Decision Analysis of Alternative Invasive Weed Management Strategies for Three Montana Landscapes

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1. Introduction

The ecological impact of invasive non-indigenous species has been variously described for terrestrial and aquatic systems around the world. In Montana, noxious weeds infest about 8 million acres, or roughly 9% of the state (Montana Department of Agriculture 2005). Spotted Knapweed (*Centaurea maculosa*) and Leafy Spurge (*Euphorbia esula*) are among the most widespread of these weeds, each infesting more than 1 million acres in the western United States (DiTomaso 2000). To address the spread of invasive weeds, Montana and other western states have established various state laws to combat the spread of weeds. Additionally, Cooperative Weed Management Areas have been created to implement coordinated management between state, federal, and private landowners. Despite regulatory and organizational efforts, noxious weeds continue to spread at a rate of approximately 8-20% per year in the West (DiTomaso 2000, Svejcar 2003). The estimated cost of losses and damages to grazing in the United States is one billion dollars; this is in addition to the associated cost of controlling invasive plants in pastures which has been estimated at five billion dollars (Pimentel et al. 2005).

We believe that invasive plant species continue to spread across the West for two primary reasons. First, research and demonstration control efforts presented to land managers and land owners have focused on the refinement of control techniques at fine scales (e.g. small patches of weeds or experimental plots). As a result, management approaches across landscapes are often ad-hoc, rather than developed and tested strategic approaches to abate or manage infestations at broad scales. Ad-hoc strategies derived from fine-scale experience or arbitrary decisions ("rules of thumb") may provide adverse results at broad scales. For example, Wadsworth et al. (2000) found that the often recommended strategy of targeting small new populations of invasive species (Moody and Mack 1988) were ineffective in control of two species that spread by long-distance dispersal. Second, despite education efforts, implementation of control treatments tends to be uneven across landscapes. Non-management of a given species as a result of inadequate or changing budgets, lack of human action, or site limitations (e.g. topography, proximity to water) may result in robust source populations with profound consequences to landscape-level invasive plant distribution and abundance. Inability to predict the impact of unmanaged invasive species or the effects of varied management across large areas inhibits the design and implementation of strategies that will effectively conserve intact native plant communities.

Models of effective management of invasive species are relatively few, but these almost always exhibit a high level of organization and education among stakeholders, involve a plant with a vulnerable life history trait, and are supported by sufficient resources over the long-term (Mack et al. 2000; Anderson et al. 2003). Another critical factor is the ability to adapt rapidly in the face of tremendous uncertainty using proper planning, experimenting, monitoring, and then changing based on improved understanding of the system being managed (Shea et al. 2002; Eiswerth and van Kooten 2002; Chornesky et al. 2005).

Effective management of invasive species will require comparisons of weed management strategies at appropriate spatial and temporal scales. Comparisons must consider the feasibility of each goal within the context of sustaining viable conservation targets (e.g., desired plant communities). Due to the large spatial and temporal scales involved and the uncertainty surrounding our understanding of invasive species spread dynamics, empirical evidence alone is inadequate for evaluating management strategies at the landscape scale. GIS-based models have been used to predict the potential of strategies to abate invasive species (Higgins et al. 2000, and Wadsworth et al. 2000), as well as appraise resource costs to implement the strategies (Leung et al. 2005). The most effective models consider susceptibility of habitats to invasion and predict the rates and patterns of invasive plant spread in the context of succession dynamics (Sheley and Krueger-Mangold 2003); however; a high degree of uncertainty is associated with parameter estimates and formulations of GIS models for invasive species spread (Neubert and Caswell 2000; Bergelson et al. 1993; With 2002; Higgins et al. 2003).

Decision analysis is a formal framework for making management decisions in the face of uncertainty (Clemen 1996, Peterman and Peters 1998, Peterman and Anderson 1999). Decision analysis allows managers to evaluate alternative strategies while explicitly taking into account uncertainties about the system being managed and the strategies that are most robust to this uncertainty. Here we present a decision analysis for evaluating alternative weed management strategies in three Montana landscapes. Our alternative management strategies assign different levels of priorities and budgets to controlling large, known, existing infestations versus detecting and eradicating small new infestations. The uncertainties we address include the rates at which invasive plants spread at landscape scales and the effectiveness of management efforts at controlling local infestations.

2. Study Area

We conducted research for three landscapes in Montana, the Rocky Mountain Front (RMF), Centennial Valley (CV), and Montana Glaciated Plains (MGP) (Figure 1). These landscapes range in size from 150,000 to 700,000 ha, and each was identified through ecoregional assessments as a priority area for conservation action.[1] Each have expansive areas of grassland and/or shrub and grassland associations. They each contain riparian vegetation, as well as, coniferous forest or woodland communities, although these associations were of reduced extent in the percent of geographic scope in the MGP. The land use in all three landscapes is dominated by agricultural production, primarily ranching, although annual crop production is widespread in portions of the RMF and MGP.

