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A SPATIALLY-EXPLICIT DECISION SUPPORT SYSTEM FOR INVASIVE

WEED SPECIES MANAGMENT

By

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Dissertation

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A spatially-explicit decision support system for invasive weed species management

Chairperson: Dr. Woodam Chung

Invasive weed species are a recognized problem worldwide causing economic and environmental problems. Management of weeds is complex and challenging because of multiple decisions that need to be made when allocating limited resources to control current infestation areas including which weeds to treat, where to treat, how to treat, and when to treat. Models have been developed to simulate weed spread, however they lack the ability to simulate the short term effects of weed treatments and analyze trade-offs among control allocation options. This trade-off analysis is critical in developing cost-efficient treatment decisions especially when available budget for treatments is limited. To address the limitations of traditional weed treatment planning and provide weed mangers with a decision support tool that can enhance their decision-making process, a spatially-explicit decision support system was developed. Based on current infestation areas, treatment effects estimation, and vegetation susceptibility, the system simulates weed spread across the landscape, and develops a five-year treatment plan that minimizes total infestation area over time.

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INTRODUCTION

Since ancient times humans have been transporting different organisms worldwide such as plants and animals (DiCastri 1989). This transportation of organisms first started slowly, but expanded rapidly with the development of new and more efficient ways of transportation. New introduction of organisms not only occurs intentionally for certain benefits of humans, but also accidentally as contaminants of other organisms. No matter how invasive species are introduced, they often become a threat to the native ecosystem. According to the Executive Order 13112 issued by the President of the United States on 3 February 1999, invasive species are "alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health" (Clinton 1999).

Although successful establishment of invasive species in a new environment depends on multiple factors, such as adaptability to the new environment and capability to outcompete native species (Theoharides and Dukes 2007), invasive species, once successfully established, often become serious threats to native species, natural communities, and ecosystem processes causing major economic impacts on human activities that rely on healthy ecosystems (Walker and Smith 1997). Pimentel et al. (2005) estimated that economic damages of invasive species add up to $120 billion per year in the United States.

Alien invasive weed species, the focus of our study, are broadly recognized as one of the greatest threats to ecosystem health among many other impacts to human activities. They are known to produce negative impacts to natural ecosystems by decreasing

biodiversity, reducing wildlife habitat, displacing native species, and altering soil properties (DiTomaso 2000; Ehrenfeld 2003; Harvey and Nowierski 1989; Randall 1996; Sheley et al. 1999). Weeds also cause economic harm to human activities; examples range from reducing grazing capacity for livestock (Julia et al. 2007; Leistritz et al. 1992) to affecting human recreation activities (Eiswerth et al. 2005; Loope et al. 1988).

Responsibility for managing invasive weeds often resides primarily with landowners and land management agencies. Weed management decisions are complex, as a number of factors need to be considered, especially when managing multiple weeds simultaneously across a large landscape. Weed managers are often faced with limited budgets, yet still need to meet the objectives of both existing weeds control and prevention of weeds spread to non-infested areas. The traditional approach of decision-making based on experience and simple analyses might no longer serve for efficient and effective weeds management. A new approach that can systematically analyze trade-offs among various options might be needed for weed managers to make better and informed decisions.

Decisions related to weed management that must be made when allocating limited resources to control current infestations include which weeds to treat, where to treat, how to treat, and when to treat. Many of these decisions involve considering i) management objectives and strategies set by landowners or weed managers, ii) priorities based on risk assessment protocols (Maguire 2004; Skinner at al. 2000) or personal experience and judgment, and iii) available treatment practices based on location, size, and regulations including treatment types (e.g., herbicides, bio-control, etc.) and application methods

(e.g., helicopter, truck, backpack sprayer, etc.) In addition, cost and efficacy of each treatment option should be considered in weed management decision-making.

Scheduling annual weed treatment practices for a relatively short-term period (i.e., 5 - 10 years) and evaluating temporal aspects of treatment effects present even bigger challenges because understanding of weeds spread dynamics and predicting future infestation based on potential treatments are required. There exist several models developed to predict and simulate weed spread, such as MIGRATE (Collingham et al. 1996), SEIBS (Higgins et al. 1996), WISP (Gillham et al. 2004), TELSA (ESSA Technologies Ltd 2008), SIMPPLLE (Chew et al. 2012). However, none of them is capable of simulating the short term effects of weed treatments and analyzing trade-offs among alternatives on which weeds to treat, where to treat, and how to treat across a large landscape over multiple years. This trade-off analysis is critical in developing cost-efficient treatment decisions especially when available budget for treatments is limited.

No spatially explicit decision model for weed treatment planning has been found in the literature that combines decision making process for treatment allocations and evaluation of those control actions to optimize the use of limited resources. In this study, a spatially explicit decision support system was developed to support weed treatment planning and decision-making. The system was designed to develop a five-year treatment plan that minimizes total infestation area. For convenience, the system was developed as an extension of ArcMap®, a widely-used GIS software package developed by ESRI.

STUDY OBJECTIVES

The main goal of this study is to develop a spatially explicit decision support system for invasive weed species management planning that incorporates species specific spread dynamics and optimization of resource allocation for weed treatments. The system is hoped to improve the current practices of decision-making in weed management by providing weed mangers with an analytical tool that can enhance their ability to consider multiple options and understand their trade-offs. This study has the following specific objectives:

   i)   Develop a spatially-explicit simulation method to evaluate alternative weed treatment plans;

   ii)   Develop a decision support system for spatio-temporal optimization of weed treatments; and

   iii) Incorporate a newly developed spread modeling approach into the decision support system for more realistic prediction of weed spread under diverse management scenarios.

OUTLINE

This dissertation is composed of three additional chapters covering the specific objectives abovementioned. Chapter 1 introduces the simulation model developed to evaluate alternative weed treatment plans. This model consists of an algorithm for

treatment assignment, a linear-omnidirectional weed spread simulation, and a treatment plan evaluation component. Chapter 2 describes a decision support system developed using a heuristic algorithm for spatio-temporal optimization of weed treatments. This system was applied to a study landscape located in Idaho, and used to develop five-year weed treatment plans under various management and budget scenarios. Input data and results of the application are also presented in the Chapter. Finally, Chapter 3 describes the modified decision support system to facilitate incorporation of a newly developed weed spread simulation model. This new model uses site-specific environmental and terrain conditions to predict weed spread across a landscape over time. An application of the modified decision support system is also presented.

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CHAPTER 1:

LANDSCAPE-LEVEL SIMULATION OF WEED TREATMENTS TO

EVALUATE ALTERNATIVE TREATMENT PLANS

1.0   ABSTRACT

Invasive plants are a recognized problem worldwide causing economic and environmental problems. Models have been developed to simulate the long-term effects of treatments across a landscape to determine effective weed management strategies, but those models might not be suitable for evaluating short-term action plans of weed treatments that are specific in time and place. Weed managers often need to make annual decisions to treat weeds for a given budget. In this study, we developed a simulation model to build and evaluate five-year weed treatment plan alternatives in terms of their cost and effectiveness in minimizing total infestation area over the short planning horizon. In an iterative and interactive process between user and model, a five-year treatment plan alternative is developed based on a user-preferred weed treatment strategy, and evaluated in terms of total predicted infestation area at the end of the planning horizon. The simulation model was applied to a study area of 24,867 ha located in the Salmon River watershed in Idaho. Eight treatment plan alternatives were developed using two treatment priority strategies (sites and species) and four increasing budget levels, and compared for their effectiveness. The results showed that the plan alternatives developed under the site priority strategy were more cost-effective than the species priority strategy in reducing total infestation area over time regardless of budget levels. This simulation model can provide weed managers with a useful tool to evaluate short term treatment plan alternatives and thus support informed decision-making for effective weed management.

Key words: Noxious weeds, weed control, weed spread modeling.

1.1   INTRODUCTION

Invasion of noxious weeds is a recognized problem worldwide that causes major environmental damages and economic losses. A large body of literature has documented such negative impacts of weed species. Trammell and Butler (1995) reported a reduction of 83% of bison use in areas infested with leafy spurge (*Euphorbia esula L.*) as compared to non-infested areas. Sheley et al. (1999) described that dense Yellow starthistle (*Centaurea solstitialis L.*) infestations can negatively affect wildlife habitat by reducing forage availability, displacing native plants and decreasing plant and animal diversity. Weeds also can modify the severity, seasonality, and intervals of fire regimes. For example, both Spotted knapweed (*Centaurea biebersteinii DC.*) and Canada thistle (*Cirsium arvense (L.) Scop.*) can increase fire frequency, and Canada thistle has the potential to increase fire severity on invaded sites (Xanthopoulos 1998; Hogenbirk and Wein 1995). Weeds can also modify soil nutrients. Harvey and Nowierski (1989) found that Spotted knapweed significantly reduces the availability of potassium, nitrogen and phosphorous in the soil. Later, Ehrenfeld (2003) reported that exotic plants alter soil nutrients dynamics because they differ from native species in biomass, productivity, tissue chemistry, plant morphology, and phenology. Moreover, taprooted weeds such as Spotted knapweed could affect soil structure, leaving it prone to erosion (Duncan 2005). Water availability in the soil could also be modified by weed species. Enloe (2002) found in areas invaded by Yellow starthistle a significant reduction in soil moisture relative to un-invaded annual grass communities.

Exotic invasive species are reported to cause up to $120 billion of environmental damages and economic losses every year in the United States (Pimentel et al. 2005). Their estimation of annual economic loss in agriculture due to weeds is about $27 billion consisting of $24 billion in crop losses and $3 billion of herbicide treatment costs. Weeds have negative impacts on livestock grazing. Leistritz et al. (1992) reported economic losses of more than $75 million annually in North Dakota, caused by reduction in grazing capacity in leafy spurge invaded areas. It is known that outdoor recreational activities and services, such as fishing, hunting, hiking, and water-based recreation are also affected by invasive species because they modify the attributes of resources that are important for recreation. For example, some weeds can infest and clog rivers, estuaries, shorelines, etc. (Eiswerth et al. 2005). Other weeds with spines, such as Puncturevine (*Tribulus terrestris L.*), can cause injuries to bare feet and the paws of pets, or damages to air mattresses, bicycle tires, etc. (Loope et al. 1988).

Understanding the dynamic of weeds invasion is critical in management of such species, especially for determining effective management actions, allocating control resources, and prioritizing treatments of weeds and locations. The classic conceptual model for the invasion of plants in a new area consists of four phases relevant to management strategies (Hobbs and Humphries 1995): i) "quarantine" or prevention stage, which represents the initial intervention opportunity, when weed invasion to a new geographic area may be prevented, ii) "eradication" stage, which is a lag phase before the weed begins to rapidly increase its geographic range, iii) "control priority" or suppression stage, where weeds are already established, and thus management strategies shift to treat more satellite colonies and less core population (Moody and Mack 1988), and iv)

"effective control unlikely without massive resource inputs", where the invasion has reached the full carrying capacity of the site and thus only the highest priority sites can be controlled.

In order to determine effective strategies for weeds management, some past studies have simulated the effects of treatments across a landscape for periods of over 40 years. Frid and Wilmshurst (2009) and Frid et al. (2013) used a decision analysis framework, in which they incorporated a spatially explicit simulation model to predict the outcomes of alternative weed management strategies. This model considered the full range of the invasion process from the "quarantine" phase to the "unlikely effective control" phase described by Hobbs and Humphries (1995). The two main modeling components in their simulations were: i) a semi-Markovian state and transition vegetation simulation model; and ii) a weed spread simulation model which considers disturbances and management actions (ESSA Technologies Ltd. 2008). Three ways of weed spread were considered in their studies: new infestations from outside of the landscape, long-distance spread within the landscape, and expansion of existing infestations. A stochastic approach was used to model which polygon became infested, and weed spread rates and control efficacy.

The studies in the previous paragraph found that early detection and treatment of newly infested polygons is a more effective management strategy in general than targeting already-established large polygons. Exceptions may occur under certain circumstances. Frid and Wilmshurst (2009) found that it would be more effective to direct resources targeting large infested areas when weeds have long-distance spread. For landscapes in early states of invasion, Frid et al. (2013) recommended managers

should direct their efforts to detecting and controlling new infestations before weeds reach larger extensions and become sources of new weed populations. They also suggested that early detection and control would be preferred actions even for landscapes with large infestations.

Although the modeling approaches developed by Frid and Wilmshurst (2009) and Frid et al. (2013) may allow weed managers to address long-term weed management strategies and resource allocation throughout the entire invasion process (i.e., 40 to 50 years), it does not provide short-term action plans for weed treatments that are specific to time and location. Weed managers often need to make decisions annually in terms of where, when and how to treat weeds for a given budget. Prioritizing resource allocation for weed species during the first and fourth stages of the invasion process is relatively straight forward because of the "standard practice" of public land managers to follow: aggressively attack new invaders with the objective of eradication, and treat only the highest priority sites among the areas where weeds are saturated (Gil Gale and Pat Green[1], personal communication). However, late in the second stage and during most of the third stage where weeds are already established, it is difficult to allocate suppression resources to maximize the effectiveness of treatments. An analytical tool with a function to simulate and evaluate alternative short-term treatment plans (i.e., 1 to 5 years) may be able to help the managers identify the most cost-effective treatment action plan for implementation during the second and third stages. The model should also be able to account for treatments costs and effects on multiple weeds over time in order to measure the cost-effectiveness of weed treatments.

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[1] Gil Gale USDA Forest Service Officer/Program Leader, Bitterroot National Forest and Pat Green USDA Forest Service Soil Scientist/Ecologist, Nez Perce National Forest.

In this study, we developed a simulation model to semi-automatically build short-term weed treatment action plans and evaluate them in terms of their cost and effects on reducing total infestation area over a five-year planning horizon. The purpose of our modeling approach is to identify the most cost-effective treatment plan alternative for an efficient containment of established infestations where eradication may not be an option. Identifying the most effective treatment action plan among alternatives will certainly help weed managers efficiently achieve their management goals. Unlike the previous studies that used a stochastic approach to incorporate the uncertainties in predicting weeds long distance spread, we used a deterministic spread model to predict short-term neighbor-to-neighbor spread. Our simulation model was implemented as a series of functions in ArcMap®, a widely used Geographic Information System (GIS) computer program among land management agencies.

1.2   MATERIALS AND METHODS

1.2.1   Model Description

The simulation model developed in this study is composed of three main modules: treatment development, spread simulation and treatment plan evaluation (Figure 1.1). Treatment plan alternatives are developed and evaluated in an interactive process between user and model. Spatial and non-spatial data are required to provide the current infestations across a landscape of interest, as well as user-defined treatment options (i.e.,

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herbicides) and application methods (AM) (i.e. helicopter, backpack, etc.) for treatment development. Initially, the simulation model uses current infestation areas provided by the user to determine candidate treatment units (TU), which are defined as spatially contiguous area (i.e., polygons) that are homogeneous in terms of land attributes, such as weeds composition, upland or riparian (i.e., areas within a user-defined distance from water bodies), and proximity to roads and trails. The model presents these units to the user for prioritization. User-prioritized units are then entered into the model which determines herbicides based on weed species composition and location of each TU (i.e. riparian or upland), and AMs for each TU based on vehicles accessibility. Treatment locations for the first planning period are used to predict weed species spread across the landscape for the following planning period. Predicted weed species spread is then used by the simulation model to determine candidate TUs for the next planning period which are presented to the user for prioritization. This iterative process continues until a five-year treatment plan is completed for the landscape. This treatment plan alternative is then evaluated by the plan evaluation module in terms of total predicted infestation area and treated area. Details on each module as well as the required user input data are presented below.
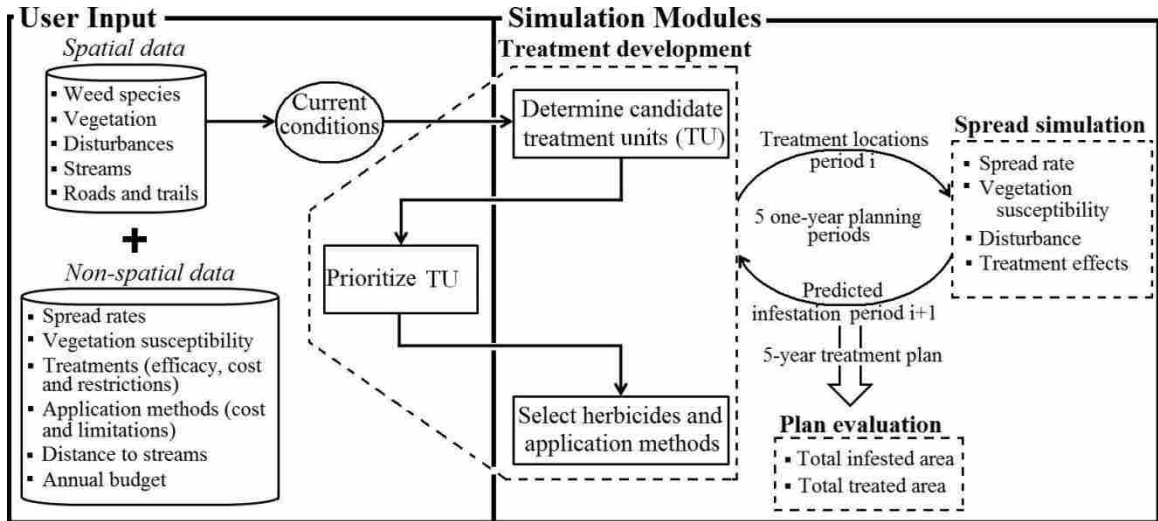
Figure 1.1. Overview of the simulation model consisting of three main modules:

treatment development, spread simulation, and plan evaluation.

1.2.1.1 User Input

Spatial data required for the simulation model include the current infestation areas

as vector polygons with attributes of weed species, vegetation cover, disturbed areas,

streams, roads, and trails across a landscape of interest. Current infestation polygons

provide initial TUs for weed treatments. These polygons are converted into a raster while

their sizes and shapes change dynamically over time based on predicted weed spread and

effects of selected treatment (or no action) scheduled for each polygon. Grid-cell size

used in this simulation model was set to 30 by 30 m. Streams are used to delineate

riparian areas where some herbicides are not allowed for treatments, while roads and

trails are used to determine the accessibility of different AMs (e.g., truck, horse,

backpack sprayer, etc.). Other spatial data required by the model are vegetation cover

and known disturbances for the landscape. These spatial data are used to determine area

susceptibility to weed invasion.

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Non-spatial input data include treatment options (herbicides), cost, efficacy and restrictions of each treatment option, AMs with their costs and limitations (e.g., minimum treatment size, proximity to roads and trails, etc.), distance from stream network to designate riparian areas, and annual budget available for treatment selection. In addition, annual weed spread rates and vegetation susceptibility are required for weed spread simulation. Finally, a user-defined priority of TUs is required per each planning period to determine the order in which TUs will be considered for treatment in the model.

1.2.1.2 Treatment Development

Selecting treatments requires the determination of TUs with the attributes of homogeneity described above (i.e., weed composition, land type, and vehicle accessibility). We selected these attributes because they are important factors in deciding herbicides and AMs. For example, specific herbicides are often selected based on weeds and land class, while feasible AMs depend on the accessibility to TUs. The model begins by creating buffers around the stream network to designate riparian areas based on user-input distance from the stream, and then identifying accessible areas by each AM by creating buffers around trails and roads based on user-input distance limits.

We created a treatment development algorithm to build annual alternative treatment plans for a landscape of interest, which is described in detail in Figure 1.2. The algorithm first develops candidate TUs from known infestation areas. These TUs are then prioritized by the user based on preferred treatment strategy (i.e., weed species, site priorities, or a combination of the two). The algorithm begins with the highest priority TUs and selects an applicable herbicide and AM for the TU. This process repeats until

the given annual budget is used up or no more unassigned TUs are available. Herbicides are selected based on weed species and land type attributes of TUs. If more than one herbicide option is available, the algorithm chooses the least cost per hectare. It is important for the user to provide herbicide options not only based on costs but also their effectiveness because there might exit a tradeoff between duration of effects and costs that will affect herbicide selection. For AM, the algorithm first considers the least cost method on a hectare basis up to the most expensive one and examines its feasibility. Low cost AMs usually have a large minimum treatment size requirement in order to recover high fixed costs (e.g., aerial spraying). If the current TU is not large enough, it becomes a seed TU and the algorithm searches for neighbor TUs that can be treated with the same herbicide and method as the seed TU in order to form a cluster (Figure 1.3).
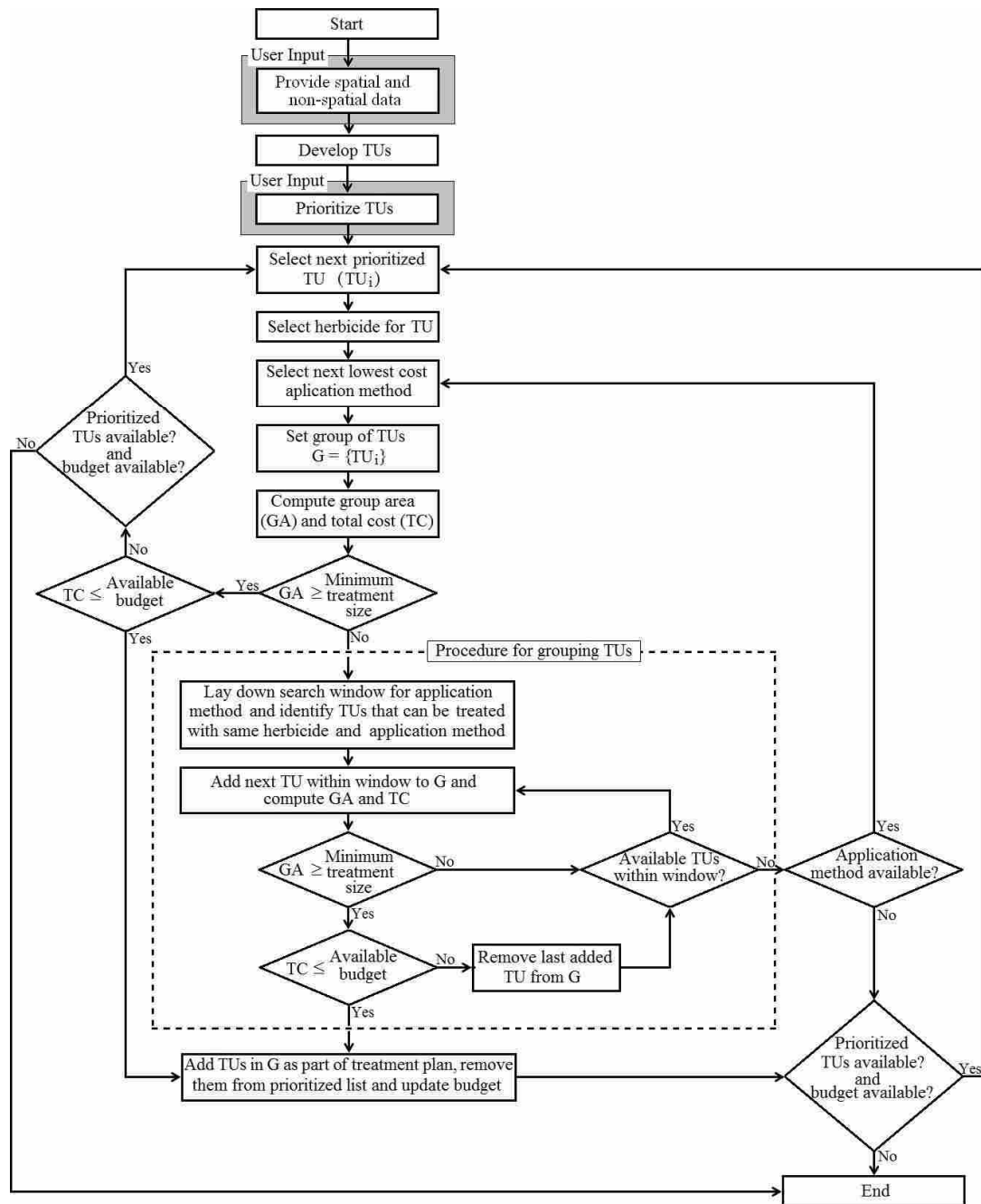
Figure 1.2. An algorithm developed to build an annual treatment plan based on TUs, user-defined priorities, herbicides, AM, and available budget. The shaded box represents user inputs.
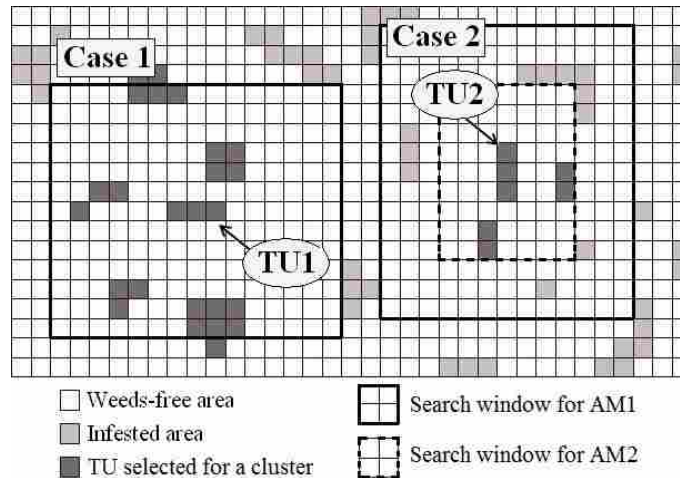
Figure 1.3. Building a cluster of TUs by the simulation model to meet the minimum treatment size requirement for a given AM. TU1 and TU2 are high priority units serving as the center of search windows. Application Method 1 (AM 1, e.g., helicopter) is the least cost method available and considered first for its feasibility. Case 1 shows that there are sufficient TUs near TU1 that collectively meet the minimum treatment size requirement for AM 1 (e.g., 20 grid-cells), whereas in case 2, AM 2 (e.g., truck with a minimum treatment size of 5 grid-cells) is selected for TU2 and its neighbor units due to insufficient area for treatment using AM 1.

This proximity-based clustering function of the algorithm uses a rectangular search window centered at the seed TU with a size approximately seven times larger than the minimum treatment size requirement of the AM being examined (e.g., helicopter). If the cluster size exceeds the minimum treatment size requirement and budget is available for the treatment, the cluster becomes part of the treatment plan for the given year (Case 1 in Figure 1.3). Otherwise, the algorithm moves to the next least cost AM (e.g., truck) that requires a smaller minimum treatment size, and examines its feasibility (Case 2 in Figure 1.3).

1.2.1.3 Spread Simulation

Modeling dynamics of weed species spread is challenging because there exist many influencing factors. Both biotic and abiotic components of the environment affect their movement, as well as the effects of treatments that may change the spread dynamic over time and space. In this study, we considered the currently infested areas, vegetation susceptibility to infestation, and selected treatments (i.e., herbicides) as influencing factors to determine newly infested areas over time for the purpose of developing and evaluating short-term action plans.

The spread of weeds was considered to be affected by vegetation susceptibility in the surrounding area of current infestation and existence of treatments. Vegetation susceptibility is assumed to be in one of three categories which vary with weed species and vegetation cover types: i) closed to invasion; vegetation is not susceptible to the particular weed species, ii) disturbance allows invasion; in normal condition the vegetation is not susceptible, but becomes susceptible if disturbed, and iii) susceptible; vegetation is susceptible to weed species. The modeled spread of weed species is linear in all directions at a user-provided spread rate (Figure 1.4).
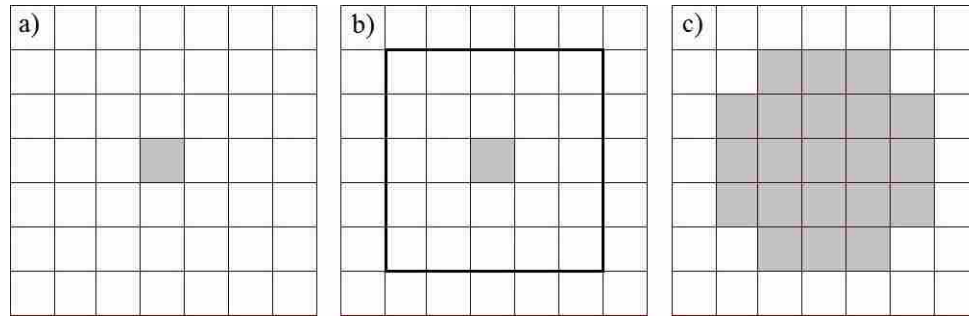
Figure 1.4. Simulation of a linear spread of weed using a raster analysis assuming that vegetation is susceptible without disturbance: a) initial infestation area, b) surrounding area that could be potentially infested; and c) a resulting raster showing a larger infestation area after the linear spread logic was applied.

