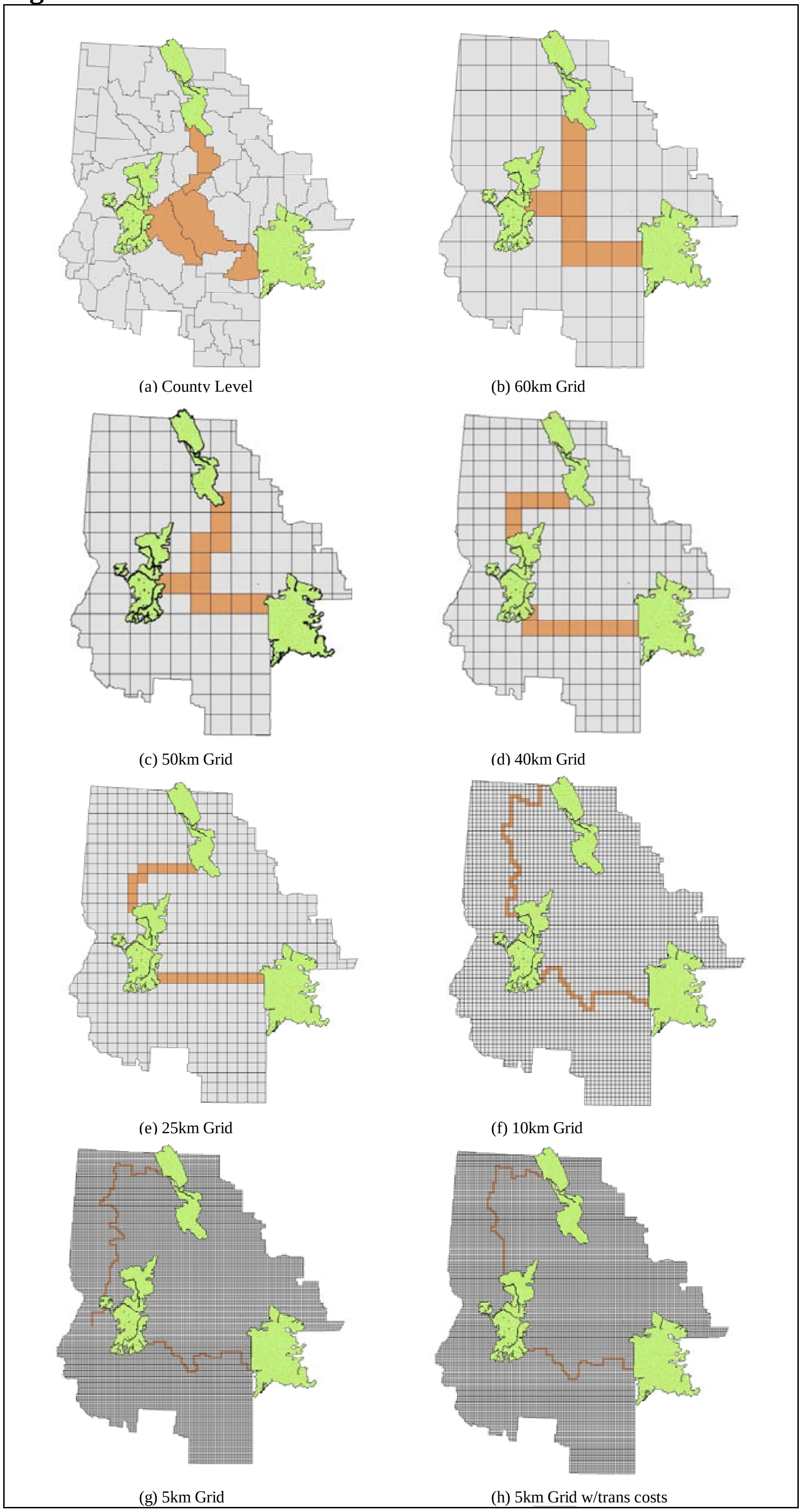
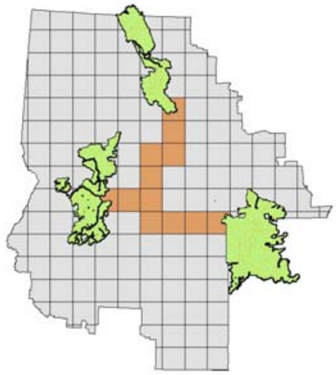
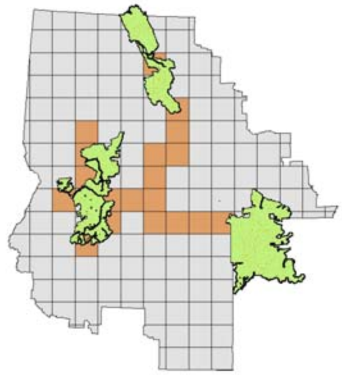


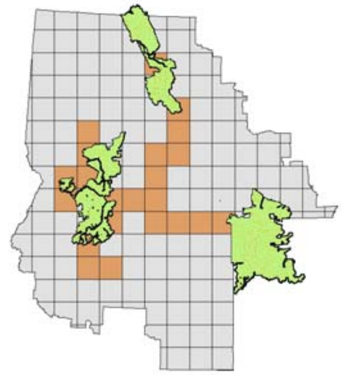
Figure 5. Cost Constrained Utility Maximization of 50km Parcels



