A Spatial Decision Support System

for Optimizing the Environmental Rehabilitation of Borderlands

by

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ABSTRACT

The border policies of the United States and Mexico that have evolved over the previous decades have pushed illegal immigration and drug smuggling to remote and often public lands. Valuable natural resources and tourist sites suffer an inordinate level of environmental impacts as a result of activities, from new roads and trash to cut fence lines and abandoned vehicles. Public land managers struggle to characterize impacts and plan for effective landscape level rehabilitation projects that are the most cost effective and environmentally beneficial for a region given resource limitations. A decision support tool is developed to facilitate public land management: Borderlands Environmental Rehabilitation Spatial Decision Support System (BERSDSS). The utility of the system is demonstrated using a case study of the Sonoran Desert National Monument, Arizona.

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CHAPTER 1

INTRODUCTION

Spatial Decision Support Systems (SDSS) have been developed to assist decision makers in addressing a variety of environmental and natural resource management problems. Examples include applications for forestry (Church, Murray, Figueroa, & Barber, 2000), watershed management (Choi, Engel, & Farnsworth, 2005; Dymond, Regmi, Lohani, & Dietz, 2004; Sugumaran & Davis, 2004), biodiversity (Bottero, Comino, Duriavig, Ferretti, & Pomarico, 2013; Larson & Sengupta, 2004), non-point source pollution (Leon, Lam, Swayne, Farquhar, & Soulis, 2000; Srinivasan & Engel, 1994) and contaminated sites (Carlon, Critto, Ramieri, & Marcomini, 2007; Critto, et al., 2007) to name a few. On top of existing land use issues, a more recent challenge for public land managers along the United States and Mexico border is effectively dealing with impacts from illegal immigration and drug smuggling.

Since the deployment of Operation Gatekeeper in 1994 and other Border Patrol operations, the number of agents, amount of fencing and barriers, and motions sensors have increased in the San Diego, California and El Paso, Texas sectors, resulting in immigrants being pushed to more remote areas. Within 100 miles of the border, over 70% of the land is publically or tribally owned (U.S. Department of the Interior, Bureau of Land Management, 2010). Public lands, while sparsely populated, contain sensitive and unique cultural and natural resources, but have become corridors for human and drug smuggling and are suffering significant environmental consequences from these activities.

Both federal and state public land agencies have little to no influence in shaping border policy. Agencies therefore find themselves in a reactive situation, as they are bound to their missions to protect the natural, cultural and aesthetic resources under their jurisdictions. Groups of immigrants and smugglers move through borderlands leaving large concentrations of trash along the way, especially at places of rest or while waiting for further transportation, so-called layup sites. The litter includes clothing, shoes, plastic bottles, glass jars, baby bottles, food cans, plastic bags, wrappers, backpacks, wallets, makeup kits, religious writings, toilet paper, diapers, photographs, razors, brushes, and medication containers (U.S. Department of the Interior, Bureau of Land Management, 2007). Miles of routes have been created by vehicles and foot traffic, causing erosion, destroying vegetation, and fragmenting wildlife habitat. Other impacts include the abandonment of vehicles and horses, use of wildlife waters, range improvement troughs and wells for bathing and washing, and cutting of fence lines that ultimately displace livestock (U.S. Department of the Interior, Bureau of Land Management, 2010).

Unfortunately, it is not possible to rehabilitate all degraded areas due to annual budget and labor constraints. Some areas are much worse off than others, and located within variable levels of resource sensitivity. Resource specialists (archaeologists, wildlife biologists, recreation planners, and others) perceive the borderland activity as a law enforcement issue, as much of the funding and human capital is invested in policing efforts. Little to no data are given to the specialists for environmental assessment purposes. This leads to a lack of knowledge on the part of the specialists as to the distribution and severity of degradation to resources they are tasked to manage. Additionally, public land managers would like to be able to plan for large-scale rehabilitation efforts in the most cost effective and environmentally beneficial way.

The purpose of this paper is to create a spatial decision support system utilizing GIS and optimization methods offers potential to bridge these gaps. This paper proposes a methodology and SDSS to achieve this. The utility of the Borderland Environmental Rehabilitation Spatial Decision Support System (BERSDSS) in quantifying impacts and determining rehabilitation site priorities is explored in studying the Sonoran Desert National Monument of Arizona.

CHAPTER 2

BACKGROUND

2.1 Decision Support Tools

Decision Support Systems (DSS) are computer software that can be used to analyze and solve complex decision making problems. Components typically include a database and data retrieval system, analytical models or algorithms, graphic and visualization tools, simulation and optimization models (Agostini, Critto, Semenzin, & Marcomini, 2009; Church, Murray, Figueroa, & Barber, 2000). Geographical information systems (GIS) from their inception have been seen as a facilitating technology, conducive to integrating related analytical approaches, such as Multi-Criteria Decision Making, simulation, etc. (Jankowski, 1995; Murray, 2010). The integration of DSS and GIS effectively results in a Spatial Decision Support System (SDSS), where a spatial problem can be analyzed using a range of spatial and aspatial methodologies (Murray, 2002). Today, there are many examples of Spatial Decision Support Systems, where GIS is the platform on which the systems' architecture is built and executed (Church, Murray, Figueroa, & Barber, 2000; Snediker, Murray, & Matiziw, 2008; Sugumaran & Degroote, 2010; Zhu, Healey, & Aspinall, 1998).

In a time of diminishing budgets, land managers must get the greatest possible return on investment and utilize taxpayer funds as efficiently as possible. A cost-benefit analysis is well suited to address the type of resource allocation problem discussed above. The goal is improving the provision of environmental services or actions based on estimates of the monetary value of environmental changes (Atkinson & Mourato, 2008). Cost benefit analysis is useful not only because of its efficiency-test property, but also because it allows for the incorporation of social values in decision making. It explicitly brings in values other than those of scientific experts on complex, dynamic environmental properties. The exercise of determining costs and benefits during the decision making process are likely to lead to more desirable outcomes for decision makers and the general public (Hanley, 2001).

Unfortunately, a traditional cost-benefit analysis falls short of adequately addressing inherently spatial problems, such as the rehabilitation of borderlands.

Currently, these degraded areas are treated in a triage fashion. First, they are as reported by law enforcement or the public, and then as resources become available in terms of equipment and labor it is allocated for cleanup. This approach can result in spatially and functionally disconnected sites, perpetuating further loss of ecological function (Noss, Neilsen, & Vance-Borland, 2009). Utilizing the outputs of a cost-benefit analysis without spatial considerations ignores spatial equity or functionality. Added logistical and economic efficiencies can also be achieved by considering contiguity and/or spatial proximity.

Location science and spatial optimization facilitate the integration of geographic issues and relationships through the use of GIS and optimization solver platforms. Spatial relationships can be stated as objectives and as constraints in a model (Williams, ReVelle, & Levin, 2005). Contiguity can be represented in a number of ways (Nalle, Arthur, & Sessions, 2002). Spatial optimization approaches enable benefit, costs and contiguity issues to be simultaneously considered (Wright & Cohon, 1983; Church & Murray, 2009).

2.2 Borderlands and Environmental Impacts

Over the last fifteen years, policy makers and researchers have become more interested in the environmental impacts from immigration on borderland areas. A handful of researchers have explored the use of GIS to understand aspects and impacts of immigration itself. Giovando and Zhang (2005) proposed a framework for analyzing U.S. Border Patrol datasets, calling for an integration of visualization and data mining to find both spatial and attribute patterns. Rossmo et al. (2008) used a variety of statistical methods to create a "jeopardy surface" of interdictions along the Texas border in order to determine areas immigrants consider most favorable for border crossings. These areas are found to be those in proximity to rivers, streams or Mexican urban areas.

McIntyre and Weeks (2002) used GIS and GPS data for the Cleveland National Forest near San Diego, California to quantify the average environmental impact created from each illegal immigrant per year in terms of trash production, illegal and harmful routes created, and wildfires sparked. A more recent study by Lawrence and Wildgen

(2012) used Theissen polygons and hydrologic modeling concepts to create a model of border crossing behavior, and was used to detect high use corridors within Arizona's Tohono O'odham Reservation. They discovered a funnel effect behavior with trail braiding that leads to multiple destinations in Arizona. A few studies have focused on the efficiency of U.S. Border Patrol resources, and how they should be re-allocated in case of a serious threat to security (Pulat, 2005; Wein, Liu, & Motskin, 2009).