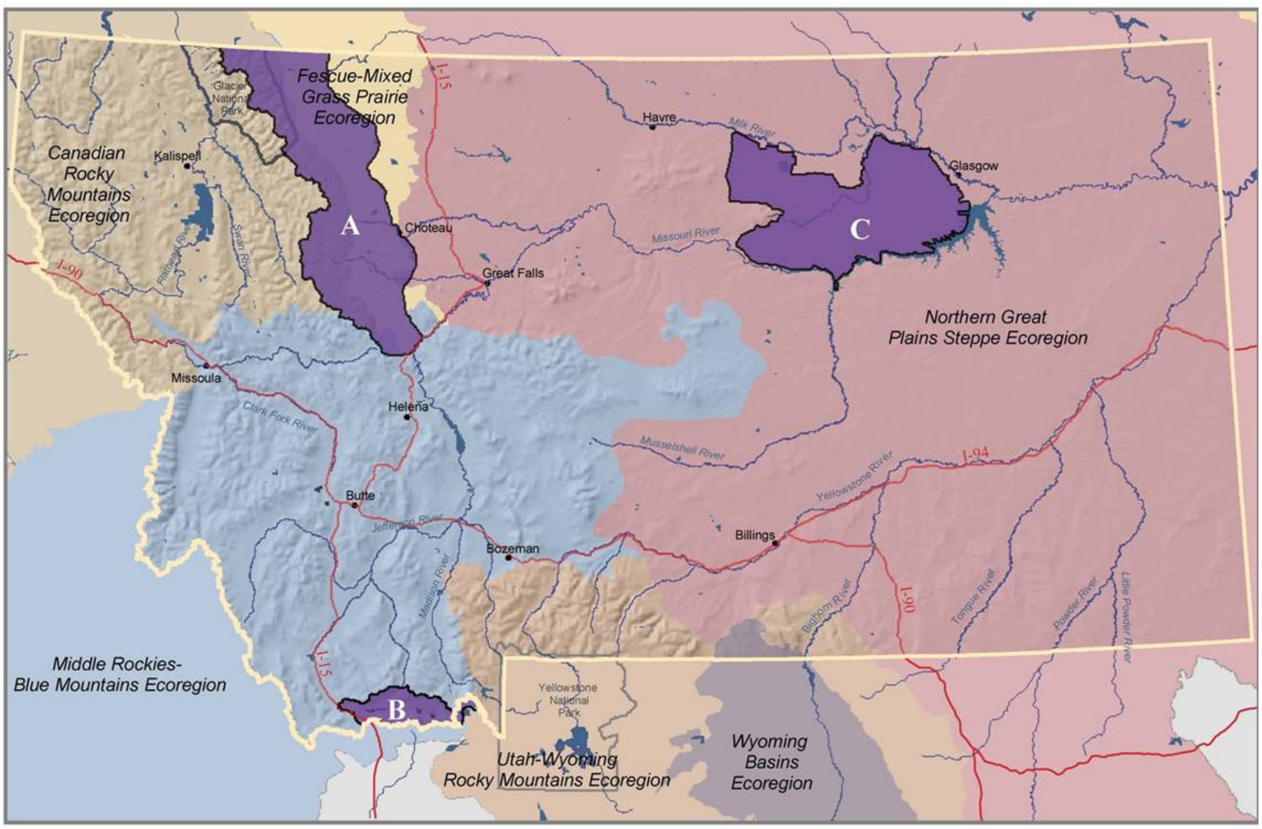

Figure 1. The state of Montana showing study area locations for: (A) the Rocky Mountain Front, (B) the Centennial Valley, and (C) the Montana Glaciated Plains.

Each of these landscapes differ by the current relative extent of noxious weed invasion, with the MGP being relatively free of noxious weeds, the CV having isolated infestations that are mostly small, and the RMF having the greatest variety of weeds and the most widespread infestations. We selected spotted knapweed as the primary noxious weed species to model (*Centaurea maculosa*) for all three areas, and also included leafy spurge (*Euphorbia esula*) for the MGP and RMF. These two species do not reflect all

[1] See conserveonline.org/docs/2002/05/ERP_with_appendices.pdf for the Middle Rockies Ecoregion and conserveonline.org/docs/2000/11/NGPS.pdf for the Northern Great Plains Steppe Ecoregion.

of the noxious weeds in each landscape; rather they were selected since they represent the species with the greatest management concern across a variety of native habitats within and outside of the study area. Each of these species could also serve as surrogates for other noxious weeds with similar ecology and life histories.

3. Methods

3.1 Decision analysis framework

We calculated the consequences of alternative management strategies against invasive weeds, probability weighted for alternative hypotheses by the rate of spread and the effectiveness of control. Our decision analysis had six components: (1) alternative actions, (2) performance measures, (3) uncertainties related to the dynamics of invasive species spread and control, (4) a model to predict outcomes, (5) a decision tree, and (6) sensitivity analyses. Each of these components is described below.

3.1.1 Alternative actions

Treatment strategies tested differed between landscapes based on the presence and distribution of the selected noxious weed. For the Centennial Valley we considered alternative management strategies based on combinations of two components: the annual budget allocated to invasive weed treatment, and the treatment prioritization of large existing patches versus small new populations. Our alternative budgets were expressed in terms of the ceiling applied to the annual area that could be treated. The budget alternatives were representative of current capacity (200 polygon hectares),[2] or a doubling of current capacity (400 polygon hectares). The strategy alternatives considered the tradeoffs between applying all available resources to containing large known infestations vs. investing some resources in early detection in order to control small new infestations before they become established. As a benchmark we also considered inaction (no treatments) as a hypothetical alternative.

For the Rocky Mountain Front we considered a broader range of alternatives ranging from inaction, unlimited treatment (no budgetary constraints), closing portions of the landscape to treatment, prioritizing large existing infestations or small new infestations, prioritizing small infestations along with edges of large infestations, prioritizing knapweed over leafy spurge for treatment, and using biological control agents to reduce leafy spurge. Treatment ceilings that were used in some RMF alternatives were designed to recognize that current levels of infestation are close to or exceed the time and financial budgets of managers to treat all infestations. For our treatment ceilings we used 90% of the area treated in the first time step of the corresponding unlimited treatment scenario (3400 ha/year under slow spread and 4500 ha/year under fast spread).

For the Montana Glaciated Plains we have only considered inaction vs. an unlimited budget for treating all infestations, due to the limited extent of existing infestations.[3]

3.1.2 Performance measures

The performance measures we used to evaluate each strategy were: (1) the cumulative area treated over a forty (RMF and MGP) or fifty year period (CV) as an indicator of the total cost of each treatment strategy, and (2) the final state of the landscape (area invaded) after that period, as an indicator of the

[2] Our simulations were conducted at a resolution of 1 ha polygons. Budget ceilings were set at 200 or 400 polygon ha recognizing that these polygons are not 100% covered by noxious weeds. In the future, we plan to incorporate real area ceilings into our simulations.

[3] The number of simulations conducted for the Rocky Mountain Front and Montana Glaciated Plains is limited because of their larger size. We plan to conduct more detailed analyses for both of these landscapes.

outcome of each management strategy. Model results are reported in terms of polygon areas treated over the entire simulation period and polygon areas invaded at the end of the simulations. These results were converted to more realistic values by multiplying polygon areas against the average percent cover of weeds for the state of the polygon (we assumed that the average percent cover was 20% for the first 6 years post invasion and 60% if weeds were present for more than 6 years). For each management strategy these performance indicators were probability weighted by alternative hypothesis and summed.

3.1.3 Uncertainties

We focused our analysis of uncertainty on what are perceived to be two key uncertainties in invasive weed dynamics, both in the literature and among the experts and stakeholders that participated in our model development workshops. These key uncertainties are: (1) the rate at which invasive weeds spread across the landscape over time, and (2) the effectiveness of site-specific control efforts.

The **spread** of an exotic species through native vegetation is a highly complex ecological process (With 2001; Bergelson et al. 1993). Despite considerable research, there remain few models whose utility extends beyond the theoretical to predict spread of individual weed species across actual landscapes. One reason for this is the lack of mid-scale time-series of invasions (i.e. spread across 500-1000 square mile areas over time periods of 20-50 years). County-level presence-absence data, which depict the spread of species across the nation, is too coarse to have meaningful applications for modeling spread within a landscape. Substantial research has measured the physical distances and mechanisms by which individual plants spread via roots, shoots, and seed dispersal, but these studies fail to capture the actual spread of patches, or groups of plants. Patches produce several orders of magnitude more seeds, thereby increasing the probability of any given seed being transported further by wind, water, animals, or other vectors. Long-distance dispersal can have a dramatic effect on the distribution of annual spread distances (Clark et al. 1998; Neubert and Caswell 2000); but is difficult to quantify due to relatively rare occurrences and inability to confirm the seed source of new infestations (Higgins et al. 2003).

