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Landscape-Level Simulation of Weed Treatments to Evaluate Treatment Plan Options

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Models have been developed to simulate the long-term effects of weed treatments across a landscape to determine effective 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. In this study, we developed a simulation model to build and evaluate 5-yr weed treatment plan options in terms of their cost and effectiveness in minimizing total infestation areas over the short-term planning horizon. In an iterative, interactive process, 5-yr treatment plan options are developed based on user-defined weed treatment preferences, and evaluated in terms of total projected infestation areas at the end of the planning horizon. The simulation model was applied to a study area of 24,867 ha (61,447 ac) located in the Salmon River watershed in Idaho. Eight treatment plan options were developed using two treatment priority strategies and four increasing budget levels, and compared for their effectiveness. The application results showed that regardless of budget levels, site priority strategies were more cost-effective than the species priority strategies in reducing total infestation areas over time. This simulation model can provide weed managers with a useful tool to evaluate short-term treatment options, and thus support informed decision-making for effective weed management. Although the availability and quality of input data may be a practical limitation of using the simulation model, more data would become available and improved as more invasive species monitoring programs are implemented.

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

Understanding the dynamic of weed invasions is critical for their management, especially for identifying effective management actions, allocating control resources, and prioritizing treatments of weeds and locations. To identify effective strategies for weeds management, some studies have simulated the long-term effects of treatments across a landscape. Frid and Wilmshurst (2009) and Frid et al. (2013) used a decision analysis framework, in which they incorporated a spatially explicit model to simulate the outcomes of weed management strategies. The two main modeling components in their simulations are a semi-Markovian state and transition vegetation simulation model, and a weed spread simulation model that considers disturbances and management actions (ESSA Technologies Ltd. 2008). Three modes 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 method was then used to select which area becomes infested, weed spread rates and control efficacy.

The aforementioned studies found that early detection and treatment of newly infested areas is a more effective management strategy in general than treating already-established large areas. 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.

Although the modeling methods 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 yr), they do not provide guidance for shorter-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 early invasion stage or the late out-of-control stage of invasion is relatively

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Management Implications

Managing multiple weed species over time and space is a challenging task. To help with this task, we developed a simulation model to build and compare 5-yr weed treatment plans. The model includes three modular components for treatment development, spread simulation and treatment plan evaluation. The model is capable of developing spatially-explicit, directly implementable, short-term treatment plan options based on user-preferred treatment strategies, as well as simulating the effects of treatments in terms of weeds spread to evaluate the given plan options. The simulation model can help weed managers analyze trade-offs among multiple treatment options and identify the most cost-effective treatment plan. This simulation model allows weed managers to direct resources towards areas where greater treatment effects can be realized across multiple weeds, and thus helps them achieve their weed management objectives efficiently. In addition, comparisons of the estimated effects of treatment plans developed under different budget levels can be used to measure budget efficiency in weed management and justify the current and future budget requests. Finally, the use of this simulation model may reveal critical data and knowledge gaps for efficient weed management. Although these limitations, the ongoing and future weed databases and monitoring programs may serve as source of input data for the simulation model.

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, personal communication). However, when 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 1- to 5-yr treatment plans may be able to help weed managers identify the most cost-effective treatment plans. The model should also be able to account for treatment costs and effects on multiple weeds over time in order to measure the cost-effectiveness of weed treatments.

In this study, we developed a simulation model to build short-term weed treatment action plans and compare them in terms of their cost-effectiveness in reducing total infestation areas over a 5-yr planning horizon. The ability to compare treatment strategies in this manner will certainly help weed managers understand the potential of each treatment plan option and thus make informed decisions in achieving their management goals. An application of the simulation model is presented in this paper, including a complete set of input data and a comparative analysis of multiple treatment plan options, to demonstrate the use of the model in a real size weed management problem.

Materials and Methods

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). Treatment plans 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., 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 areas (i.e., polygons) that are homogeneous in terms of land attributes, such as weed 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 to determine herbicides and AMs for each TU based on application feasibility (e.g., riparian areas, vehicle accessibility, etc.). Treatment locations for the first planning period are used to simulate weed spread across the landscape for the following planning period. Simulated weed spread is then used by the model to select candidate TUs for the next planning period, which are presented to the user for prioritization. This iterative process continues until a 5-yr treatment plan is completed for the landscape. This treatment plan is then evaluated by the plan evaluation module in terms of total simulated infestation area and total treated area. All three modules are implemented as a series of functions in ArcMap®, a Geographic Information System (GIS) computer program widely used among land management agencies. Details on each module as well as the required user input data are presented below.

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 simulated weed spread and effects of selected treatments scheduled for each polygon. 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.