To date, aside from inventories, no framework for evaluating immigration impacts on borderland natural resources exists. The proposed SDSS offers potential to fill this gap through the integration of GIS and spatial optimization to assist decision makers in the visualization of borderland impacts, the quantification of impact, and the prioritization of rehabilitation sites within a specified budget. A description of the individual components of the developed system follows.

CHAPTER 3

SYSTEM DESIGN

The foundation of any SDSS is GIS, but components and functionality are linked to the management objectives to address the problem at hand. The components, the level of interaction with GIS, and the application makes each SDSS unique. The developed SDSS and its components (Figure 1) are linked to three management objectives regarding the overall goal of the selection of rehabilitation sites: 1) the sites with the greatest environmental benefit; 2) cost to rehabilitate; and 3) the sites within proximal distance to each other for logistical efficiency.

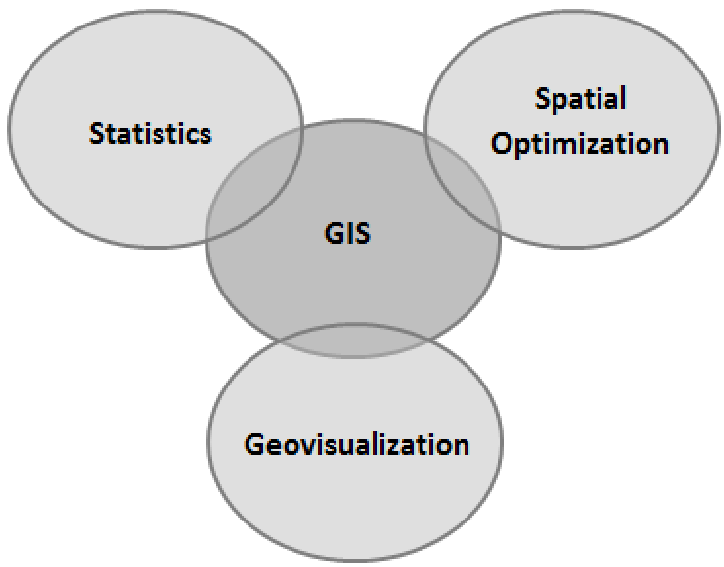

Fig. 1. Key components of the BERSDSS.

ArcGIS 10.1 was utilized for creating the user interface and provided access to various geo-processing and operational functionalities. As a result, spatial analysis tools, visualization capabilities, and database management approaches are readily accessible through the system.

The other three key components of the SDSS include statistics, spatial optimization, and geovisualization. Statistics aid in the valuation of non-market resources; spatial optimization is used to identify the best siting scenarios; and geovisualization facilitates simulation of the scenario impacts. Generally speaking, GIS and associated components are loosely coupled; the data from GIS is passed to the other components for analysis, with solutions being passed back to GIS for further manipulation and interpretation.

The SDSS is structured using Python and ArcObjects on a desktop computer by resource specialist staff, enabling data exploration (formatting of data, selections, and visual overlays), as well as decision makers to develop and analyze possible siting scenarios, and hopefully a better understanding of associated tradeoffs. The four major components of the SDSS are further discussed below.

3.1 GIS

The GIS platform allows for geo-processing and operational functionalities. This includes data integration of multiple input layers into the same format, storage of multiple scenarios, and data creation. A key component and method of deriving data is map algebra. Map algebra is the processing of multiple input layers to produce a composite output layer(s) using mathematical operations. Other overlay methods are available, such as intersections, unions, and zonal overlays and statistics. The GIS component of the SDSS is the lynch pin that allows the other three components to interact more tightly. While statistics, optimization and geovisualization methods can all be done separately and passed between each other loosely, GIS allows for a common platform to calculate, process, and analyze data.

3.2 Statistics

Statistical methods are needed to assess the value of non-market goods, such as natural resources, and how much they are impacted from one event versus another. This valuation could be done with statistics being tightly coupled and within the SDSS, using spatial hedonic analysis or kernel density estimates. Statistics could also be loosely coupled or conducted outside of the SDSS using methods such as ranking and rating methods, as in this case study. The first weighting method is used to evaluate the different border events' impact on individual natural resources. This is accomplished as follows:

$$w_j = \frac{r_j}{100} \tag{1}$$

where w_j is the normalized weight ranging in value from 0 to 1 for the criterion j and r_j is the rating (ranging 0-100) assigned to the jth criteria.

The second weighting method is used to evaluate the overall vulnerability of each resource as a whole, compared to others in the area by utilizing a pairwise comparison method as follows:

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lim_{k \to \infty} \frac{\begin{bmatrix} a_{ij} & \cdots & a_{nj} \\ \vdots & \ddots & \vdots \\ a_{nj} & \cdots & a_{nn} \end{bmatrix}^k \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}}{[1 \quad \ldots \quad 1] \begin{bmatrix} a_{ij} & \cdots & a_{nj} \\ \vdots & \ddots & \vdots \\ a_{nj} & \cdots & a_{nn} \end{bmatrix}^k \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}} \tag{2}$$

where n is the number of objectives, and a_{ij} the pairwise comparison value of one resource over another according to the evaluator. The statistics component interacts most with the GIS and geovisualization components to support the derivation of measures, integration or creation of spatial data, basic tests, and visual comprehension of the distribution of data.

3.3 Spatial Optimization

Spatial optimization is needed to assist in the selection of sites to be rehabilitated. The process of selecting these sites could be done a number of ways (ad hoc, an existing or new heuristic, etc.). The borderland problem, however, requires a spatial optimization model to select the sites with the greatest environmental benefit given limited resources (money, personnel, time, etc.). The shape model is a multiobjective optimization problem detailed in Wright et al. (1983) and Church and Murray (2009). It is structured to select a subset of parcels while encouraging contiguity of selected parcels by minimizing perimeter and tracking spatial relationships. The model formulation is as follows:

$$Maximize \qquad \sum_i b_i X_i \tag{3a}$$

$$Minimize \qquad \sum_i \sum_{j \in \Omega_i} P_{ij}\left(E_{ij}^+ + E_{ij}^-\right) + \sum_{i \epsilon \Psi} P_{ii} X_i \tag{3b}$$

Subject to:

$$\sum_i c_i X_i \leq \mu \tag{4}$$

$$X_i - X_j - E_{ij}^+ + E_{ij}^- = 0 \qquad \forall i, j \in \Omega_i \tag{5}$$

$$X_i = \{0,1\} \qquad \forall i \tag{6}$$

$$X_i = 0 \qquad \forall i \in \Delta \tag{7}$$

$$E_{ij}^+, E_{ij}^- \geq 0 \qquad \forall i, j$$

where,

$$X_i = \begin{cases} 1 \; if \; parcel \; j \; is \; selected \\ 0 \; otherwise \end{cases}$$

$$E_{ij}^+ = \begin{cases} 1 \; if \; x_i = 1 \; and \; x_j = 0 \\ 0 \; otherwise \end{cases}$$

$$E_{ij}^- = \begin{cases} 1 \; if \; x_i = 0 \; and \; x_j = 1 \\ 0 \; otherwise \end{cases}$$

$$\Delta = \{i | b_i = 0\}$$

The model objective is structured to select a subset of parcels that maximize total benefit, (3a) and minimize total perimeter, (3b). The decision variable X_i represents the decision of whether to select/include parcel i or not. The objective considers benefit as well as resulting perimeter. Constraint (4) limits the sum of costs associated with parcel remediation to an overall budget limit, μ. Constraints (5) track the perimeter resulting from selected parcels. Constraint (6) ensures parcels selected have a benefit value above zero. Finally, constraints (7) impose binary and non-negative restrictions on decision variables.

To solve this multiobjective model, one approach is to use the weighting method (Cohon, 1978). That is, both objectives are integrated into one equation as follows:

$$Maximize \qquad (1-w)\sum_i b_i X_i - w\left[\sum_i \sum_{j\in\Omega_i} P_{ij}\left(E_{ij}^{+}+E_{ij}^{-}\right)+\sum_{i\epsilon\Psi} P_{ii} X_i\right] \qquad (8)$$

By varying the weight, *w*, ranging from zero to one, this changes the emphasis on the objective, representing trade-off solutions for exploration. The model is solved using commercial solver software for each case of *w*, and solutions can be sub sequentially evaluated.