We used a negative exponential distribution of annual spread distances for modeling short and intermediate spread distances (i.e. 1-100 meters). Most weed seeds disperse within a short distance of a source patch, but some proportion of the annual seeds produced may be transported considerable distances. Although these long-distance dispersal events may be rare, their effect on the spread distribution can be overwhelming (Neubert and Caswell 2000). Spread distributions for leafy spurge and spotted knapweed were developed from existing spread and seed dispersal studies and were calibrated with time-series data from mapping efforts at Pine Butte Swamp Preserve[4] since 1995. We coupled that data with historic information from the mid-1970s to complete 30-year time series. For the Centennial Valley, we used expert-based, historic information about knapweed distribution in early 1980s to calibrate spread to its present distribution.

Our decision analysis considered two alternative hypotheses for spread rates by varying the shape parameter for the exponential distribution between the values of 0.1 and 0.05 for *C. maculosa* and 0.3 and 0.15 for *E. esula*. These values represent the minimum and maximum rates of spread expected in these landscapes based on expert opinion and the time-series analysis at Pine Butte. Spread distributions were reduced for initial infestations and *E. esula* patches with biological control. Seed production and successful establishment of each species vary with the vegetation type (e.g. conifer forest or sagebrush grasslands), therefore spread distributions were also modified to reflect the relative competitiveness and success of the weeds across habitat classes. To illustrate our approach, Figure 2 shows inverse cumulative

[4] The Nature Conservancy's Pine Butte Swamp Preserve is ca. 6,000 ha on the Rocky Mountain Front.

C. maculosa dispersal kernels for our alternative spread rate hypotheses and for different source and destination vectors among vegetation types.

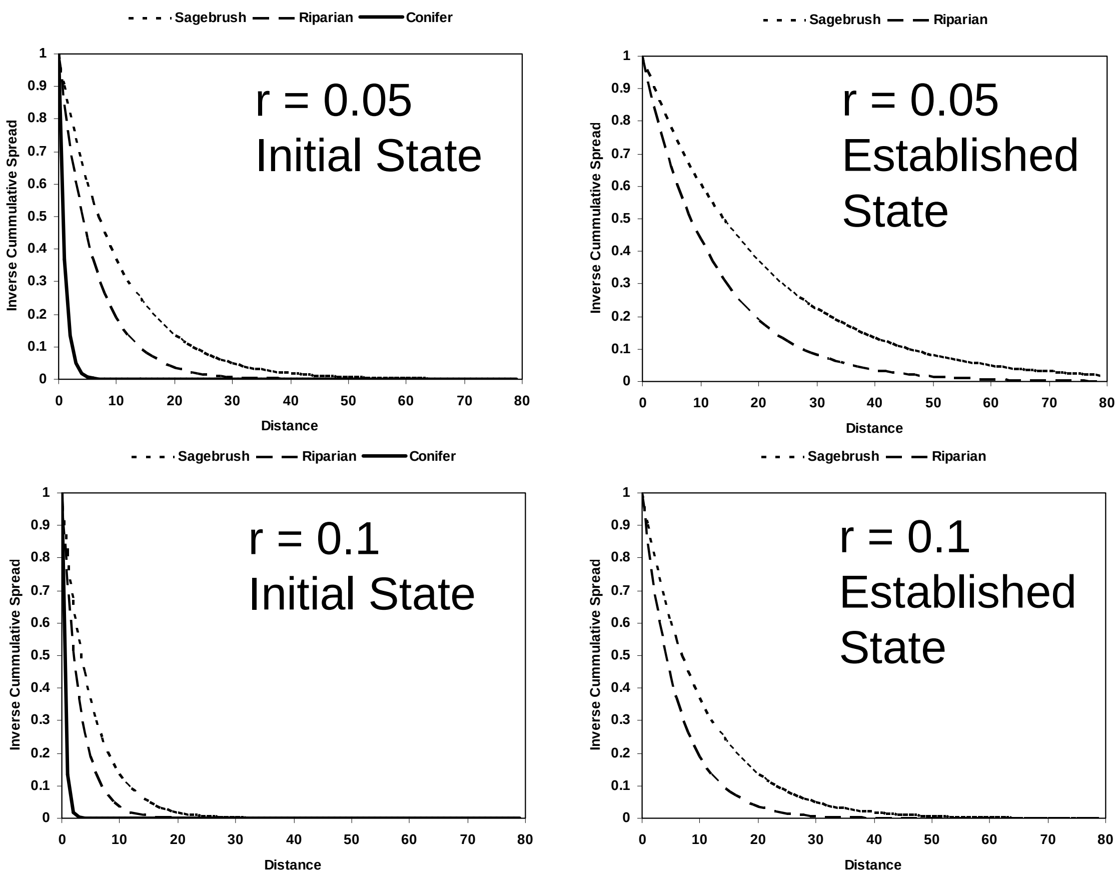

Figure 2. Inverse cumulative spread probabilities for knapweed under two hypotheses: fast spread (r = 0.05, top row) and slow spread (r = 0.1, bottom row). Different lines represent hypothesized spread distance distributions for three of the vegetation communities in the Centennial Valley. Graphs represent spread distance distributions (meters) when the source polygon is in the initial state (left) or in the established state (right). Curves were calibrated with a retrospective analysis of knapweed and spurge spread over 30 years at the Nature Conservancy's Pine Butte Swamp Preserve.

The **effectiveness of control efforts** is another factor that is considered highly uncertain by observations of research scientists, professional weed sprayers, and weed managers who participated at our model development workshops. We defined control effectiveness as the proportion of the time that the application of treatments at a site significantly reduces or eliminates the density of knapweed of leafy spurge. Estimates for this parameter at model development workshops in the three landscapes varied between 50% and 99%. These estimates varied widely due to the high level of variation in the timing of treatments, allocation of resources, applicator expertise, and spatial-temporal environmental differences influencing treatment success (DiTomaso 2000). We chose 70% and 95% effectiveness as alternatives based on the majority of the feedback provided by experts and stakeholders.

3.1.4 Model

We developed a spatially explicit simulation model to compare different landscape level control strategies and to determine the sensitivity of these strategies to uncertainties in the spread dynamics of invasive weeds. The model consists of two main components: first, a state and transition sub-model that considers the site-specific dynamics of weed succession and control at a 1 ha scale; and second, a spatially explicit spread model that considers how weeds arrive at un-invaded areas from within invaded areas or from outside of the modeled landscape.