The simulation model also takes into account multiple weeds and the effects of treatments that might vary on different species. If the selected treatment is known to work on a particular weed, the model assumes that such treatments stop weed spread for a given number of years (i.e., user-defined duration of treatment effect). After this duration of treatment effects expire, weed reestablish in the TU and start spreading at a given spread rate. If there exist multiple weeds in the same TU, only the ones that are affected by the treatment stop spreading. Figure 1.5 illustrates our assumptions on weed spread with treatment effects in three different cases with multiple species. Figure 1.5a shows weed spread with no treatment, where weeds spread along the perimeters of existing infestation at a given linear spread rate per year. Figures 1.5b and 1.5c present the two cases where only one weed (Weed B) is treated, while there is an overlap area with other weeds. Weed A spreads into the overlap area (Figure 1.5b) unless herbicide used for Weed B also affects Weed A (Figure 1.5c). Figure 1.5d shows the last case scenario where both Weeds A and B are treated, and therefore both weeds stop spreading.
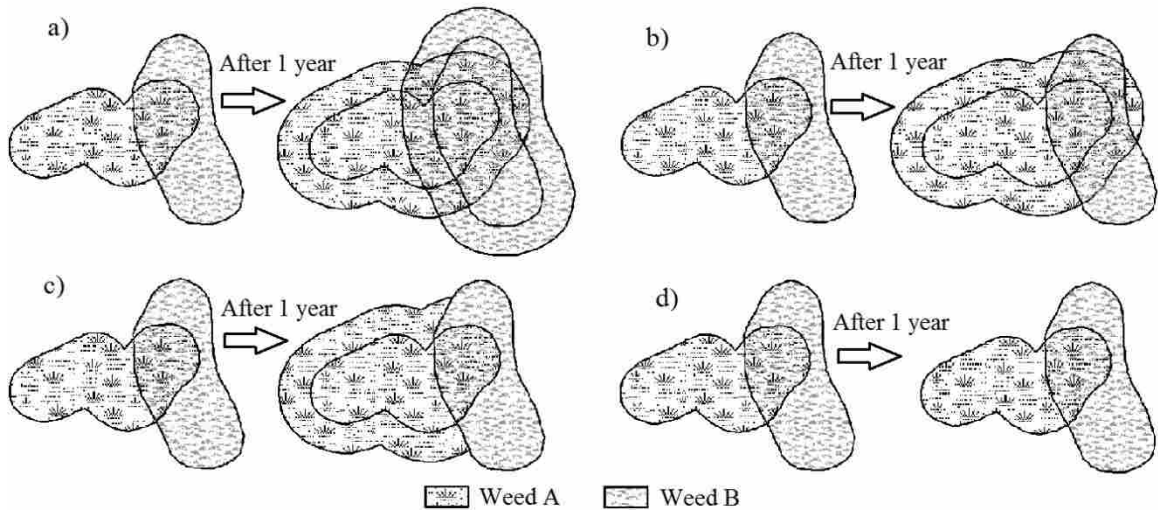
Figure 1.5. Weed spread logic with treatment effects on multiple weed species. Assuming surrounding vegetation is susceptible to invasion of Weeds A and B: a) no treatment, both Weeds A and B spread, b) Weed B is treated, and the herbicide affects only Weed B, c) Weed B is treated, and the herbicide affects both Weeds A and B, and d) Both Weeds A and B are treated.

1.2.1.4 Plan Evaluation

After a five-year treatment plan is built for a landscape of interest, the plan is evaluated in terms of total predicted infestation area, the total amount of selected area for treatment, and cost-effectiveness of treatments. The total predicted infestation area represent future infestation potential, while the total selected area for treatment account for the amount of containment efforts on an area basis. For cost-effectiveness of treatments, we calculate a cost-effectiveness ratio (CE) using Equation 1.1. The denominator of the ratio represents the effects of weed treatments in terms of area (ha) to be maintained weeds free due to treatments. This area can be obtained from a comparison between the simulation results of a treatment plan and the no action plan.

Lower CE values indicate the more cost-effective the treatment plans. This ratio can be also interpreted as the cost of maintaining 1 ha free of weeds from the area that would have been infested without treatments. However, any of these measures do not represent qualitative aspects of treatments that might be necessary to assess for the overall goodness of each alternative plan. Diverse evaluation criteria should be explored to assess alternative plans and conduct trade-off analysis based on given management goals. Since our simulation model automatically generates a spatial database for selected treatments on a yearly basis and the estimates of infestation over time, individual treatments and their effects can be further analyzed per species, herbicide, and AM.

$$\text{CE} = \frac{\text{Total treatment costs (\$)}}{\text{Reduction in infestation area due to treatments (ha)}} \qquad [1.1]$$

1.2.2 Model Application

We applied our simulation model to a study landscape of 24,867 ha located in the Salmon River watershed in the southwestern portion of the Nez Perce National Forest in North-Central Idaho (Figure 1.6). In 1994, the Idaho State Department of Agriculture created the Salmon River Weed Management Area (SRWMA) to coordinate weed management efforts among federal, county and private land managers (Idaho State Department of Agriculture 2009). Because weed treatments have been actively applied in the drainage, and geospatial databases required for our model have been well established, it was deemed as an appropriate application landscape for our model.

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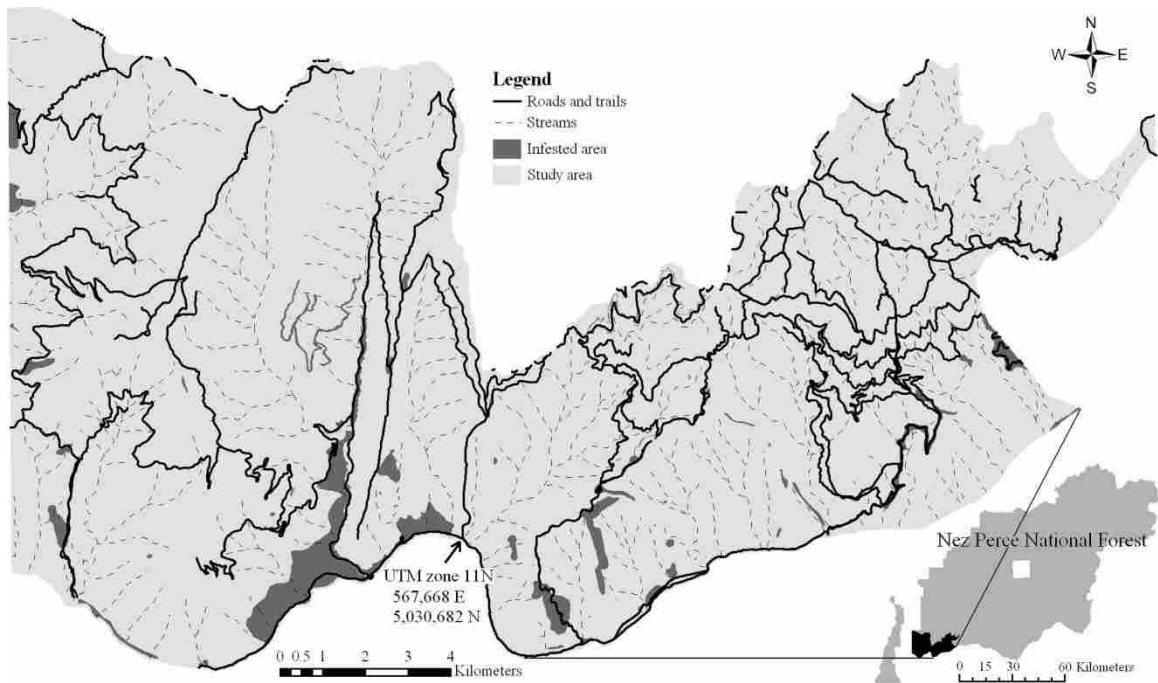
Figure 1.6. The 24,867 ha study landscape in the Nez Perce National Forest.

1.2.2.1 User Input

i) Weed species and vegetation susceptibility

Ten weed species were found in the study landscape in 2009 (data provided by the SRWMA, Idaho County Weed Management Department in 2009). The total estimated current infestation areas per species in the landscape vary from 0.2 ha for Diffuse knapweed (*Centaurea diffusa Lam.*) to 664.4 ha for Rush skeletonweed (*Chondrilla juncea L.*) (Table 1.1). We consulted with local weed ecologists and managers, who are familiar with the weeds and management efforts in the region to determine spread rates of weed species, management priorities, and susceptibility (Peter Rice, Pat Green, Carl Crabtree and Timothy Prather[2], personal communication). Vegetation cover types across

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[2] Peter Rice, Research Associate, Division of Biological Sciences, The University of Montana; Pat Green, USDA Forest Service Soil Scientist/Ecologist, Nez Perce National Forest; Carl Crabtree, Idaho County Weed Superintendent; and Timothy Prather, Associate Professor, Weed Ecology, University of Idaho.

the landscape were obtained from the SRWMA and a susceptibility matrix developed by local weed ecologists (Table 1.2) was used to determine susceptibility of vegetation to individual weeds. According to the susceptibility matrix, a large number of vegetation cover types require disturbances to be susceptible to invasion. A 6,674 ha fire in 2006 is the major contributor to disturbance, including a 16 ha area that was also affected by prescribed burn in 2004 (Figure 1.7). Durations of disturbance effect were assumed to last until the first and third year of the five-year planning horizon for the 2006 and 2004 fires, respectively.

Table 1.1. Common and scientific names of weed species, US codes, initial infestation areas, priorities and spread rates for the study area.

Weed Common name (Scientific name)	Weed (US Code)	Area (ha)	Priority (1: highest - 5: lowest)	Spread Rate (m yr^{-1})
Cheatgrass (*Bromus tectorum L.*)	BRTE	2.3	5	10
Spotted knapweed (*Centaurea biebersteinii DC.*)	CEBI2	332.2	2	10
Diffuse knapweed (*Centaurea diffusa Lam.*)	CEDI3	0.2	1	100
Rush skeletonweed (*Chondrilla juncea L.*)	CHJU	664.4	2	1,000
Common crupina (*Crupina vulgaris Cass.*)	CRVU2	9.3	5	10
Dalmatian toadflax (*Linaria dalmatica (L.) P. Mill.*)	LIDA	1.8	4	50
Scotch thistle (*Onopordum acanthium L.*)	ONAC	101.1	3	1,000
Sulfur cinquefoil (*Potentilla recta L.*)	PORE5	4.9	5	10
Puncturevine (*Tribulus terrestris L.*)	TRTE	0.7	5	25
Common mullein (*Verbascum thapsus L.*)	VETH	32.9	4	50
Total		1,149.8		

Table 1.2. Vegetation cover types and susceptibility matrix for the study area.

Vegetation	Area (ha)	Weed species (US Code)									
		BRTE	CEBI2	CEDI3	CHJU	CRVU2	LIDA	ONAC	PORE5	TRTE	VETH
Abies grandis (dry type)	1,694	D	I	D	D	C	D	C	D	C	D
Abies grandis (moist type)	5,423	D	I	D	D	C	D	C	D	C	D
Abies grandis (wet type)	2,116	D	I	D	D	C	D	C	D	C	D
Abies lasiocarpa (cold type)	17	I	D	D	D	C	D	C	D	C	D
Abies lasiocarpa (dry type)	2,831	I	D	D	D	C	D	C	D	C	D
Abies lasiocarpa (moist type)	248	I	D	D	D	C	D	C	D	C	D
Abies lasiocarpa (wet type)	570	I	D	D	D	C	D	C	D	C	D
Dry species grassland type	3,473	I	D	D	D	D	D	D	I	D	D
Dry species shrubland type	137	D	I	D	D	C	D	D	I	D	D
Festuca idahoensis (grassland type)	378	I	I	D	D	D	D	D	I	D	D
Mesic species shrubland type	6	I	D	D	D	C	D	D	D	D	D
Pinus albicaulis	191	C	C	C	C	C	D	C	C	C	C
Pinus contorta	113	D	D	D	D	D	D	C	D	D	D
Pinus ponderosa	2,272	I	I	D	D	D	D	D	I	D	D
Pseudotsuga menziesii (cool dry type)	142	I	I	D	D	D	D	C	I	D	D
Pseudotsuga menziesii (moist type)	4,144	I	I	D	D	D	D	C	I	D	D
Pseudotsuga menziesii (warm dry type)	231	I	I	D	D	D	D	C	I	D	D
Rock, barren areas, and mines	719	C	D	D	D	C	D	I	D	I	I
Water	162	C	C	C	C	C	C	C	C	C	C

Where, I: vegetation is susceptible to invasion, C: vegetation is closed to invasion, and D: disturbance allows invasion.
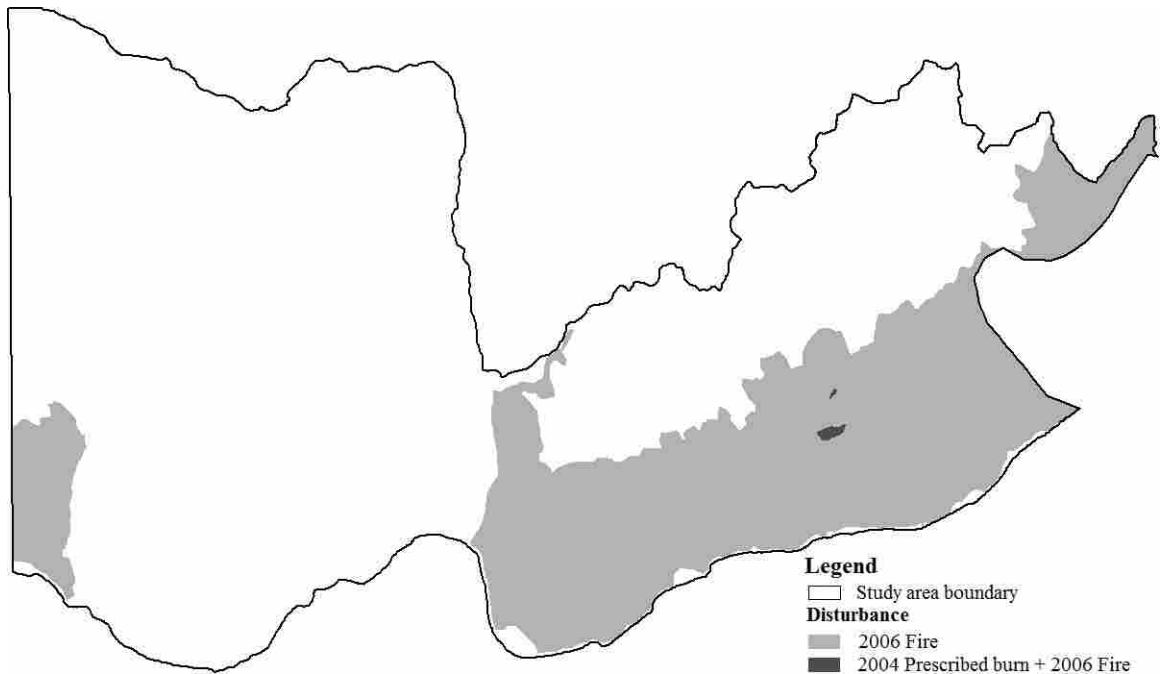
Figure 1.7. Disturbances (past prescribed burn and fire) identified across the landscape

study area. Disturbance is used to determine susceptibility of individual weed species in

our model.

ii) Herbicides treatment options

We identified herbicide treatment options applicable to the weeds in consultation

with local weed managers (Peter Rice and Gil Gale[3], personal communication) (Table

1.3). Cost of herbicide includes only the cost of chemical per hectare. Two different

treatment options were identified for Common crupina (*Crupina vulgaris Cass.*) and

Scotch thistle (*Onopordum acanthium L.*) because one possible treatment option for them

may not be used in riparian areas. Due to this restriction, we created 60 m buffers around

stream networks to designate riparian areas, and allowed the herbicides within the

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[3] Peter Rice, Research Associate, Division of Biological Sciences, The University of Montana and Gil Gale
USDA Forest Service Officer/Program Leader, Bitterroot National Forest.

riparian areas that are known to cause no harm to water quality. The study landscape

includes 384 km (238 mi) of streams resulting in a total of 4,608 ha of riparian areas.

Table 1.3. Treatment options available to treat weed species within the study area. Each

treatment is attributed with its cost per unit area, duration of effects, and applicability in

riparian areas.

Weed	Treatment per hectare	Cost ($ ha^{-1})	Duration (years)	Riparian
Cheatgrass	Imazapic (Plateau) 0.2 kg ai[4] + 0.25 % v/v NIS	69.60	2	Yes
Spotted knapweed	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Diffuse knapweed	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Rush skeletonweed	2,4-D 2.1 kg ae[5]	13.15	1	Yes
Common crupina	Metsulfuron (Escort) 0.04 kg ai + 0.25 % v/v NIS[6]	37.22	1	Yes
Common crupina	Picloram (Tordon) 0.3 kg ae	28.35	3	No
Dalmatian toadflax	Chlorsulfuron (Telar) 0.1 kg ai + 0.25 % v/v NIS	92.83	1	Yes
Scotch thistle	Metsulfuron (Escort) 0.1 kg ai + 0.25 % v/v NIS	73.06	1	Yes
Scotch thistle	Picloram (Tordon) 0.2 kg ae	21.26	2	No
Sulfur cinquefoil	Aminopyralid (Milestone) 0.11 kg ai	36.48	3	Yes
Puncturevine	2,4-D 2.1 kg ae	13.15	1	Yes
Common mullein	Metsulfuron (Escort) 0.04 kg ai + 0.25 % v/v NIS	37.22	1	Yes

[4] kg ai: kilograms of active ingredient.
[5] Kg ae: kilograms of acid equivalent.
[6] % v/v NIS: volume-volume percent of non-ionic surfactant.

iii) Herbicide application methods

Five herbicide application methods were considered for the study landscape: all-terrain-vehicle (ATV), horse, truck, backpack sprayer, and helicopter. Cost, minimum treatment size, and distance limit for accessibility from the existing roads and trails were obtained in consultation with local weed managers (Peter Rice and Gil Gale[7], personal communication) (Table 1.4). Cost of herbicide AMs correspond to equipment costs and they do not include herbicides costs. We did not separate fixed costs from the total application costs to simplify user inputs, but assumed the cost of each AM shown in Table 1.4 on a hectare basis is valid only when the treatment size exceeds the minimum requirement given for the method to recover fixed costs. In other words, costs per hectare of AMs would be much higher than those shown in Table 1.4 when applied to only a small area. Therefore, we considered an AM to be infeasible if the treatment size does not meet the minimum requirement. In addition, an area assigned for treatment does not have to be a continuous polygon, but a group of small TUs in the neighborhood can form a cluster of TUs that satisfies the minimum size requirement.

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[7] Peter Rice, Research Associate, Division of Biological Sciences, The University of Montana and Gil Gale USDA Forest Service Officer/Program Leader, Bitterroot National Forest.

Table 1.4. Herbicide AMs considered in the analysis with their cost, minimum treatment

size and distance limit from the existing roads and trails.

Application method	Cost ($ ha^{-1})	Minimum treatment size (ha)	Distance limit from trails or roads (m)
ATV	74.2	0.20	15
Horse	370.7	0.04	15
Truck	123.6	8.00	20
Backpack	494.3	0.04	unlimited
Helicopter	49.4	20.00	unlimited

The feasibility of some AMs also depends on accessibility of vehicles through the

existing roads and trails. For example, ATV and horse can be used along trails and roads,

whereas roads are required for a truck application. To limit the use of these methods to

the areas in the proximity to the existing roads and trails, we created buffers around roads

and trails with distance limits and considered the buffers as accessible areas for treatment

for ground-based AMs (Table 1.4). The study landscape contains 238 km of roads and

119 km of trails, resulting in a total of 933 ha suitable for ATV and horse applications,

and 905 ha for truck application.

iv) Treatment Plan Alternatives

It is often impractical to treat the entire infestation area because of limited

resources, and thus weed managers are required to prioritize and select treatment

locations and time. It is a common practice among weed managers to prioritize

treatments based on weed species and sites (Timmins and Owen 2001). Usually when

control is based on weed priorities, manager's objective is to contain recently-established

species, whereas when control is based on sites the aim is to protect the site's value (Timmins and Owen 2001). Although we recognize that weed managers often combine the two prioritization schemes in order to take care of weed species and protect valuable sites when they make decisions about when and where to treat, we exclusively chose one prioritization scheme at a time to develop and evaluate two distinct alternative treatment plans using our simulation model for demonstration purposes.

Treatment prioritization based on weed species. This prioritization scheme of TUs is based on the weed species priorities established in consultation with local weed managers (Table 1.1). When multiple weeds exist in a TU, the priorities of multiple species are combined and considered in prioritization. Therefore, a TU infested by multiple high-priority weeds would most likely get the highest priority for treatment. Spatial distribution of weed priorities (Figure 1.8a) shows high priority areas (1 to 2) are mainly located in the south-central region towards the east, while low priority areas (3 to 5) are found in the west of the study landscape.
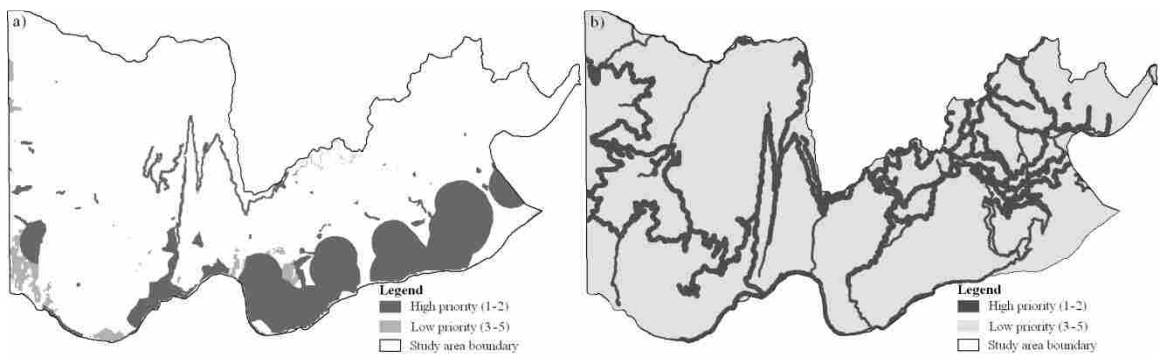
Figure 1.8. Spatial prioritization for alternative weed treatment plans: a) prioritization based on weed species and b) prioritization based on sites.

Treatment prioritization based on sites. In this prioritization scheme, TUs are prioritized based on their locations (Figure 1.8b). Road and trail buffers were considered as high priority sites (i.e., areas within a distance of 120 m and 60 m from roads and trails, respectively), and overlapping areas between road and trail buffers received the highest priority for treatment due to high potential of weed seed transport by vehicles and human activities.

v) Annual Budget Scenarios

We considered four increasing annual budgets (i.e., $25,000, $50,000, $100,000, and $150,000) and two prioritization schemes (i.e., based on weed species and sites) to develop and compare a total of eight alternative weed treatment plans.

1.3 RESULTS AND DISCUSSION

1.3.1 Treatment Plan Alternatives

The total selected areas for treatment in hectares were constrained by annual budget (Figure 1.9). Compared to the lowest budget level at $25,000, the highest annual budget at $150,000 allowed additional treatments of more than 8,000 ha. However, the treatment locations were highly affected by the prioritization scheme employed in selection of TUs (Figure 1.9). For example, in the $25,000 budget level scenario, the 23 ha area located in the north-west corner of the study landscape was selected for

treatments under the sites priority scheme, whereas it was not selected under the species priority scheme. In the $150,000 budget level scenario, large differences in areas selected for treatment between the two prioritization schemes were observed in the south-central region of the study landscape owing to the different priorities assigned to those areas under each prioritization scheme (Figures 1.8a and 1.8b).

The results on the areas selected for treatment also show that many low priority units were selected for treatment especially under the site priority scheme. This is because of the clustering function of the simulation model. Nearby low priority TUs are included in a cluster which is developed to treat a high priority TU at relatively low costs. This essentially mimics the common practice of treatments where larger infestation areas are often treated together with the target area when the AM has a sufficient spraying capacity (e.g., aerial spraying).

Because the duration of treatment effects considered in this analysis last not more than 3 years (Table 1.3), some areas were selected for treatment multiple times during the five-year planning horizon. It appears that the prioritization schemes also affect the selection of TU for retreatment (Figure 1.9). For example, a 23 ha area in the north-west corner of the study landscape was not treated in the weed priority plan at the $25,000 budget level, and treated only once in the other budget levels. However, the same area was treated at least three times in all budget levels in the sites priority plans due to its high site priority for treatment. Another difference between the two prioritization schemes in terms of TU selected for retreatment was found in the south-central region of the study area. The areas were retreated more times in the weeds priority plans than the sites priority plans across all the budget levels because of high priority weeds in the area.
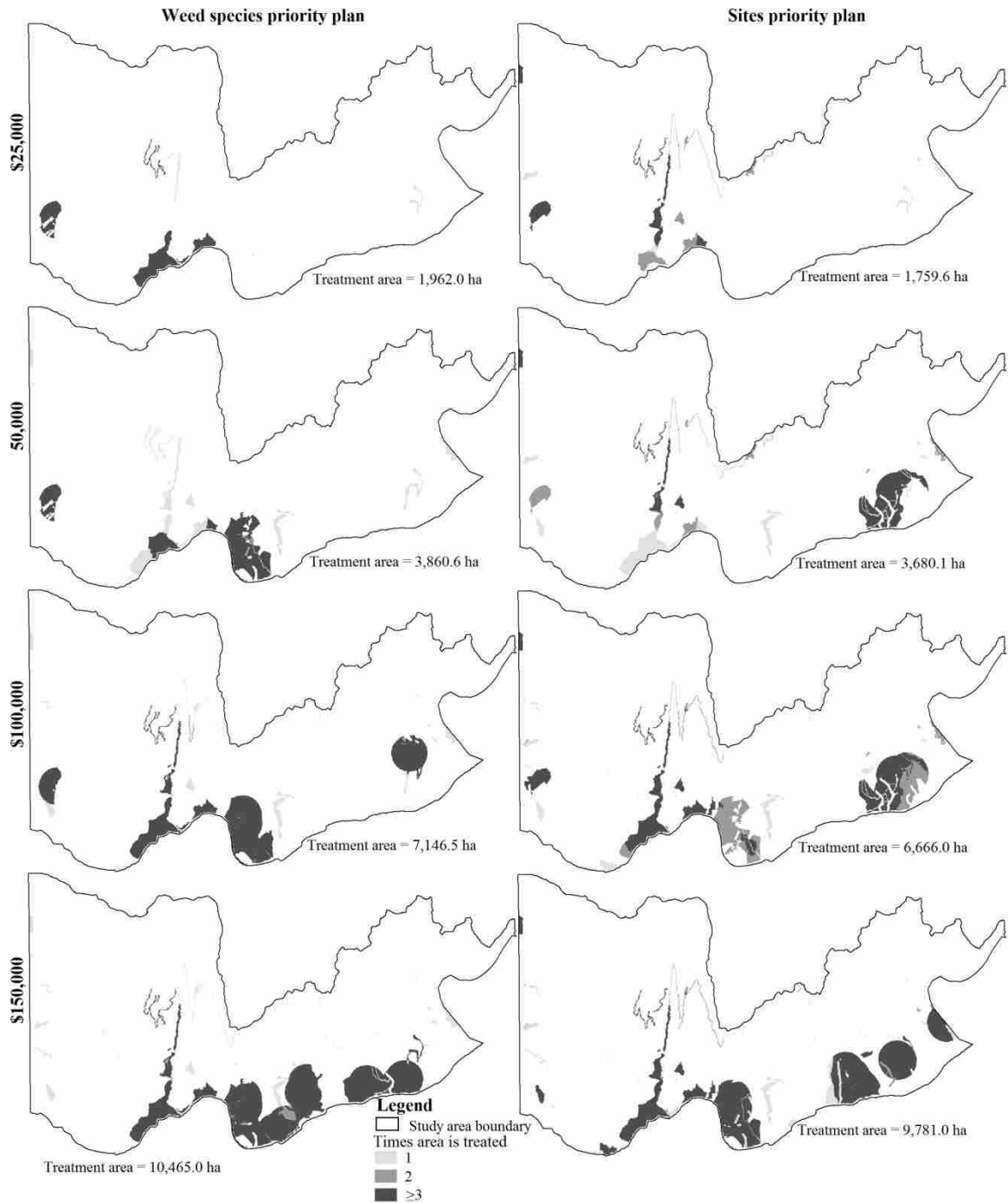
Figure 1.9. Treatment locations selected for the five-year treatment plans shown with the number of times the areas were assigned for treatment under different prioritization schemes and annual budget levels.