The optimization component interacts with all three SDSS components to support the selection of sites to be rehabilitated. The statistics component provides the input values to the model, while GIS enables analysis and codification of spatial relationships. Geovisualization supports visual comprehension of the measures, metrics, and results received from the optimization component.

3.4 Geovisualization

Inputs and results from the GIS, statistics, and spatial optimization components can all be thoroughly explored through the use of geovisualization capabilities. Tools include interaction with the system using selection, identification, visual overlays, and histograms. Mapping and graphing capabilities are available as output products. The SDSS is capable of rendering 3-dimensional displays, enabling analysis of terrain impacts over space and time. This component interacts with all three SDSS components and is vitally important due to its nature of facilitating interaction between the user and the data. These interactions and displays lead to visual comprehension, a better understanding of the data and results, and enable new insights to be obtained.

CHAPTER 4

CASE STUDY

4.1 Study Area

The Sonoran Desert National Monument (SDNM) is located approximately sixty miles southwest of Phoenix, Arizona. Created by President Bill Clinton in 2001, the monument is managed by the U.S. Department of the Interior's Bureau of Land Management (Phoenix District Office). The monument earned the designation due to the notable plant and animal biodiversity, vast saguaro forests, rich cultural resources (including the Juan Batista de Anza National Historic Trail), and picturesque Sonoran Desert landscape (Clinton, 2001). The nearly 500,000 acre monument contains three wilderness areas and is bisected by Interstate 8. Since the 2000's, the southern portion of the monument near the Table Top wilderness area have become a major north-south corridor leading up to Interstate 8. For most immigrants and smugglers, the interstate is the end of their journey across the desert, and a point of contact for further transportation to major cities. The area of the monument south of Interstate 8 is the spatial extent of this case study (Figure 2).

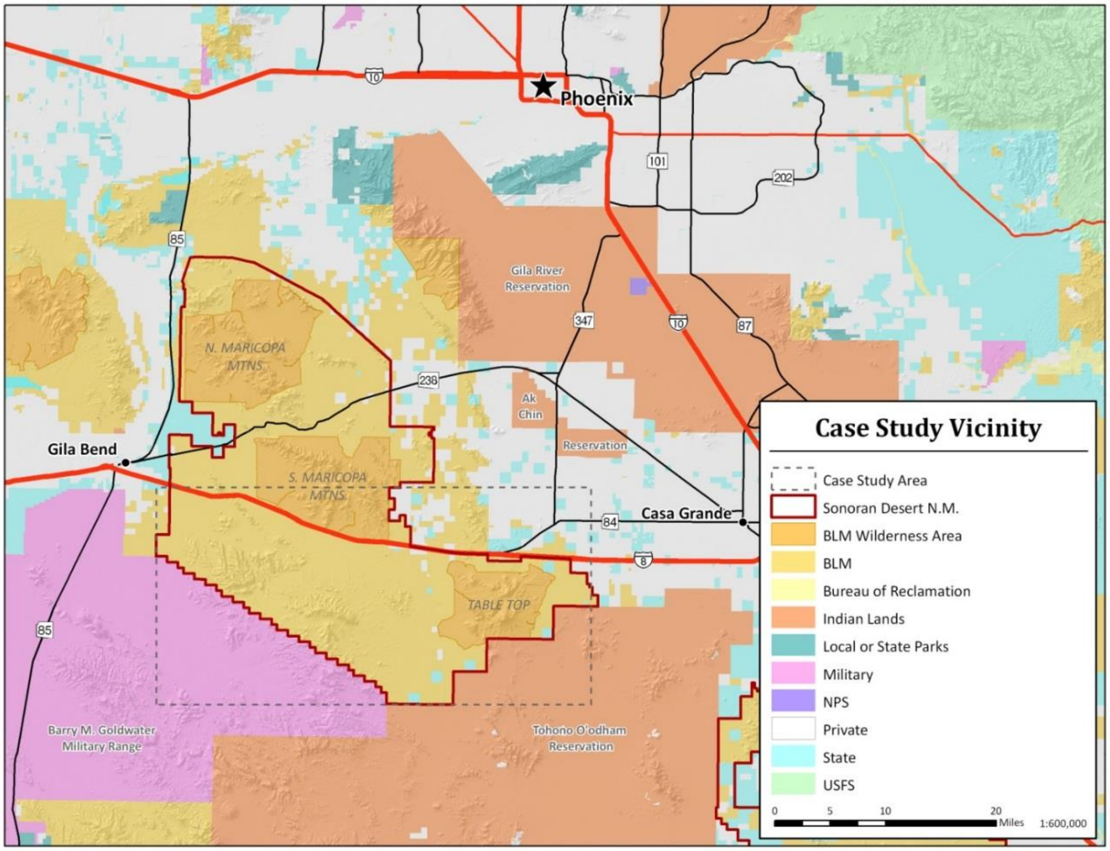

Fig. 2. Map of the case study and vicinity.

4.2 Data

Three categories of data was acquired from the Phoenix District Office for fiscal year 2012. This includes the border events, natural resource distributions, and budget expenditures. Law enforcement and dispatch recorded 448 borderland events in point format, and two new illegal routes within the SDNM. These events include new roads, new trails, trash sites, abandoned vehicles, cut fence lines, fires, sites hazardous to public safety, and layup or campsites. Another linear dataset depicting illegal roads derived from remote sensing techniques was also integrated. Shapefiles depicting the distribution of fourteen impacted resources within the project area were also acquired. These resources include desert tortoise habitat, Lesser-Long Nosed Bat habitat (an endangered species), big game habitat (including white-tailed deer and big horn sheep), wildlife waters, saguaro forests, creosote bursage vegetation community, soils with high erosion potential, washes, visual resources, travel management, visitor and camping sites, cultural sites, designated wilderness, and areas with wilderness characteristics.

Budget information from Fiscal Year 2012 was gathered for the cost of rehabilitation efforts. Youth crews are often contracted to conduct the labor of collecting trash, rehabilitating trails, and repairing fence lines. These crews work for weeks at a time on the monument and require additional travel costs. A number of informational signs and kiosks are erected each year informing the public of safety precautions when visiting the SDNM. The labor costs for full time permanent employees were not factored into these calculations, as it is assumed that if not for the borderland situation, they would still be working elsewhere on other projects.

The total budget allocations were used to calculate an average cost per rehabilitation type. The SDNM manager, park ranger, and other involved staff helped to articulate these calculations. Table 3 summarizes the cost estimates.

Table 1: Estimated Cost per Rehabilitation Type

Borderland Event	Cost/Unit
Routes	\$4,579.70 per mile
Trash Collection	\$2,638.80 per ton
Abandoned Vehicles	\$500.00 per vehicle
Fence Line Repair	\$2,984.00 per mile
Public Information	\$50.00 per sign
Layup Sites	\$927.63 per acre

4.3 Resource Severity Index

The resource severity index utilizes the first weighting method as described in Section 3.2. Resource specialists were asked to distribute \$100 theoretical dollars to rehabilitate different border related events occurring in their respective resources, to imply the severity of the event's occurrence. Table 2 displays the results. Map algebra was then used to integrate these weights into GIS, by multiplying each border event extent by the respective weight, summed together, then clipped to the resource extent.

Table 2: Resource Sensitivity Index, Ranking of Borderland Events

Resource	Foot/ Horse Traffic	Vehicle Traffic	Trash	Aban-doned Vehicle	Fence Line	Fire	Public Safety	Layup Sites
Tortoise Habitat	7	18	22	5	1	24	1	22
Bighorn Sheep	7	11	24	5	1	26	1	25
Lesser Long Nosed Bat	7	7	6	6	6	60	1	7
Wildlife Waters	15	25	20	5	15	3	2	15
Saguaro Forests	7	19	19	5	5	35	5	5
Creosote Bursage	7	18	17	5	5	25	5	18
Fragile Soils	15	20	20	20	2	2	1	20
Washes	5	12	22	12	5	27	5	12
Visual Resources	5	5	20	20	1	29	10	10
Travel Network	15	21	15	5	10	5	21	8
Visitor Sites	5	7	25	17	5	13	18	10
Cultural Sites	10	16	10	15	15	16	1	17
Wilderness	15	25	15	8	1	25	1	10
Wilderness Characteristics	11	22	22	8	1	25	1	10

4.4 Landscape Severity Index

The landscape severity index utilizes the second weighting method as described in Section 3.2. The Analytical Hierarchy Process (AHP) (Saaty, 1990) was used to determine which resources as a whole were more vulnerable or more desirable for rehabilitation as a whole compared to the other fourteen. Decision makers completed a pairwise matrix containing all fourteen resources considered in this study to evaluate which resources are higher valued or more vulnerable overall to borderland impacts.