We developed our state and transition models using The Vegetation Dynamics Development Tool (VDDT). VDDT is a software tool for creating and simulating semi Markovian state and transition models (ESSA Technologies 2005a). VDDT has been used to simulate various ecosystems including the dynamics and restoration of sagebrush steppe communities (Forbis et al. 2006), historic fire regimes across the Continental US for the LANDFIRE project (www.landfire.gov/ModelsPage2.html) and others (Merzenich and Frid 2005, Merzenich et al. 2003, Hemstrom et al. 2001 and Arbaugh et al. 2000).[5]

Models developed in VDDT outline the possible vegetation states on the landscape as well as transitions between states. These transitions are either deterministic and occur after the passage of time or stochastic, having a given probability of occurring each time step. VDDT models are simulated numerically and track both the state of the landscape over time as well as the occurrence of transitions.

The model we developed for noxious weeds consists of five possible states: un-invaded, initial, established, bio-control and seed-bank (Figure 3). Box A represents the un-invaded state. The risk of invasion in the un-invaded state varies depending on the vegetation community and invasive plant species (Table 1). Box B represents an initial infestation. In this state, weeds are present at lower densities and spread less than established infestations, due to lower seed production and limited vegetative spread by rhizomatous species (e.g. leafy spurge). In the absence of any treatments, six annual time steps after a polygon first transitions from un-invaded to an initial infestation it will "Escape" to an established infestation. If a control treatment is applied to an initial infestation during its first three years, three transitions are possible: (1) the infestation will be controlled and the polygon will transition to the seed-bank state, (2) the age and density of the infestation will be setback by two years, which will consequently reduce its ability to infect other polygons, or (3) the control efforts will fail and have no effect on the infestation age or density. In our simulations we varied the ratios between these three outcomes to represent different scenarios of resource allocation. If an initial infestation is more than three years old, two transitions are possible when treatment is applied. Either invasive plant density will be reduced by two years as noted above, or the treatment will have no effect. As with the first three years in the initial infestation the success ratio was varied to represent different scenarios of success levels. The setback transitions can reduce the "age" of a polygon such that control leading to the seedbank state becomes possible again. Experts at model development workshops estimated treatment success (Control + Setback) somewhere between 70-95%.

[5] VDDT is available for download at http://www.essa.com/downloads/vddt/download.htm.

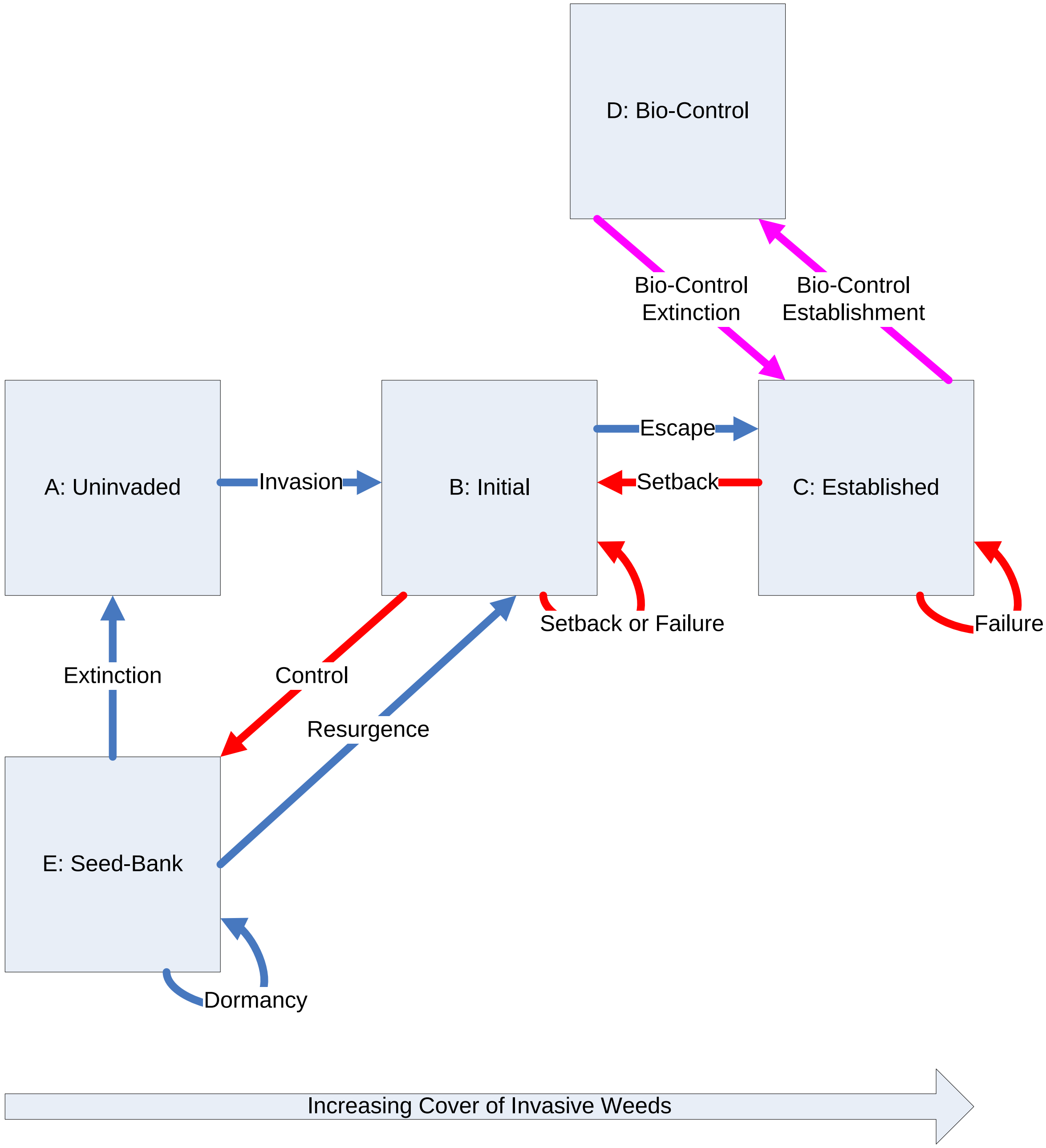

Figure 3. State and transition model representing the state and transition dynamics of noxious weeds. Invasion is a stochastic process influenced by proximity to neighboring infestations and vectors such as roads, vegetation community and the proportion of the landscape invaded. Escape from initial to established infestations occurs after six years of inaction. Control efforts either **setback** population densities and prevent the onset of establishment, kill all weeds and cause a transition to seed-bank or fail to have an effect. Extinction of the seed-bank occurs after 10 years. Resurgence of the seed-bank is a stochastic process. Bio-control agents establish with a six year lag after introduction.