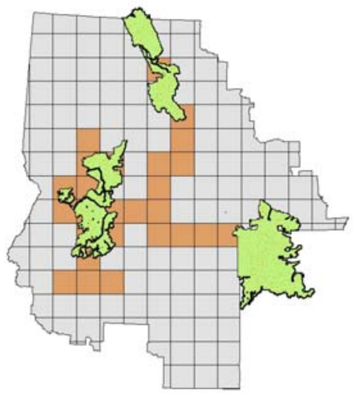
(a) Min Cost



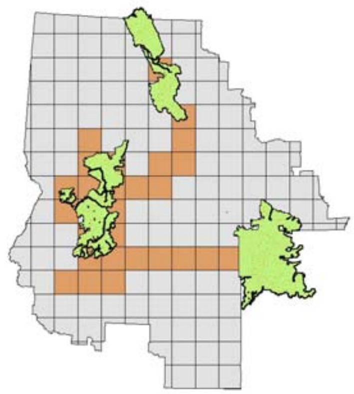
(b) Min Cost + 5%



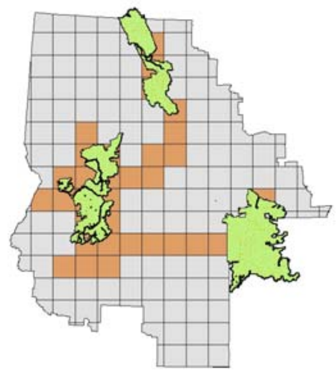
(c) Min Cost + 10%



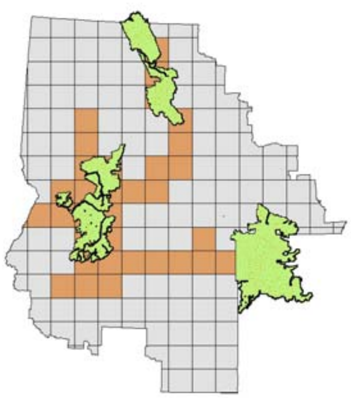
(d) Min Cost + 15%



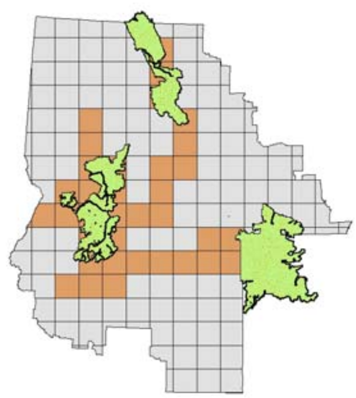
(e) Min Cost + 20%



(f) Min Cost + 30%



(e) Min Cost + 40%



(f) Min Cost + 50%

Figure 6. Corridor Efficiency Frontier for 50km grid

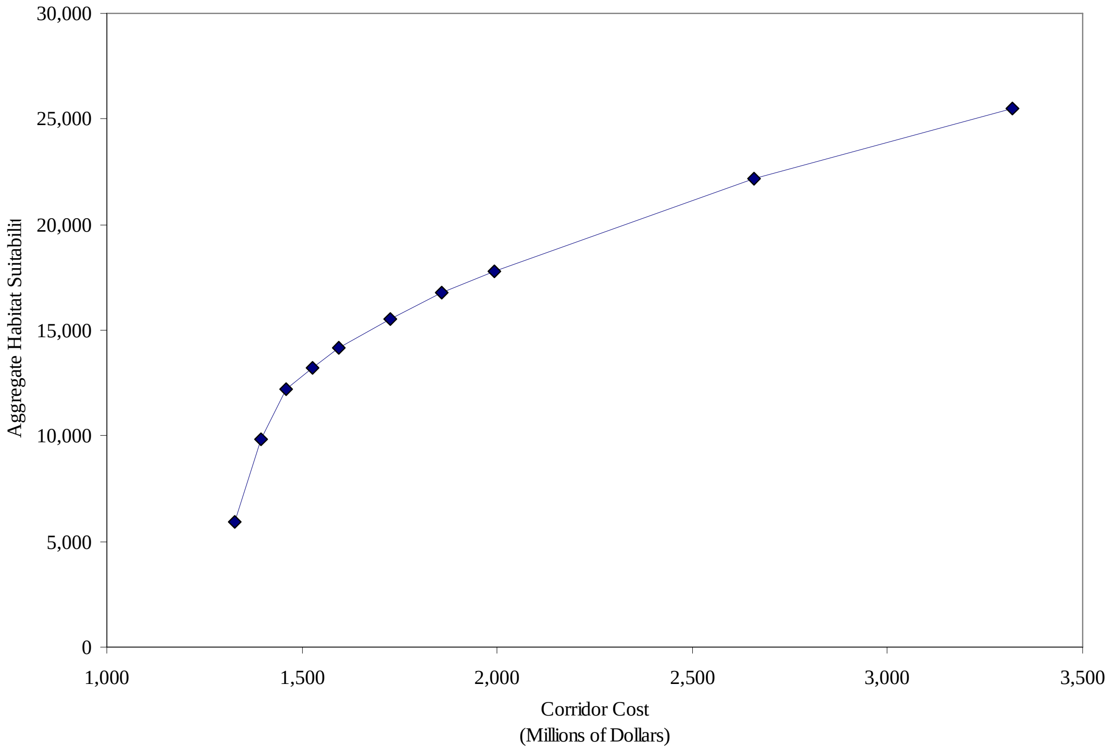


Figure 7. Optimal and Minimum Cost Extension 40km Grid Efficiency Frontier