Each decision maker's response was calculated separately, and the resulting weights for each resource were averaged. (Table 3). Of the four decision makers, all four were considered not random. Map algebra was again used to integrate these weights into GIS, by multiplying each of the resulting weights times each respective output of the resource severity index, then summed together for one normalized, landscape level indicator of environmental damage.

Table 3: Averaged results of the AHP pairwise matrix.

Resource	Averaged Weight
Tortoise Habitat	1.21
Big Game Habitat	0.37
T&E Habitat	1.79
Wildlife Waters	0.46
Saguaro	0.74
Creosote-Bush Vegetation	0.52
Fragile Soils	0.48
Washes	0.4
Visual	0.16
Travel	0.22
Visitor Sites	0.2
Cultural Sites	1.39
Wilderness Areas	1.25
Wilderness Characteristics	0.81

4.5 Cost Distribution

Map algebra was again used to multiply the event occurrence times the estimated cost per borderland event (Table 1) and summed. The illegal roads had an additional multiplier. If represented by a point, features were multiplied by its distance – assumed to be .25 miles while roads collected by GPS were multiplied by the actual length of the road.

4.6 Potential Rehabilitation Sites

All potential rehabilitation sites (882) were represented by a 1500 meter grid of regular polygons spanning the project area. Zonal statistics were calculated, resulting in two tables with a summary figure for each potential site: the total rehabilitation cost (sum of the cost distribution raster within the 1500m parcel) and total resource benefit (sum of the Landscape Severity Index within the 1500m parcel). These data served as input for the project selection optimization model.

4.7 Optimization Model

The SDSS uses input data and derived spatial relationships to produce a text file representing the optimization model. The neighborhood relationships between the potential rehabilitation sites were calculated utilizing Geoda software (GeoDa 2011). The projected fiscal year 2013 budget for borderlands of $273,000 was used for total project budget. LINGO optimization solver software (Version 13.0) was used to solve the optimization problem. The model was solved ten times with varying weight values, ranging from 0.0 to 0.9, in order to derive multi-objective trade off solutions. These solutions then serve as a basis for further discussion and evaluation.

CHAPTER 5

RESULTS

5.1 GIS

The GIS platform enabled both problem analysis and decision making by meaningfully interacting with the three other components of the SDSS. This included formatting multiple data types, geoprocessing the statistical measures and metrics, codified spatial relationships, and conducting spatial analysis. Specifics of the results involving the three other components follow.

5.2 Statistics

The output of the Resource Severity Index was a raster layer for each of the fourteen resources with values ranging from zero (no impact) to one (maximum resource impact). Figure 3 illustrates one resource output for tortoise habitat. At this point, resource specialists explored both the map and the histogram to visualize the distribution of impact. The histogram information was exported to an excel table, where the quantification of impact was analyzed further in terms of the distribution of severity and the percent of the resource impacted (Table 4). No resource suffered very high impact (0.61-0.8).

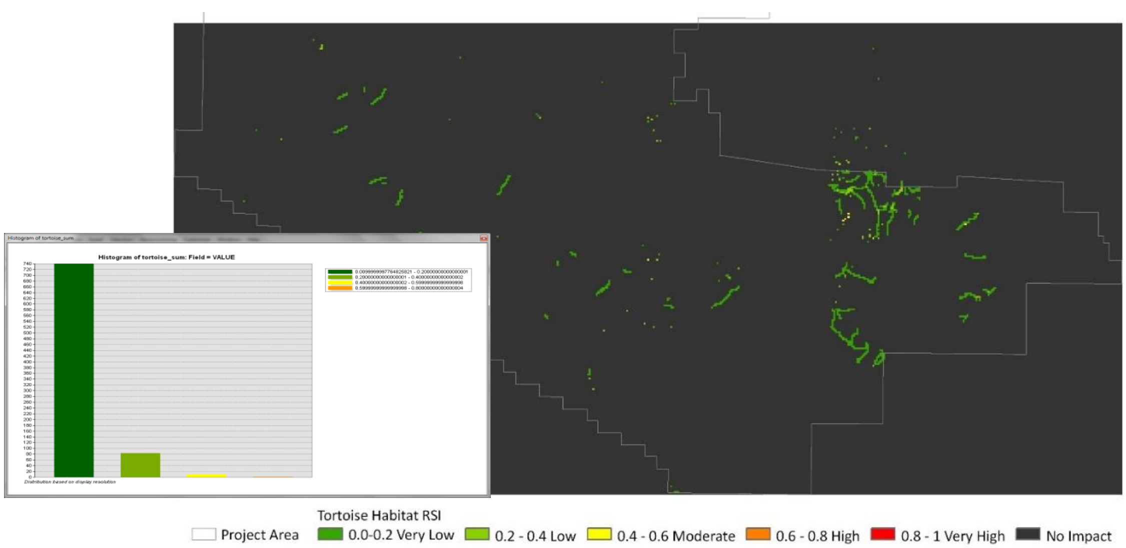

Fig. 3. The output and histogram of the tortoise habitat Resource Severity Index.

Table 4: Distribution of Impact by Resource

	Very Low (0.01-0.2)	Low (0.21-0.4)	Moderate (0.41-0.6)	High (0.61-0.8)	Total Acres	% of Total
Tortoise Habitat	2,633	295	32	4	2,964	1.9
Big Game Habitat	1,694	107	7	0	1,808	1.7
Lesser Long-Nosed Bat Habitat	9,533	21	0	21	9,575	2.0
Wildlife Waters	57	0	0	0	57	6.6
Saguaro Forests	3,491	270	11	0	3,772	3.7
Creosote/ Bursage Vegetation	1,413	43	0	0	1,455	2.5
Fragile Soils	4,765	1,288	50	11	6,113	4.9
Washes	1,605	68	7	0	1,680	3.5
Visual Resources	6,213	256	7	0	6,476	2.7
Travel Management	2,633	295	32	4	2,964	6.4
Visitor Sites	192	11	0	0	203	19.4
Cultural Sites	28	4	0	0	32	2.4
Wilderness	1,576	153	32	0	1,761	2.8
Wilderness Characteristics	914	85	4	0	1,003	0.9

The Landscape Severity Index results are shown in Figure 4. The normalized index ranges between zero (no resource impact) and ten (maximum resource impact). The highest cell value in the resulting raster dataset is 2.544; relatively low. Overall impact is heaviest around the Table Top wilderness area, and high impact sites are dispersed throughout the study area.

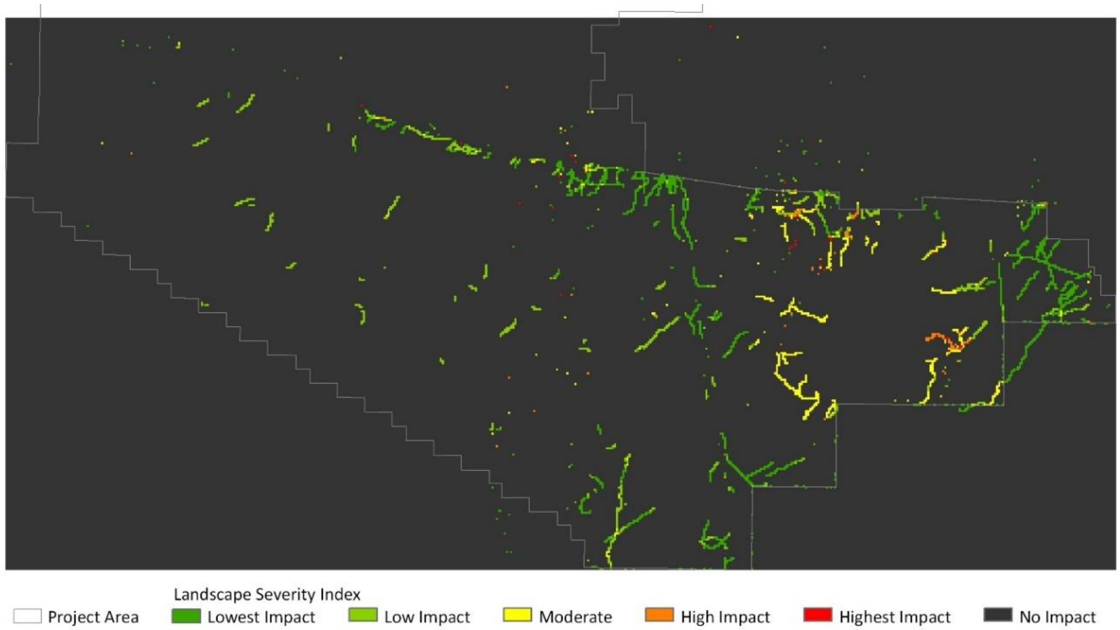

Fig. 4. Spatial variability for Landscape Severity.