Table 1: Relative susceptibilities of vegetation communities to invasion by *C. maculosa* and *E. esula*. These values were derived from our model development workshops with stakeholders and experts at the three landscapes. A value of one is assigned to the most susceptible state; values less than one reduce the probability of invasion (e.g. limber pine is 40% as susceptible to invasion as gravel riparian in the RMF).

Landscape	Vegetation Community	Relative Suceptibility	
		C. maculosa	*E. esula*
Rocky Mountain Front	Gravel Riparian	1	1
	Limber Pine	0.4	0.4
	Tamegrass	0.4	0.6
	Fescue	0.2	0.2
	Mixed Grass	0.2	0.2
	Riparian	0.15	1
	Aspen	0.1	0.15
	Conifer	0.05	0.05
Centennial Valley	Sagebrush	1	0.5
	Sandhill	0.7	0.5
	Riparian	0.5	1
	Meadow	0.2	1
	Aspen	0.1	0.7
	Conifer	0.05	0.05
Glaciated Plains	Riparian	1	1
	CRP	0.3	0.3
	Mixed Grass	0.2	0.25
	Shrubland	0.2	0.2
	Badlands	0.2	0.2
	Ponderosa Pine	0.1	0.05

Box C represents an established infestation of a site that has an age of six years or more, and has longer spread distribution than the initial state. The infestation may have reached this age due to lack of treatment, treatment failure, or lack of consistent treatment over time to keep the "age" under six years. When conventional treatment is applied to this state either it fails to have an effect or it sets the age of the polygon back to the initial infestation state for one (leafy spurge) or two years (spotted knapweed). If a biological control agent is introduced to an established leafy spurge state, it will take six years to become established and move the polygon to the bio-control state. Successful establishment of the biological control agent is dependent on vegetation type, and has been estimated between 50-90% (Table 2). The remaining 10-50% of bio-control introductions have no effect and eventually result in extinction of the bio-control agent.

Table 2. *E. esula* Bio-Control establishment rates by vegetation type.

Landscape	Vegetation Community	Bio-Control Establishment Rate
Rocky Mountain Front	Gravel Riparian	0.5
	Limber Pine	0.75
	Tamegrass	0.9
	Fescue	0.9
	Mixed Grass	0.9
	Riparian	0.5
Glaciated Plains	CRP	0.9
	Mixed Grass	0.9
	Shrubland	0.9
	Riparian	0.5

Box D represents a weed infestation that has its vigor reduced by biological control agents. Extinction or population crash of the biological control agent results in a transition back to the established infestation state. In this study we only simulated biological control for leafy spurge because this is the only species for which biological control has resulted in consistent, effective results at multiple sites in Montana (Lesica and Hanna 2004, Lajeunesse at al. 1999, Swaidon et al. 1998).

Box E represents a polygon where weeds have been killed, but seeds may remain dormant with the potential of germinating and transitioning back to an initial infestation. Each time step there is a 10% chance that this state will transition to an initial infestation. After ten annual time steps, this state transitions to the un-invaded state and the weeds are considered fully eradicated.

Because knapweed and spurge can often coexist at the same site, we combined the state and transition models for both species into a single model. To do this we had to divide the initial infestation state into two separate states (I1, representing the stage where control to the seed-bank state is still possible, and I2 representing the state where control is no longer possible). Knapweed has five possible states un-invaded, initial-1, initial-2, established and seed-bank. Spurge has the same five states as well as the biological control state. The total possible number of combinations for the two species is 30. For this model we assumed that there was no competition or facilitation between the two species, so the rate of succession for each species remains the same and is independent of whether only one or both species are present at a site. However, we assume that any control efforts in polygons with both species present could affect both species. State and transition model parameters are documented in Table 3.

Table 3. States and transitions for our model of *C. maculosa* and *E. esula* at the scale of 1 ha. Invasion is stochastic and its probability is influenced by proximity to existing infestations, dispersal vectors such as roads, and vegetation community (Table 1). Control, Setback and Failure represent the possible outcomes of treatment efforts. The frequency of these outcomes depends on our hypothesis about how effective control efforts may be. Bio-Control Establishment and Extinction are the alternative outcomes of an introduction event after a six year lag time.

State	Age	Transition	Destination State	Change in Age
Uninvaded	Any	Invasion	Initial	Reset
Initial	1 to 3	Control	Seedbank	Reset
	1 to 6	Setback	Initial	-2
	1 to 6	Failure	Initial	0
	6	Escape	Established	0
Established	Any	Setback	Initial	-2 or -1
	Any	Failure	Established	0
	Any	Bio-Control Intro	Established	0
	Any	Bio-Control Establishment	Bio-Control	0
	Any	Bio-Control Extinction	Established	0
Bio-Control	Any	Bio-Control Setback	Bio-Control	-2
	Any	Bio-Control Extinction	Established	0
Seed-Bank	< 10	Dormancy	Seedbank	0
	< 10	Resurgence	Initial	Reset
	10	Extinction	Uninvaded	Reset

The state and transition model described above is not spatially explicit and describes the dynamics of weeds only within each 1 ha cell. We simulated the spread of weeds among polygons in our three landscapes using the Tool for Exploratory Landscape Scenario Analyses (TELSA). TELSA was developed to simulate landscape-level terrestrial ecosystem dynamics over time to assist land managers in assessing the consequences of various management strategies (ESSA Technologies 2005b, Beukema et al. 2003, Kurz et al. 2000).[6]

For this study, the inputs for our TELSA simulations in each landscape include:

1. State and transition models for the different vegetation communities on the landscape (see Figure 3).
2. Spatial, GIS data layers representing: vegetation types, current weed distribution of the landscape, spatial restrictions on management actions, and features influencing the probability of new invasions (Table 5).
3. Parameters governing the spatial spread and control of invasive species and biological control agents. These parameters include: the distribution of neighbor-to-neighbor spread distances for each annual time step (Figure 2) and the average number (Poisson) of new infestations from outside the landscape for each time step (Table 4).

Table 4. Spatial spread parameters for the three landscapes. Note that Leafy Spurge was not simulated for the Centennial Valley so parameters for this species and for Bio-Control do not apply. Multiple values specify alternative hypotheses for uncertain parameters.

Model Parameters	Centennial Valley	Glaciated Plains	Rocky Mountain Front
Bio-Control Dispersal Kernel[1]	NA	-0.04	-0.04
Mean Number of Bio-Control Introductions per Year[2]	NA	12	80
Knapweed Dispersal Kernel[1]	-0.05 or -0.1	-0.05 or -0.1	-0.05 or -0.1
Mean Number of Knapweed Introductions per Year[2]	7	12	24
Spurge Dispersal Kernel[1]	NA	-0.15 or -0.3	-0.15 or -0.3
Mean Number of Spurge Introductions per Year[2]	NA	21	24

[1]Dispersal kernels are exponential. Parameter provided is the exponential constant.
[2]The number of introductions from outside of the landscape is stochastic and follows a Poisson distribution.