Considering total area selected for treatment for the five-year planning horizon, helicopter was the most selected AM in all scenarios ranging from 1,752.4 ha to 10,271.7 ha (Table 1.5), leaving only small and spread out areas for other more expensive AMs. Backpack, the second most selected AM but far below helicopter, was assigned to satellite treatments where there were not enough continuous areas for helicopter or other AMs could not reach due to inaccessibility.

Table 1.5. Total area selected for treatment (ha) by AM selected in each of the five-year treatment plan alternatives.

Application method	$25K	$50K	$100K	$150K
	Weeds priority plan			
Helicopter	1,957.1	3,851.1	7,045.2	10,271.7
Backpack	4.5	8.9	99.7	192.3
Horse	0.5	0.6	1.0	0.5
ATV	0.0	0.0	0.5	0.5
Truck	0.0	0.0	0.0	0.0
Total	1,962.0	3,860.6	7,146.5	10,465.0
	Sites priority plan			
Helicopter	1,752.4	3,675.5	6,572.0	9,588.0
Backpack	3.1	4.1	93.3	191.8
Horse	0.5	0.5	0.5	0.5
ATV	3.6	0.0	0.3	0.8
Truck	0.0	0.0	0.0	0.0
Total	1,759.6	3,680.1	6,666.0	9,781.0

The number of weeds targeted for treatment was different between the two priority schemes with the exception of the $50,000 annual budget (Table 1.6). In general, the weed species priority plans targeted fewer weeds for treatment than the sites priority plans. This is because the weed species priority plans aimed to treat the highest priority weeds first as much as budget permits, whereas the sites priority plan selected treatment locations based on sites resulting in a wider weed species mix.

Table 1.6. Total area selected for treatment (ha) per weed species selected in each of the five-year treatment plan alternatives.

Weed	Weeds priority plan				Sites priority plan			
	$25K	$50K	$100K	$150K	$25K	$50K	$100K	$150K
Cheatgrass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spotted knapweed	0.0	94.1	173.1	222.5	210.0	307.8	374.9	398.8
Diffuse knapweed	0.0	0.0	0.2	0.2	0.0	0.0	0.2	0.2
Rush skeletonweed	1,962.0	3,743.2	6,924.2	10,193.4	1,433.1	3,228.4	5,785.3	8,689.6
Common crupina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1
Dalmatian toadflax	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.8
Scotch thistle	0.0	23.3	49.0	49.0	116.6	143.9	500.5	668.4
Sulfur cinquefoil	0.0	0.0	0.0	0.0	0.0	0.0	3.9	5.0
Puncturevine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Common mullein	0.0	0.0	0.0	0.0	0.0	0.0	1.1	8.2
Total	1,962.0	3,860.6	7,146.5	10,465.0	1,759.6	3,680.1	6,666.0	9,781.0

It is noteworthy that the wider species mix targeted in the sites priority treatment plans also resulted in higher total treatment costs per hectare (i.e., herbicide plus AM) mainly because more expensive herbicides were selected in the sites priority treatment plans in order to contain multiple weeds (Table 1.7).

Table 1.7. Total costs of herbicides and AMs per unit area ($ ha^{-1}) resulting from each of the treatment plan alternatives.

Prioritization scheme	$25K	$50K	$100K	$150K
Weed species	63.7	64.8	70.0	71.7
(Herbicide + Application method)	(13.2+50.5)	(14.3+50.5)	(14.3+55.7)	(14.1+57.6)
Sites	71.0	67.9	75.0	76.7
(Herbicide + Application method)	(20.6+50.4)	(18.0+49.9)	(19.3+55.7)	(18.6+58.1)

1.3.2 Weed Spread Simulation

Total predicted infestation area by weed species at the end of the five-year planning horizon show differences between the base case scenario and each of the treatment plan alternatives (Table 1.8). The base case, which does not consider weed treatments, represents the worst case scenario resulting in the total infested area of 5,626 ha after 5 years. The model predictions indicate that the total infestation area is reduced by 1.6% from the base case scenario when an annual budget is $25,000, but the reduction rate would go up to 25.9% when an annual budget level is increased to $150,000 (Table 1.8).

Results also show that the site prioritization scheme was more effective in reducing the total infestation area across all the budget levels (Table 1.8) despite the fact that fewer hectares were to be treated under this prioritization scheme (Table 1.6). This is mainly because a larger number of weeds are treated under the site priority plans. The results show that more infestation areas of Rush skeletonweed, a high priority weed, were predicted generally under the site prioritization scheme, but other weeds such as Spotted knapweed and Scotch thistle seem to be more effectively contained by the site prioritization scheme (Table 1.8).

Predicted infestation areas of certain weeds such as Diffuse knapweed, Common crupina and Puncturevine do not increase from their initial infestation (Table 1.8). This is mainly because most areas in the study landscape are not susceptible to invasion of those species unless disturbed, and the current infestations are not near the existing disturbance areas.

Locations of predicted infestation areas for all scenarios show differences across budget levels and prioritization schemes (Figure 1.10). The higher budget results in less infestation area because the more area can be treated. Differences between the two prioritization schemes at the same budget level, however, are caused mainly by treatment locations and timing. This indicates that it would be important to analyze trade-offs among different priority schemes and refine treatment plans in order to obtain the maximum benefits of treatments.

Table 1.8. Total infestation area (ha) per weed species predicted at the end of five-year planning horizon in each of the treatment plan alternatives.

Weed	No treatment	Weeds priority plan				Sites priority plan			
		$25K	$50K	$100K	$150K	$25K	$50K	$100K	$150K
Cheatgrass	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Spotted knapweed	710.6	710.6	710.6	707.0	710.6	638.0	639.5	645.4	640.6
Diffuse knapweed	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Rush skeletonweed	4012.2	3,924.6	3,644.8	3,449.6	2,757.0	3,754.2	3,754.2	3,692.7	3,141.3
Common crupina	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
Dalmatian toadflax	2.7	2.7	2.7	2.7	2.7	2.7	2.7	1.8	1.8
Scotch thistle	815.4	815.4	815.4	760.2	760.2	815.4	657.4	578.5	302.3
Sulfur cinquefoil	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Puncturevine	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Common mullein	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	60.3
Total	5,626.0	5,538.4	5,258.6	5,004.6	4,315.6	5,295.4	5,138.9	5,003.5	4,168.7
% reduction in total infestation area from base case	0.0%	1.6%	6.5%	11.0%	23.3%	5.9%	8.7%	11.1%	25.9%

Figure 1.10. Predicted infestation areas at the end of five-year planning horizon
resulting from each of the treatment plan alternatives.

Changes in predicted infestation areas over time across the five-year planning
horizon show that a large amount of hectares are newly infested during the first year
and then the increase in infestation areas slows down afterwards (Table 1.9). This
large influx of newly infestation areas in the first year is mainly due to the effects of

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the disturbed area of 6,658 ha (Figure 1.7) that was considered susceptible to invasion during the first year of simulation. These results suggest that managers might need to prioritize disturbance areas for treatment if such areas are indeed more prone to invasion after a disturbance event.

Table 1.9. Predicted infestation area in each time period resulted from each of the treatment plan alternatives.

Prioritization scheme	Annual budget	Time period					
		Current condition	1	2	3	4	5
	No treatment	1,149.8	5,185.7	5,228.2	5,507.9	5,512.8	5,626.0
Weed priority	$25,000	1,149.8	5,098.1	5,140.6	5,420.3	5,425.2	5,538.4
	$50,000	1,149.8	4,818.3	4,860.8	5,130.2	5,145.4	5,258.6
	$100,000	1,149.8	4,568.0	4,608.4	4,800.3	4,895.1	5,004.6
	$150,000	1,149.8	3,875.3	3,914.7	4,034.7	4,202.4	4,315.6
Site priority	$25,000	1,149.8	4,927.8	4,970.3	5,210.9	5,223.0	5,295.4
	$50,000	1,149.8	4,752.3	4,794.9	5,043.6	5,067.5	5,138.9
	$100,000	1,149.8	4,584.8	4,647.3	4,811.6	4,931.5	5,003.5
	$150,000	1,149.8	3,702.7	3,802.1	3,933.6	4,083.2	4,168.7

1.3.3 Cost-effectiveness of Treatment Plans

To assess the cost-effectiveness of each treatment plan alternative, we calculated a CE value for each alternative. Both total treatment cost and reductions in infestation area due to treatments over five years are required to determine CE values.

Total treatment cost can be determined for each treatment plan alternative by adding up the annual budget for treatment. Reduction in infestation area due to treatments for each budget level can be obtained by the difference between no treatment (i.e., 5,626.0 ha) and each one of the predicted infestation areas with treatments in the last column of Table 1.9. In our application, the treatment plans developed under the site prioritization scheme are more cost-effective than the weed species priority plans across all the budget levels (Figure 1.11). It is noteworthy that large differences in CE values between the two prioritization schemes occur at the low budget levels.
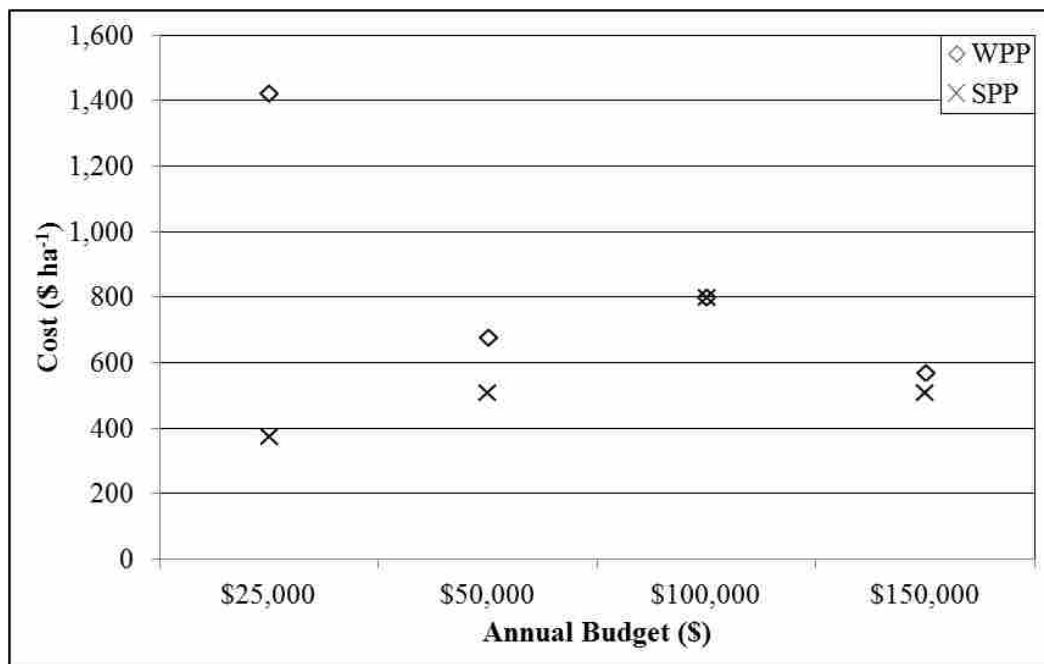
Figure 1.11. Cost-effectiveness ratio values calculated from the treatment plan alternatives. WPP and SPP indicate the weed species priority plans and the site priority plans, respectively.

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These results suggest that more careful planning for treatment locations and timing should take place when budget is tighter because of the large number of options that are available for treatment selection and the cost-effectiveness of individual treatments may vary widely.

In our application, the site priority plan with the annual budget of $25,000 appears to be the most cost-effective plan alternative. However, due to CE value approach that does not account for differences in project scales we cannot explicitly undertake a specific scenario as the best option to implement. If the management objective is to minimize total infestation area, higher budget levels seem to be required (Table 1.8).

One of the reasons that is probably contributing to the sites prioritization scheme being more cost-effective than the weed species prioritization scheme is that the lowest cost herbicides was always chosen as part of the implementation of the alternative treatment plans. Hence, if it were possible to choose species specific lowest cost herbicides for weed species prioritization scheme, more cost-effective plans could have been developed because the herbicides could allow the control of other species only with a small increase in cost.

1.4   CONCLUDING REMARKS

Our simulation model provides a semi-automated approach to develop treatment plan alternatives based on the user's management strategies. This process of

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plan development requires extensive guidance from the model user especially in prioritizing TUs. Although this interaction between the user and the simulation model would be still beneficial, a mathematical optimization modeling approach, when combined with this simulation model, would provide additional benefits by identifying the optimal treatment plan for a given management objective. This simulation model is capable of generating and evaluating alternative plans, which can provide an essential component for full optimization for weed treatment planning.

Our simulation model considers that spread of weed species is linear and constant to all directions in a neighbor-to-neighbor movement fashion without explicit consideration of existence of other weeds or density. Regarding treatment effects, it is assumed that an application of herbicides would stop weeds from spreading for a given duration of years, but no shrinkage or eradication of current infestations is modeled. We also assumed that the treatment effects and costs do no vary with number or density of weeds, and that vegetation susceptibility is deterministic and known. It is important for the user of our simulation model to be fully aware of these assumptions for proper use of the model and proper interpretation of the results. Outcomes from future research on weed spread dynamics and data from robust weed management monitoring programs would certainly provide more accurate and reliable data for weed spread simulation and therefore improve the quality of model results.

Evaluating treatment plan alternatives using our simulation model would allow weed managers to analyze trade-offs and identify the best alternative plan that effectively meets the management goal. Evaluation criteria used in the model include predicted infestation areas over time and areas selected for treatment with spatial,

temporal, and operational attributes. However, our model does not consider any measures of economic losses or impacts caused by invasion of weeds (e.g., market and non-market costs and benefits). Since the economic, ecological, and social impacts of one hectare of invasion can vary substantially by location, weed species, plant communities, and human activities in the area, more inclusive evaluation metrics and criteria should be developed and incorporated in the model in the future.

Targeting single weed species has been the norm in weed management perhaps because of the lack of analytical tools to evaluate spatial and temporal effects of treatment decisions on multiple weeds. Our modeling approach can provide a means to develop, simulate and evaluate alternative weed treatment plans, while considering multiple weed species and their spread dynamics across a landscape over time. Despite the model limitations aforementioned, we hope our model can be used as an analytical approach that helps weed managers better allocate limited resources to efficiently and effectively accomplish their management goals.

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CHAPTER 2:

GIS-BASED DECISION SUPPORT SYSTEM FOR SPATIO-TEMPORAL OPTIMIZATION OF INVASIVE WEED TREATMENTS

2.0   ABSTRACT

Managing multiple invasive weed species is a complex and challenging problem due to multi-dimensional decisions that need to be made in terms of where, when and how to treat current and future infestations. Traditionally, these decisions are made relying on weed managers' personal experience and judgment. In this study, we developed a spatially-explicit decision support system in order to address the limitation of the current practices of weed treatment planning and provide weed mangers with an analytical tool that can enhance their decision-making processes. Using a heuristic optimization framework, the system automatically develops and evaluates five-year weed control alternatives to determine the treatment plan that minimizes total infestation area over time. The system was applied to a 24,867-ha study landscape located in the Salmon River watershed in Idaho. Comparisons between the optimized and random solutions show that the system was able to allocate treatments to reduce infestation area more effectively than random treatment plans.

Key words: Weed control, simulated annealing, weed spread, spatial optimization

2.1 INTRODUCTION

In a globally interconnected world where people and goods can easily move or be transported to different regions, the likelihood of invaders reaching new areas becomes high. In invasive species management, there is agreement that prevention of new exotic species reaching different locations is the key to reduce unwanted invasions (Rejmanek and Pitcairn 2002; Mack et al. 2000). Although possible measures are taken to avoid introductions of invaders, such measures cannot be perfect and there are still a large number of invasive species reaching new areas.

In invasive weeds management, early detection followed by eradication is considered the most effective strategy in reducing spread of new invaders (Frid et al. 2013; Jarnevich et al. 2010; Frid and Wilmshurst 2009; Moody and Mack 1988). However, it is not always feasible to aim for eradication because of lack of adequate early detection programs, lack of resources for intensive and frequent treatments, or simply because weeds are already established in a large area (Levine and D'Antonio 2003). When eradication becomes no longer an effective method, weed mangers have to prioritize their activities in order to contain current and future infestations as much as possible using their limited budget.

Management of invasive weed species is a recognized complex and challenging problem that often requires large amount of resources to manage them effectively (Panetta and Timmins 2004; Pimentel 2002). The control of weed species also involves considering a variety of factors that affect weed spread, such as the extent of invasion, the ecology of weed species, the dynamics of spread, and how they

respond to different management actions (Regan et al. 2011). Additionally, land

managers with limited budget must react to immediate threats, leaving only few

resources remaining for developing and implementing comprehensive invasive species

management plans (Larson et al. 2011).

The complexity of dealing with multiple weed species with unique traits and

different treatment options suggests the use of optimization through computer software

programs as a tool to overcome the limitations in human information processing that

can impede decision making. There exist several decision tools developed for forest

resources management decisions (Rauscher 1999; Reynolds 2005), but none of them

addresses the issue of invasive weed species as a central concern. In Chapter 1, we

developed a spatial and analytical approach to build and evaluate weed treatment plan

alternatives, but the approach requires manual development of treatment plans, and

thus only a handful of alternative plans can be evaluated in a reasonable time.

The problem of selecting the best alternative plan among a set of treatment

options can be modeled as a combinatorial optimization problem with an objective

function of minimizing total infestation area over time. Different solution techniques,

such as exhaustive search (Nievergelt 2000), mixed integer programming (Ibaraki

1976) and heuristic techniques (Pearl 1984), can be used to find the optimal or near-

optimal solution for such problems. Exhaustive enumeration is a basic solution

approach that chooses the best one among the full enumeration of alternatives. This

approach is not usually efficient for real-world management problems that are large

and complex. An alternative is mixed-integer programming. Due to discrete and

spatial nature (i.e., binary or integer) of some decision variables in weeds management

planning problems, mixed-integer programming is one of the mathematical programming approaches that may solve the problems optimally. However, the mixed-integer programming approach presents two drawbacks: i) the algorithm often becomes inefficient or even fails to solve the problems when there are too many integer variables employed in problem formulation (Nemhauser and Wolsey 1988), and ii) independence of decision variables are required. As described in Chapter 1, weed treatment planning problems are complex combinatorial problems, and decision variables are interdependent because treatment decisions on a given treatment unit and timing affect decisions on surrounding areas in subsequent time periods.

Heuristic optimization techniques coupled with a simulation approach for solution evaluation have been widely used to overcome the abovementioned limitations of mixed-integer programming. In this study we applied simulated annealing algorithm (SA), one of the most popular heuristic optimization techniques, to solve the weed treatment planning problem. SA, first proposed by Metropolis et al. (1953), is a Monte Carlo search method that uses a local search in which a subset of solutions is explored by moving from one solution to a neighbor solution. SA has been widely applied to solve large combinatorial optimization problems in a variety of disciplines, where exact solution techniques (i.e., mixed-integer programming) cannot efficiently find a feasible solution due to problem complexity, non-linearity, or a large amount of computing time required (Boyland et al. 2004; Bettinger et al. 2002).

Because of the spatial nature of the weed treatment planning problem, the use of Geographic Information System (GIS) and a heuristic optimization technique would be an ideal match for such complex spatial problems. GIS technology can provide the

efficiency and portability of spatial data storage, data processing, and cartographic display of spatial data (Arampatzis et al. 2004). In addition, the existing GIS systems such as ArcMap® by ESRI, offer development tool kits for other system or tool development that requires large data process and management.

In this study, we developed a spatially explicit decision support system (DSS) named Weed Treatment Planner (WTP), for weed management control decisions and scheduling at a landscape scale. WTP automatically develops and evaluates five-year alternative weed control options in a heuristic optimization framework to determine the best treatment plan that minimizes total infestation area over time. WTP incorporates the treatment development and spread simulation modules developed in Chapter 1. The simulated annealing search algorithm employed in WTP was uniquely designed to optimize treatment locations over multiple time periods while considering available treatment options, application methods and annual budgets. The system was developed as an extension of ArcMap®, a widely-used GIS software package developed by ESRI.

2.2   MATERIALS AND METHODS

2.2.1 Description of the Decision Support System

WTP is an integration of the simulation model described in Chapter 1 and an optimization framework developed in this Chapter using a SA iterative search

algorithm (Figure 2.1). The system automatically generates and evaluates a large

number of treatment plan alternatives (i.e., solutions) to optimize weed treatment

locations and schedules to minimize total infestation area weighted by weeds and sites

priorities. The system developed in this study consists of three main components:

solution generation, solution evaluation and heuristic solver.
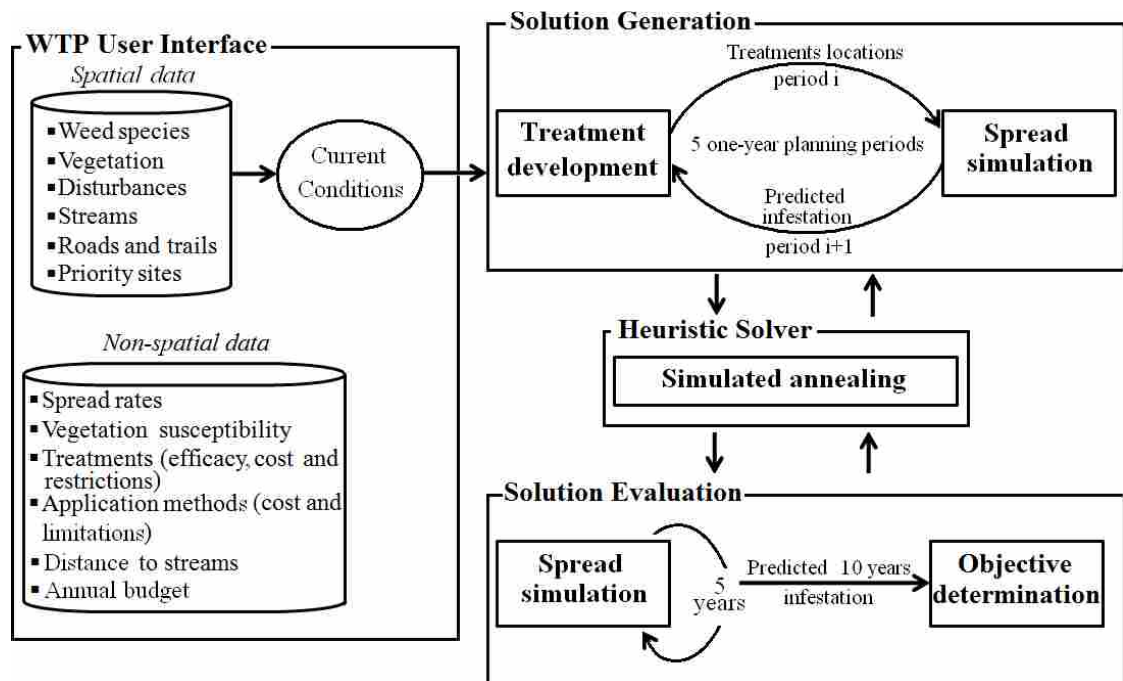
Figure 2.1. Outline of the decision support system, Weed Treatment Planner (WTP),
consisting of three components: solution generation, solution evaluation and heuristic
solver.

The main spatial data required for the system include current infestation and

vegetation polygons in a vector form with associated attributes such as weed spread

rates and priorities, and vegetation susceptibility. These vector data are converted into

a raster for weed spread simulation in the system. The system also requires non-

spatial data, such as user-defined treatment options (i.e., herbicides), application methods (i.e., helicopter, truck, etc.), and weeds and sites prioritization. The heuristic solver employing an iterative process generates and evaluates a large number of five-year alternative weed treatment plans (i.e., alternative solutions). At each iteration, the solver develops one alternative solution using the treatment development and spread simulation modules described in Chapter 1. The solver randomly selects infested areas for treatment until budget is exhausted per time period. Herbicides are randomly selected for treatment of infested areas based on weeds composition and land position (i.e., upland or riparian). The effects of selected treatments as well as vegetation susceptibility are considered to predict infested areas across the landscape for the following year in the spread simulation module. This process is repeated five times to complete one alternative treatment plan. This plan is then evaluated in terms of total infestation area weighted by weeds and sites priorities.

The SA algorithm in WTP uses the solution evaluation results to guide the search for the next alternative plan, hoping to improve the plan in reducing total infestation area across the landscape of interest. User-input budget levels for each planning period are considered as constraints for the development of feasible treatment plans. At the end of the search process, the system produces the best five-year treatment plan that results in the minimum weighted total infestation area along with spatial and tabular data associated with the plan including selected treatment locations, herbicides, application methods, and predicted infestation per species over time.

WTP was developed using ArcObjects® as a toolbar embedded in ArcMap®. The toolbar provides access to the main window (Figure 2.2) where users can set up

input data and management scenarios for a given landscape of interest. Below we describe data requirements and functional components of WTP in detail, user guide and program code are presented in Appendix 1 and 2 respectively.

Figure 2.2. WTP toolbar in ArcMap and the initial dialog window of the system.

2.2.1.1 Input Data and User Interface

Spatial data required for WTP include current infestation polygons over the landscape with weed species information, streams, location of roads and trails, vegetation cover, disturbed areas, and sites for prioritization (such as trailheads, campsites or any other area that users may want to prioritize for treatment). The initial selection of treatments is based on current infestation areas. Streams are required to

define riparian areas where some herbicides are not allowed because of potential

negative impacts to water resources. Trails and roads are required to determine the

accessibility of application methods (e.g., truck, horse, backpack spryer, etc.). Both

riparian and accessibility areas are automatically created as buffers around the

respective features in the system. Other spatial data such as vegetation cover and

disturbed areas affect vegetation susceptibility to invasion, and are thus used to predict

newly infested areas, while user-defined priorities on sites and weed species are used

for treatment location selection and solution evaluation. All vector data are

automatically converted into raster using the functionality of ArcMap to facilitate

systems processes.

Non-spatial data include i) herbicides with associated costs, efficacy and

restriction, ii) application methods with their costs and limitations such as minimum

treatment size and maximum distance from road and trails, iii) distance from streams

to determine riparian areas, iv) annual budget for treatment selection, and v) weed

spread rates and vegetation susceptibility to invasion for weed spread simulation

across the landscape over time.

Graphic user interfaces were created to support data input and integrate spatial

and non-spatial data. All spatial and non-spatial data provided by the user are stored

in an ArcGIS database, so users can use the existing ArcMap functionality to edit and

manage any of the input data.