The output raster of the cost distribution calculation (Figure 5) ranged from $80 to over $22,000. Based on this estimation, the total cost of rehabilitating all border events within the project area would be over $10 million, a figure far beyond the allocated budget.

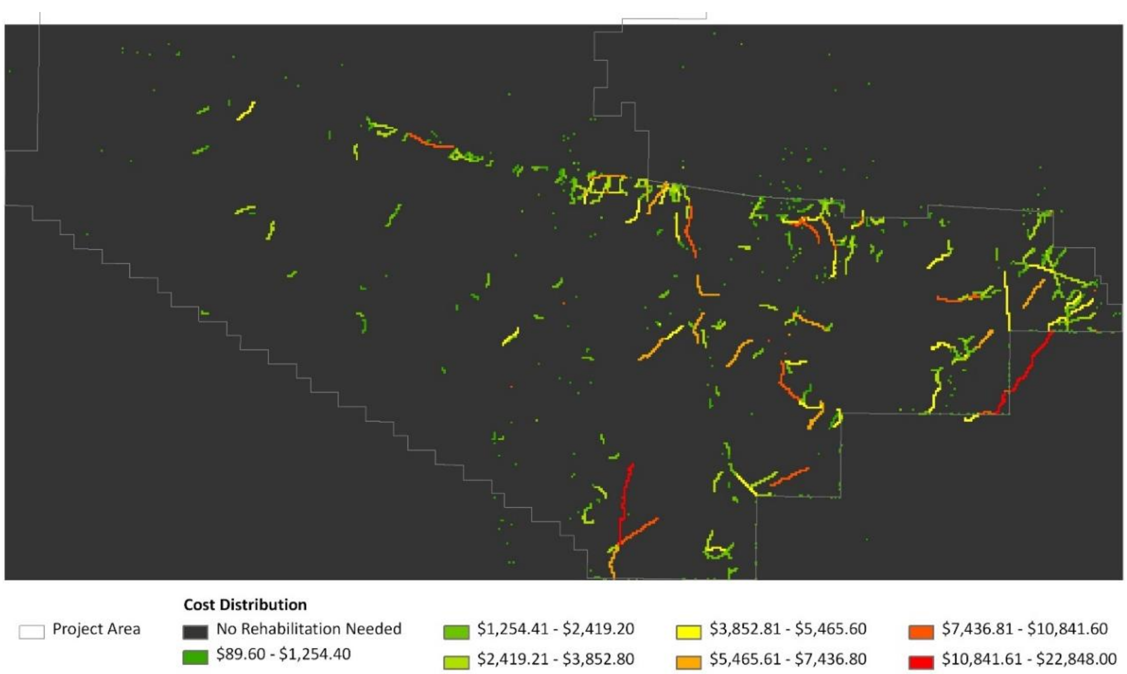

Fig. 5. The output of the Cost Distribution calculation.

The results of the zonal overlays and statistics in display the sum of the costs and benefits (Figure 6 and 7) for each of 882 potential rehabilitation sites. If selecting these sites in an ad way, the highest benefit sites immediately stand out as candidates to rehabilitate, until the cost is considered and found to be near or over the allocated project budget. Viewing these two distributions underscores the difficulty of selecting the sites in a makeshift way, and the need for them to be selected mathematically by the shape model.

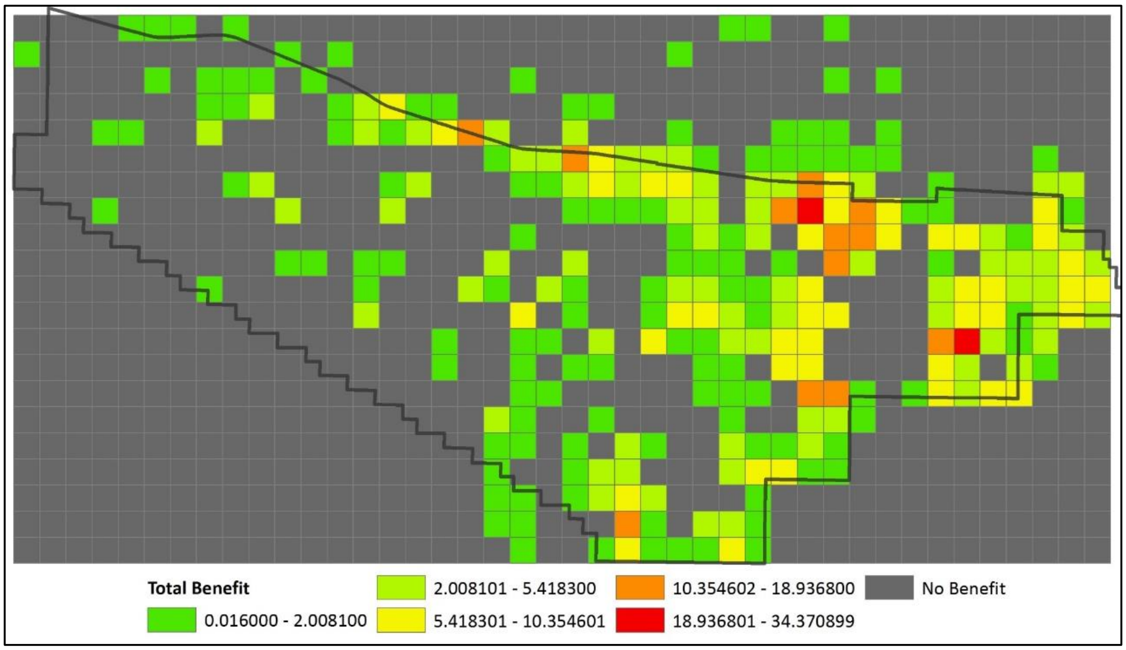

Fig. 6. The total benefit calculated by zonal statistics for each of the 882 potential rehabilitation sites.

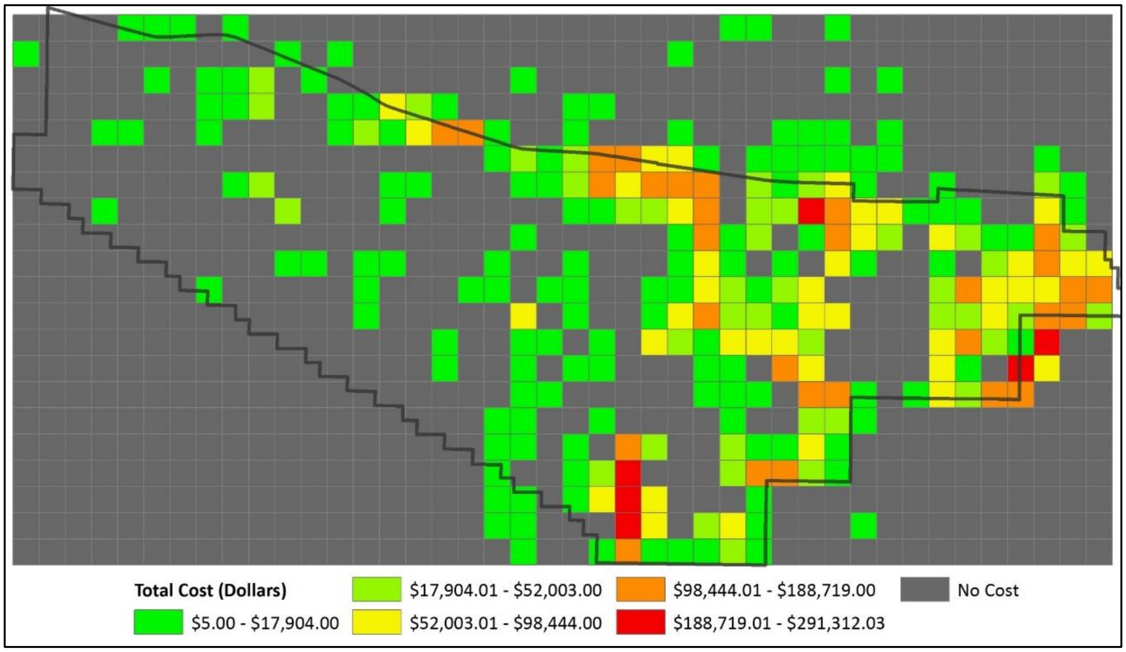

Fig. 7. The total cost calculated by zonal statistics for each of the 882 potential rehabilitation sites.