[6] TELSA is available for download at: www.essa.com/downloads/telsa/download.htm.

Table 5. Relative probability of invasion by *C. maculosa* or *E. esula* in relation to landscape features that influence the dispersal of invasive weeds into the landscape. We used data from Pine Butte Swamp Preserve to develop probabilities for high and low use roads, probabilities for other features were set relative to roads based on input from expert workshops.

Feature	Relative Probability	Explanation
Public access point	1	High use sites with high probability of invasion and establishment. Drawn polygons.
Gravel pit	1	Highly disturbed sites with high probability of invasion and establishment. Drawn polygons.
Reservoir edge	0.5	Disturbed sites with high probability of establishment; also connected to source popluation. Only used reservoirs filled from main streams with significant infestations. Buffered 25m out from reservoir edge.
Irrigation ditch	0.5	Disturbed sites connected to source populations. High probability of invasion and establishment. Only used ditches connected to streams or reservoirs with known significant infestations. Buffered to 15m width since most ditches in layer are larger ditches coming from main streams or reservoirs
Crop edges	0.5	Disturbed sites, elevated risk of invasion and establishment. Buffered 15m out from crop edge.
Small parcels	0.5	Represents small homesites and other intensive use. High probability of invasion and establishment. Some experts wanted this to be 2x+ value for roads. However, only a portion of the overall parcel is at elevated risk, so used a 1x factor as an average over the whole parcel.
High use road	0.5	County roads or other roads with significant or public use. High probability of invasion and establishment. Buffered to total width of 30m.
Low use road	0.25	Private roads and two-tracks with low/moderate use levels. Invasion and establishment like high use road, but less. Buffered to total width of 15m.
Trails	0.125	Like low use road but less. Buffered to total width of 5m.
None	0.005	Any other polygon is much less likely to be the source of new infestations.

Input polygons defining the initial state and vegetation community of the landscape are subdivided into simulation polygons through a process called ‘tessellation’. Unlike the use of a grid, this process divides original polygons into smaller units for simulation without loosing any of the original information. While computationally more demanding, the resolution of features that are important for weed spread, such as riparian corridors, is maintained. For our simulation polygons we used an average polygon size of 1 ha.

Algorithms for simulation follow the sequence of events outlined in Figure 4. After initializing the landscape at year zero, for each time step the following events occur: (1) springtime treatment of infestations, (2) output of treatment results and polygons infested, (3) aging, (4) age dependent succession, (5) new infestations, and (6) expansion of existing infestations. Although there are fall herbicide treatments in these landscapes, managers recognize that the primary goal of timing treatment is to prevent current year plants from producing seed.

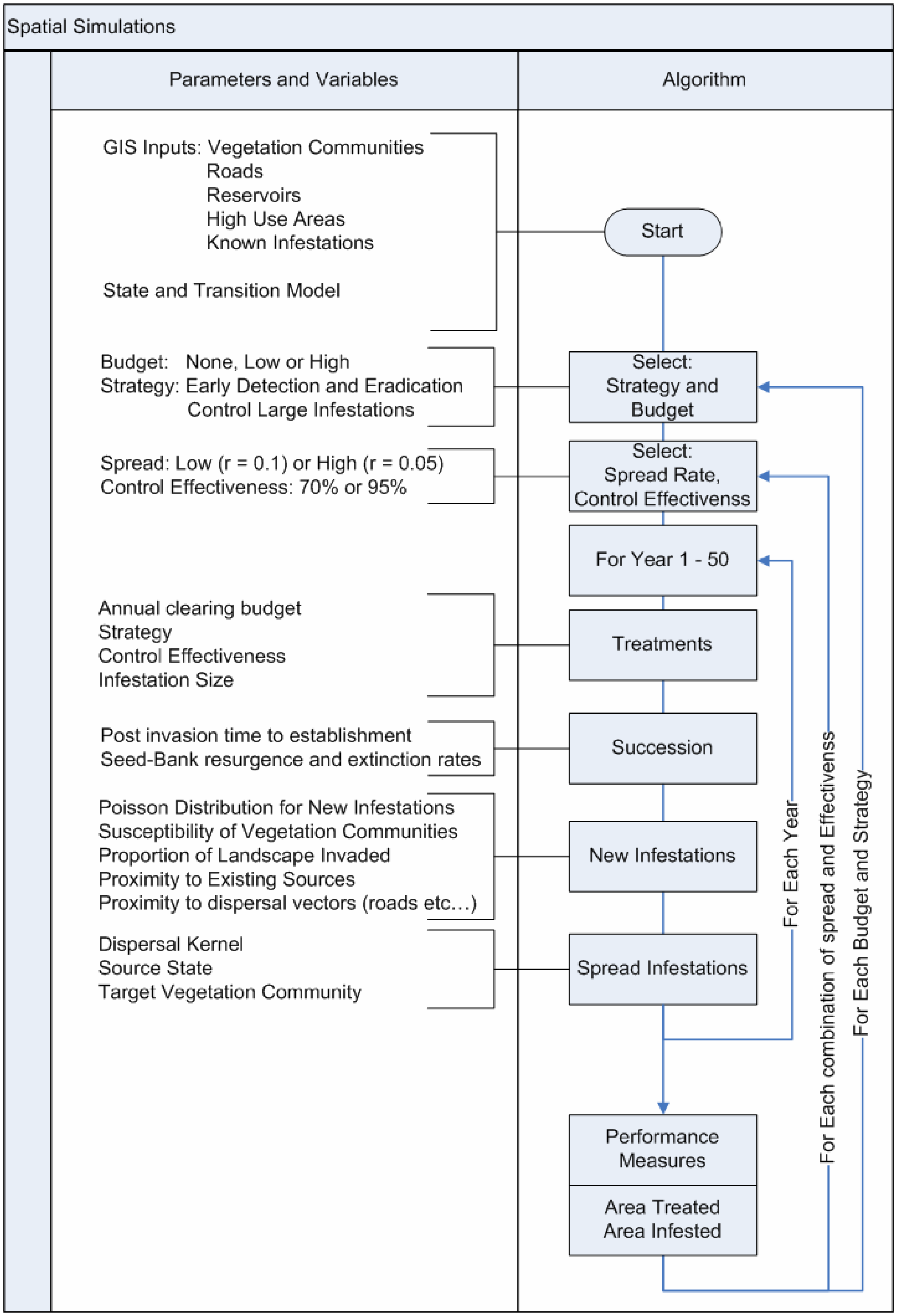

Figure 4. Flowchart depicting simulation model to asses the consequences of alternative management strategies and budgets given different hypotheses about spread and control effectiveness.