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,

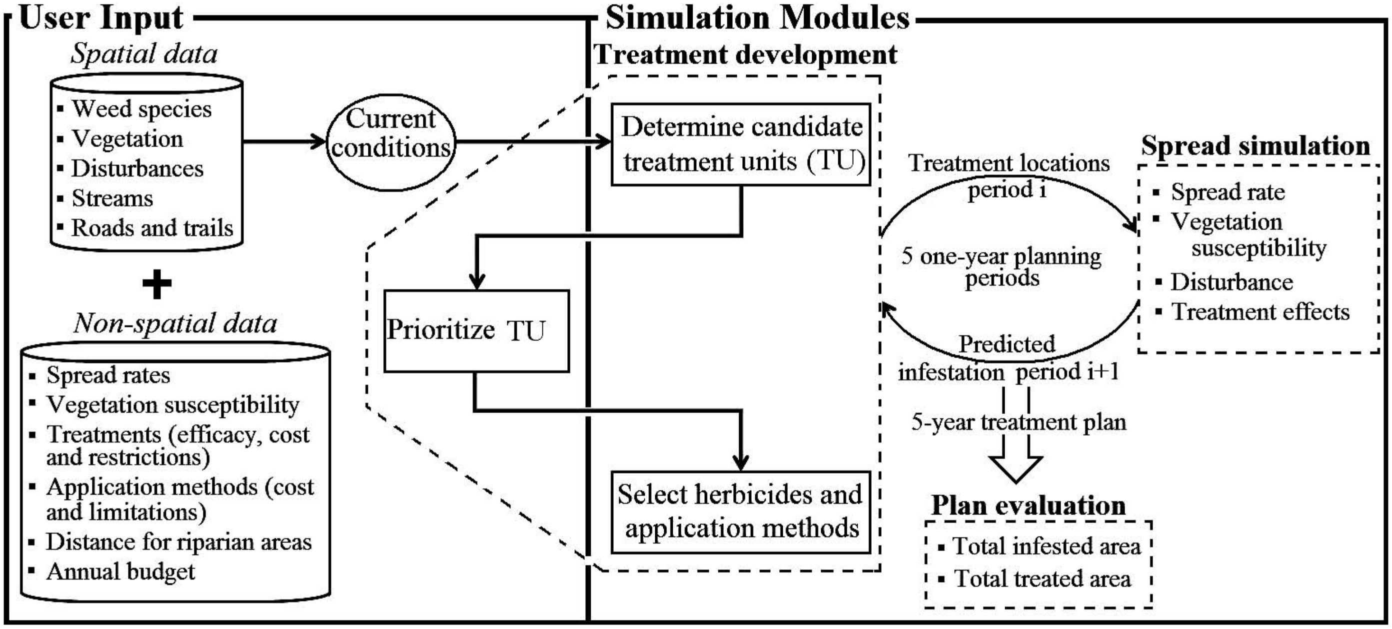

Figure 1. Overview of the simulation model consisting of three main modules: treatment development, spread simulation, and plan evaluation.

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.

Treatment Development. Selecting treatments requires TU with the attributes of homogeneity described above. We selected these attributes because they are important factors in deciding herbicides and AMs. For example, specific herbicides are often selected based on weed species and land class, while feasible AMs depend on the accessibility to TUs. The model begins with 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 treatment plans for a landscape of interest, which is described in detail in Figure 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 TU 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 TU is available. Herbicides are selected based on weeds and land type attributes of TUs. If more than one herbicide option is available, the algorithm chooses the least cost option per hectare. For AM, the algorithm first considers the least cost method on a hectare basis 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 to form a cluster that can be treated with the same herbicide and AM (Figure 3).

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. 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 3). Otherwise, the algorithm moves to the next least cost AM that requires a smaller minimum treatment size, and examines its feasibility (Case 2 in Figure 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 affecting 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.