2.2.1.2 Heuristic Solver

The heuristic solver developed in this study is the core component of WTP because it provides linkage between other system components (i.e., solution generation and evaluation), facilitates data transfer, and conducts solution search. The heuristic solver was designed to minimize weighted infestations over time while meeting given annual budget. Therefore, the objective function of the problem is set to minimize total infestation area at the end of the evaluation period weighted by weed species and site priorities (Equation 2.1). Including both weeds and sites priorities in the objective function as weight factors allows the user to mimic common practice of weed management that prioritizes treatments based on both control strategies (Gil Gale[8], personal communication).

$$\text{Minimize} \sum_{c \in C} \sum_{w \in W} \left(I_{c,w} \times WPI_w \times SPI_c \right) \qquad [2.1]$$

Where c is an index of grid cells out of a total of C grid-cells representing the landscape, w is a weed species index out of a total of W weed species in the study landscape, $I_{c,w}$ is a binary variable that takes value one if the grid cell c is infested by weed species w, and zero otherwise, WPI_w is the weed priority for weed species w, and SPI_c is the site priority for grid cell c. Priority values for both weeds (WPI_w) and sites (SPI_c) range from 1 to 5, where 1 was given to the lowest priority and 5 to the highest priority weed or site. For example a given infested grid cell with 5 priority weed specie and a 5 priority site will contribute with a 25 value to the objective

[8] Gil Gale USDA Forest Service Officer/Program Leader, Bitterroot National Forest.

function. To convert these values to area we multiplied the final value by grid-cell size.

WTP employs a SA heuristic optimization algorithm as a solution approach (Figure 2.3). It begins with developing an initial feasible five-year treatment plan, which includes selection of treatments (i.e., herbicides) for randomly selected treatment units in each year. The algorithm then evaluates the initial solution and stores it as the current solution along with its objective function value. In the next iteration, the algorithm creates a new neighbor solution to the current solution by slightly changing the current solution (i.e., randomly swapping a subset of treatment units). The objective function value of this neighbor solution is computed, and if the new solution has a better objective function value then it replaces the current solution. If the objective function value of the neighbor solution is worse than the current solution, the algorithm calculates an acceptance probability as $\exp(-\Delta E/T)$, where exp is the exponential function, ΔE is the difference in objective function value between the current and neighbor solutions, and T is the current temperature level which is one of the algorithm parameters (Ingber 1993). This acceptance probability is then compared to a random number to determine whether a worse solution can be accepted. By occasionally accepting worse solutions, SA can avoid being trapped on local minimum (or maximum). SA repeats this process for a defined number of iterations at each temperature level. Temperature gradually decreases by a cooling rate parameter. Once the temperature is below a given minimum value, SA stops and reports the best solution found throughout the solution process (Wu et al. 2008). More

details on the process of solution generation and evaluation in each SA iteration are described below.
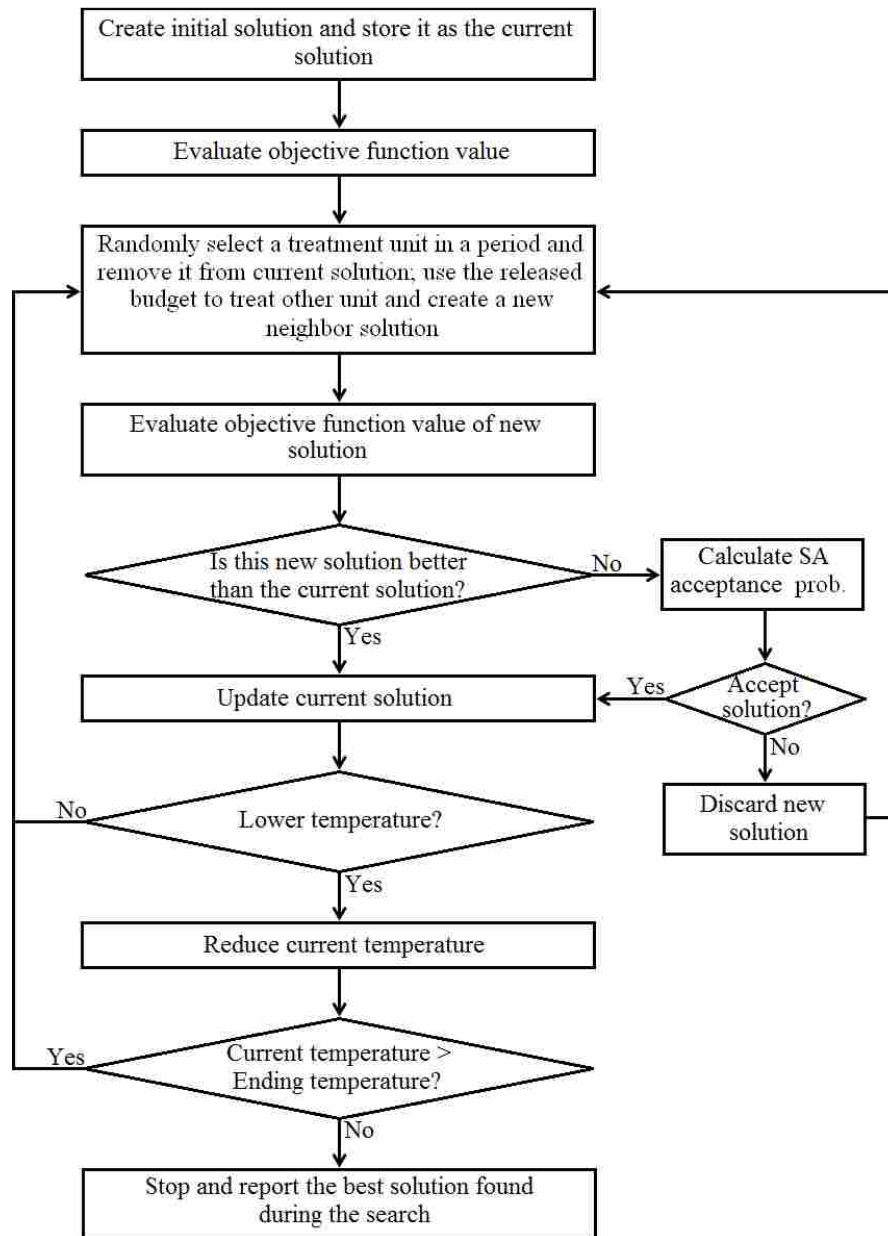
Figure 2.3. Flow chart of the simulated annealing search process used in the heuristic solver of WTP to optimize five-year weed treatment plan.

2.2.1.3 Solution Generation

An alternative solution is developed in each iteration of the SA search process that contains five-year action plans for weed treatments with specific locations and timing of treatments using the same approach developed in Chapter 1. To be able to develop a five-year treatment plan, treatment locations, herbicides and application methods for each treatment unit are selected for the first year. Then, weed spread is simulated to estimate infestation areas for the next year which reflect previous year infestation by weed species, treatment locations and efficacy, and weed spread logics and rates. Based on this estimation of weed spread, the second year treatments are selected. This process repeats until the fifth year plan is completed (Chapter 1).

Unlike the manual prioritization of treatment units described in Chapter 1, WTP automates the selection of treatment units within the SA algorithm. For an initial solution, WTP randomly selects treatment units and herbicides. When the current solution needs to be modified to create neighbor solutions in the subsequent iterations, the algorithm randomly selects a treatment unit that was included in the current solution, withdraws the treatment selected for the unit releasing the budget used for the treatment in its particular time period, and then selects new treatment unit(s) to replace the withdrawn treatment. This swap of treatment units in a given period will affect weeds infestation in the subsequent years, and thus the algorithm re-simulates weeds spread and updates future treatment units based on the simulation outputs.

2.2.1.4 Solution Evaluation

The heuristic solver evaluates a new alternative plan developed in each iteration by calculating its objective function value (i.e., total weighted infestation area). Although a complete weed treatment plan includes only five year action plans, the solver evaluates the plan after ten years in order to account for the remaining effects of the treatments scheduled in the later periods of the five-year planning horizon. For the additional five years beyond the planning horizon, no additional treatment is added, but the spread of weeds is simulated and counted in the objective function.

2.2.2 Solution Visualization and Report

WTP automatically creates the following maps and a summary table to describe the resulting solution (i.e., the best five-year treatment plan): i) weeds distribution showing the location of weed infestation by weed species and year; ii) treatment units by year with selected herbicide, application method, and total treatment costs for each unit, iii) map of application methods showing group of adjacent treatment units treated by the same method at the same time, and iv) tables summarizing total treatment areas, weeds targeted by treatments, selected herbicides and methods, and total treatment costs. All the output maps and tables are produced within ArcMap, thus users can easily conduct further analyses and create customized maps for their purposes.

2.2.3 Decision Support System Application

WTP was applied to the same study landscape used in Chapter 1. The study

landscape is 24,867 ha in size located in the Salmon River watershed in the southwest

part of Nez Perce National Forest in North-Central Idaho (Figure 2.4). The landscape

contains 10 weed species with a total infested area of 1,150 ha, 384 km of streams, 238

km of roads, 119 km of trails, and 19 different vegetation cover types.
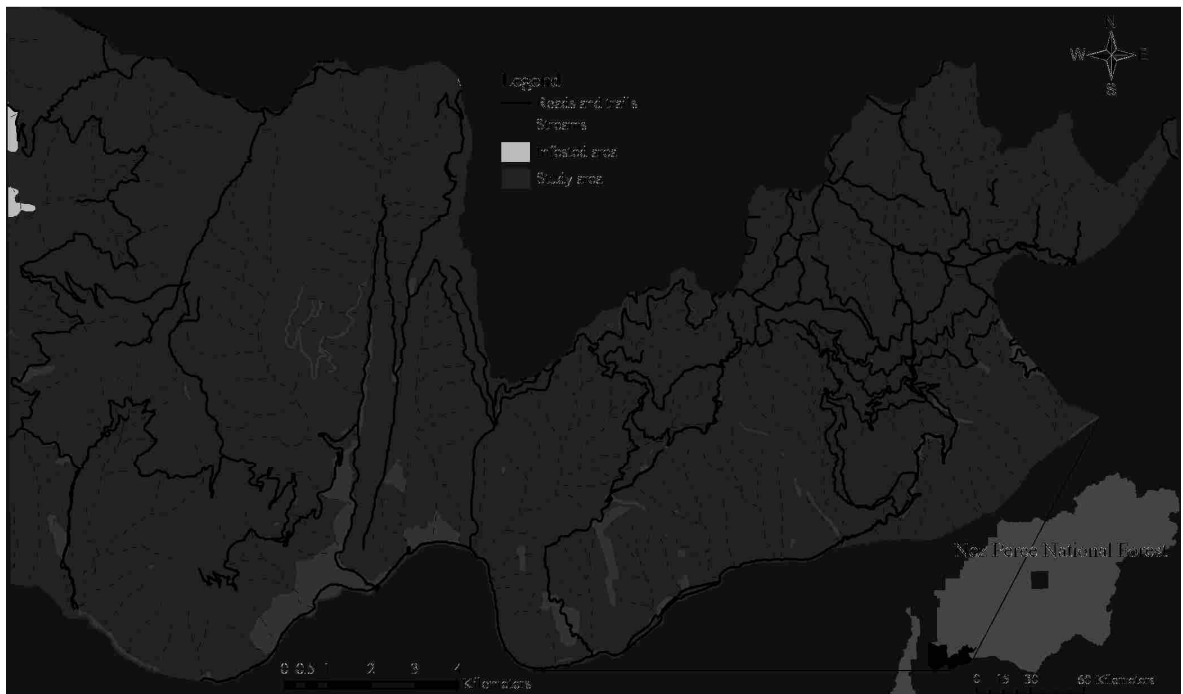
Figure 2.4. Study landscape for WTP application located in the Nez Perce National

Forest.

The same input data as described in Chapter 1 were used in this application

including weed species locations, vegetation susceptibility, disturbance information,

herbicides, and application method options. Two additional herbicides were

considered in this application including clopyralid (Transline) 0.4 kg ae and

chlorsulfuron (Telar) 0.075 kg ai + 0.25 % v/v for Rush skeletonweed and

Puncturevine, respectively (Table 2.1). A total of five herbicides application methods

were considered in this application (i.e., ATV, horse, truck, backpack sprayer, and

helicopter) with the same costs, accessibility and treatment size requirements as used

in Chapter 1.

Table 2.1. Treatment options available to treat weed species within the study area, for each treatment we provide its cost per unit area,

duration of its effects as well as it is suitable for riparian zones.

Weed Common name (Scientific name)	Weed (US Code)	Treatment	Cost ($ ha^{-1})	Duration (years)	Riparian
Cheatgrass (*Bromus tectorum L.*)	BRTE	Imazapic (Plateau) 0.2 kg ai + 0.25 % v/v NIS	69.60	2	Yes
Spotted knapweed (*Centaurea biebersteinii DC.*)	CEBI2	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Diffuse knapweed (*Centaurea diffusa Lam.*)	CEDI3	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Rush skeletonweed (*Chondrilla juncea L.*)	CHJU	2,4-D 2.1 kg ae	13.15	1	Yes
Rush skeletonweed (*Chondrilla juncea L.*)	CHJU	Clopyralid (Transline) 0.4 kg ae	103.29	2	No
Common crupina (*Crupina vulgaris Cass.*)	CRVU2	Metsulfuron (Escort) 0.04 kg ai + 0.25 % v/v NIS	37.22	1	Yes
Common crupina (*Crupina vulgaris Cass.*)	CRVU2	Picloram (Tordon) 0.3 kg ae	28.35	3	No
Dalmatian toadflax (*Linaria dalmatica (L.) P. Mill.*)	LIDA	Chlorsulfuron (Telar) 0.1 kg ai + 0.25 % v/v NIS	92.83	1	Yes
Scotch thistle (*Onopordum acanthium L.*)	ONAC	Metsulfuron (Escort) 0.1 kg ai + 0.25 % v/v NIS	73.06	1	Yes
Scotch thistle (*Onopordum acanthium L.*)	ONAC	Picloram (Tordon) 0.2 kg ae	21.26	2	No
Sulfur cinquefoil (*Potentilla recta L.*)	PORE5	Aminopyralid (Milestone) 0.11 kg ai	36.48	3	Yes
Puncturevine (*Tribulus terrestris L.*)	TRTE	2,4-D 2.1 kg ae	13.15	1	Yes
Puncturevine (*Tribulus terrestris L.*)	TRTE	Chlorsulfuron (Telar) 0.075 kg ai + 0.25 % v/v	69.97	2	Yes
Common mullein (*Verbascum thapsus L.*)	VETH	Metsulfuron (Escort) 0.04 kg ai + 0.25 % v/v NIS	37.22	1	Yes

2.2.3.1 Prioritization Scheme

WTP evaluates the effectiveness of alternative treatment plans based on total infestation area weighted by weeds and sites priorities for specific locations on the landscape (Equation 2.1). Highest priorities are given to areas overlapping high priority weed species and high priority sites such as road and trails buffers. Weed species and sites priorities used in this application are the same established for the application developed in Chapter 1. The highest site priority was given to the areas within 120m from roads, and the second highest priority was given to the trail buffers with a buffer distance of 60m.

2.2.3.2 Annual Budget Level Scenarios

The following four increasing annual budget levels were considered in this application to analyze the effects of various treatment intensities: $25,000, $50,000, $100,000, and $150,000. Simulation of weed spread without treatments (i.e., no budget) was carried out and used for comparisons.

2.2.3.3 Random Solutions

To measure the relative quality of the optimized solutions, we generated a total of 30 random solutions under each budget scenario and compared them with the WTP solutions. The variability of these multiple random solutions can be also used to describe the feasible solution space outlined by each budget constraint. When budget constraints are more relaxed (i.e., larger budget amounts), we expect to observe larger variability of feasible solutions. In each random solution, treatment units were

randomly selected, herbicides and application methods were randomly selected from feasible options. Spread of weed species were then simulated using the spread simulation module of WTP, and objective function values were calculated for the random solutions.

2.2.3.4 SA Algorithm Parameters

The SA search algorithm requires setting up parameters such as initial temperature, ending temperature, cooling rate, and number of iterations at each temperature level. We carried out initial trials of the SA algorithm in this application with different sets of parameters, and then chose the best set of parameters that resulted in the highest performance of the algorithm (Table 2.2). We limited the total number of iterations to 1,500 in order to maintain a reasonable solution time.

Table 2.2. Simulated annealing algorithm parameters.

Algorithm parameter	Value
Initial temperature	145,814
Ending temperature	10
Cooling rate	0.88
Number of iterations at each temperature level	20

2.3 RESULTS AND DISCUSSION

2.3.1 Optimized Treatment Plans

The total areas selected for treatments ranged from 1,485 to 7,134 ha across four different annual budget levels (Figure 2.5). It is observed that lower priority areas are considered for treatment only when budget is still available after high priority areas are exhausted; high priority areas predominated for treatment in low budget scenarios (i.e., $25,000 and $50,000), whereas low priority areas started appearing in the solution at higher budget levels.
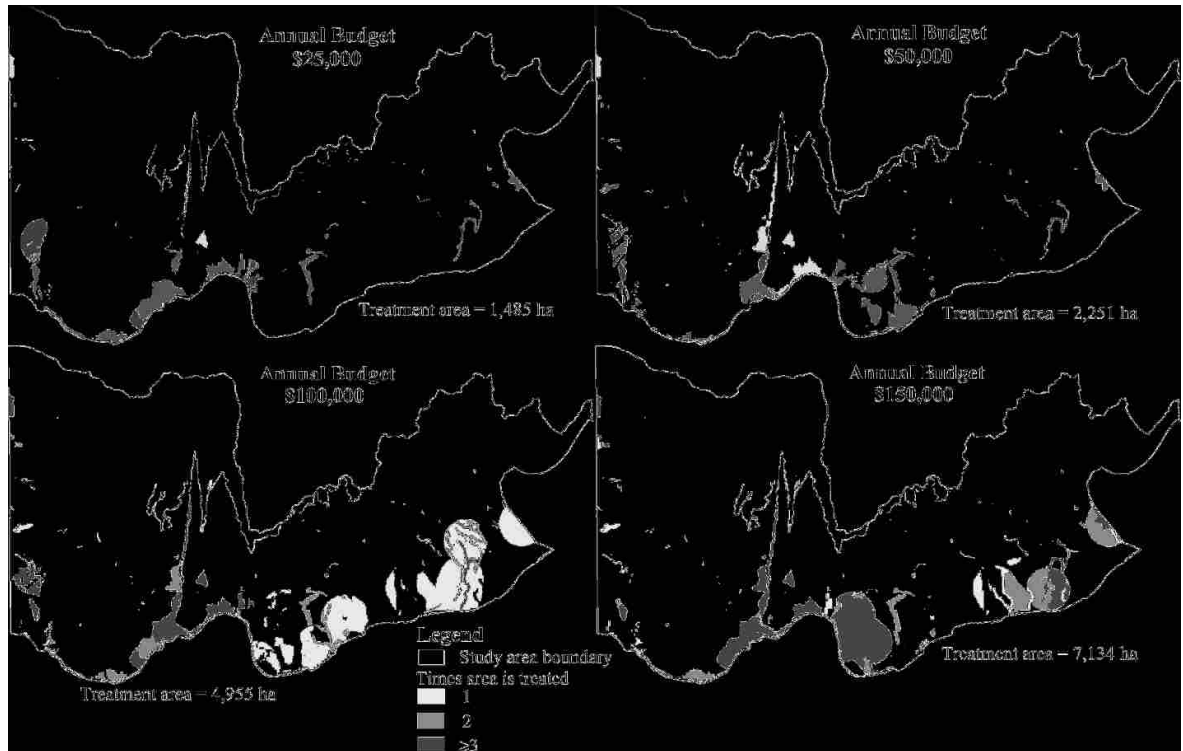
Figure 2.5. Treatment locations selected in the optimized five-year treatment plans under different annual budget levels. Gray tones indicate how many times the same area gets treated within 5 years (i.e., retreatment).

Because the duration of treatment effects considered in this application lasts no more than 3 years, the system selected some areas for retreatment during the five-year planning horizon. The total areas selected for retreatment (i.e., at least three times) ranged from 75 ha to 1,455 ha across budget levels (Table 2.3). In low budget scenarios (i.e., $25,000 and $50,000), WTP put treatment efforts towards high priority areas across the landscape, resulting in most areas receiving a single treatment. When budget becomes less restrictive, many areas could afford multiple treatments over five years, especially where treatment effects do not last long.

Table 2.3. Retreated areas (ha) during the five-year planning horizon in each budget level scenario.

Number of treatments	Annual budget (K$)			
	25	50	100	150
1 (single treatment)	688	807	1,620	315
2 (retreatment)	261	146	518	694
at least 3 (retreatment)	75	304	646	1,455

Although most weeds targeted for treatment followed the established prioritization (Table 2.4), Diffuse knapweed, the highest priority weed in this application, received only small areas of treatment between 0.0 and 0.5 ha across budget levels. This was due to the effects of the small initial infestation (i.e., 0.2 ha), the low spread rate of the species, and the fact that in the model the size of the infestation is not considered in the prioritization for treatment. The next priority species (i.e., Spotted knapweed, Rush skeletonweed, and Scotch thistle) were assigned with the largest amount of treatments across budget levels. Unlike Diffuse knapweed, these three species have large initial infestations and high spread rates. Therefore, the system put control efforts toward these three weeds in order to minimize infestation area over time. Puncturevine did not receive any treatment under any budget levels because it has a low priority and small initial infestation.

Table 2.4. Total area (ha) selected for treatment per weed in the five-year treatment plans under different budget levels.

Weed	Priority	$25K	$50K	$100K	$150K
Cheatgrass	5	0.2	0.5	0.5	0.5
Spotted knapweed	2	255.1	422.7	570.5	642.3
Diffuse knapweed	1	0.0	0.5	0.5	0.4
Rush skeletonweed	2	843.2	1304.7	3,445.3	5,946.1
Common crupina	5	0.0	1.8	9.0	17.0
Dalmatian toadflax	4	0.0	1.4	1.5	2.8
Scotch thistle	3	378.6	487.9	883.7	470.9
Sulfur cinquefoil	5	0.8	1.7	9.6	9.8
Puncturevine	5	0.0	0.0	0.0	0.0
Common mullein	4	7.3	29.8	34.4	44.6
Total		1,485.2	2,251.0	4,955.0	7,134.4

Results on selected application methods show that helicopter was the dominant method across all budget level scenarios (Table 2.5). ATV and backpack were the next most selected methods. The selection of the remaining application methods was marginal and limited to very small areas. These results are mainly because WTP was designed to prioritize the least-cost application method (e.g., helicopter), as long as there exists a group of infestation areas nearby that can be treated with the same

herbicides at the same time and is also large enough in size to warrant high fixed-cost

application methods.

Table 2.5. Total treatment area (ha) summarized by application method under each

budget level.

Application method	$25K	$50K	$100K	$150K
Helicopter	1,362.3	1,847.4	4,475.5	6,499.4
Backpack	9.6	147.6	253.0	381.3
ATV	108.0	236.2	201.0	226.3
Horse	5.3	19.8	25.5	27.4
Truck	0.0	0.0	0.0	0.0
Total	1,485.2	2,251.0	4,955.0	7,134.4

2.3.2   Total Predicted Infestation Area

Total predicted infestation areas at the end of the five-year planning horizon

range from 3,187 to 5,626 ha (Table 2.6). The results show that the larger the

allowable budget is the larger reduction in total infestation areas are realized compared

to the no treatment scenario. The reductions range from 5.7% when annual budget is

$25,000, to 43.4% when budget level is set at $150,000. If compared with the manual

treatment plan developed in Chapter 1 at the same budget level of $150,000, the

manual plan achieved only a 25.9% reduction in total infestation area, far less than the

amount of reduction realized by the optimized plan.

Predicted infestation area by weed species without treatment show that there would be large infestations of Spotted knapweed, Rush skeletonweed, and Scotch thistle at the end of the fifth year (Table 2.6). This can be explained by the large initial infestation area and the large spread rates of the last two weed species (i.e., 1,000 m yr^{-1}). Although Spotted knapweed has a slower spread rate than the other two species, the future infestation of the species is also large because most all vegetation types in the application are susceptible to its invasion without disturbance.

Under the treatment scenarios, the abovementioned three species receive a large amount of treatment (Table 2.4), and thus present a relatively large reduction in predicted infestation compared to that of the no treatment scenario (Table 2.6). Some other species such as Diffuse knapweed, Common crupina and Puncturevine do not show any increase from their initial infestation even without treatments because the vegetation surrounding their current infestation is not susceptible to invasion unless disturbed.

Table 2.6. Predicted infestation area (ha) per weed species at the end of five-year planning horizon under each budget scenario.

Weed	Initial infested area	No treatment	$25K	$50K	$100K	$150K
Cheatgrass	2.3	4.8	4.8	4.8	4.7	4.8
Spotted knapweed	332.2	710.6	599.0	611.9	579.0	583.3
Diffuse knapweed	0.2	0.2	0.2	0.2	0.2	0.2
Rush skeletonweed	664.4	4,012.2	3,816.1	3,591.6	3,143.8	2,201.1
Common crupina	9.3	9.3	9.3	9.3	9.3	9.3
Dalmatian toadflax	1.8	2.7	2.7	2.7	1.8	1.8
Scotch thistle	101.1	815.4	804.1	803.7	424.7	322.7
Sulfur cinquefoil	5	7.4	7.4	6.7	7.4	6.7
Puncturevine	0.7	0.7	0.7	0.7	0.7	0.7
Common mullein	32.9	62.7	62.2	56.1	59.6	56.1
Total	1,149.9	5,626.0	5,306.5	5,087.7	4,231.2	3,187.3

2.3.3 WTP Solution Quality

Compared to the no treatment scenario, optimized weed treatment plans were able to reduce the objective function values (i.e., total weighted infestation measured at the tenth year) by 7%, 11%, 18% and 32% under $25K, $50K, $100K and $150K budget levels, respectively, while the reductions made by random solutions under each budget level were only 2%, 3%, 7% and 11% (Table 2.7). We also compared total infestation area in hectares measured at the fifth year between optimized and random solutions, where optimized solutions also resulted in larger reductions than random

solutions (Table 2.8). These comparisons indicate that WTP was able to find more

effective treatment plans than random solutions at the same budget level.

Table 2.7. Comparison of objective function values between optimized solutions and

the average of 30 random solutions in each budget scenario.

Annual budget ($)	Optimized solutions		Average of random solutions	
	Objective function	% reduction from no treatment	Objective function	% reduction from no treatment
No Treatment	47,709	0	47,709	0
25,000	44,507	7	46,562	2
50,000	42,598	11	46,242	3
100,000	39,137	18	44,599	7
150,000	32,381	32	42,422	11

Table 2.8. Comparison of total infested area (ha) measured at the end of fifth year between optimized solutions and the average of 30 random solutions in each budget scenario.