The first step in the simulation process is the simulation of management actions and transitions. There are two distinct types of management transitions. These are the introduction of biological control agents for leafy spurge and the use of conventional management techniques against all types of weeds. Conventional management techniques may include both chemical and mechanical methods.

For conventional management the model loops over all infestations in order of size. Depending on the scenario, we prioritized either the largest or smallest infestations for management. For each infestation the model will apply treatment to the polygons on the infestation edge first and then move toward the infestation centers. In the CV scenarios that prioritized large infestations we applied treatments only to the infestation edges. The model will continue to manage infected polygons in this order until either a management area ceiling for the time-step is reached or, all infested polygons have been managed. Each time a management transition is applied there are multiple outcomes possible including control, setback, or failure (Figure 3). Conventional management was subject to certain restrictions in the model. In the Rocky Mountain Front conventional management was not allowed in riparian areas once a weed became established, in recognition that in the established state the levels of pesticide required to treat weeds is generally unacceptable within riparian areas. Also, for certain simulations portions of the landscape were closed to management in order to reflect areas where weeds are not treated by private landholders.

For specific time step intervals, the state of every polygon after treatments is written to the database. This output can be used to generate maps of the predicted state of the landscape. Any time a transition occurs to a polygon, management, bio-control, invasion or succession this transition is written to the database. These outputs can be used to summarize the area affected by different transitions as well as to generate maps of these transitions.

Aging is the process of incrementing the effective time since invasion for each noxious weed on every polygon that that weed is present. After aging, the model determines, for each polygon, whether there should be an age dependent transition (e.g. from the initial to the established state).

The next step in the simulation is the creation of new infestations. This process begins by determining the target number of new infestations from outside of the landscape based on a Poisson distribution. The model then loops over potential polygons in a random sequence. Potential polygons consist of all polygons that are not invaded by the particular species for which new infestations are being created. While the actual number of new infestations remains lower than the target number of new infestations, the model determines, based on a random draw, if target polygons will be invaded or not. The relative probability of invasion for a polygon is based on its vegetation community, as well as, its location relative to high use features, such as roads and agricultural fields.

Once the target number of infestations from outside of the landscape has been reached for a time step, the model simulates long-distance spread within the landscape (i.e. non-neighbor spread) by drawing a random source polygon for each potentially invaded polygon. If the source polygon contains weeds, the model draws a random spread distance from the negative exponential spread distance distribution for the weed. If this spread distance is greater than the polygon-to-polygon distance, then the model checks the relative invasion probability and determines whether a new infestation will occur at the polygon. This process continues until all potential target polygons have been examined, thus making non-neighbor, long-distance dispersal within the landscape a consequence of the proportion of the landscape currently infested with noxious weeds.

After the simulation of new infestations, the model simulates the expansion of existing infestations (i.e. neighbor-to-neighbor spread). For each invasive species and each polygon that is contagious, the model loops over each neighbor of that polygon. Neighbors include polygons whose edge-to-edge distance is < 100m. For each source to neighbor pair, the model determines the potential spread distance and compares that to the centroid-to-centroid distance for the pair. The potential distance is determined by taking a draw from the spread distance distribution for the species for each time step that the source has been contagious. A draw is taken for each time step to capture the gradual spread of propagules along the centroid-to-centroid polygon vector. The sum of these distances is then multiplied by the source strength variable which is dependent on the state of the source (Initial=0.5, Established=1.0, Biocontrol=0.75) and by the relative vulnerability of the target polygon vegetation community (Table 1). Spread distances from established polygons are greater than those from initial and bio-control polygons. Spread distances into the most vulnerable vegetation communities are greater than spread distances into the least vulnerable communities (Figure 2). If the spread distance is greater than the centroid-to-centroid distance between source and target polygons, the target polygon is invaded and it transitions to an initial infestation.

Biological control is simulated like the spread of the weeds themselves. Every time-step there is a Poisson distributed number of new biological control introductions. These introductions can only take place in the established state of leafy spurge. After a six time step lag the biological control agents on these polygons either become extinct or established. If they become established there is a transition to the biological control state. As with the weeds, established biological control agents can spread to neighboring polygons.

3.1.5 Decision tree

For the Centennial Valley, our five management strategies and the two uncertain components of weed spread dynamics resulted in 18 possible simulations of the model (Figure 5). For the Rocky Mountain Front, our 10 management strategies had 20 possible outcomes. For each simulation, the expected outcome is calculated as the product of the simulation outcome and the probabilities assigned to the hypotheses assumed for that simulation. For each strategy, the sum of its probability products adds to one and the expected outcome is calculated as the sum of the expected outcomes for each combination of hypotheses possible. Initially we assigned each alternative hypothesis for our management strategies equal probabilities.