5.3 Spatial Optimization

Table 5 and Figure 8 provide a summary and depiction of the solutions for each weight value (0.0-0.9) along the trade-off curve. The first objective decreases steadily as the first part of the objective (maximize benefit) is weighted less compared to the second part (maintain contiguity). The second objective quickly decreases as the weight increases. The cost stayed close to the budget, dropping off gradually. There were no improvements to the objective beyond w = 0.8.

Table 5: Model Solutions

Weight	Objective 1 Maximize Benefit	Objective 2 Minimize Perimeter (km)	Cost ($)
0.0	115.15	489.5	272,992
0.1	102.08	117.5	272,901
0.2	91.19	61	272,005
0.3	86.17	44	272,757
0.4	81.44	36	268,129
0.5	78.73	32	263,107
0.6	59.41	16	263,758
0.7	59.41	16	263,578
0.8	34.37	8	117,280

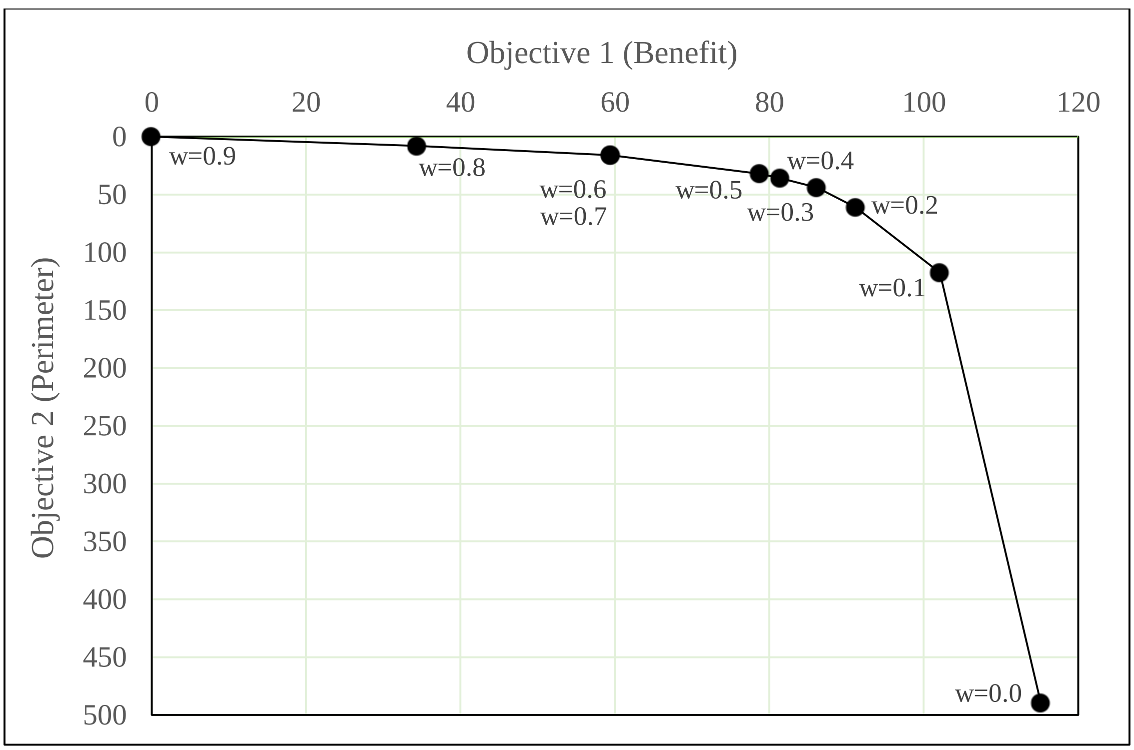

Fig. 8. The solutions of the shape model along the trade-off curve.

5.4 Alternatives to Be Considered

After analyzing the results of Table 5 and Figure 8, decision makers chose to consider solutions for *w*=0.2-0.5 as alternatives for further analysis. These solutions were brought into GIS and intersected with borderland events to contrast the rehabilitation that would be completed for each alternative. Figures 9-12 display the results.

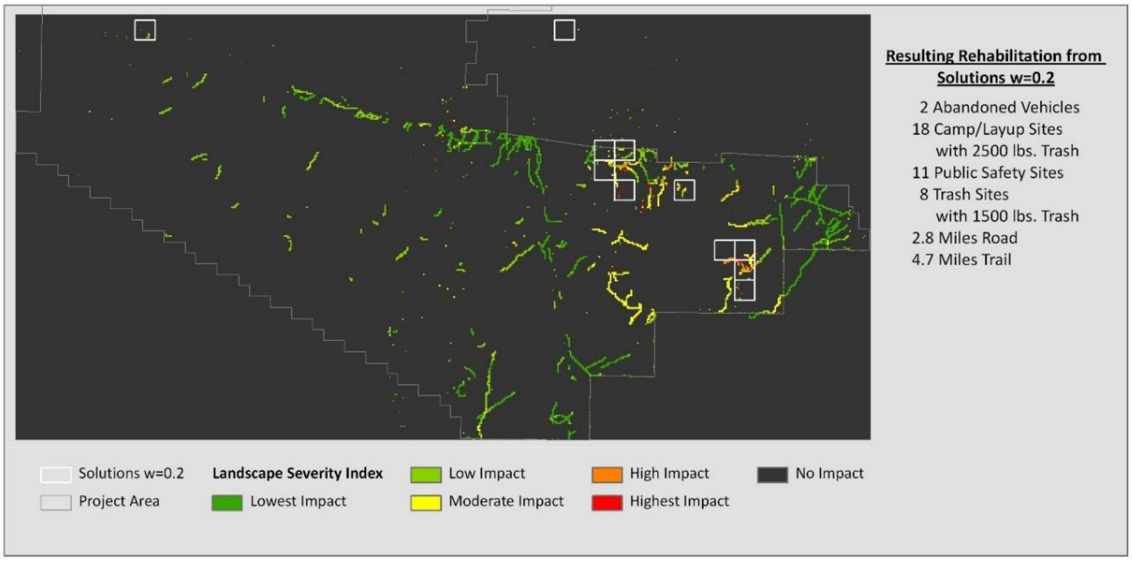

Fig. 9. Site selection trade off solution (w=0.2).

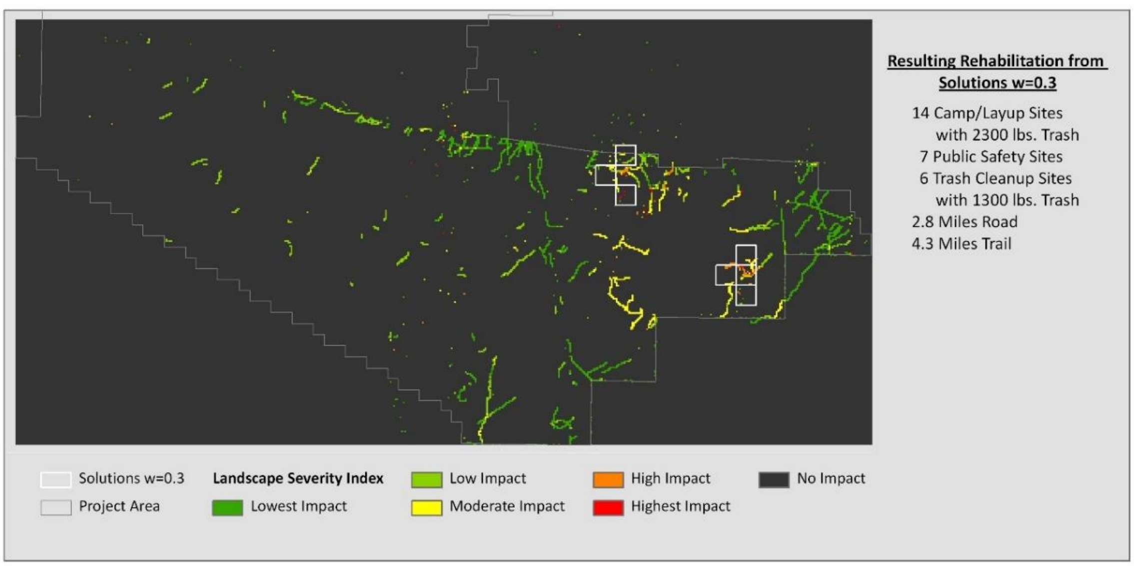

Fig. 10. Site selection trade off solution (w=0.3).