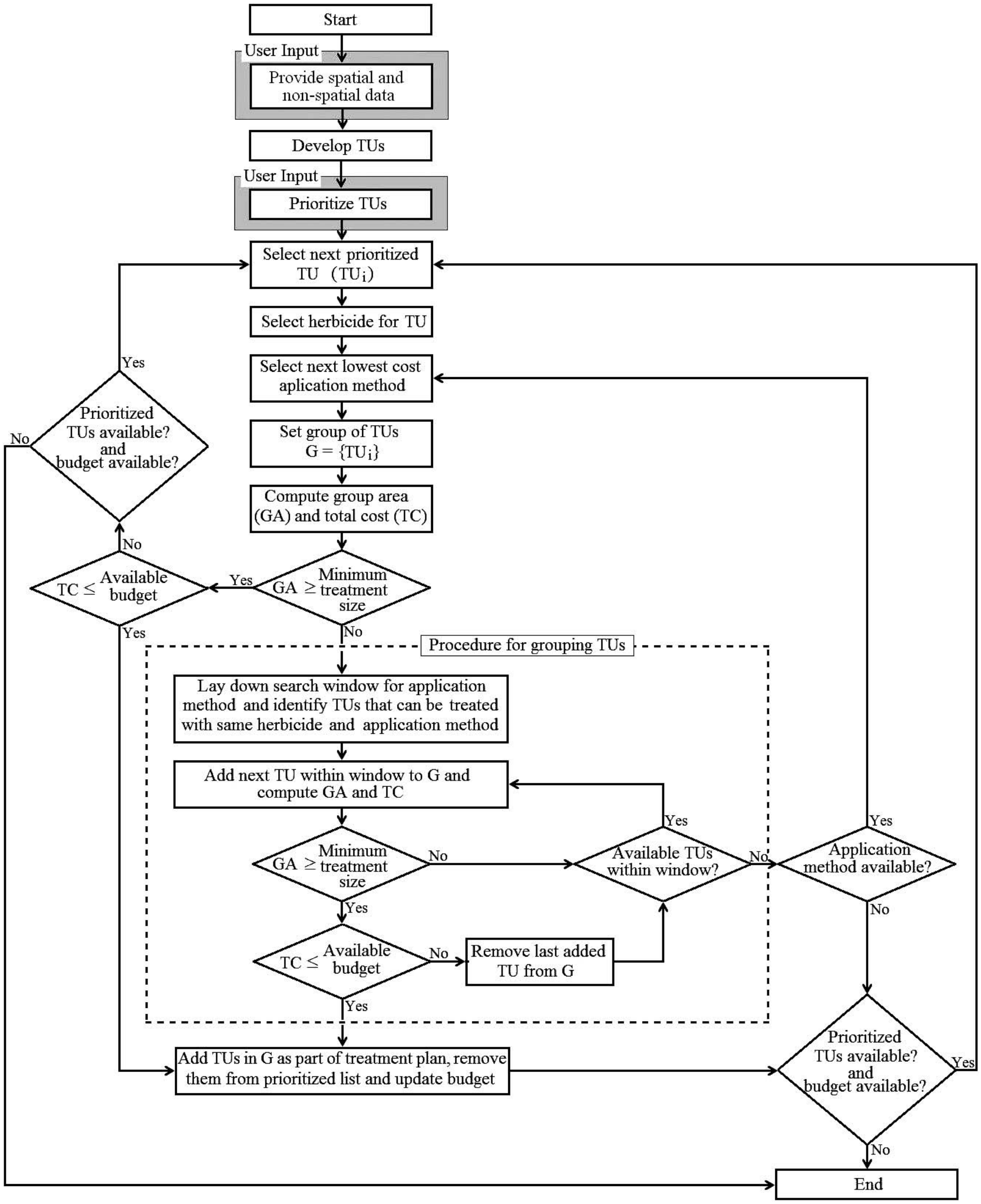

Figure 2. An algorithm developed to build an annual treatment plan based on TUs, user-defined priorities, herbicides, application methods, and available budget. The shaded box represents user inputs.

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: (1) closed to invasion; vegetation is not susceptible to the particular weed species, (2) disturbance allows invasion; in normal condition the vegetation is not susceptible, but becomes susceptible if disturbed, and (3) susceptible; vegetation is susceptible to weed species. The modeled spread of weeds is linear in all directions at a user-provided spread rate.

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 expires, weeds 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 4 illustrates our assumptions on weed spread with treatment effects in three different cases with multiple species.

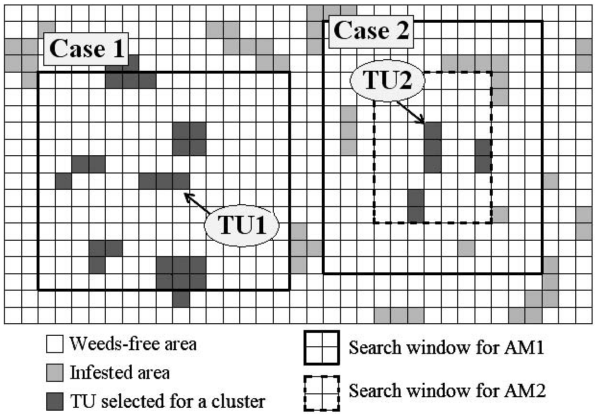

Figure 3. Building a cluster of treatment units (TU) by the simulation model to meet the minimum treatment size requirement for a given application method (AM). TU1 and TU2 are high priority units serving as the center of search windows. AM 1 (e.g., helicopter) is the least cost method available and 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, whereas in case 2, AM 2 (e.g., truck) is selected for TU2 and its neighbor units because of insufficient area for AM 1.

Figure 4a shows weed spread with no treatment, where weeds spread along the perimeters of existing infestation at a given linear spread rate per year. Figures 4b and 4c 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 4b) unless herbicide used for Weed B also affects Weed A (Figure 4c). Figure 4d shows the last case scenario where both Weeds A and B are treated, and therefore both weeds stop spreading.

Plan Evaluation. After a 5-yr treatment plan is built for a landscape of interest, the plan is evaluated in terms of total infestation areas, the amount of selected areas to be treated, and cost-effectiveness of treatments. The total infestation areas represent future infestation potential, while the total selected areas 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. The denominator of the ratio represents the effects of weed treatments in terms of areas (ha) to be maintained weed-free because of treatments. These areas can be obtained from a comparison between the simulation results of a treatment plan and those of no action plan. The lower CE value indicates the more cost-effective the treatment plan would be. This ratio can be also interpreted as the annual 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 treatment plans. Diverse evaluation criteria should be explored to assess plans and conduct trade-off analysis based on given management goals. Since our simulation model 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, herbicides, and AMs.

$$\begin{aligned} \mathrm{CE} = {} & \text{Total treatment costs}(\$) \\ & /\text{Reduction in infestation area} \\ & \text{because of treatments (ha)} \end{aligned} \qquad [1]$$