Annual budget ($)	Optimized solutions		Average of random solutions	
	Total infested area	% reduction from no treatment	Total infested area	% reduction from no treatment
No Treatment	5,626	0	5,626	0
25,000	5,307	6	5,539	2
50,000	5,088	10	5,433	3
100,000	4,231	25	5,165	8
150,000	3,187	43	4,786	15

In order to describe the solution space of the weed treatment planning problem, variations in the 30 random solutions are presented in box plots in terms of objective function value and total infestation area (Figure 2.6). In both objective function value and total infestation area, it is observed that variability increases as budget level increases. This is because a large budget can simply allow more treatment options to be considered. It is noteworthy that WTP was able to find solutions that are far better than the best random solutions. Black dots in Figure 2.6 indicate: a) the objective function value, and b) total infestation area of the WTP solutions.
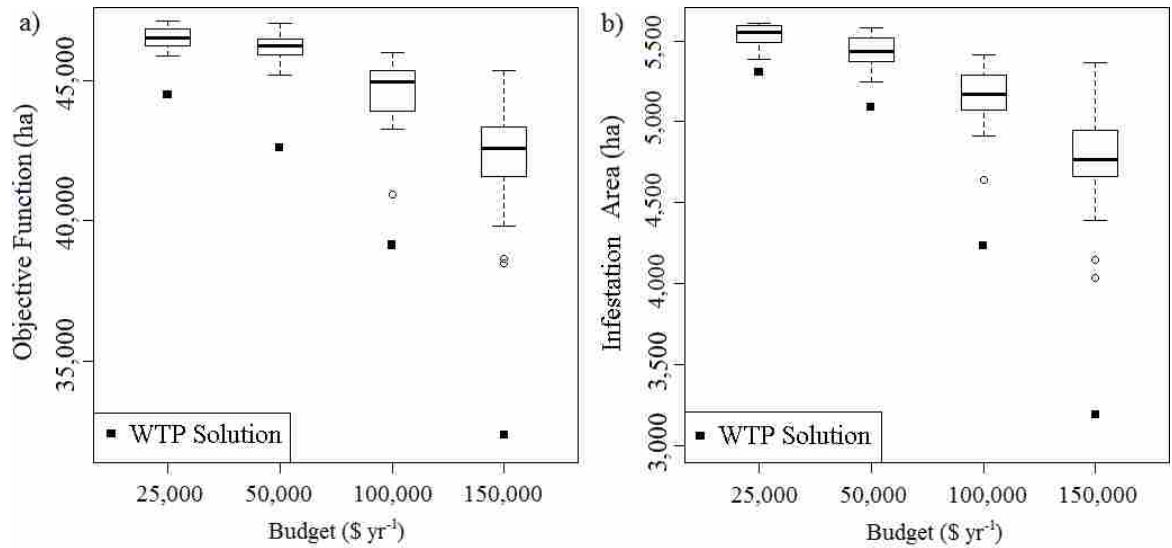
Figure 2.6. Box plots of 30 random solutions in each budget level scenario in terms of a) objective function value and b) total infested area. Outliers are represented by void circles.

2.3.4 Performance of SA Algorithm

Figure 2.7 presents changes in objective function value of intermediate solutions accepted by the SA algorithm throughout the search process. It is observed that the algorithm occasionally accepts worse solutions (i.e., solutions with higher objective function value than the previously selected solution) prior to making a large improvement (i.e., large drops in Figure 2.7). Large pulses of objective function value can be found in the early iterations of the search process where the temperature, one of the algorithm parameters, is high allowing extensive exploration of solution space. This amplitude of fluctuation decreases as the algorithm moves towards the end where

the temperature is low. At this stage, the SA algorithm accepts inferior solutions less frequently and the search becomes merged into a final solution.
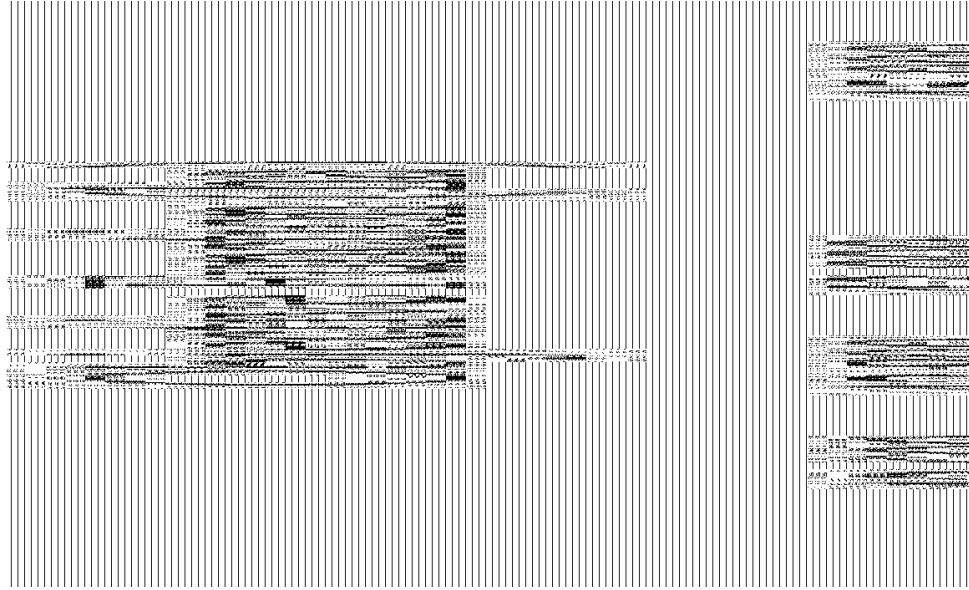
Figure 2.7. Performance of the SA algorithm in finding less infestation areas over time solutions throughout the search process for the $50,000 annual budget scenario.

Table 2.9 presents the computation times required to solve the treatment planning problems using WTP. WTP was run on a 3.39 GHz computer with 4GB of RAM. The average computation time per iteration of the SA algorithm was 3.87 minutes. Although the SA algorithm ran the same number of iterations (i.e., 1,500) on each budget scenario, total solution times were different across the budget scenarios. We noticed that simulation of weed spread was the most time consuming process in the search process and less budget scenario requires more solution time because larger areas of infestation need to be simulated.

Table 2.9. Solution time required by WTP to solve weed treatment planning problems.

Annual budget (K$)	Solution time (hours)
25	115
50	102
100	91
150	79

2.4   CONCLUDING REMARKS

WTP was able to automatically generate and analyze multiple weed treatment plans under each budget level, and then choose the best solution in terms of a given objective function using a modern heuristic optimization technique. However, the system relies heavily on accuracy and quality of input data, which are not always readily available. Obtaining surrogates or using expert judgment could be a way to overcome the unavailable data issue, but users should be cautious in interpretation of the solutions when input data are incomplete or less accurate.

The system's ability to consider budget constraints allows trade-off analyses among different budget levels. These analyses can assist weed managers to evaluate costs and potential benefits of alternative treatment plans and determine the most suitable treatment plan to accomplish their desired goals. Furthermore, the use of this system would also help weed managers prepare and justify their budget use and request, as they can predict outcomes of various budget scenarios.

Although the objective function combines weeds and sites priorities to capture weed managers' common practices on determining areas for treatment, it does not consider the size of polygons. Size of infested polygons could also serve as a factor affecting selection of treatment areas because it may be easy to contain small polygons before they get larger and more difficult and costly to manage.

Our DSS developed as an extension tool for ArcMap® offers an easy-to-use tool for complex and difficult planning tasks. Weeds database in the United States are already in ArcGIS database formats (USDA 2013), and so it would be easy for land management agencies to adopt and use this system without additional workforce development.

Although SA is known as a highly efficient heuristic algorithm, it requires a large solution time to run WTP due to complexity of simulation over multiple weed species, multiple time periods across a large landscape. We noticed that the most time consuming process is the simulation of weed spread, especially ones with large spread rates. Future studies should investigate modification to the SA algorithm and weed spread logics to further improve the current solution search process.

Finally, WTP considers only herbicides as treatment options for weed control. Future studies should also investigate incorporation of other treatment options such as mechanical and biological controls to provide the capability of trade-off analysis on full suite of weed control options. However, the efficacy of such controls need to be quantified prior to incorporation.

2.5 ACKNOWLEDGEMENTS

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CHAPTER 3:

INCORPORATING A PREDICTIVE WEED SPREAD MODEL OF YELLOW

STARTHISTLE (*Centaurea solstitialis L.*) INTO WEED TREATMENT

PLANNER (WTP)

3.0   ABSTRACT

Weed management is complex due to a multiplicity of factors, and thus it is not an easy task for weed managers to analyze trade-offs among treatment options. Weed Treatment Planner (WTP) a computer-based decision support system may offer weed managers a tool to facilitate treatment decisions. However, WTP requires among other information accurate prediction of weed spread across a landscape to produce reliable results. A recent study developed a new spread model for Yellow starthistle (*Centaurea solstitialis L.*) based on cost surface analysis (CSA). This approach allows the consideration of site specific characteristics of each location on a landscape that influence weed spread. In this study we incorporated this new weed spread prediction model into WTP in order to reflect more realistic movement of weeds in treatment decision-making. A case study was developed to evaluate the effects of the new weed spread model used in WTP on treatment decisions. Comparisons with linear spread model results show that the total predicted infestation areas are similar between the two weed spread modeling approaches, but locations selected for treatment in WTP solutions are significantly different. For demonstration purposes, we developed five-year weed treatment plans using WTP in a multiple weeds management scenario where Yellow starthistle was considered one of the target weed species.
Key words: cost surface analysis, spread model, weed management.

3.1   INTRODUCTION

Weed management is complex because of the diversity of species, treatment
options, and many possible locations and timing of treatments. Because of this
complexity, it is not an easy task to develop and analyze trade-offs among treatment
alternatives, and make best decisions for efficient use of limited resources. A
computer-based decision support system, such as Weed Treatment Planner (WTP)
described in Chapter 2, may offer weed managers a tool to simulate, analyze, and
optimize the effects of treatment options and thus help them make informed decisions
in weed management. However, such decision support systems require accurate
information on current infestation, prediction of weed spread across a landscape, and
efficacy of treatments in order to produce reliable results. Accurate prediction of weed
spread over time is particularly important in treatment scheduling, but it is difficult
because there are many influencing factors and their combined effects on weed spread
that have not been understood.

Chapter 2 describes the use of WTP with simple linear weed spread models.
However, there is a consensus in the weed ecology community that the spread of
weeds over heterogeneous landscapes cannot be simply described in terms of linear
spread rates (Hastings et al. 2005; With 2002). To improve weed spread prediction,
there has been large effort in studying and modeling weed spread by using a wide
range of techniques from diffusion to spatially explicit individual-based models.
Diffusion models use partial differential equations to predict population density across
a two-dimensional space over time series usually by using two parameters: the rate of

spread and a probability density distribution of plants per unit area. This approach predicts weed spread across an arbitrary landscape assuming the landscape is homogenous, and thus it does not consider site-specific conditions existing in a real landscape (Allen et al. 1991; Higgins and Richardson 1996). In contrast, individual-based models explicitly incorporate site-specific conditions across a given landscape, but require significant amount of data to characterize realistic behavior of each plant in a given space and time (Ruckelshaus et al. 1997). Cost surface analysis (CSA), on the other hand, is another spatially explicit spread model but demands less data than individual-based models.

CSA is a spatially-explicit modeling approach based on graph theory (Bunn et al. 2000) that uses a network model to calculate the cost of traveling from one point to another. CSA applications widely vary from routing problems (Collischonn and Pilar 2000) to ecological applications such as landscape connectivity (Bunn et al. 2000; Adriaensen et al. 2003) and dispersal of organisms (Driezen et al. 2007; Gonzales and Gergel 2007; Lass et al. 2011a). The basic input data for CSA to model weed spread include two geographic information system (GIS) layers; a source layer representing current infestations and a "friction" or "cost surface values" layer that characterizes the permeability of each location on a landscape for weed spread. The underlying assumption of this modeling approach is that there exist landscape features that present different degrees of resistance for weed movement, which allows consideration of spatial and site specific characteristics of each location on a landscape that influence distance and direction of weed spread.

CSA usually performs well when weed movement is primarily driven by landscape itself, not by animals or anthropogenic factors (Gonzales and Gergel 2007). Lass et al. (2011a) developed friction values for movement of Yellow starthistle (*Centaurea solstitialis L.*) based on a productivity model that was derived from factors such as topography, solar radiation, and vegetative productivity. Using these values in a CSA framework, the authors predicted Yellow starthistle spread and evaluated the accuracy of the predictions against historic data. They found that the CSA modeling approach was able to estimate Yellow starthistle more accurately than commonly used linear spread rates.

The objective of this study is to incorporate this new weed spread prediction model into Weed Treatment Planner (WTP) in order to reflect more realistic movement of weeds in treatment decisions. We developed an algorithm to predict movement of Yellow starthistle over time based on the friction values computed by Lass et al. (2011a) across a study landscape in Idaho. We then incorporated the algorithm into WTP to spatially estimate the effects of potential treatments on spread of Yellow starthistle. For demonstration purposes, we developed five-year weed treatment plans using WTP in a multiple weeds management scenario where Yellow starthistle was considered one of the target weed species. Yellow starthistle is selected for this study because its friction values are currently available, and it is considered as one of the most serious rangeland, grassland and wildland weeds in the northwestern United States. The species is known to have negative impacts on wildlife habitat and forage, displacement of native plants and their diversity, and fragmentation of plant and animal habitat (Sheley et al. 1999, Scott and Tratini 1995, DiTomaso 2006).

Although this study compares the WTP outputs (i.e., five-year weed treatment plans) between the two weed spread modeling approaches (i.e., CSA and linear rates), it is out of the scope of this study to validate the accuracy of either of the modeling approaches.

3.2   MATERIALS AND METHODS

Prediction of weed spread using the CSA approach requires friction values computed for each location across a given landscape. In this study, we used friction value surface developed by Lass et al. (2011a) for Yellow starthistle as site-specific permeability to the movement of the weed. In order to predict annual distance and direction of Yellow starthistle movement, we developed a cost-distance algorithm and incorporated it into WTP to provide users with the CSA approach as an additional weed spread modeling option in WTP.

3.2.1   Cost-distance Algorithm

The cost-distance algorithm requires two raster datasets of a given landscape: a source raster layer showing currently infested grid cells and a cost surface or friction value raster layer representing the permeability of each grid cell to weed movement. The value in each grid-cell in the friction layer indicates relative "resistance" or "cost"

per unit distance of annual weed movement through the cell. In the cost-distance

algorithm, all grid cells are represented as links and nodes forming a network, where

each grid cell is connected to its eight neighbor grid cells (Figure 3.1). Since the

center of each grid cell is assumed to serve as a node in the network, the "cost" of

weed movement from one cell to the next can be estimated by averaging the costs of

two associated grid cells multiplied by distance between the centers of the two grid

cells. Equation 3.1 is used to estimate the cost when weed moves horizontally or

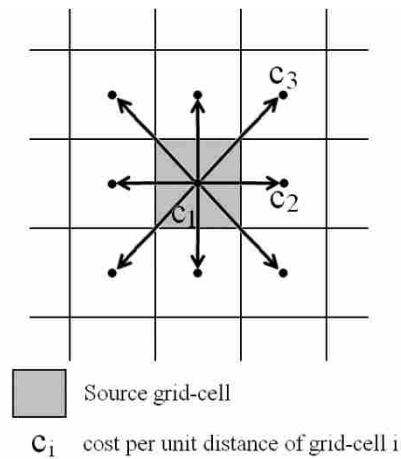vertically, whereas Equation 3.2 represents the case when weed moves diagonally.

Figure 3.1. Link connection representation.

$$\text{cost} = \frac{c_1 + c_2}{2} csize \qquad [3.1]$$

$$\text{cost} = \frac{c_1 + c_3}{2} \sqrt{2 \times csize^2} \qquad [3.2]$$

98

Where, c_1 is the cost value of source grid cell, c_2 is the cost of adjacent grid cell when weed moves horizontally or vertically, c_3 is the cost of adjacent grid cell when weed moves diagonally, and *csize* is the size of grid cell. In a centrifugal fashion starting from the source grid-cells, the algorithm determines minimum accumulated cost of weed movement to reach every grid-cell in the landscape. Weed moves during a given time span along the paths of least resistance in terms of cost of movement. Figure 3.2 is an example of algorithm results showing new infested grid-cells. Weed moves in an anisotropic pattern, faster toward the east than the west from the source grid-cell, indicating that cost is less toward the east than the west.

Figure 3.2. An example result of the cost-distance algorithm showing an anisotropic pattern of weed spread.

Two additional functions are necessary in the cost-distance algorithm prior to being incorporated into WTP: i) prediction of treatment effects and ii) "undo" of weed spread to facilitate neighbor solution generation during the Simulated Annealing

search process (Chapter 2). For the first function, we designed the algorithm to check previous treatments and duration of treatment effects on each grid cell prior to determining whether or not the target weed would spread to adjacent cells in a particular year. For the second function, we developed a reverse spread function using the idea of the Cost Back Link tool in ArcGIS (ESRI 2011). While running the cost-distance algorithm, for each grid cell we record the direction (i.e., grid-cell) from which the weed comes from, and we use this information to backtrack the spread of weed to undo the treatment when necessary.

3.2.2   Application - A Case Study

We applied the modified WTP to a study landscape of 13,250 ha located in the western portion of the Nez Perce National Forest in Idaho (Figure 3.3) where friction data are available for Yellow starthistle (Lass et al. 2011a). Currently infested area in Figure 3.3 considers eleven weed species with individual infested areas presented in Table 3.1.
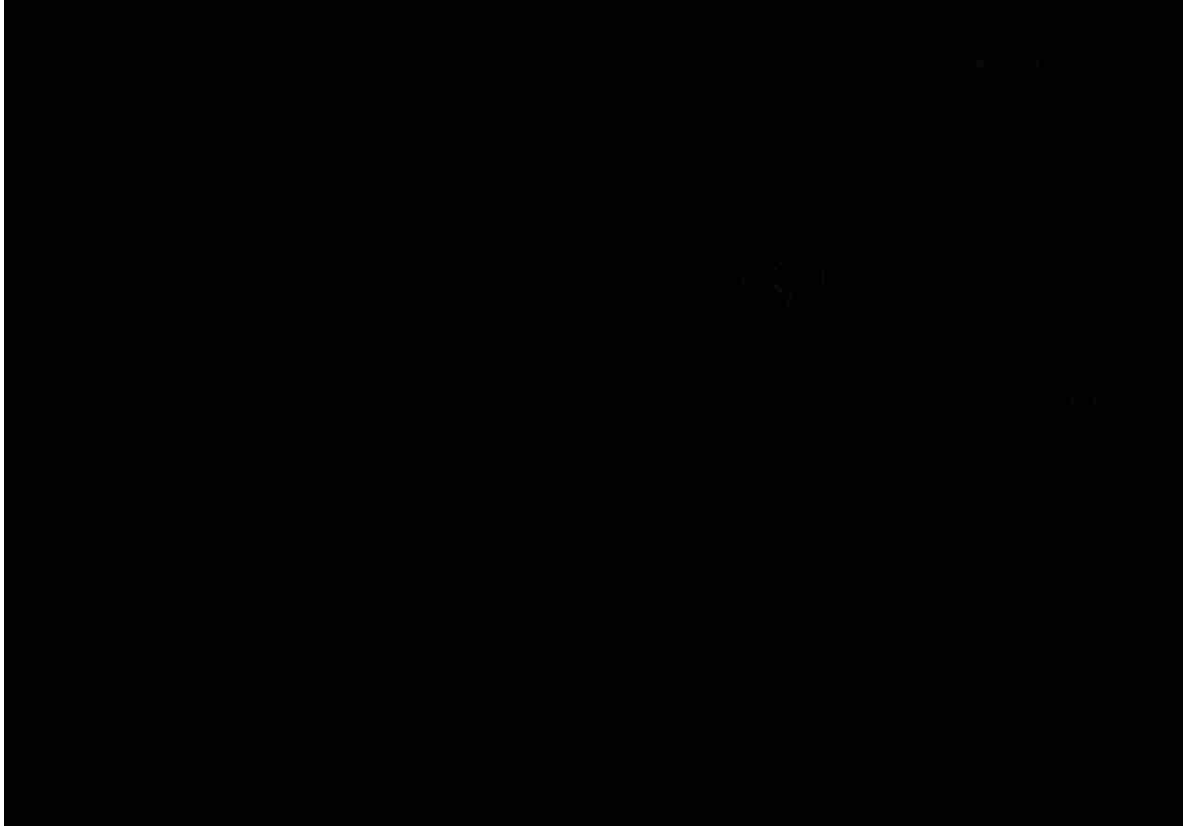
Figure 3.3. Study landscape located in the Nez Perce National Forest in Idaho.

3.2.2.1 Cost surface data for Yellow starthistle

Friction values developed by Lass et al. (2011a) for Yellow starthistle movement across the study landscape (Figure 3.4a) range from 0 (i.e., no friction) up to 10 (i.e., maximum force). The lighter areas in Figure 3.4a represent the more favorable environment for the spread of Yellow starthistle. We observe a correspondence between current locations of Yellow starthistle and low friction values, particularly the larger polygons towards the south-east corner of the study landscape (Figure 3.4b). These areas might have a high risk of invasion of Yellow starthistle due to the proximity to the current infestation and the favorable environment for invasion.
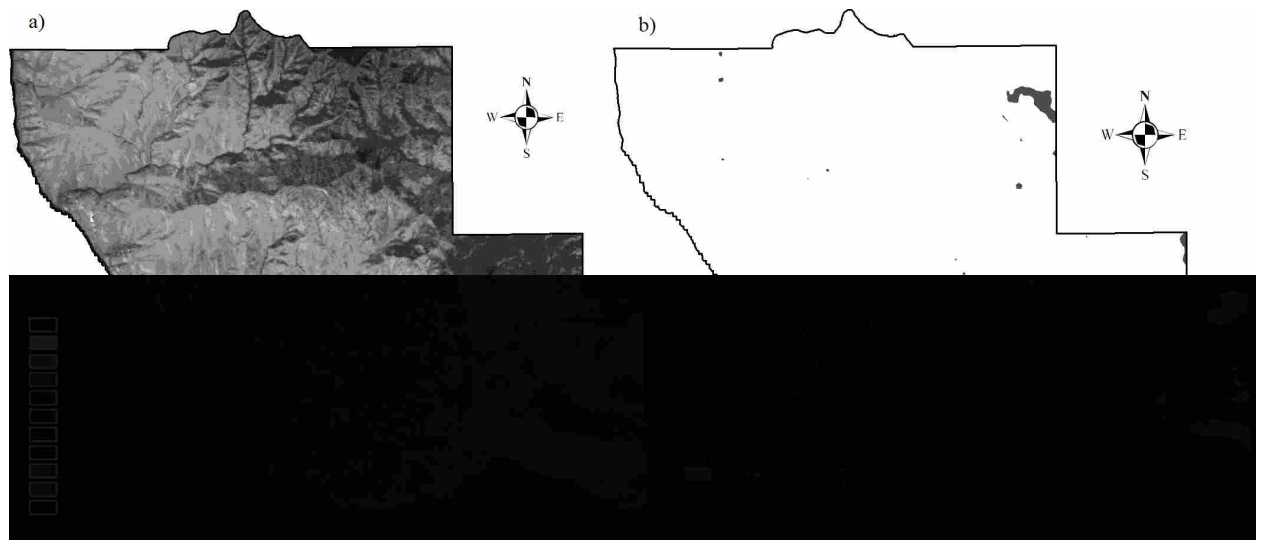
Figure 3.4. Study landscape with a) friction values for Yellow starthistle, where 0 represents no friction (i.e., weed can move through without landscape resistance) and 10 represents the highest friction against weed movement, and b) initial infestation areas of Yellow starthistle.

3.2.2.2 Treatment Planning Scenarios

Two scenarios were developed in this application: one considering a single weed species (Yellow starthistle) to evaluate the effects of the two weed spread modeling approaches (i.e., CSA and linear spread) on treatment decisions, and the second scenario considering treatments of multiple weeds where the CSA approach was used for Yellow starthistle while linear spread models were used for all the other species.

In the first scenario, we ran WTP with a low annual budget of $3,000 because there is only one target species. We also ran WTP without treatment to provide a base case for comparison. In the second scenario, we ran WTP on eleven weed species including Yellow starthistle assuming an annual budget for treatment of $75,000. We

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also ran no treatment scenario on the eleven weed species as a base case for comparison.

3.2.2.3 Multiple weed species and other WTP input data

Eleven weeds were found in the study landscape ranging from 0.3 ha for Dalmatian toadflax (*Linaria dalmatica (L.) P. Mill.*) to 496.4 ha for Rush skeletonweed (*Chondrilla juncea L.*) (Table 3.1).   In consultation with local weed ecologists and managers we estimated spread rates, management priorities (Table 3.1), and susceptibility of vegetation cover types for the study landscape (Table 3.2) (Peter Rice, Pat Green, Carl Crabtree and Timothy Prather[9], personal communication). Predominantly, vegetation in the study landscape requires disturbance to be susceptible to invasion (Table 3.2), and then a wildfire in 2007 affecting 10,317 ha of the landscape (Figure 3.5) was considered to produce effects on weed spread until the second year of the five-year planning horizon.

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[9] Peter Rice, Research Associate, Division of Biological Sciences, The University of Montana; Pat Green, USDA Forest Service Soil Scientist/Ecologist, Nez Perce National Forest; Carl Crabtree, Idaho County Weed Superintendent; and Timothy Prather, Associate Professor, Weed Ecology, University of Idaho.

Table 3.1. Common and scientific names of weeds, US codes, initial infestation areas, priorities and spread rates for the study landscape.

Weed Common name (Scientific name)	Weed (US Code)	Area (ha)	Priority (1: highest - 5: lowest)	Spread Rate (m yr^{-1})
Musk thistle (*Carduus nutans L.*)	CANU4	0.5	1	50
Spotted knapweed (*Centaurea biebersteinii DC.*)	CEBI2	36.9	2	10
Diffuse knapweed (*Centaurea diffusa Lam.*)	CEDI3	7.0	1	100
Yellow starthistle (*Centaurea solstitialis L.*)	CESO3	223.2	2	15
Rush skeletonweed (*Chondrilla juncea L.*)	CHJU	496.4	2	1,000
Canada thistle (*Cirsium arvense (L.) Scop.*)	CIAR4	0.5	3	1,000
Common crupina (*Crupina vulgaris Cass.*)	CRVU2	126.2	5	10
Dalmatian toadflax (*Linaria dalmatica (L.) P. Mill.*)	LIDA	0.3	4	50
Scotch thistle (*Onopordum acanthium L.*)	ONAC	171.2	3	1,000
Sulfur cinquefoil (*Potentilla recta L.*)	PORE5	1.6	5	10
Puncturevine (*Tribulus terrestris L.*)	TRTE	3.6	5	25
Total		1,067.4		

Table 3.2. Vegetation susceptibility matrix for the study area.

Vegetation	Area (ha)	Weeds (US Code)										
		CANU4	CEBI2	CEDI3	CESO3	CHJU	CIAR4	CRVU2	LIDA	ONAC	PORE5	TRTE
Abies grandis (dry type)	1,659	D	I	D	D	D	I	C	D	C	D	C
Abies grandis (moist type)	1,617	D	I	D	D	D	I	C	D	C	D	C
Abies grandis (wet type)	857	D	I	D	D	D	I	C	D	C	D	C
Dry species grassland type	1,509	D	D	D	D	D	D	D	D	D	I	D
Dry species shrubland type	11	D	I	D	D	D	D	C	D	D	I	D
Festuca idahoensis (grassland type)	46	I	I	D	D	D	I	D	D	D	I	D
Mesic species shrubland type	33	D	D	D	D	D	D	C	D	D	D	D
Pinus ponderosa	991	D	I	D	D	D	D	D	D	D	I	D
Pseudotsuga menziesii (cool dry type)	33	I	I	D	D	D	I	D	D	C	I	D
Pseudotsuga menziesii (moist type)	5,378	I	I	D	D	D	I	D	D	C	I	D
Pseudotsuga menziesii (warm dry type)	3	I	I	D	D	D	I	D	D	C	I	D
Rock, barren areas, and mines	1,090	C	D	D	D	D	C	C	D	I	D	I
Water	23	C	C	C	C	C	C	C	C	C	C	C

Where, I: vegetation is susceptible of invasion, C: vegetation is closed to invasion, and D: disturbance allows invasion.
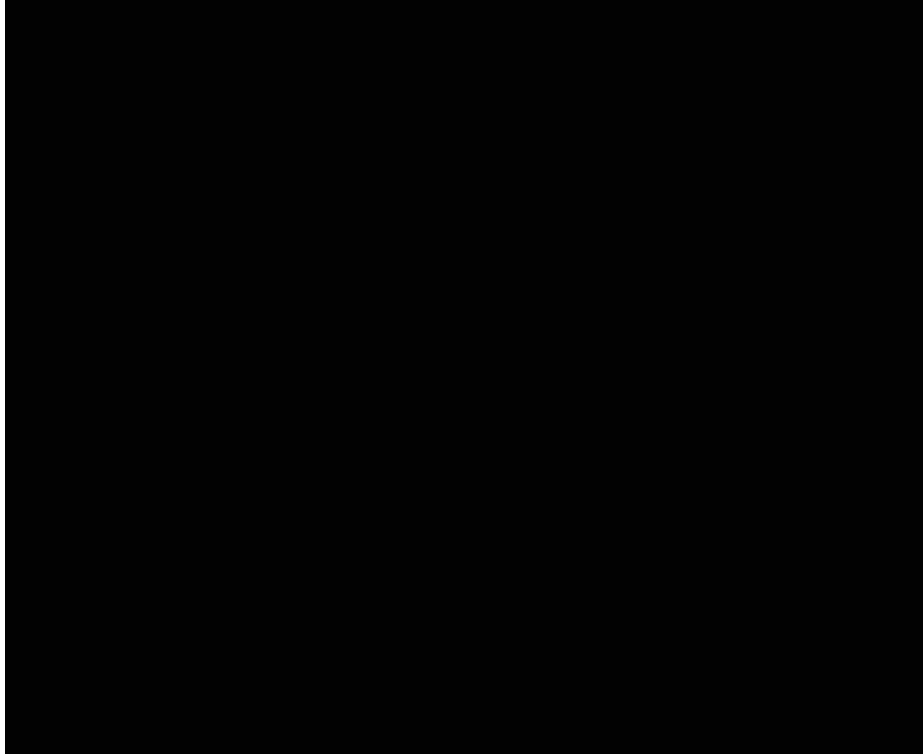
Figure 3.5. Past disturbances (fire) identified across the landscape study area.