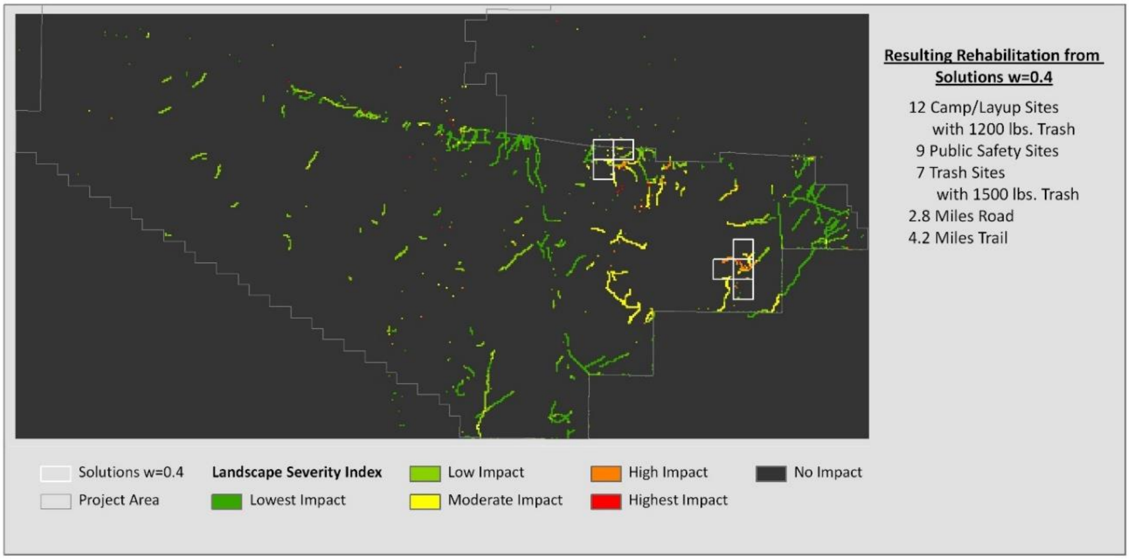

Fig. 11. Site selection trade off solution (w=0.4).

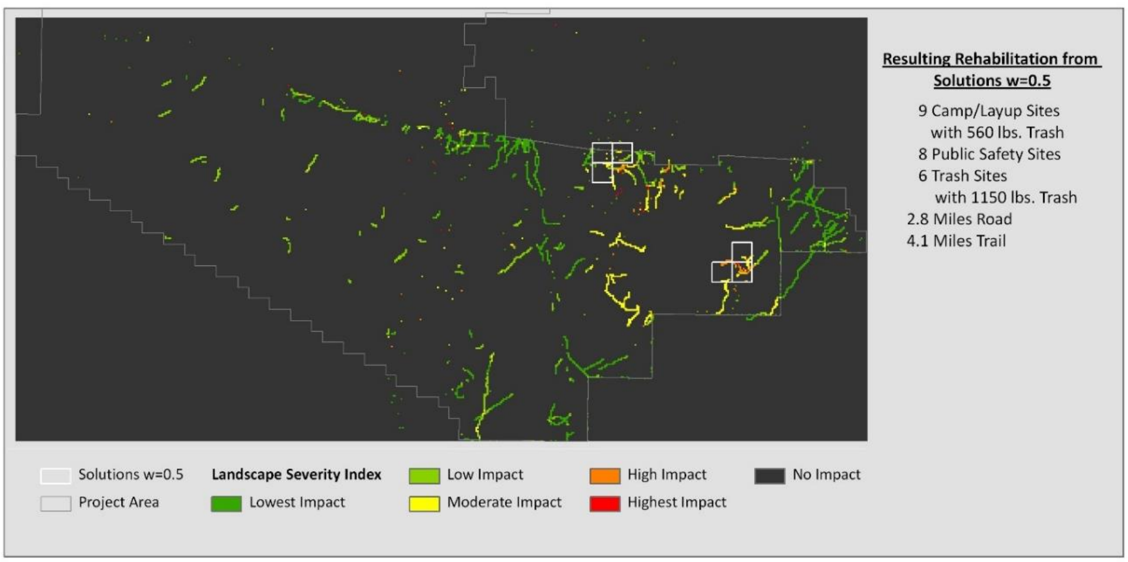

Fig.12. Site selection trade off solution (w=0.5).

5.5 Findings

Figures 9-12 reflect the results in Table 5 and Figure 8, but with greater specificity. As the weight is increased, the selected sites become noticeably closer together, fewer in number, and utilizing less of the total budget. The amount of rehabilitation, however, remains relatively similar but also slightly dropping off as the weight increases.

CHAPTER 6

DISCUSSION

In the case of the SDSS presented here, public land managers and resource specialists are charged with the task of effectively dealing with impacts from illegal immigration and drug smuggling along the U.S. and Mexico border on the Sonoran Desert National Monument. There is currently a lack of knowledge on resource specialists' behalf regarding the distribution and severity of the degradation on natural resources, and managers attempt to plan large-scale rehabilitation efforts in the most cost effective and environmentally beneficial way. The components of the developed SDSS, BERSDSS, addressed the problem analysis knowledge gap, facilitated an improved decision making process, and resulted in a greater number of rehabilitation efforts compared to the current ad hoc identification of sites.

The SDSS, specifically the GIS and statistics components, enabled the analysis that resource specialists desired, but was not previously available. The Resource Severity Index took existing border event data and provided a method to quantify the impact of the individual resources affected. The Landscape Severity Index aggregated the Resource Severity Index, weighted by vulnerability or agency significance, to measure degradation at a landscape level. This is an improvement from the current situation where border event data is used for purely law enforcement purposes, with little conveyance of the situation to resource specialists and managers.

The SDSS facilitated the decision making process of large-scale rehabilitation efforts through the GIS, optimization, and geovisualization components of the SDSS. The optimization model adequately articulated the management objectives of selecting sites that: 1) were of the greatest environmental benefit; 2) within a stated cost to rehabilitate; and 3) within proximal distance to each other for logistical efficiency. The multi-objective nature of the optimization problem allowed for a range of alternative solutions to be compared and analyzed through geovisualization methods of overlay, identification, and selection. This resulted in the identification of four reasonable alternatives with the rehabilitation summaries to compare, as seen in Figures 6-9.

This decision making process as facilitated by the SDSS is also an improvement from the current identification of rehabilitation sites. Currently, decision makers rely on reports from law enforcement, field staff, and the public to inform where rehabilitation should take place. Sites are generally selected in an ad hoc manner, focusing on areas with large concentrations of degradation. While this is a reasonable approach, it fails to take into account the resources at risk, the cost (go until the money runs out), and the logistics of moving from one site to the next. In fiscal year 2013, 9.3 miles of routes, 13 bicycles, and 10,000 pounds of trash was removed from the Sonoran Desert National Monument with the budget of $273,000. This is compared to the results found in Figures 6-9 from the SDSS, in which the same budget was used as a threshold. While the numbers actually completed in fiscal year 2013 are close to or exceed some of those identified by BERSDSS, sites containing other events such as abandoned vehicles and public safety sites were additionally selected as shown in Figures 9-12. It is likely that by using the SDSS in the beginning of the year, additional planning and organizational efficiencies would be found because of the fact that the sites were selected in advance versus as-you-go. Additionally, the components are flexible and could be easily adjusted and recalculated due to fluctuations in the budget, resources considered, geographical extent, and even the shape of the potential rehabilitation sites to better accommodate linear features.