Model Application. We applied our simulation model to a study landscape of 24,867 ha (61,447 ac) located in the

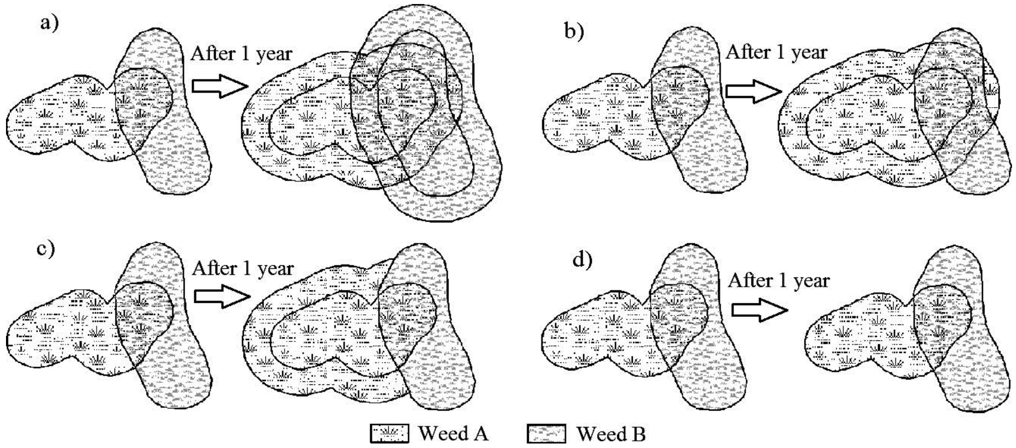

Figure 4. Weed spread logic with treatment effects on multiple weed species. Assuming surrounding vegetation is susceptible to invasion of Weeds A and B: a) no treatment, both Weeds A and B spread, b) Weed B is treated, and the herbicide affects only Weed B, c) Weed B is treated, and the herbicide affects both Weeds A and B, and d) Both Weeds A and B are treated.

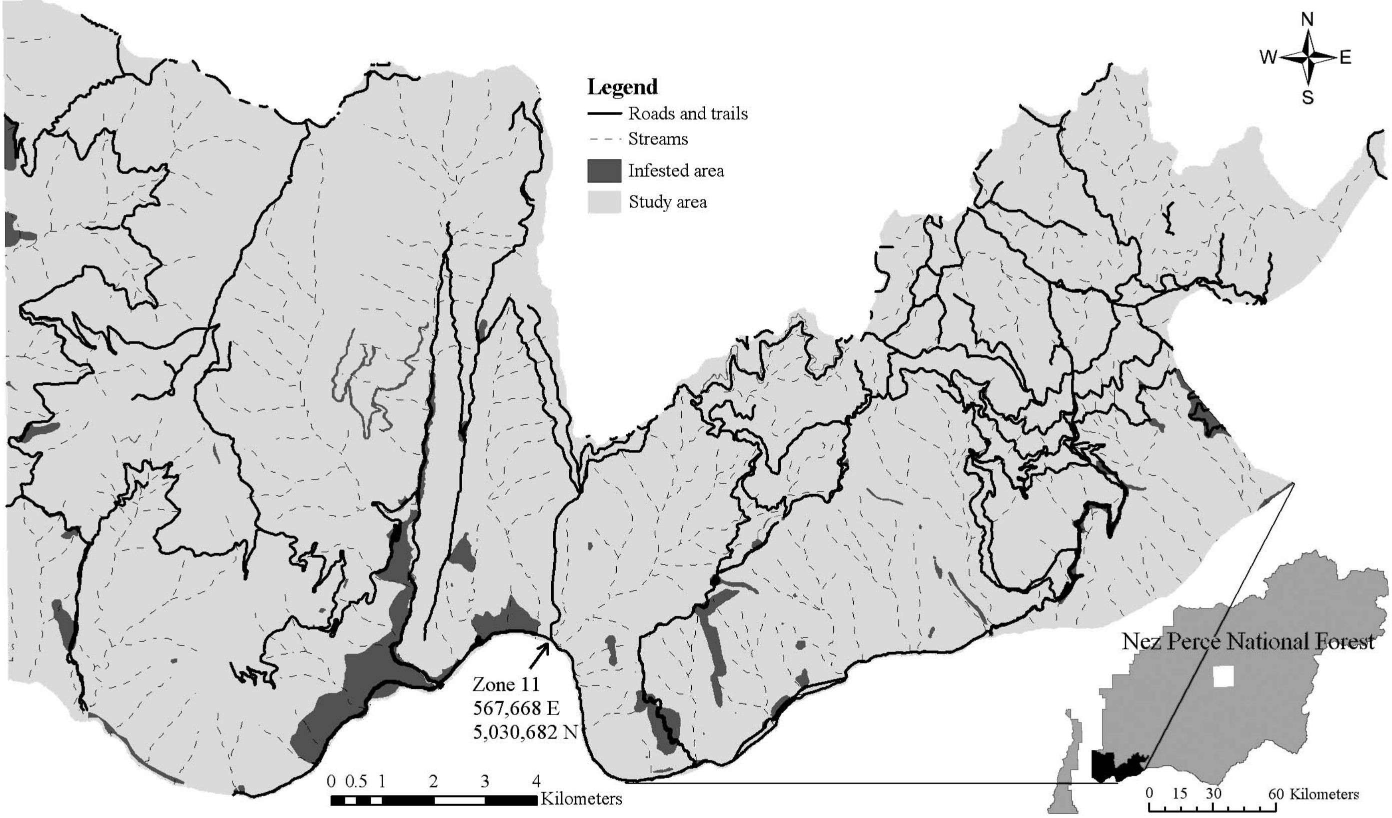

Figure 5. The 24,867 ha study landscape located in the Nez Perce National Forest.