Herbicide treatment options applicable to the weeds were identified in consultation with local weed managers (Table 3.3). For Musk thistle (*Carduus nutans L.*), Rush skeletonweed (*Chondrilla juncea L.*), Common crupina (*Crupina vulgaris Cass.*), Scotch thistle (*Onopordum acanthium L.*), and Puncturevine (*Tribulus terrestris L.*) two options were developed because one of them may not be used in riparian areas or because of differences in the duration of effects such as the case of Puncturevine. Riparian areas totaling 578 ha were designated around streams to protect water resources. Five herbicides application methods were considered for the study landscape (all terrain vehicle (ATV), horse, truck, backpack sprayer, and helicopter) with the same costs, accessibility and treatment size requirements as described in Chapter 1.

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Table 3.3. Herbicides treatment options available to treat weeds within the study landscape.

Weed	Treatment per hectare	Cost ($ ha^{-1})	Duration (years)	Riparian
Musk thistle	Picloram (Tordon) 0.3 kg ae	28.35	3	No
Musk thistle	Aminopyralid (Milestone) 0.09 kg ai	30.4	3	Yes
Spotted knapweed	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Diffuse knapweed	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Yellow starthistle	Aminopyralid (Milestone) 0.09 kg ai	30.4	3	Yes
Rush skeletonweed	2,4-D 2.1 kg ae	13.15	1	Yes
Rush skeletonweed	Clopyralid (Transline) 0.4 kg ae	103.29	2	No
Canada thistle	Aminopyralid (Milestone) 0.12 kg ai	42.56	3	Yes
Common crupina	Metsulfuron (Escort) 0.04 kg ai + 0.25 % v/v NIS	37.22	1	Yes
Common crupina	Picloram (Tordon) 0.3 kg ae	28.35	3	No
Dalmatian toadflax	Chlorsulfuron (Telar) 0.1 kg ai + 0.25 % v/v NIS	92.83	1	Yes
Scotch thistle	Metsulfuron (Escort) 0.1 kg ai + 0.25 % v/v NIS	73.06	1	Yes
Scotch thistle	Picloram (Tordon) 0.2 kg ae	21.26	2	No
Sulfur cinquefoil	Aminopyralid (Milestone) 0.11 kg ai	36.48	3	Yes
Puncturevine	2,4-D 2.1 kg ae	13.15	1	Yes
Puncturevine	Chlorsulfuron (Telar) 0.075 kg ai + 0.25 % v/v	69.97	2	Yes

Both weed species and sites priorities were considered in the same way as in previous chapters. Weed species priorities in Table 3.1 show that Musk thistle and Diffuse knapweed are the largest priority species. In terms of sites, two sites were considered for prioritization, the highest site priority was given to the areas within 120m from roads, and the second highest priority was given to the trail buffers with a buffer distance of 60m.

3.3   RESULTS AND DISCUSSION

3.3.1   Scenario 1: Two spread modeling approaches for Yellow starthistle

The comparison of the results with the no treatment scenario shows that the two spread modeling approaches yielded similar total hectares of infestation at the end of the five-year period, but different locations of new infestation.

The CSA modeling approach yielded a total of 273.4 ha of infestation whereas the linear spread approach resulted in 257.1 ha, approximately 6% less than the CSA approach. In terms of infestation locations, a total of 38.3 ha of infestation area predicted by the CSA modeling approach were not predicted as infestation by the linear spread approach (red areas in Figure 3.6). Conversely, a total of 22.1 ha of infestation predicted by the linear modeling approach were located in high friction value areas, where infestation was not predicted by the CSA approach (green areas in Figure 3.6).
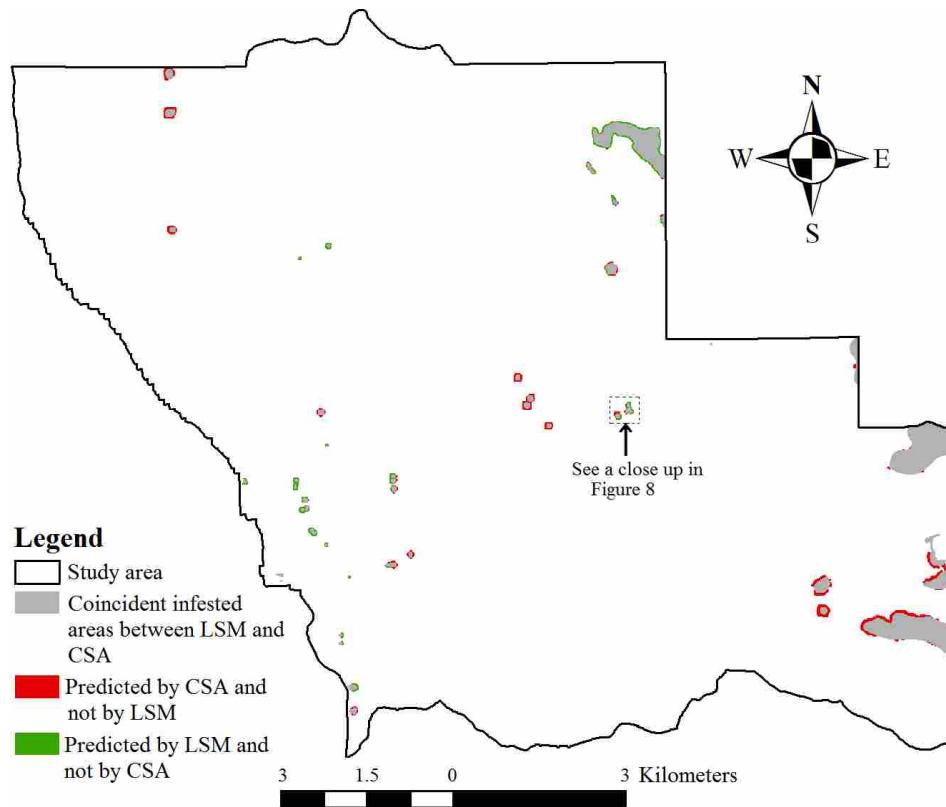
Figure 3.6. Predicted infestation areas without treatment for Yellow starthistle at the end of the five-year period (no treatment scenario). Gray areas show coincident infestation areas between CSA and linear spread modeling (LSM) approaches, this includes initial infestation; red areas are predicted infestations areas by CSA modeling approach and not predicted by linear model approach; and green areas are prediction of infestations by the linear spread modeling approach not predicted by CSA approach.

A close-up view of two infested polygons helps to explain how differences in predictions of the two modeling approaches are produced (Figure 3.7). In Figure 3.7a, the underlying friction layer shows varying values across the infestation area. These variations are responsible for anisotropic predictions of the CSA modeling approach

shown in Figure 3.7b (areas in red and yellow). On the contrary, predictions from the

linear spread modeling approach show isotropic patters of spread as vegetation in the

surrounding area was considered susceptible in all directions (areas in yellow and green

in Figure 3.7b). These discrepancies in locations obviously indicate weed spread logic

(i.e., isotropic or anisotropic) highly influences future infestation prediction, and thus an

appropriate spread modeling approach should be carefully chosen considering data

availability and management purposes.
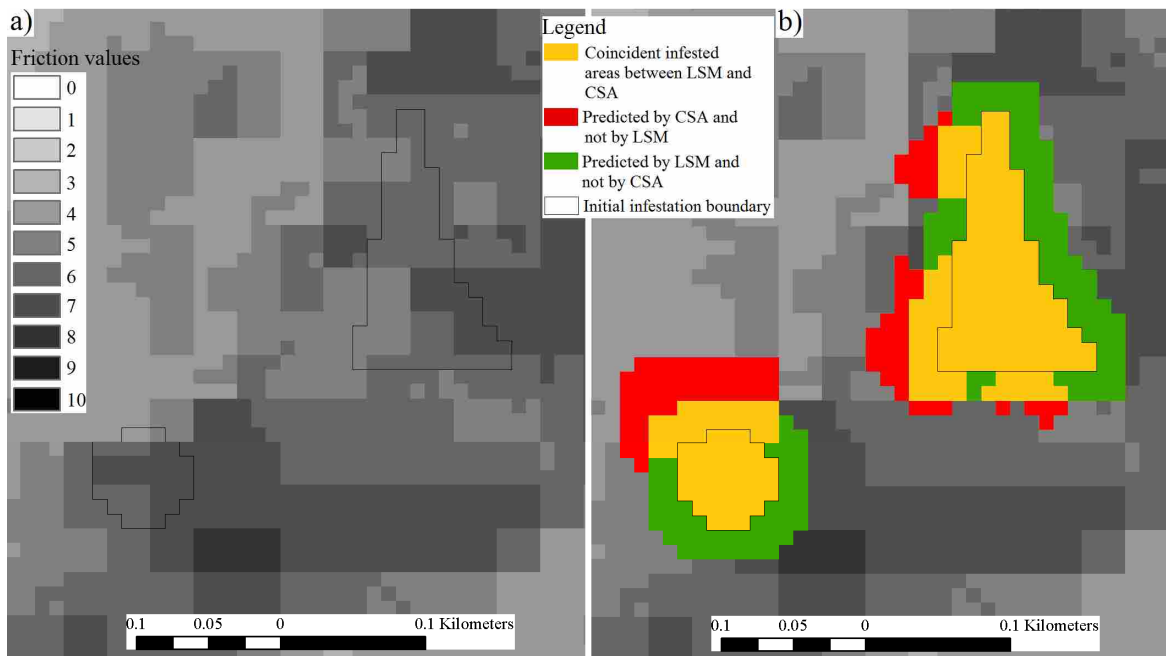
Figure 3.7. A close-up view from Figure 3.6, showing a) friction values and initial

infestation boundary, and b) predicted infestations for Yellow starthistle with common

areas (yellow) in both modeling approaches, areas (red) predicted by CSA modeling

approach not predicted by linear approach and areas (green) predicted by linear approach

and not predicted by CSA modeling approach.

Marginal difference (less than 1%) was observed on total selected treatment area, as well as treatment areas per application method between the two spread modeling approaches (Table 3.4), mainly because total treatment area is constrained by the given annual budget. However, locations of individual treatments show relatively large discrepancies when different spread model approached were used (Figure 3.8). A total of 13.2 ha of treatment areas were in common between the two spread approaches. In terms of discrepancies, a total of 5.4 ha were selected by the CSA modeling approach, but not by the linear spread approach, whereas 5.6 ha were selected by the linear spread modeling approach, but not by the CSA approach. We need to note that these areas differ from the total treatment areas in the five-year planning horizon presented in Table 3.4 because of retreatments. These differences emphasize the importance of accurate spread predictions in decision-making on treatment allocations. Prioritizing a treatment area of low risk of spread over a high risk area would not be a wise decision. A good assessment of weed spread potential is necessary for better and informed decision-making in weed management.

Table 3.4. Total treatment area (ha) by application method selected in each of the five-year treatment plan alternatives.

Spread model	ATV	Backpack	Horse	Total
Based on CSA	6.8	24.1	3.1	34.0
Linear spread	6.9	23.7	3.2	33.8
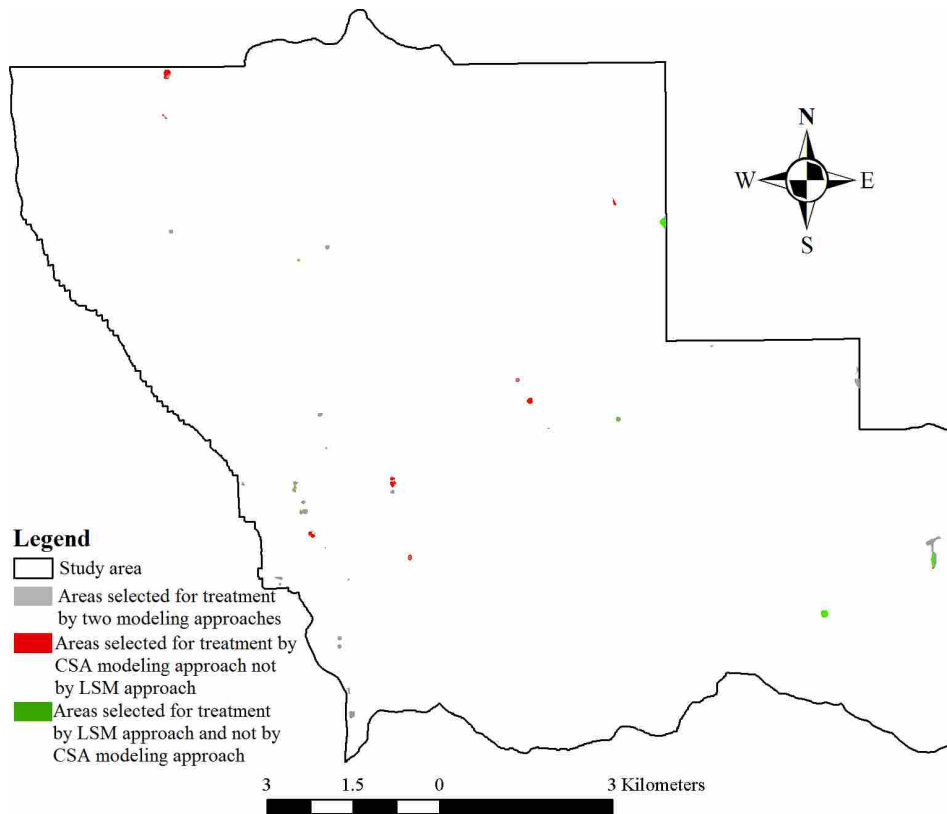
Figure 3.8. Treatment locations selected for the five-year treatment plans. Gray areas show selected treatment areas in common between CSA and linear spread modeling (LSM) approaches; red indicates the areas selected for treatment by CSA modeling approach, but not by linear model approach; and green indicates the areas selected for treatment by the linear spread modeling approach, but not by CSA approach.

3.3.2   Scenario 2: Multiple weed species management with mixed spread model approaches

We developed a five-year treatment plan for management of eleven weed species. The CSA spread modeling approach was used for Yellow starthistle, and linear spread approaches were used for the remaining species to demonstrate the WTP's capability of handling multiple spread approaches. Total treatment area selected for each weed species range from 0.8 to 3,403.3 ha (Table 3.5). Among eleven weed species, only five with highest priorities (1 and 2) were assigned treatments because of the limited budget and the weights of high priority areas largely affecting the objective function of WTP. It appears that the allocation of treatments to control a fast spreading weed such as Rush skeletonweed was using much of the budget, resulting in less resources available to treat lower priority weeds.

Table 3.5. Total treatment area (ha) per weed species selected for the five-year treatment plan.

Weed	Area
Musk thistle	0.8
Spotted knapweed	63.5
Diffuse knapweed	12.3
Yellow starthistle	418.1
Rush skeletonweed	3,403.3
Total	3,898.0

Most of the large areas selected for one-time treatment were for Rush skeletonweed (Figure 3.9), a fast spreading weed species that uses most of the budget for treatment. The WTP solution appears to be largely driven by treatments of Rush skeletonweed because of its fast spread rate and high priority.

Figure 3.9. Treatment locations selected for the five-year treatment plan shown with the number of retreatments.

Herbicides selection was performed accordingly to the weeds selected for treatment. For example, 2,4-D 2.1 kg ae and clopyralid (Transline) 0.4 kg ae were selected to treat large infestation areas of Rush skeletonweed (Table 3.6). On the other hand, picloram (Tordon) 0.3 kg ae was selected to treat musk thistle in upland areas since it is cheaper than aminopyralid (Milestone) 0.09 kg ai that is applicable in riparian areas.

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For application methods, helicopter was dominant as this method is the cheapest on a per hectare basis among the available options (Table 3.7). Some other more expensive methods are used in small treatment areas where helicopter is not economically justifiable.

Table 3.6. Total area (ha) selected for treatment by herbicides plan.

Herbicide	Area
Aminopyralid (Milestone) 0.09 kg ai	418.7
Aminopyralid (Milestone) 0.12 kg ai	75.8
Picloram (Tordon) 0.3 kg ae	0.2
Clopyralid (Transline) 0.4 kg ae	604.2
2,4-D 2.1 kg ae	2,799.1
Total	3,898.0

Table 3.7. Total area (ha) selected for treatment by application methods.

Method	Area
Helicopter	3,757.9
Backpack	110.0
ATV	26.6
Horse	3.5
Total	3,898.0

Predicted infestation areas (Table 3.8) show a large increase of Canada thistle and Scotch thistle due to their large spread rates (i.e., 1,000 m yr^{-1}). Predicted infestations of these two weeds (Canada thistle and Scotch thistle) without treatment reach 62% and 17% of the entire study landscape, respectively. This difference is produced despite the

same linear spread rates because Canada thistle can invade most vegetation types in the study landscape regardless disturbance (Table 3.2) whereas invasion of Scotch thistle is possible to some vegetation types only if disturbance occurs. The other weeds that were not selected for treatment, such as Common crupina, Dalmatian toadflax, Sulfur cinquefoil and Puncturevine, showed limited increase from their initial condition. Individual weeds selected for treatment also have different outcomes in terms of infestation growth (Table 3.8). While Musk thistle and Yellow starthistle were contained completely, others showed partial expansions of infestation, such as Spotted knapweed, Diffuse knapweed, and Rush skeletonweed, due to limited duration of treatment effects and number of retreatments allowed under limited budget.

Table 3.8. Predicted infestation area (ha) with and without treatment per weed at the end of five-year planning horizon.

Weed	Initial infestation	No treatment	With treatment
Musk thistle	0.5	3.0	0.5
Spotted knapweed	36.9	88.2	80.6
Diffuse knapweed	7.0	113.9	51.9
Yellow starthistle	223.2	273.4	223.2
Rush skeletonweed	496.4	6,984.9	5,595.9
Canada thistle	0.5	8,277.9	8,277.9
Common crupina	126.2	126.2	126.2
Dalmatian toadflax	0.3	1.6	1.6
Scotch thistle	171.2	2,271.2	2,271.2
Sulfur cinquefoil	1.6	4.1	4.1
Puncturevine	3.6	4.5	4.5
Total	1,067.4	18,148.9	16,637.6

Predicted infestation without treatment shows that almost the entire landscape would be infested at the end of the fifth year (Figure 3.10a). This large infestation range is produced mainly because of the three weed species with a spread rate of 1,000 m yr^{-1} (i.e., Rush skeletonweed, Canada thistle and Scotch thistle). The treated landscape shows the similar range of infestation to that of the untreated landscape (Figure 3.10b), but the areas to be occupied by multiple weed species (i.e., 2 or 3 weeds) become less in the treated landscape than the untreated landscape (Figure 3.10). The reason why both treated and untreated landscapes have similar range of infestation is mainly because the fast spreading weeds (Canada thistle and Scotch thistle) that were not selected for treatment due to low priority. This result indicates that treatment selection in WTP may be heavily influenced by weed and site priorities which sometimes overwhelms the spread rates of individual species. It would be important to appropriately develop weed species priorities and weights for WTP applications in order to meet the needs of weed management for a given landscape.
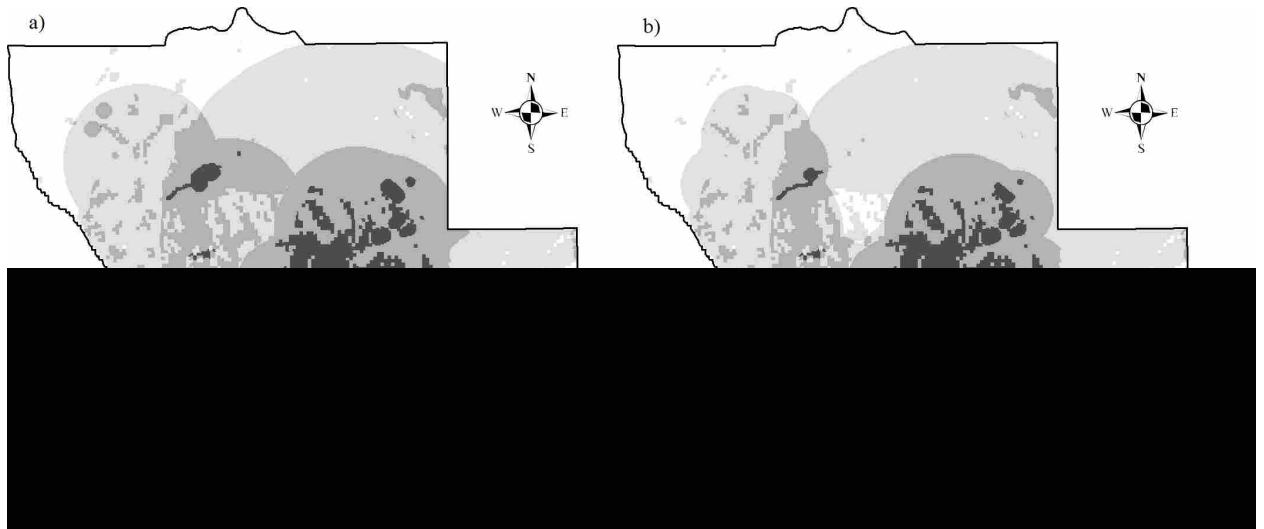
Figure 3.10. Predicted infestation areas at the end of five-year planning period showing number of weeds for a) no treatment, and b) with treatments.

3.4   CONCLUDING REMARKS

Accurate prediction of weed spread is important in weed treatment planning. In this Chapter, an algorithm was developed and incorporated into WTP to accommodate different spread modeling approaches, such as linear spread and CSA models. Although different predictive models can produce similar total infestation areas by averaging out site specificities across a large landscape, they can cause significant difference in treatment locations, which essentially affects the effectiveness and cost-efficiency of treatments. Spread models with the capability of incorporating spatial and site-specific conditions would enhance treatment selection in WTP because the areas prone to infestation can be identified and prioritized for further protection in spatial context. Although CSA models may provide more realistic weed spread based on site-specific

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conditions, it also poses another challenge that the friction values need to be updated if there are any disturbances or substantial changes in vegetation structure due to other resources management activities. WTP should evolve with more advanced modeling approaches of weed spread and knowledge in weed ecology as they become available.

3.5   ACKNOWLEDGEMENTS

3.6   LITERATURE CITED

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4.0   GENERAL CONCLUSION

Our decision support system for optimizing spatio-temporal weed treatments provides an analytical tool for determining a cost-effective way to use limited resources when managing multiple weed species. The system is able to consider weeds specific spread dynamics and the effect of treatments on multiple weeds. Also, the system's ability to consider budget constraints would help weed managers to perform trade-off analyses, as well as budget preparation and justification.

Like all models, the results of our decision support system rely on accuracy and quality of input data. Obtaining accurate input data for the system is a significant challenge because data might be limited or out of date or not exist. During this study, we realized that there are large knowledge gaps in our understanding of weed spread, lack of data from which spread rate can be derived, as well as lack of understanding of treatment effects. Consultations with local weed managers and ecologists were used in this study to obtain the required input data and develop assumptions for system applications. We hope that the use of our system can further emphasize the necessity of research and weed monitoring programs that can fill the existing knowledge and data gaps.

Application results of the system demonstrate the usefulness of the methodology and decision support system developed in this study. However, further research needs to be conducted to enhance the performance of the system and eliminate various assumptions made to simplify the real-world weed management problem. The solution search process requires a large computation time mainly due to the simulation of weed spread. In the future, it might be worthy to explore other optimization algorithms, such

as genetic algorithm, that can easily accommodate parallel processing in which multiple solutions (i.e., simulation of weed spread) can be evaluated simultaneously.

Our system assumes the application of herbicides stops weeds from spreading for a given duration of years. In reality, however, shrinkage or eradication of weed infestation may occur depending on treatment frequency and intensity. Unfortunately, there exists no spread model that can predict the efficacy of treatments in such detail. If more advanced models are available in the future, such models should be incorporated into the decision support system to improve the solution quality and practicality.

Finally, while the approach incorporated in the decision support system to evaluate alternative treatment plans might align well with common land manager practices, it does not explicitly consider the economic, ecological and social impacts of invasive weeds. As these impacts may vary by location, weed species, landscape attributes, and affected human activities, future research should also include consideration of such criteria in evaluating alternative treatment plans.

APPENDIX 1. WTP USER GUIDE

WEED TREATMENT PLANNER (WTP) USER GUIDE

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Introduction

The Weed Treatment Planner (WTP) is a spatially explicit decision support system for planning which weed species to treat, how to treat, where and when to treat based on desired objectives, predetermined constraints (such as excluding specific herbicide treatments in specific locations), and limited treatment budgets. WTP incorporates species-specific spread dynamics in a heuristic solver that is designed to indentify spatial treatment strategies for limiting weed spread over time. This process provides the capability to analyze trade-offs among alternative spatial and temporal treatment strategies in the "control priority' stage. This capability to perform trade-off analyses is critical to developing cost-effective treatment decisions in the usual case of limiting resources and budgets.

The first step in applying the WTP is providing key GIS data, including layers for the known locations of weed infestations, roads, trails, streams, vegetation types, and treatment site priorities. Next, the user enters data such as budget limits, chemicals used, application methods (backpack sprayer, ATV sprayer, etc.) and costs, chemical application rates by weed species, invasive species spread rates, and treatment site priorities. Buffers are generated for roads and trails layers to approximate accessibility for the application methods applied from them. A streams layer is used to buffer riparian areas where certain chemicals cannot be applied. A susceptibility matrix is generated from the vegetation cover type layer and the user-defined rules that determine whether the cover type is generally susceptible to invasive species, is only susceptible to invasive species after vegetation disturbances have occurred, or whether it is resistant to specific

invasive species. An optional vegetation disturbances layer can be used to designate areas that have been disturbed recently or where future vegetation treatments are planned that will result in future disturbed areas. After data entry is complete, the solver is run to find the spatial and temporal weed treatment schedule that minimizes the number of acres of infestations for weed species that are priorities for treatment, as well as priority sites, while satisfying specified budget levels for each of five treatment years. The predicted extent of weed infestations, both with and without treatment, can be compared to help evaluate the effectiveness of a treatment schedule. Alternative weed treatment schedules can be developed by modifying budget levels for individual years, changing weed species or site priorities, or changing the treatment options.

This manual describes how to down-load the WTP program and test data and install it on your computer. It also identifies the necessary spatial and non-spatial data, and how to operate the system to develop spatial and temporal weed treatment strategies for your weed treatment planning area.

Software requirements: The WTP is an extension to ArcMap, and is packaged as a toolbar. It runs on a standard Windows GIS-capable desktop PC, with ArcGIS 9.2 or 9.3 installed. The programming language used in WTP is Visual Basic, ArcObject.