CHAPTER 7

CONCLUSION

The development of the Borderland Environmental Rehabilitation Spatial Decision Support System enhances the problem analysis and decision making of public land managers along the U.S. and Mexico border. The integration of GIS, statistics, spatial optimization, and geovisualization assisted decision makers in the identification of borderland impacts on the environment, the quantification of that impact, and the prioritization of sites to be rehabilitated within a specific budget. Public land management is already challenging, and effectively dealing with environmental impacts from the border is an additional challenge. Budgets for public land management agencies are limited and dwindling on both the federal and state levels, leading to more difficult decisions on how to allocate scarce resources. This is especially true in cases such as the border, in which agencies have little control over the problem, but the mandate to react. Hence the need for systems such as the BERSDSS, created general enough for multiple agencies to modify to their goals, but specific enough to assist and facilitate the site selection process. Tools such as these are just what agencies need to stay true to their difficult missions, and their public constituents.

REFERENCES

Agostini, P., Critto, A., Semenzin, E., & Marcomini, A. (2009). Decision Support Systems for Contaminated Land Management: A Review. In A. Marcomini, G. Suter, & A. Critto (Eds.), *Decision Support Systems for Risk Based Management of Contaminated Sites* (pp. 1-20). Springer.

Atkinson, G., & Mourato, S. (2008). Environmental cost-benefit analysis. *Annual Review of Environment and Resources, 33*, 317-344.

Bottero, M., Comino, E., Duriavig, M., Ferretti, V., & Pomarico, S. (2013). The application of a multi-criteria spatial decision support system (MCDSS) for the assessment of biodiversity conservation in the Provinc of Varese (Italy). *Land Use Policy, 30*, 730-738.

Carlon, C., Critto, A., Ramieri, E., & Marcomini, A. (2007). DESYRE: Decision support system for the rehabilitation of contaminated megasites. *Integrated Environmental Assessment and Management, 3*(2), 211-222.

Choi, J., Engel, B., & Farnsworth, R. (2005). Web-based GIS and spatial decision support system for watershed management. *Journal of Hydroinformatics, 7*(3), 165-174.

Church, R., & Murray, A. (2009). Area-Based Location. In R. Church, & A. Murray, *Business Site Selection, Location Analysis, and GIS* (pp. 187-207). John Wiley & Sons, Inc.

Church, R., Murray, A., Figueroa, M., & Barber, K. (2000). Support system development fo forest ecosystem management. *European Journal of Operational Research, 121*, 247-258.

Clinton, W. J. (2001, January 17). *BLM-Arizona, Sonoran Desert National Monument.* Retrieved March 29, 2013, from United States Department of the Interior, Bureau of Land Management: http://www.blm.gov/pgdata/etc/medialib/blm/az/images/son_des.Par.30940.File.dat/proclamation.pdf

Cohon, J. (1978). *Multiobjective programming and planning.* Academic, New York.

Critto, A., Torresan, S., Semenzin, E., Giove, S., Mesman, M., Schouten, A., . . . Marcomini, A. (2007). Development of a site-specific ecological risk assessment for contaminated sites: Part 1. A multi-criteria based based system for the selection of ecotoxicological tests and ecological observation. *Science of The Total Environment, 379*(1), 12-33.

Dymond, R., Regmi, B., Lohani, V., & Dietz, R. (2004). Interdisciplinary web-enabled spatial decision support system for watershed management. *Journal of Water Resource Planning and Management, 130,* 290-300.

Environmental Systems Research Institute. (2012). *ArcGIS Desktop: Release 10.1*. Redlands, California.

Giovando, C., & Zhang, T. (2005). Spatial knowledge discovery through an integration of visual data exploration with data mining. *ICA Seminar on Internet-Based Cartographic Teaching and Learning: Atlases, Map Use, and Visual Analytics.*

Hanley, N. (2001). Cost-benefit analysis and environmental policymaking. *Environment and Planning C: Government and Policy, 19*, 103-118.

Jankowski, P. (1995). Integrating geographical information systems and multiple criteria decision-making methods. *International Journal of Geographic Information Systems*, *9*(3), 251-273.

Larson, B., & Sengupta, R. (2004). A spatial decision support system to identify species-specific critical habitats based on size and accessibility using US GAP data. *Environmental Modelling and Software, 19*, 7-18.

Lawrence, S., & Wildgen, J. (2012). Manifold Destiny: Migrant deaths and destinations in the Arizona desert. *Growth and Change*, *43*(3), 482-504.

Leon, L., Lam, D., Swayne, D., Farquhar, G., & Soulis, E. (2000). Integration of a nonpoint source pollution model with a decision support system. *Environmental Modelling and Software, 15,* 249-255.

LINDO Systems, Inc. (2011). LINGO 7.0.1.403. Chicago, Illinois.

Maceachren, A. (1985). Compactness of geographic shape: Comparison and evaluation of measures. *Geografiska Annaler, Series B, Human Geography, 67*(1), 53-67.

McIntyre, D., & Weeks, J. (2002). Environmental impacts of illegal immigration on the Cleveland National Forest in California. *The Professional Geographer, 54*(3), 392-405.

Murray, A. (2002). Scale and unit spcification influences in harvest scheduling with maximum area restrictions. *Forest Science, 48*(4), 779-789.

Murray, A. (2010). Advances in location modeling: GIS linkages and contributions. *Journal of Geographical Sciences, 12,* 335-354.

Nalle, D., Arthur, J., & Sessions, J. (2002). Designing compact and contiguous reserve networks with a hybrid heuristic algorithm. *Forest Science*, *48*(1), 59-68.

Noss, R., Neilsen, S., & Vance-Borland, K. (2009). Prioritizing ecosystems, species, and sites for restoration. In A. Moilanen, K. Wilson, & H. Possingham (Eds.), *Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools* (pp. 158-171). Oxford University Press.

Pulat, H. (2005). A two-sided optimization of Border Patrol interdiction. *Masters Thesis*. Monterey, California: Naval Postgraduate School.

Rossmo, D., Thurman, Q., Jamieson, J., & Egan, K. (2008). Geographic patterns and profiling of illegal crossings of the southern U.S. border. *Security Journal, 21*, 29-57.

Saaty, T. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 40,* 9-26.

Snediker, D., Murray, A., & Matiziw, T. (2008). Decision support for network disruption mitigation. *Decision Support Systems*, *44*, 954-969.

Srinivasan, R., & Engel, B. (1994). A spatial decision support system for assessing agricultural nonpoint source pollution. *Water Resources Bulletin*, *30*(3), 441-452.

Sugumaran, R. M., & Davis, J. (2004). A web-based environmental decision support system (WEDSS) for environmental planning and watershed management. *Journal of Geographical Systems, 6*, 307-322.

Sugumaran, R., & Degroote, J. (2010). *Spatial decision support systems: Principles and practices.* CRC Press.

U.S. Department of the Interior, Bureau of Land Management. (2007). *Southern Arizona Project to Mitigate Environmental Damages Resulting from Illegal Immigration.* Retrieved March 2012, from http://www.blm.gov/pgdata/etc/medialib/blm/az/pdfs/undoc_aliens.Par.7527.File.dat/FY07_Summary.pdf

U.S. Department of the Interior, Bureau of Land Management. (2010). *Southern Arizona Project to Mitigate Damages Resulting from Illegal Immigration and Smuggling.* Retrieved March 2012, from http://www.blm.gov/pgdata/etc/medialib/blm/az/pdfs/undoc_aliens.Par.0977.File.dat/09-report.pdf

Wein, L., Liu, Y., & Motskin, A. (2009). Analyzing the homeland security of the US-Mexico border. *Risk Analysis, 29*(5), 699-713.

Williams, J., ReVelle, C., & Levin, S. (2005). Spatial attributes and reserve design models: A review. *Environmental Modelling and Assessment, 10*, 163-181.

Wright, J., & Cohon, J. (1983). A multiobjective integer programming model for the land acquisition problem. *Regional Science and Urban Economics, 13*, 31-53.

Zhu, Z., Healey, R., & Aspinall, R. (1998). A knowledge-based systems approach to design of spatial decision support systems for environmental management. *Environmental Management*, *22*(1), 35-48.

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