Salmon River watershed in the southwestern portion of the Nez Perce National Forest in North-Central Idaho (Figure 5). 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 applied actively 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.

User Input. *Weed species and vegetation susceptibility.* Ten weed species were found in the study landscape in 2009 (data provided by the SRWMA). The total estimated current infestation areas per species in the landscape widely vary from 0.2 ha for diffuse knapweed (*Centaurea diffusa* Lam.) to 664.4 ha for rush skeletonweed (*Chondrilla juncea* L.) (Supplemental Appendix 1; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). 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, personal communication). Vegetation cover types across the landscape obtained from the SRWMA and a susceptibility matrix developed by local weed ecologists (Supplemental Appendix 2; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA) were used to determine susceptibility of 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 of prescribed burn in 2004 (Supplemental Appendix 3; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). Durations of disturbance effect were assumed to last until the first and third yr of the 5-yr planning horizon for the 2006 and 2004 fires, respectively.

Treatment options. We identified herbicide treatment options applicable to the weeds in consultation with local weed managers (Supplemental Appendix 4; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). 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. Because of this restriction, we created 60 m (196.6 ft) buffers around stream networks to designate riparian areas, and allowed the herbicides within the 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.

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 (Supplemental Appendix 5; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). We did not separate fixed costs from the total application costs to simplify user inputs, but assumed the cost of each AM 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 of AMs would be much higher than those used in this application 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.

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. 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 a truck application.

Treatment Plan Options. It is often impractical to treat the entire infestation areas because of limited resources and extension of infestations; 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 or sites (Timmins and Owen 2001). Although we recognize that weed managers often combine the two prioritization schemes when they make decisions about when and where to treat, we exclusively chose one prioritization scheme at a time to develop and compare two distinct treatment plans using our simulation model for demonstration purpose.

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 (Supplemental Appendix 1; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). 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 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 (Supplemental Appendix 6a; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA).

Treatment prioritization based on sites. In this prioritization scheme, TUs are prioritized based on their locations (Supplemental Appendix 6b; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA). 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 because of high potential of weed seed transport by vehicles and human activities.

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 weeds species and sites) to develop and compare a total of eight weed treatment plan options.

Results and Discussion

Treatment Plan Options. The total selected areas for treatment in hectares were mainly constrained by annual budgets (Figure 6). 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 6). 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 (Supplemental Appendix 6a and 6b; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA).

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 yr (Supplemental Appendix 4; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA), some