Installation and Startup

Weed Treatment Planner (WTP) is an extension to ArcMap, and is packaged as a toolbar. To install WTP toolbar in your machine you first need to unpack the provided zip file (WTP installer.zip) into an appropriate directory, as an example (figure below) we unzipped the files into "C:\WTP\WTP installer" folder.
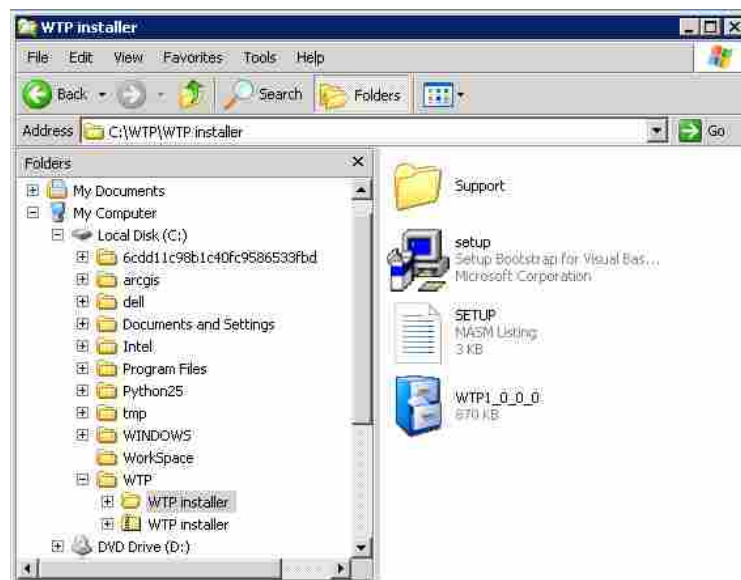

To start the installation process you need to run the setup ( ) program. An initial window will ask you to close running applications before proceeding, so save and close all your work and click on the **OK** button.

In the next window you can either accept or change the directory where you want

to install the application.
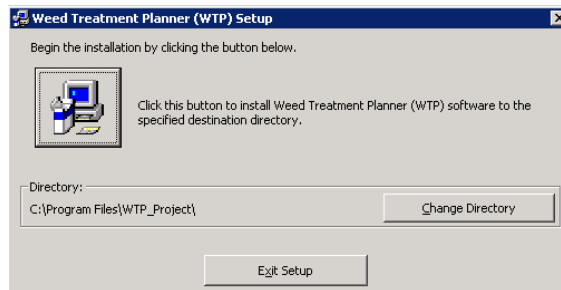
After clicking the install button the tool will be installed and registered in your

machine. The following message should appear warning you that the installation was

successful.
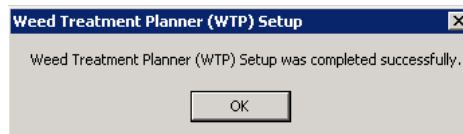
Start ArcMap and go to View/Toolbars and select WTP 1.0 Toolbar to activate it.
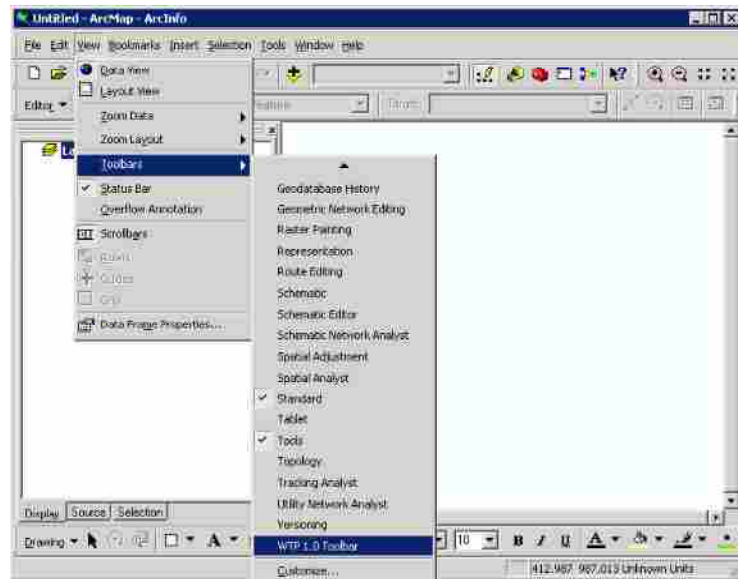
The WTP toolbar should look like this:

Start a new project

Before starting a new project using WTP, add the GIS data to the map document,

and save the map document in your project folder. These GIS data consist of a Weed

layer, Roads layer, Roads and Trails, Priority sites for treatment, Streams, Disturbances

(optional), and Vegetation (as cover type relevant to invasive species susceptibility). See

Appendix for a data dictionary at the end of this tutorial. There are minimum

requirements for each layer and table.

Once the GIS data are added to the map document, start WTP by clicking the

Weed Treatment Planner (WTP 1.0) button.

This starts the main menu which looks like this:

Screen item descriptions:

(Enter data) -- start the data entry process.

(Load dataset) -- use when you are editing an existing project. The project should have previously been saved by selecting the save project data after saving the map document itself. You will be prompted to select a table from the map document with the information about the project you want to open. To load the tutorial dataset, select **Project 1:**

(Save dataset) -- select when some project data have been entered, and after saving the map document to the same project folder.

(Run No Action Scenario) – projects the spread of weeds without treatment, over a 10-year prediction horizon. This generates a layer for each weed species.

(Solve (optimize)) – runs the solver to generate the optimal five-year schedule of treatments, based on the budget constraints, weed species, site priorities, etc.

 (Close WTP) – exit WTP

Initial Information Screen (accessed by Enter Data on Main Menu)

For a new project, select the **Enter data** button on the Main Menu to display the following screen.

Screen Items:

Select Project Folder: Browse to the folder in which you wish to keep project information. It is recommended to save the map document to this folder. Other data could be kept in this folder for simplicity, but it is not required that they be here. All new layers and tables created by the application will be stored in subfolders here. No action results will be stored in "project folder\Project name\NoAction" folder. When the solver is run, results will be in "project folder\Project name\OptSolution" folder.

Project Name: This name is used to label treatment scenarios that may differ in budget or other aspects.

Chemical Options: Used to create or edit the chemicals table, which is a list of the chemicals that can be used to treat weeds. It has two fields, Chemicals (text, 10) and Remarks (text, 200). The screen items for this table are:

1) **Browse** - select a pre-existing dbf from your computer directory,

2**) Edit** - click to edit the selected table, a chemical editor screen will appear,

3) **Create** - creates a new blank table and opens the editor,

4) **Load from map** – loads a table that has already been added to the map document as a source file. You will be prompted to select a table from the map document (the path-name in the text field is filled automatically). You then select the 'edit' button to make changes.

Application Methods: Used to create or edit the application methods table, which is a list of application methods that can be used to treat weeds. It has two fields, Method (text, 30) and Remarks (text, 100). The screen items for this table are:

      1) **Browse** - select a pre-existing dbf from your computer directory,

      2) **Edit** - click to edit the selected table, an application methods editor screen will appear,

      3) **Create** - creates a new blank table and opens the editor,

      4) **Load from map** – loads a table that has already been added to the map

        document as a source file.

Initial Year: Enter the first year for scheduling treatments.

Annual Budget for Periods (Years) 1 to 5: Enter the weed-treatment budget for EACH year for the 5-year plan.

Continue data entry: Save the information entered and continue to the **Select Layers** screen.

Cancel: Close the screen without saving the information entered.

The following exhibit shows this screen after the tutorial data have been loaded:

Select Layers Screen

The following screen is used to identify the GIS layers to be used in the current project (these GIS layers should have already been added to the Map Document) and to access layer-specific screens (via the **Go>** buttons) which add specific data or selections to each layer. After completing and saving the data for each layer, the user is returned to this screen. The GIS layers accessed on this screen can be completed in any order. The **Done** button is used to exit this screen and return to the main menu.
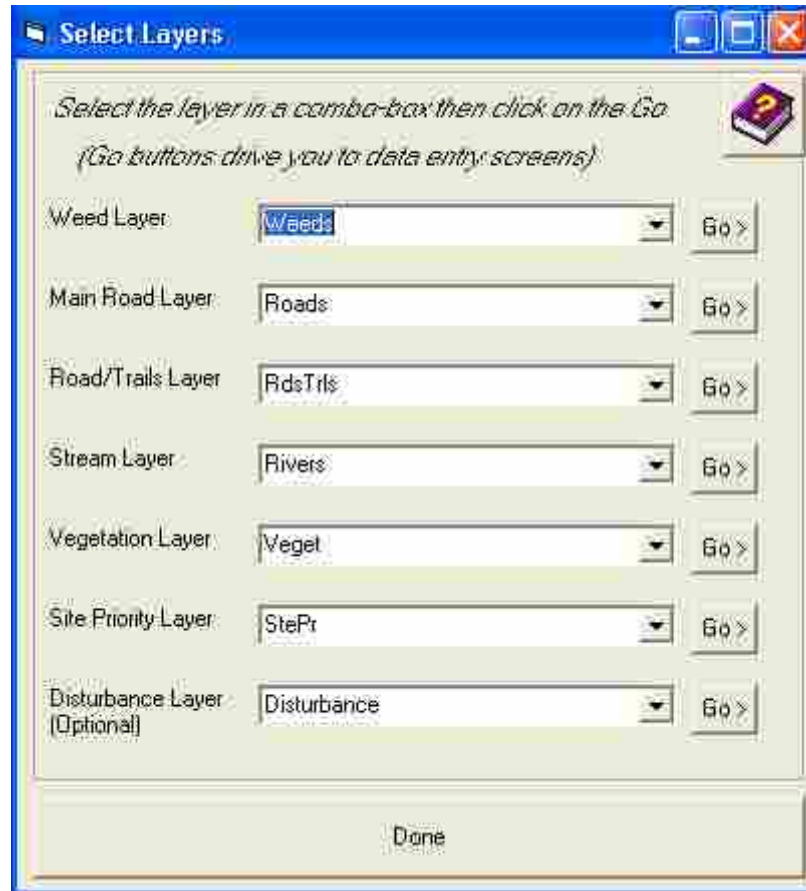
After **Go>** is clicked, a dialog box is displayed for some layers for entering key field names in the associated attribute table. For example, the dialog box for **Weed Layer** requests the name of the column that stores the weed names.

General operations used on the screens and tabs for entering layer-specific data (accessed via **Go>** buttons) follow:

Load dBase from file: Use to select a database table that was previously developed for another project.

Load dBase from Map: Use to select a database table that was previously added to the map document.

Add>>: Click to add the selected items to the table displayed on lower half of the screen.

Save: Click to save changes and to create the table displayed on lower half of the screen and added to the map document.

Clear Table: Click to clear the table displayed on lower half of the screen. That button clears just the information in the table, to store any changes the Save button must be clicked as well.

Items (rows) in the table displayed on lower half of the screen cannot be edited. If a change is needed in a row, delete that row (right mouse click on row, in first column, to be deleted and select delete), make the appropriate selections in the fields on the screen, then use the **Add** button to create the corrected row. The option to sort a table by a selected column is accessed by a right mouse click on the title of that column. This can help the user check tables for completeness. Remember to save the changes before leaving the window.

After **Go>** is clicked for **Weed Layer** (**Select Layers** screen), a dialog box is displayed for entering the name of the field that stores the weed names in the Weed Layer:

After this name is supplied, the **Weed: Treatments, Weeds, and Application Method Data** form (shown below) is displayed. On this data entry form you will identify, for each invasive species, a chemical treatment to be analyzed, its application rate per acre, how much of which surfactant, and the cost per acre for the chemical (we will add the application method cost later). This form contains four tabs: **Treatments data**, **Weed rank and spread rates**, **Application methods data**, **Treatment/Method**.

Weed: Treatments, Weeds and Application Methods Data

| Treatments data | Weed rank and spread rates | Application methods data | Treatment/Method |

Select Weed
Rush skeletonweed
Spotted knapweed

Chemical [▼]

☐ Applicable for riparian zones

Rate [ ] ○ pt ○ oz (per acre)

Surfactants [ ] ○ % w/v NIS ○ qt MSO

Effectiveness (years) [ ]   Chemical Cost ($/acre) [ ]

[Add >>] [Save] [Clear Table]

[Load dBase from File]
[Load dBase from Map]

	Weed	Treatment	Cost ($/acre)	Duration (years)	Riparian (Y/N)
	Rush skeletonweed	Transline 1 pt	41.79	2	No
	Rush skeletonweed	2,4-D 4 pt	5.32	1	Yes
	Spotted knapweed	Tordon 1 pt	11.47	3	No
	Spotted knapweed	Milestone 7 oz	17.22	3	Yes

Done

Treatments data tab

This tab (shown above) is used to specify the weed treatment options. Selections are made from the available options on the top portion of the screen, then the **Add>>** button is used to enter a fully-specified treatment option (row) in the table in the lower portion of the screen.

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Select Weed: Select one (or more).

Chemical: Select one.

Applicable for riparian zones: Check if the selected chemical can be applied in riparian zones.

Rate: Enter the application rate in **pt** (pints) or **oz** (fluid ounces) (select one) per acre.

Surfactants: Enter the type and solution specification in **% w/v NIS** (percent weight/volume NIS - Nonionic Surfactants) or **qt MSO** (quart MSO - Methylated Seed Oil).

Effectiveness (years): Enter the time in years the treatment is effective for stopping spread (length of time between treatments).

Chemical Cost ($/acre): Enter the cost per acre for chemical and surfactant. Do not include application costs here (those costs are entered separately on the **Application methods data** tab).

Weed rank and spread rate tab

This tab is used to specify a treatment priority ranking for each weed species, and to enter a rate of spread that is expected in the absence of treatment.

Selections and data entry are made on the top portion of the screen, then the **Add>>** button is used to enter a data row in the table in the lower portion of the screen.

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Select Weed: Select a weed for ranking and spread rate. Two or more may be selected (using shift or control keys) providing they share the same ranking and spread rate.

Rank (1-6): Specify a ranking from 1 - 6 for the weed(s) selected, where 1 = the highest priority for treatment and 5 = the lowest priority for treatment. Select 6 if the weed(s) selected does not have a treatment priority. This relative priority is used by the objective function to minimize the infested acres over time by invasive species priority and site priority.

Spread rate (ft/year): Enter a rate of spread (feet/year) for the weed(s) selected. This rate estimates the expansion potential (without treatment) of an infested area and is used as an omnidirectional growth rate, that is, each year of expansion uses this spread rate in every direction from the perimeter of the previous year's extent.

Application methods data tab

This tab is used to specify the treatment costs and minimum treatment size for each application method.

The application method selection and data entry are made on the top portion of the screen, then the **Add>>** button is used to enter a data row in the table in the lower portion of the screen.

Select Application Method: Select a method from the pick list.

Cost ($/acre): Enter the application cost per acre. Do not include the cost of chemicals or Surfactants here (those costs are entered separately on the **Treatments data** tab).

Minimum Treatment Size (acres): Enter the smallest number of continuous acres you consider viable for the selected treatment type.

Treatment / Method tab

The purpose of this tab is to identify application methods that cannot be used for specific treatments.
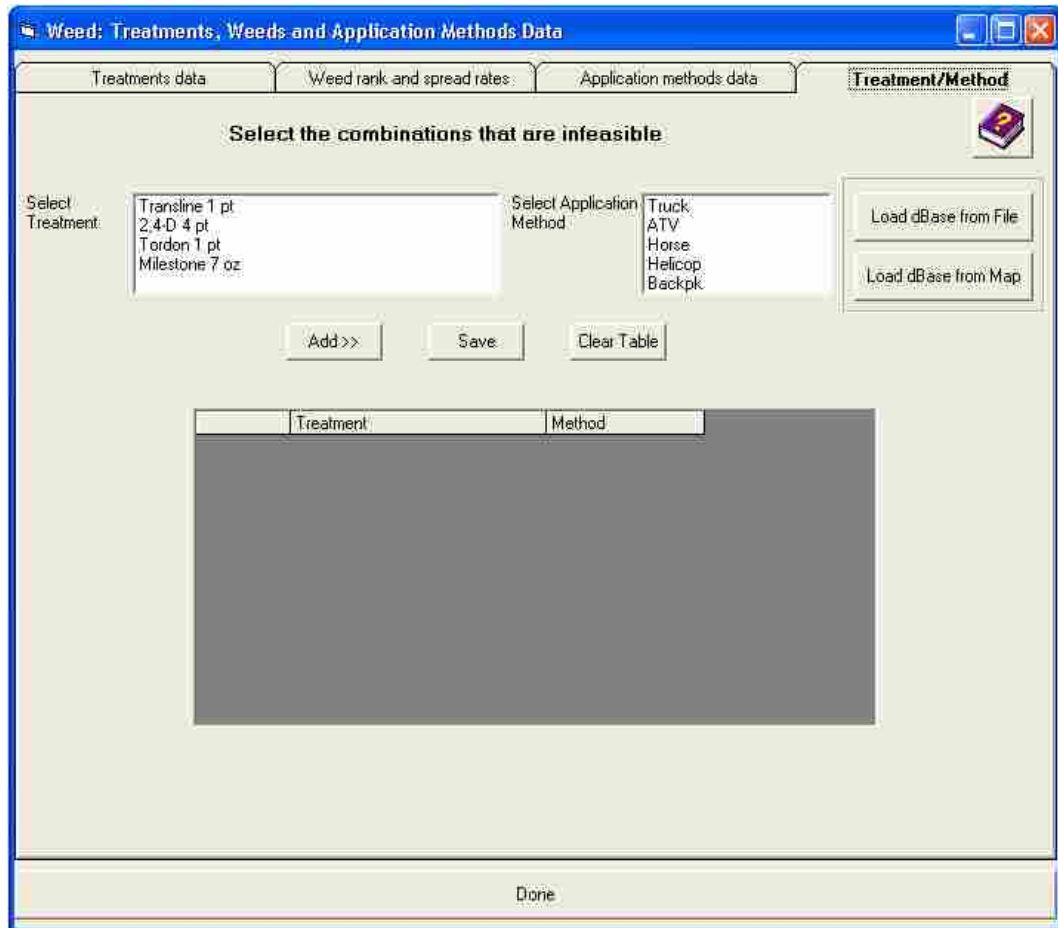
The infeasible combinations of treatments and application methods are identified in the upper portion of the screen and the **Add>>** button appends those infeasible

combinations to the table in the lower portion of the screen. Combinations listed in the

table are excluded from further analysis.

Select Treatment: Select a treatment that has application method restrictions.

Select Application Method: Select one or more application methods that cannot be used

with the selected treatment. For example, there may be restrictions to applying certain

treatment chemicals via helicopter. Multiple selections are made by holding down the

Ctrl key and clicking on the desired items.

Main Roads: Select Application Methods that can be used from Roads

After **Go>** is clicked for the **Main Road Layer** (**Select Layers** screen) the

following screen is displayed:
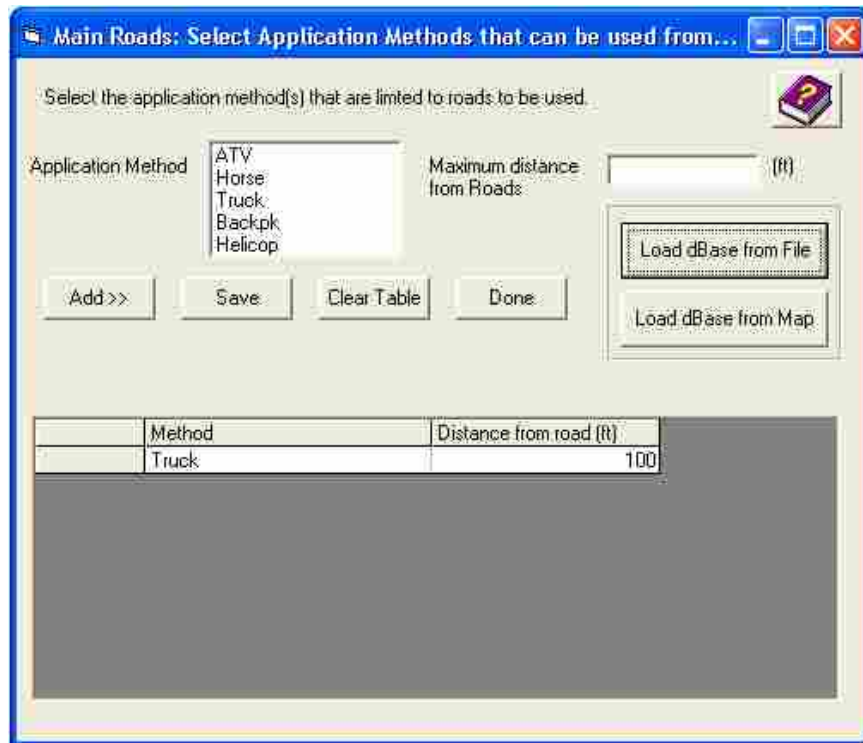
This screen is used to select the application methods that can be applied from roads and specify the maximum distance from roads the selected methods can be applied. An application method and maximum distance is selected in the upper portion of the screen and the **Add>>** button appends those combinations to the table in the lower portion of the screen.

Application Method: Select an application method that can be applied from roads. The selections on this screen should be limited to only those methods that are applied from roads. There is another screen for application methods that can be applied from either trails or roads. An application should NOT be selected both here and in the trails and roads screen.

Maximum Distance from Roads (ft): Specify the maximum distance from roads in feet that the selected method can be applied. The distance is applied from the center of the road to each side.

<u>Roads/Trails: Select Application Methods that can be used from Roads and Trails</u>

After **Go>** is clicked for the **Road/Trails Layer** (**Select Layers** screen) the following screen is displayed:

This screen is used to select the application methods that can be applied from either trails or roads, and specify the maximum distance from trails and roads that the

selected methods can be applied. An application method and maximum distance is selected in the upper portion of the screen and the **Add>>** button appends those combinations to the table in the lower portion of the screen. The only application methods that should be included in this table are those that have a distance limitation that you want to include in the analysis.

Application Method: Select an application method that can be applied from either trails or roads. The selections on this screen should be limited to only those methods that can be applied from either trails or roads. There is another screen for application methods that are restricted to roads only. An application should NOT be selected both here and in the roads screen.

Maximum Distance from Trails and Roads (ft): Specify the maximum distance from trails or roads in feet that the selected method can be applied. The distance is applied from the center of the trail or road to each side. If there is no maximum distance for a specific application method, do not add that method to the table.

Stream: Riparian Zone

After **Go>** is clicked for the **Stream Layer** (**Select Layers** screen) the following dialogue box is displayed for the user to specify a buffer distance from streams that will be considered the riparian zone where some chemical weed treatments are not permitted.

Distance from Stream (ft): Enter the maximum distance from streams where chemical weed treatments are not permitted. This distance is applied from the center the steam to each side.

Vegetation: Vegetation Susceptibility

After **Go>** is clicked for **Vegetation Layer** (**Select Layers** screen), a dialog box (shown below) is displayed for entering 1) the name of the field that stores the vegetation types, and 2) the name of the field that stores the weed names in the Weed Layer.

After these field names are supplied, the **Vegetation: Vegetation Susceptibility** screen is displayed:
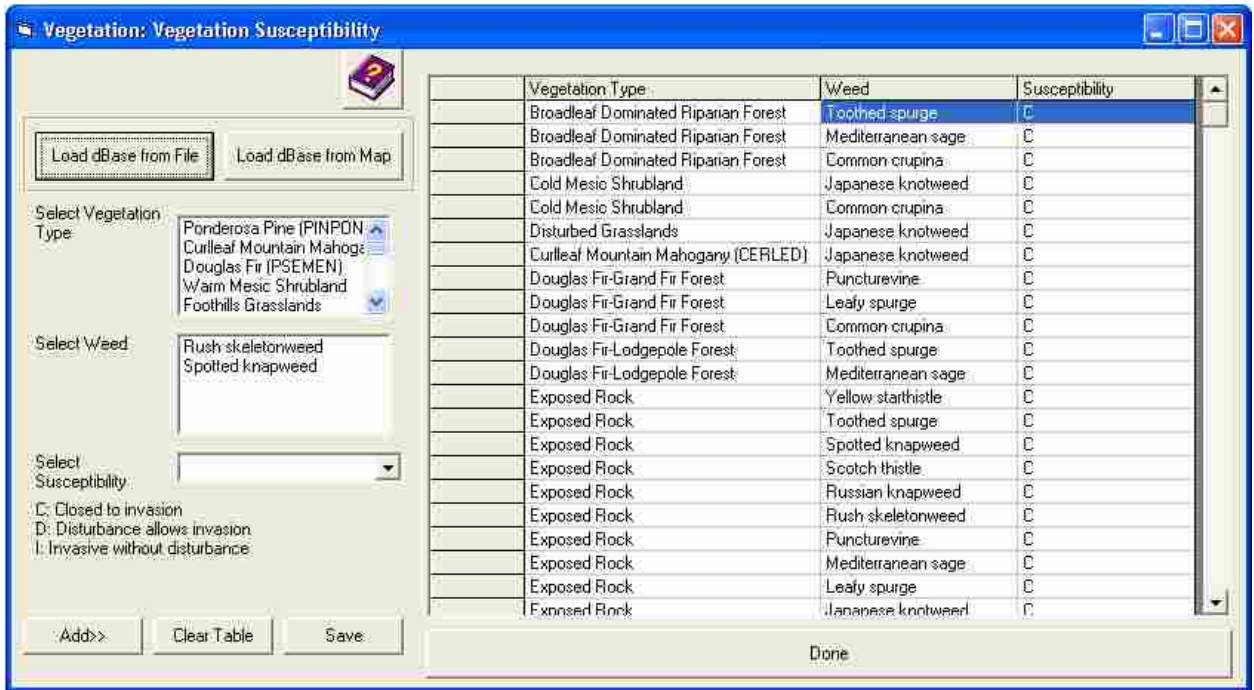
The purpose of this screen is to specify the level of susceptibility of each vegetation category to each type of weed. Selections are made on the left portion of the screen and the **Add>>** button appends those combinations to the table displayed on the right portion of the screen. This screen is completed when each combination of vegetation type and weed are displayed in the table.

Select Vegetation Type: Select a vegetation type to be rated for susceptibility.

Select Weed: Select a weed to be rated.

Select Susceptibility: Select a level of susceptibility for the selected combination of vegetation type and weed. The susceptibility categories are:

C: Closed to invasion: The selected vegetation type is not susceptible to invasion by the selected weed.

D: Disturbance allows invasion: The selected vegetation type is susceptible to invasion by the selected weed only after a disturbance.

I: Invasive without disturbance: The selected vegetation type is susceptible to invasion by the selected weed even in the absence of a recent disturbance.

Site Priority: Define Site Priorities

After **Go>** is clicked for **Site Priority Layer** (**Select Layers** screen), a dialog box is displayed for entering the name of the attribute field that stores the treatment sites to be prioritized:

After this field name is supplied, the following screen is displayed:
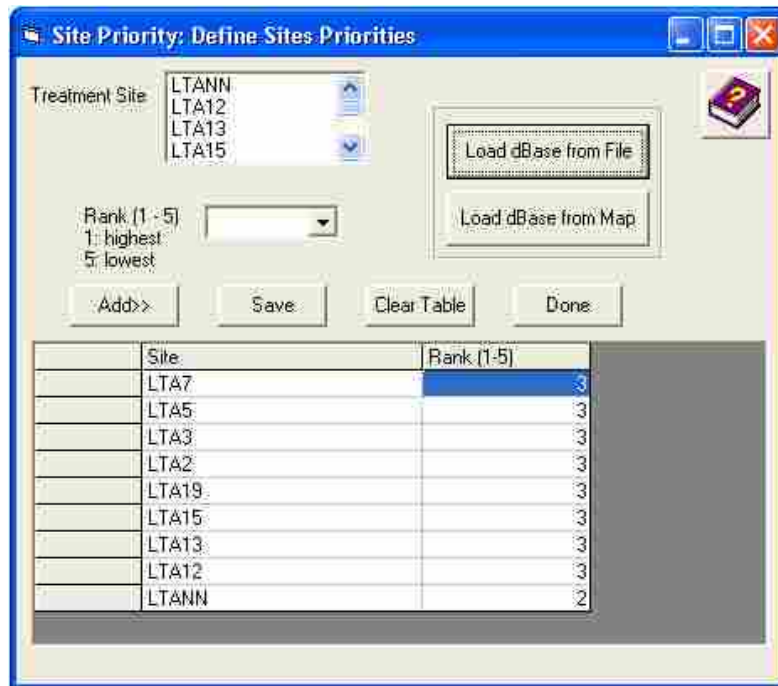
The purpose of this screen is to prioritize treatment sites that are in the site priority layer, such as trailheads, trails, and road right-of-ways. Treatment sites are selected and priorities assigned on the upper portion of the screen and the **Add>>** button appends those specifications to the table in the lower portion of the screen.