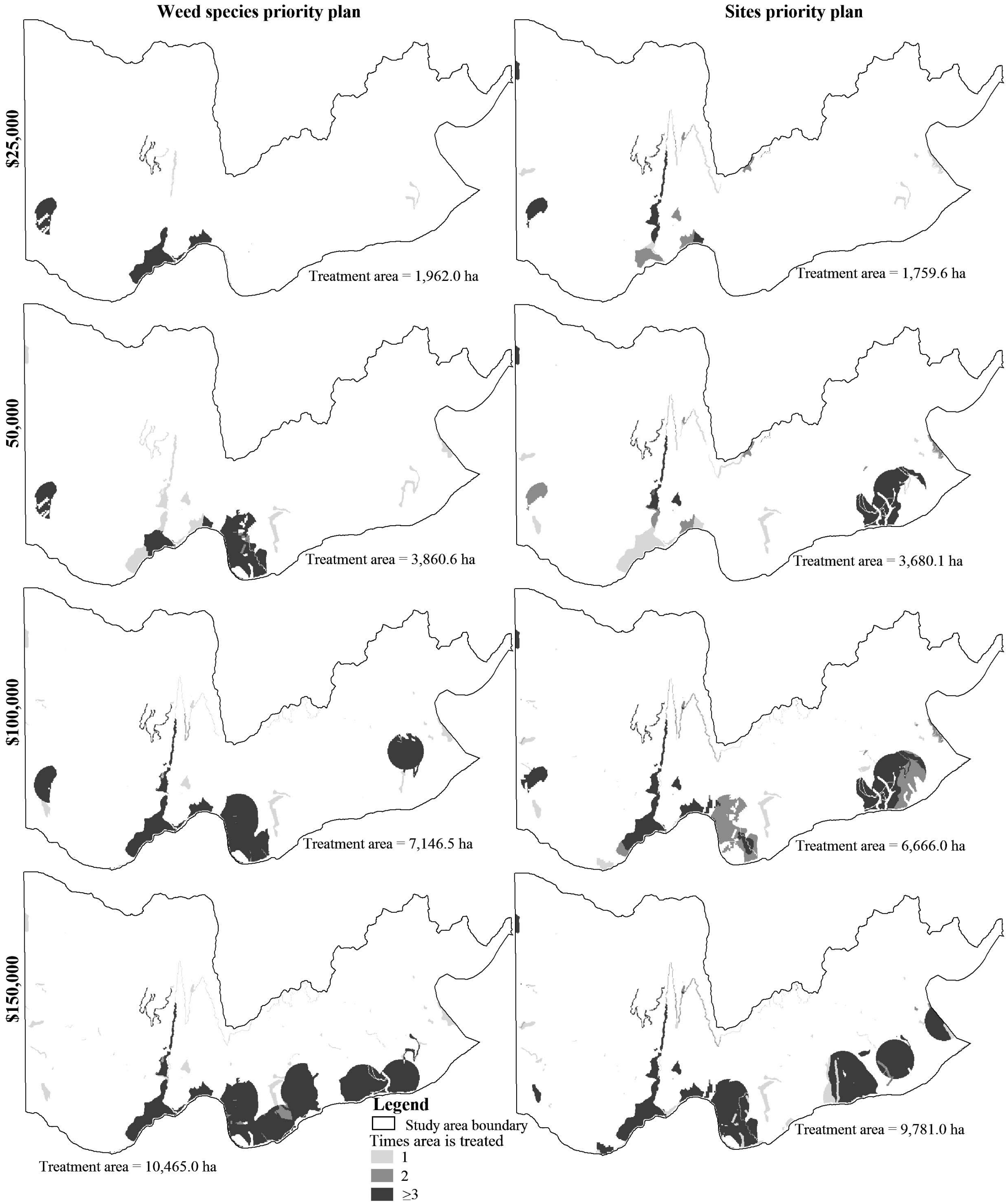

Figure 6. Selected treatment locations shown with the number of retreatments under different prioritization schemes and annual budget levels.

Table 1. Total areas selected for treatment (ha) by application method in each of the 5-yr treatment plan options.

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

areas were selected for retreatment during the 5-yr planning horizon. It appears that the prioritization schemes also affect the selection of TU for retreatment (Figure 6). For example, a 23 ha area in the north-west corner of the study area was not treated in the weeds 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 because of 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.

From the AMs considered in this study, helicopter was the most popular method in all scenarios ranging from 1,752.4 ha to 10,271.7 ha (Table 1), 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 where other AMs could not reach because of inaccessibility.

The number of weeds targeted for treatment was different between the two priority schemes with the exception of the $50,000 annual budget (Table 2). 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.

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 order to contain multiple weeds (Table 3).

Weed Spread Simulation. Total simulated infestation areas by weed species at the end of the 5-yr planning horizon show differences between the base case scenario and each of the treatment plan options (Table 4). 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 yr. The results indicate that the total infestation areas are reduced by 1.6% from the base case scenario when an annual budget is $25,000, but the reduction in infestation area would go up to 25.9% when an annual budget level is increased to $150,000 (Table 4).

Table 2. Total areas selected for treatment (ha) by weed species in each of the 5-yr treatment plan options.

Weed	Weeds priority plan				Sites priority plan			
	$25K	$50K	$100K	$150K	$25K	$50K	$100K	$150K
Downy brome (*Bromus tectorum* L.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spotted knapweed (*Centaurea stoebe* L.)	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 [*Linaria dalmatica* (L.) P. Mill.]	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 (*Potentilla recta* L.)	0.0	0.0	0.0	0.0	0.0	0.0	3.9	5.0
Puncturevine (*Tribulus terrestris* L.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Common mullein (*Verbascum thapsus* L.)	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

Table 3. Total costs per unit area ($ ha^{-1}) of herbicides and application methods in each of the treatment plan options.

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)

Results also show that the site prioritization scheme was more effective in reducing the total infestation areas across all the budget levels despite the fact that a smaller area was to be treated under this prioritization scheme (Table 2). 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 simulated 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 4).

It appears that infestation areas of certain weeds such as diffuse knapweed, common crupina and puncturevine are not projected to increase from their initial infestation in both prioritization schemes (Table 4). This is mainly because most areas in the study landscape are not susceptible to invasion by those species unless disturbed, and the current infestations are not near the existing disturbance areas.

Locations of infestation areas for all scenarios show differences across budget levels and prioritization schemes (Figure 7). The higher budget results in fewer infestation areas because more areas 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.

Changes in infestation areas modeled over the 5-yr planning horizon show that a large area is newly infested during the first yr and then the increase in infestation areas slows down (Figure 8). This large influx of newly infested areas in the first yr is due mainly to the effects of the disturbed area of 6,658 ha (Supplemental Appendix 3; http://dx.doi.org/10.1614/IPSM-D-13-00043.SA) that was considered susceptible to invasion during the first yr of simulation. This result suggests that managers might need to prioritize disturbance areas for treatment if such areas are indeed more prone to invasion.

Cost-effectiveness of Treatment Plans. To assess cost-effectiveness we calculated a CE value for each treatment plan. 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 9). It is noteworthy that large differences in CE values between the two prioritization schemes occur at the low budget levels. These results suggest that more careful planning for treatment locations and timing should take place when a budget is tighter because of the large number of options that are available for treatment

Table 4. Simulated total infestation areas (ha) per weed at the end of 5-yr planning horizon in each of the treatment plan options.

Weed	No treatment	Weeds priority plan $25K	$50K	$100K	$150K	Sites priority plan $25K	$50K	$100K	$150K
Downy brome	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	4,012.2	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 areas from base case	0.0%	1.6%	6.5%	11.0%	23.3%	5.9%	8.7%	11.1%	25.9%

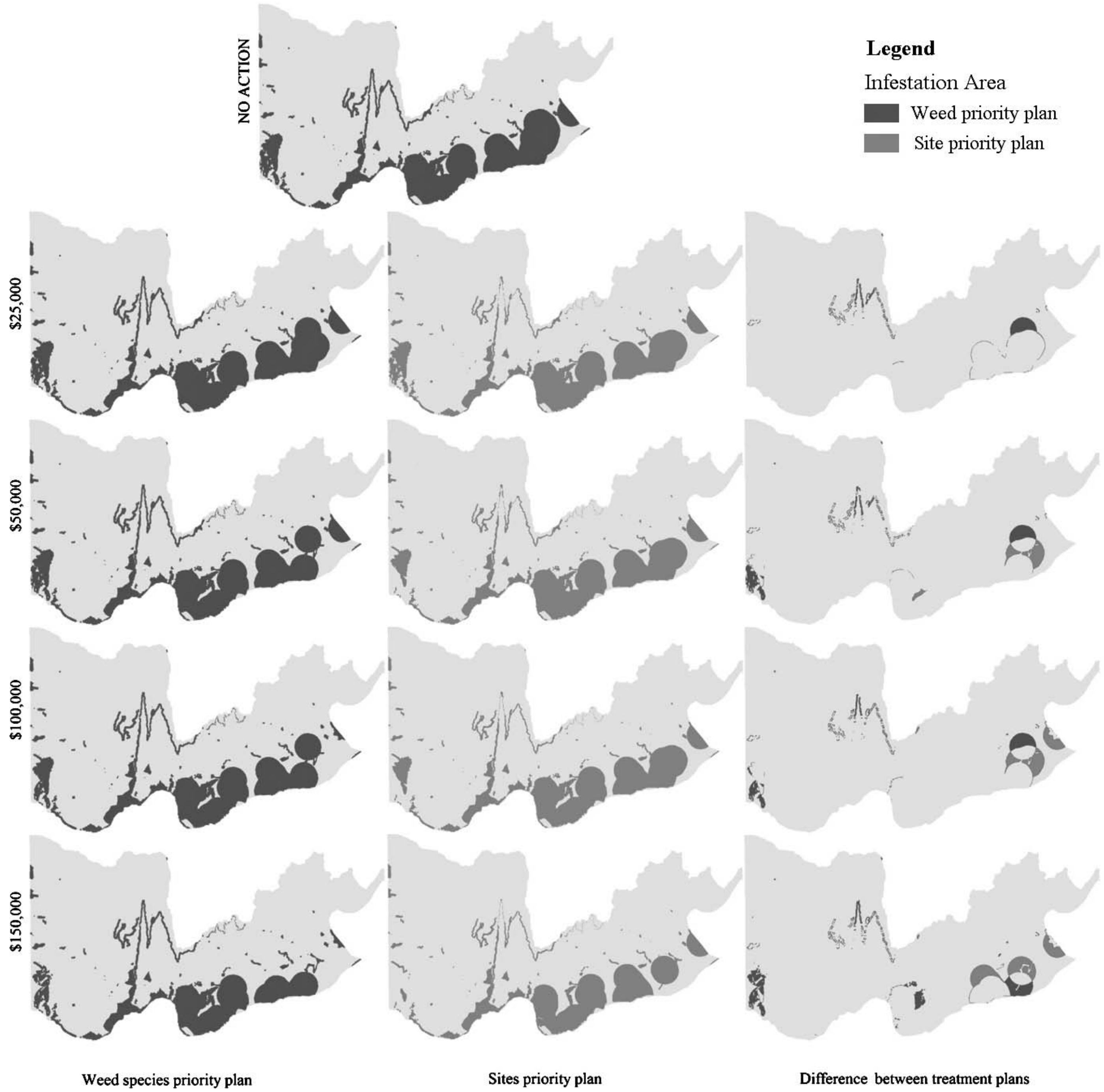

Figure 7. Simulated infestation areas at the end of 5-yr planning horizon resulting from each of the treatment plan options.

selection, and the cost-effectiveness of individual treatments may vary widely.

In our simulations, the site priority plan with the annual budget of $25,000 appears to be the most cost-effective option. However, if the management objective is to minimize total infestation areas, higher budget levels would be required (Table 4).