Treatment Site: Select the treatment site to be ranked.

Rank (1-5): Specify a ranking from 1-5 for the treatment site selected, where 1 = the highest priority for treatment and 5 = the lowest priority for treatment. This is relative

priority is used by the objective function to minimize the infested acres over time by invasive species priority and site priority.

<u>Disturbance: Define Disturbed Areas</u>

The purpose of this set of optional screens is to identify where and when future disturbances are expected to occur. This information is combined with the susceptibility data to predict weed spread (some vegetation types are susceptible to weed invasions only following a disturbance). If the user does not include the disturbance layer, the solver will assume by default that the whole study area is disturbed for the entire planning horizon.

The first screen displayed is used to access previously entered disturbance data using alternative methods:
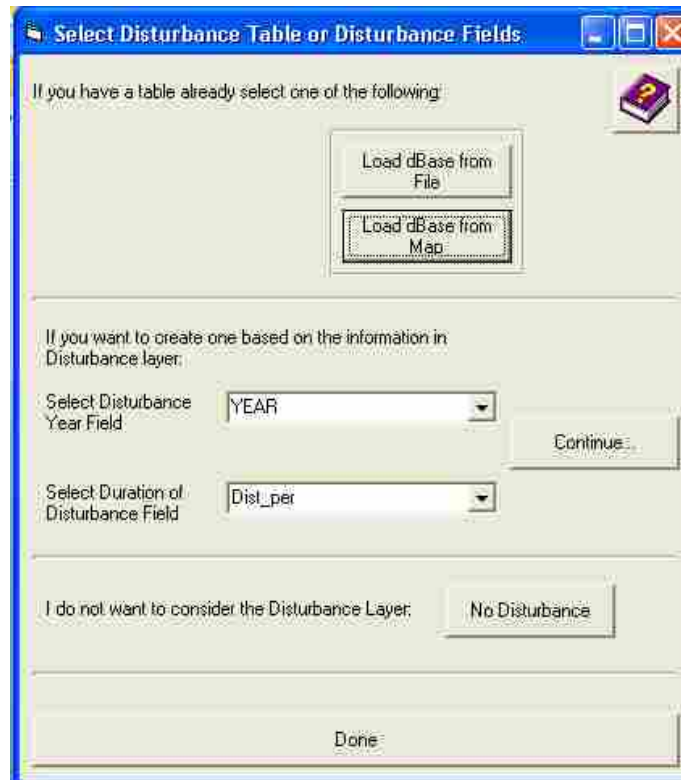
Load dBase from file: Use to select a database table that was previously developed for another project. The **Disturbance** screen (shown below) is then displayed.

Load dBase from Map: Use to select a database table that was previously added to the map document. The **Disturbance: Define Disturbed Areas** screen (shown below) is then displayed.

If you want to create one based on the information in the Disturbance layer:

    Select Disturbance Year Field: Select the field name storing the disturbance year in the attribute table in the Disturbance Layer.

Select Duration of Disturbance Field: Select the field name storing the duration of disturbance in the attribute table in the Disturbance Layer.

Continue…: Click when the Disturbance Year and Duration of Disturbance field names have been specified. The **Disturbance** screen (shown below) is then displayed.

I do not want to consider the Disturbance Layer: If you do not want WTP to consider the Disturbance Layer, the click the **No Disturbance** button. In the case that the user does not include the disturbance layer, the model will assume by default that the whole study area is disturbed for the entire planning horizon.

If a Disturbance Layer was specified by any of the available methods in the previous screen, the **Disturbance: Define Disturbed Areas** screen is displayed:
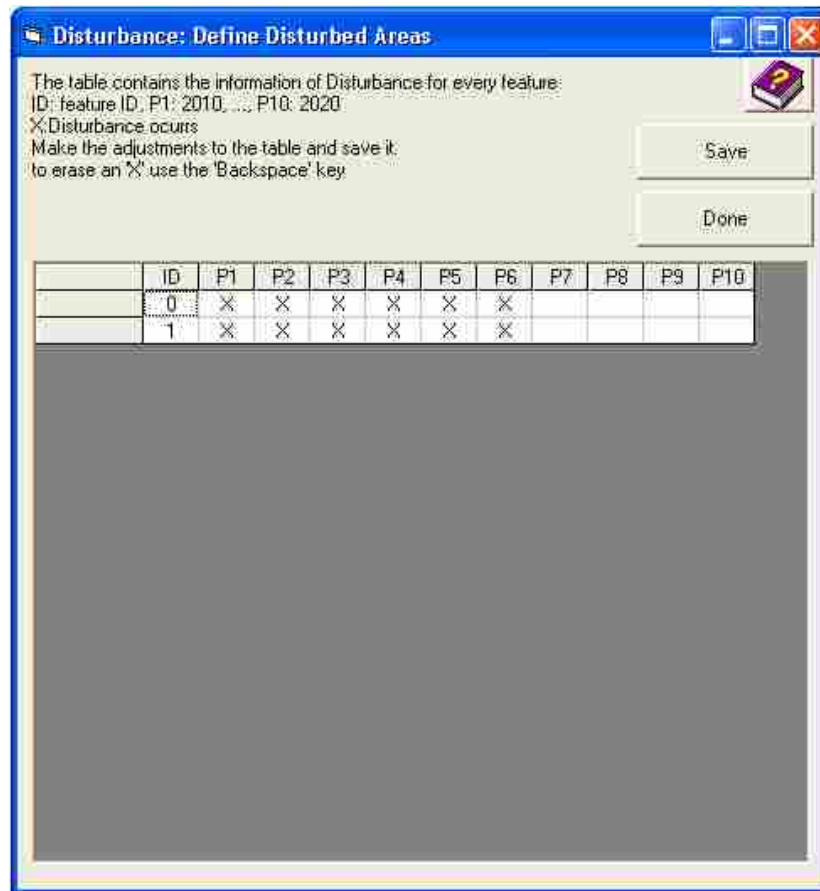
This screen is used to specify the location and years when an expected future disturbance affects susceptibility of weed spread. These locations and years of susceptibility due to disturbance are identified by 'X'.

ID: Is the GIS identifier for a location.

P1, P2….P10: P1 represents year 1 of the analysis period, P2 represents year 2 and so on to year 10.

Run No Action Scenario

Pressing the **Run No Action Scenario** button on the main menu launches the WTP solver to predict weed spread for the case in which no treatments are undertaken. The extent of the weed infestations that are documented in the weed layer are projected for each of the next ten years. These results are stored as layers in ArcMap, one for each weed species. The default display shows the weed extent predicted for the 10th year in the analysis. Use ArcMap functionality to view projections for the individual years, from the initial infestation to the 10th year.

Solve (optimize)

Pressing the **Solve (optimize)** button on the main menu launches the WTP solver to develop a spatial weed treatment schedule based on the GIS layers and data that have been entered via the **Enter data** button on the main menu. Each GIS input layer is converted to a raster format for analysis. The system uses weed locations and spread rates to simulate future infestations, based on weed spread rates that are assumed to occur in an ominidirectional fashion. Through use of the susceptibility concept, the system has the capability of taking into account the vegetation cover and its susceptibility to determine new infested areas. The priority sites provided by the user guide the treatment location selected within the heuristic solver, directing the resources to those areas of more interest for weed managers. The stream buffer locations are used to limit the application of

chemicals that can be harmful near water. (Note, depending on the computer being used, **Solve (optimize)** for the tutorial problem may take up to two hours to run. See the subtopic **Solution time** at the end of this section for more information.)

The solver creates treatment units in the solution process that are based on information specified in the GIS data, including the location of the existing weed infestations, the extent of weed infestations projected to future years, user-defined maximum treatment distances for ground-application methods, and moving windows of potential treatment units for aerial application methods. System outputs include treatment locations for each year and the predicted extent of each weed species by year with the treatment schedule. Below we describe how this can be compared with the predicted weed extents in the absence of treatment.

Optimization Criteria

WTP was designed to develop a yearly weed treatment plan for up to five years, but the effects of some treatments could last for several years after the end of the treatment period. To capture these effects the evaluation of a plan is made through the end of year ten. This evaluation is made in terms of total infested area weighted by weed species and sites priorities, the goal is to have the lowest possible objective function value over ten years. These parameters are combined in the following objective function:

$$\text{Minimize} \sum_{c \in C} \sum_{w \in W} \left(I_{c,w} \times WPI_w \times SPI_c \right)$$

Where:

I_{cw} : binary variable that takes value one if the grid cell c is infested by weed species

w.

WPI_w : weed priority for weed species w. ($1 \leq WPI \leq 5$)

SPI_c : site priority for grid cell c. ($1 \leq PPI \leq 5$)

c : from 1 to C, total number of grid cells.

w : from 1 to W, total number of weed species.

Note that both the species and site priority indices have the same importance in the objective function and that for evaluation purposes, we counted a grid cell as infested if any weed species is present in it and it does not have treatment effect in the given year.

WTP includes a heuristic optimization algorithm developed using a simulated annealing optimization technique. Simulated annealing is a Monte Carlo search method that uses a local search in which a subset of solutions is explored by moving from one solution to a neighboring solution. The goal of this random selection process is to find an acceptably good solution rather than the best possible one. Thus, due to the stochastic nature of this process the solutions obtained may vary slightly if the same problem is run more than once.

Outputs

When the solution is completed, the map document contains the following solution results:

- Five treatment layers – one for each of five years. The default display shows the treatment locations across all treatments (all are coded the same). Use ArcMap functionality to view the individual treatments for each of the five years.

- Five application method layers – one for each of five years. The default display shows the locations for weed treatment applications (all are coded the same). Use ArcMap functionality to view the individual application methods for each of the five years.

- One layer weed spread layer for each weed species analyzed showing the predicted extent of infestation for ten years into the future. The default display shows the predicted weed infestation at year ten. Use ArcMap functionality to view projections for the individual years, from the initial infestation to the 10th year.

In addition, the map document contains the original data layers for display with the solution results:

- Roads and Trails
- Streams
- Site Priorities

- Weeds

- Vegetation

- Disturbance

After the No Action Scenario is run, the map document also contains predicted extent for each of the weeds analyzed for each of the next ten years. The tutorial data set includes layers for spotted knapweed and rush skeletonweed.

Solution information is also summarized in a table, accessed from the 'Source' tab of the table of contents:
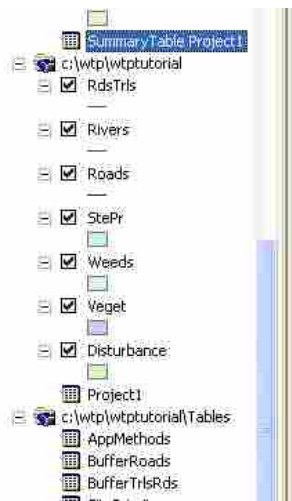
To view the table, right-click on **Summary Table** and select **Open** on the context menu. This table (shown below) provides a treatment summary by year. It shows the number of acres for each unique combination of whether a treatment occurs in a riparian area, the weed species targeted for treatment, treatment chemical, application method, and cost.

Attributes of SummaryTable Project1

OID	Year	Riparian	Weed	Treatment	Method	Cost	Acres
0	2010	No	Spotted knapweed	Milestone 7 oz	Backpk	484.820007	2.002
1	2010	No	Spotted knapweed	Tordon 1 pt	Backpk	1209.560059	5.1162
2	2010	Yes	Spotted knapweed	Milestone 7 oz	Backpk	646.419983	2.6693
3	2011	Yes	Rush skeletonweed	2,4-D 4 pt	Horse	1639.579956	15.5709
4	2011	No	Spotted knapweed	Tordon 1 pt	Backpk	210.360001	0.8898
5	2012	No	Spotted knapweed	Tordon 1 pt	Backpk	262.950012	1.1122
6	2013	Yes	Spotted knapweed	Milestone 7 oz	ATV	234.619995	2.002
7	2014	No	Spotted knapweed	Milestone 7 oz	ATV	260.690002	2.2244
8	2014	No	Spotted knapweed	Tordon 1 pt	Horse	644.549988	5.7835
9	2012	No	Rush skeletonweed	2,4-D 4 pt	Helicop	3985.810059	198.193802
10	2012	Yes	Rush skeletonweed	2,4-D 4 pt	Helicop	334.410004	16.460699
11	2013	No	Rush skeletonweed	2,4-D 4 pt	Helicop	4130.419922	203.311905
12	2013	Yes	Rush skeletonweed	2,4-D 4 pt	Helicop	334.410004	16.460699
13	2014	No	Spotted knapweed	Milestone 7 oz	Horse	547.450012	4.6713
14	2013	No	Spotted knapweed	Milestone 7 oz	Horse	234.619995	2.002

Record: 1   Show: All Selected   Records (0 out of 15 Selected)   Options ▼

A Tabular listing of treatments for an individual year is accessed by a right-mouse click on the treatments layer for the desired year and then selecting **Open Attribute Table** on the displayed dialogue box. The following display lists the treatments selected by the solver for the year 2010.

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Method
- Backpk
- Helicop

☐ Application methods 2011 Project1

☐ Application methods 2010 Project1

☐ Treatments 2014 Project1

☐ Treatments 2013 Project1

☐ Treatments 2012 Project1
  ☐ <all other values>
  Treatment
  - 2,4-D 4 pt
  - Tordon 1 pt

☐ Treatments 2011 Project1

☑ Treatments 2010 Project1

☐ Weeds
  ☐ <all other values>
  SP_NAMES
  Rush skeletonweed
  Spotted knapweed

☐ Spotted knapweed w Treatment Project1

☐ Spotted knapweed No Action Project1

☐ Rush skeletonweed w Treatment Project1

☐ RdsTrls

Display | Source | Selection

Attributes of Treatments 2010 Project1

FID	Shape *	Treat_ID	Year	App_Method	Riparian	Treatment	Cost	Acres
0	Polygon	1	2010	Backpk	No	Milestone 7 oz	161.610001	0.8672
1	Polygon	2	2010	Backpk	No	Milestone 7 oz	161.610001	0.8672
2	Polygon	3	2010	Backpk	No	Milestone 7 oz	161.610001	0.8672
3	Polygon	4	2010	Backpk	No	Tordon 1 pt	315.540009	1.1941
4	Polygon	5	2010	Backpk	No	Tordon 1 pt	157.770004	0.5219
5	Polygon	6	2010	Backpk	Yes	Milestone 7 oz	484.820007	1.7802
6	Polygon	7	2010	Backpk	Yes	Milestone 7 oz	53.869999	0.2224
7	Polygon	8	2010	Backpk	Yes	Milestone 7 oz	107.739998	0.3103
8	Polygon	9	2010	Backpk	No	Tordon 1 pt	420.720001	1.7792
9	Polygon	10	2010	Backpk	No	Tordon 1 pt	105.18	0.3103
10	Polygon	11	2010	Backpk	No	Tordon 1 pt	210.360001	0.6204

Record: 1   Show: All Selected   Records (0 out of 11 Selected)   Options ▾

Displays of Results

This section presents examples of displays that are useful for understanding the weed treatment schedule developed by the WTP solver and comparing the predicted extent of weeds with and without treatment. The examples are taken from the tutorial dataset.

After No Action and **Solve (optimize)** have been run for the tutorial data the study area with all layers turned on is displayed in ArcGIS:
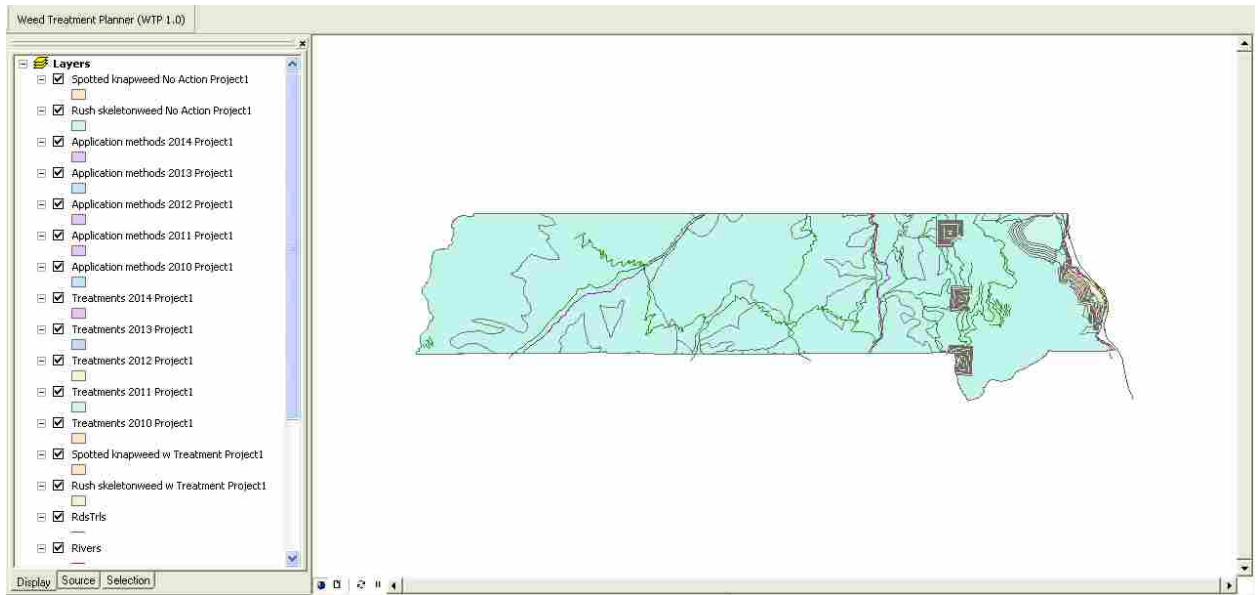
Treatment types

After a treatment schedule has been developed via **Solve (optimize)**, users will want to view locations and types of treatments and the treatment methods. The following display shows the locations of treatments for the east side of the study area in years 2010 (green), 2011 (red), and 2012 (blue hash lines). The site priority layer is turned on to see the general location of treatments).

The next two displays show the treatment attribute table, which lists all the treatments scheduled for year 2012, and treatment locations for that year (green represents 2,4-D 4 pt, and red represents Tordon 1 pt).

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Application methods

Application methods are displayed in same manner as treatments types. The following two displays show the treatment attribute table, which lists all the applications scheduled for year 2012, and application locations for that year (purple represents application by backpack sprayer, and blue represents helicopter application).

Weed spread

Weed layers for each weed species analyzed contain the predicted spread by year for both No Action and the treatment schedule developed by the solver. The following display compares the predicted extent of spotted knapweed at year ten both with and without treatment. The color red shows the extent of knapweed at the beginning of the planning period. The predicted extent at the end of year ten with treatment is represented in blue, and the year ten extent for No Action is represented in beige. Remember, this display predicts the year ten spread for the treatment schedule assuming no treatments occur after year five (treatments are scheduled for only the first five years).
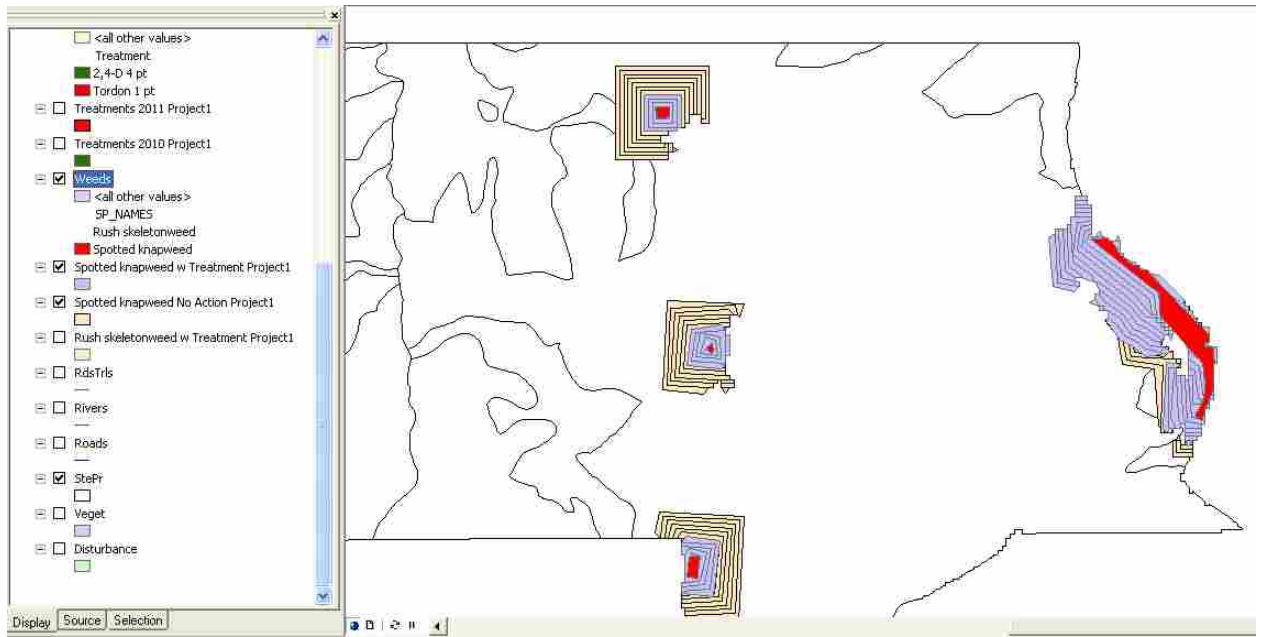
Weed spread with and without treatment can be compared for other years as well. The next display compares the predicted extent of spotted knapweed at the end of year 2014 with treatment against No Action (2014 is the fifth treatment year in the schedule). Red shows the extent of knapweed at the beginning of the planning period. The spread by year for the treatment alternative is depicted by increasingly darker blue, and the yearly spread for No Action is shown by increasingly darker green.
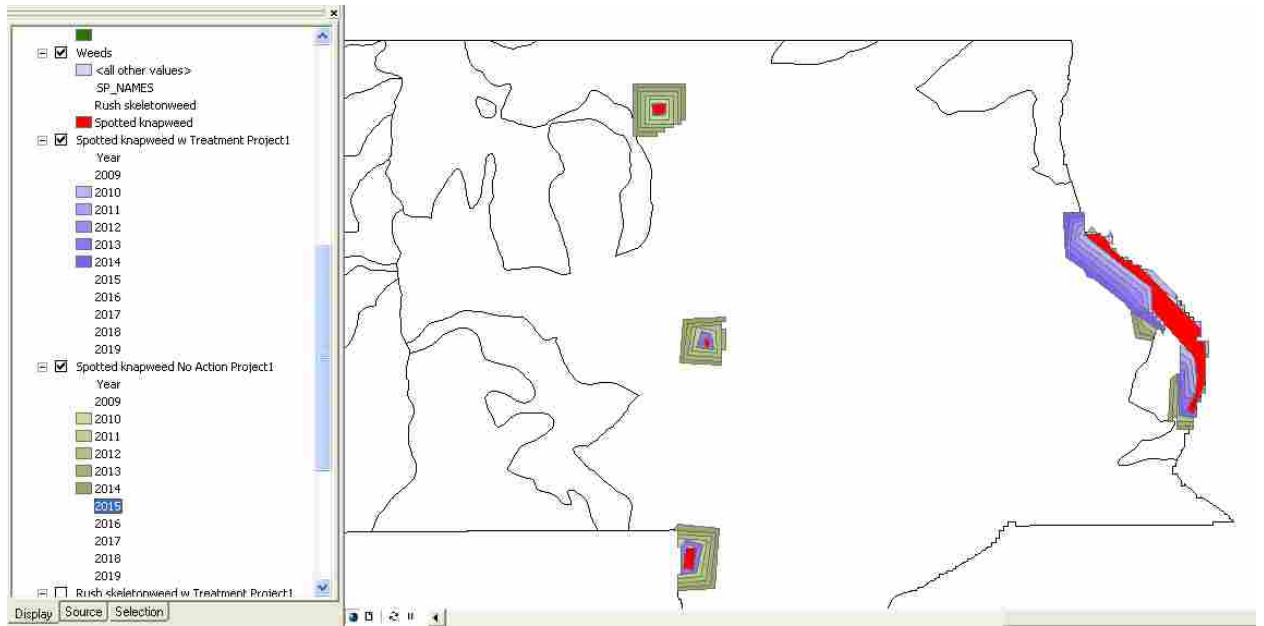
The example displays presented above illustrate only a few of the displays that can be made with ArcGIS using the input layers and the layers created by the **Run No Action Scenario** and **Solve (optimize)** options. The objective of this section was to provide the reader with ideas of how best to display the treatments and application methods selected for the spatial treatment schedules, and compare the predicted amounts of weed spread with and without treatments.

Solution time

The time required to obtain solutions can vary greatly depending on the size of the problem and the capacity of the computer. To give an idea of the time required in the table below we show the running times for two problems with different sizes, both solved using a desktop computer with a Pentium Dual Core 3.40 GHz processor, 3GB of RAM

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and running Windows XP. The table below lists the most relevant parameters that affect

computing time (number of weeds and application methods). The total time (hours)

taken in each case is shown in the last row of the table.

Area (acres)	15,927	61,460
Number of weeds	2	11
Number of application methods	5	5
Required time (hr)	1	86

Appendix – Data Dictionary

<u>GIS Layers</u>

Weed

Required Attributes:

Weed Species Name: field name identifying the weed species.

Configuration: multipart polygon shapefile. One record for each individual

species.

Roads

No required attributes

Roads-trails

No required attributes

Stream

No required attributes

Vegetation / cover type for susceptibility

Required Attributes

Vegetation Type Name: field name identifying the vegetation coverage.

Configuration: multipart polygon shapefile. One record for each individual

vegetation type.

Sites or landtypes for location priority

>Required Attributes

>Sites Name: field name identifying the sites that will be prioritize.

>Configuration: multipart polygon shapefile. One record for each individual site.

Disturbances - locations of past and planned disturbances:

>Required Attributes

>Disturbance Name: field name identifying the disturbances.

>Year of Disturbance: field identifying the year in which the disturbance occurred or will occur.

>Duration of Disturbance: field providing the number of years the disturbance lasts.

>Configuration: multipart polygon shapefile. One record for each individual disturbance.

<u>Database Tables</u>

Chemicals

>Fields:

>Chemical (text, 10)

>Remarks (text, 100)

Methods

    Fields:

    Method (text, 10)

    Remarks (text, 100)

Treatments

    Fields:

    Weed (text, 30)

    Treatment (text, 50)

    Cost (double, 10)

    Duration (integer, 10)

    Riparian (text, 5)

Weed rank and spread rates

    Fields:

    Weed (text, 30)

    Rank (integer, 2)

    Spread rate (double, 12)

Application methods

    Fields:

    Method (text, 30)

    Cost (double, 10)

Minimum treatment size (double, 15)

Treatment/Method exclusion

    Fields:

    Treatment (text, 50)

    Method (text, 30)

Application methods from roads

    Fields:

    Method (text, 30)

    Distance (double, 10)

Application methods from roads and trails

    Fields:

    Method (text, 30)

    Distance (double, 10)

Susceptibility matrix

    Fields:

    Vegetation (text, 40)

    Weed (text, 30)

    Susceptibility (text, 10)

Site priority

Fields:

Site (text, 40)

Rank (integer, 2)

Disturbance

Fields:

Polygon ID (integer, 10)

Period P1 ... P10 (text, 4)

APPENDIX 2. WTP PROGRAM CODE