Model Limitations and Strengths. Our simulation model provides a semi-automated method to develop treatment plan options based on the user's management strategies. This process of 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

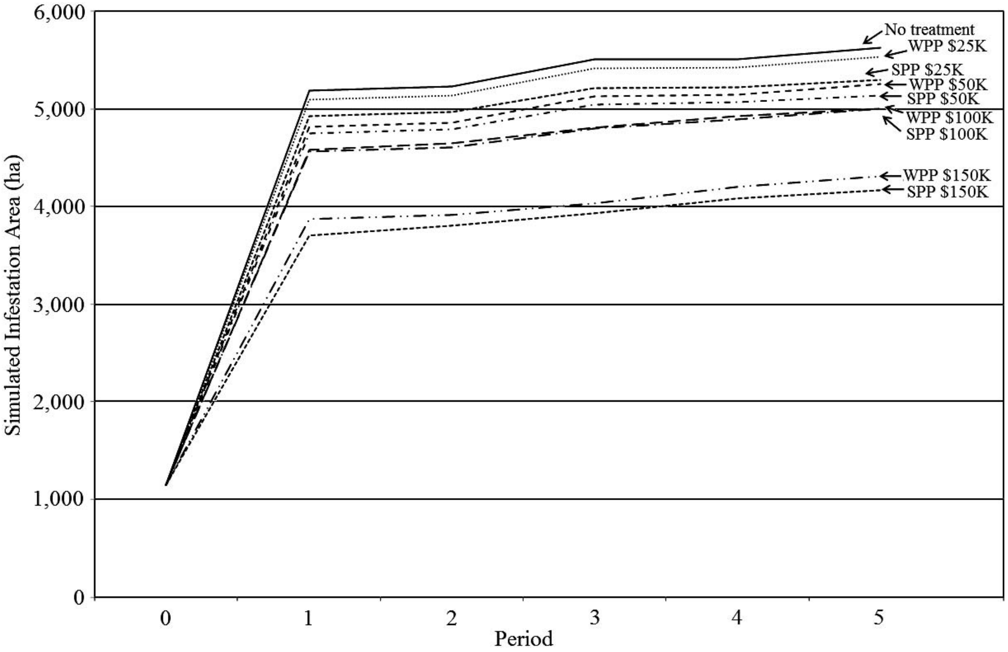

Figure 8. Simulated infestation areas in each time period resulted from each of the treatment plan options. WPP and SPP indicate the weed species priority plans and the site priority plans, respectively.

optimization modeling method, when combined with this simulation model, would provide additional benefits by automatically identifying the optimal treatment plan for a given management objective. Our simulation model capable of generating and evaluating plans can certainly provide an essential component for a future optimization tool for weed treatment planning.

Our simulation model considers that weeds spread consistently along the weed patch perimeter 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, but no shrinkage or eradication of current infestations is modeled. We also assumed that the treatment effects and costs do no vary with the density of weeds, and that vegetation susceptibility to invasion is deterministic and known. It is important to understand these assumptions for the proper use of the model and interpretation of the results.

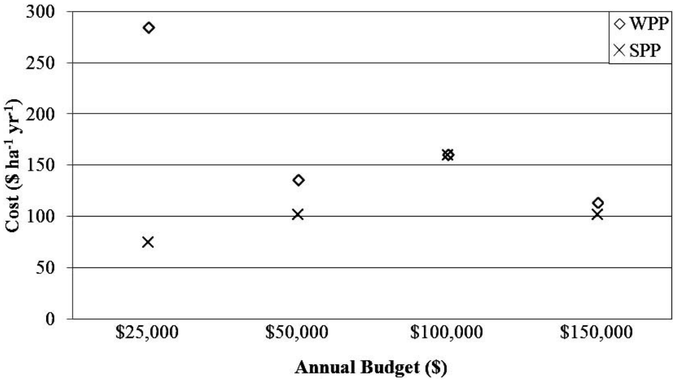

Figure 9. Cost-effectiveness ratio values calculated from the treatment plan options. WPP and SPP indicate the weed species priority plans and the site priority plans, respectively.

Evaluating treatment plans using our simulation model would allow weed managers to analyze trade-offs and identify the plan that best meets the management goal. Evaluation criteria used in the model include 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 the presence 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 community, and land use, more inclusive evaluation metrics and criteria could be developed and incorporated in the model in the future.

Targeting single weed species often becomes 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 method can provide a means to develop, simulate and evaluate weed treatment plan options for multiple weed species considering 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.

Potential Practical Application Issues. Like any other complex simulation models, our model relies on the availability and quality of required input data, as well as a workforce who can properly operate the model. Spatial data required for the model (i.e., current infestation areas, vegetation cover, streams, roads, trails, etc.) become more available and accessible as more land management agencies and other interested parties participate in invasive species monitoring programs and provide geospatial databases (Hunt et al. 2005; USFS 2013). However, obtaining certain data, such as weed spread rates and treatment efficacy, can be still challenging. When such data do not exist, model users will have to initially rely on their best estimates based on their past experiences, and refine them as more knowledge and supporting data become available. Although the model is designed to produce and evaluate 5 yr treatment plans, it should be rerun frequently with newly updated data to improve the practicality of the model results. In order to address the potential issue of workforce development, we have been incorporating our simulation modeling approach into an easy-to-use decision support tool that will be able to fully optimize weed treatment planning. Since the tool will be developed as an embedded program within a widely-used GIS system, we envision that any existing GIS users can easily operate the tool with little or no training.

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