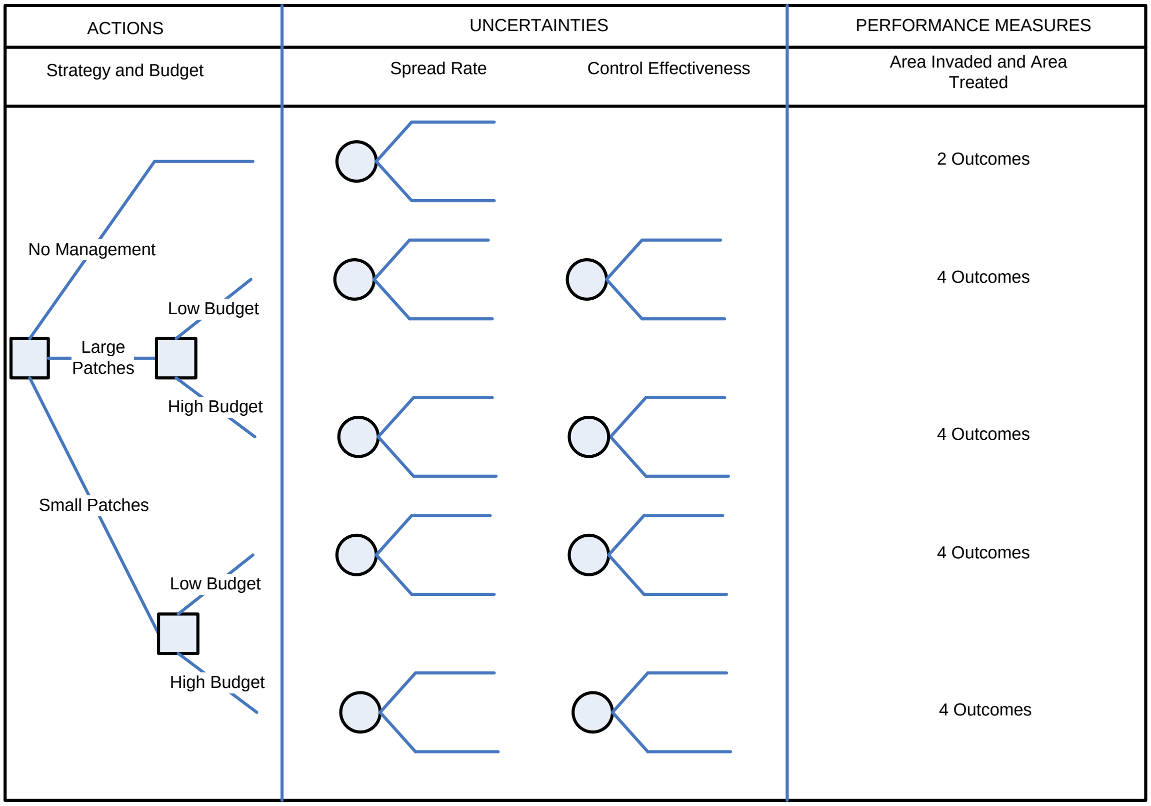

Figure 5. Decision tree depicting Centennial Valley simulation scenarios for alternative decisions about management strategies and budgets in combination with alternative hypotheses about the rate of weed spread and the site specific effectiveness of control efforts.

3.1.6 Sensitivity analyses

We conducted a sensitivity analysis to the probabilities assigned to alternative hypotheses across the full two dimensional probability space for spread and control effectiveness hypotheses. This allows us to identify strategies that are robust to uncertainty in these components and to identify data gaps that are critical for our ability to predict which management strategies are the most effective.

3.2 Retrospective analysis

In order to evaluate the adequacy of our alternative spread rate hypotheses we conducted a retrospective analysis of *C. maculosa* and *E. esula* spread at Pine Butte Swamp preserve where we have a detailed spatial time series of for these two weeds. Our analysis involved running simulations beginning with 1975 conditions using our hypothesized fast and slow spread rates for both weeds. To reflect past conditions we ran simulations with no treatments from 1975 to 1990 and with effective control applied to all infested polygons from 1991 to 2005. We then compared both area infested and maps of predictions to our data for 2005.

3.3 Spatial Data Inputs

We incorporated a variety of spatial data layers in a GIS environment as parameters that contributed to operation of the model, including: location and abundance of selected noxious weeds, coarse-scale vegetation maps, and various features, such as roads, that influence the probability of invasion. In each landscape, spatial weed data were collected from existing sources, primarily land management agencies (e.g. BLM, USFS). Additionally, TNC staff conducted extensive inventories to map weed locations in the CV and MGP and contracted with watershed-based weed management projects to map the location of noxious weeds on private lands in the RMF. Data that we utilized met standards of the Montana Noxious Weed Survey and Mapping System (Roberts et al. 1999). The one exception was in the MGP, where a section-based weed mapping database (Montana Invaders database) was used to develop a map of leafy spurge source populations along the northern boundary of the study area. We used expert opinion to crosswalk existing attribute data for infestations to parameters (e.g., age, state) used in the model. Given the size of the landscapes, our maps of existing weed locations are undoubtedly incomplete. This is particularly true for the RMF, where data was not available for some portions of the landscape which likely contain weed infestations. Our maps for the CV are the most complete, since the landscape is smaller and our surveys more comprehensive. The MGP represents our coarsest scale data, but given the paucity of existing infestations relatively few existing infestations are likely to be unknown.

Within each landscape we identified potential vegetation types (PVTs). Each of the PVTs was comprised of similar natural community associations that were relatively easy to delineate and identify (Table 1). These PVTs represent functionally different vegetation types relative to weed invasion and susceptibility. Different methods were used to map PVTs within each landscape in response to available data.

In the MGP, NRCS digitized soils maps served as the foundation for mapping. Each soil mapping unit was assigned to one of five natural vegetation types. A draft map was created and a field reconnaissance conducted in 2005 to test the map results. Corrections were made for either entire soil mapping units or individually mapped polygons of a soil mapping unit. We then further tested the results and made corrections by conducting photo interpretation. Additionally, we mapped cropland and lands enrolled in the Conservation Reserve Program (CRP) as distinct PVTs. To delineate CRP areas and cropland, we used photo interpretation, mapping the approximate boundary of fields based on a 16 ha grid.

In the Centennial Valley, the Montana Natural Heritage Program refined an existing SILC3 vegetation map developed by the University of Montana Wildlife Spatial Analysis Lab for southwest Montana and based on LANDSAT TM data (ku.wru.umt.edu/project/sagepage/). The Heritage Program conducted field sampling of vegetation types to improve accuracy of the original classification for the Centennial Valley. The detailed classes were then grouped by into six general vegetation types. Narrow riparian zones were not captured by the 30 m resolution LANDSAT data, but we considered them sufficiently important in modeling weed spread to amend the map and include these communities (Stohlgren et al. 1998). Narrow riparian zones were generated by buffering 10 m to either side of perennial streams.

For the Rocky Mountain Front, vegetation types were mapped using aerial photo interpretation of 1995 imagery. Classification was coarse, using only the general vegetation types used in the model. Accuracy was improved using field sampling data as well as preliminary vegetation maps developed by the Montana Natural Heritage Program (subsequently refined in Kudray and Cooper 2006).

For each of the PVTs we assigned a susceptibility to invasion rating for each species (Table 1). Ratings were based on expert opinion and the extent of existing infestations. Additionally, we identified landscape features that influenced the susceptibility of each of the PVTs (Table 5). Roads and subdivisions create large areas of disturbed habitat in which invasion is facilitated by lack of plant competition, altered nutrient cycling, and the increased proliferation of seeds associated with human corridors (Christen and Matlack 2006; Gelbard and Belnap 2003; Tyser and Worley 1992; Maestas et al. 2003). Although grazing and fire can influence invasions by non-indigenous plants (Parker et al. 2006; Keeley 2006), the spatio-temporal variability of these disturbance regimes was too complex to model over these large landscapes.

3.4 Model development workshops

We conducted model development workshops in each of the three landscapes with local experts familiar with noxious weed locations and management. For each of the workshops, we presented a draft state and transition model and preliminary simulation results. We solicited input on the transitions, including time required for changes between states and response of selected noxious weed species to treatment. We also received feedback on spread rate, treatment success rates, relative susceptibilities of vegetation types to invasion, and parameters influencing invasion, such as model states, time-since-invasion, disturbance factors, transportation corridors, and other factors. The current model presented here incorporates the expert opinion received at these workshops.

4. Results

4.1 Retrospective analysis

Visual analysis of model outputs on the locations infested by *C. maculosa* and *E. esula* at Pine Butte Swamp Preserve in 2005, suggests high overlap with actual infestations for both the high and low spread rates (Figure 6). Additionally, retrospective predictions of the total area infested by both weeds are within the range of model predictions (Figure 7). For *E. esula*, area infested suggests that the lower spread rate is probably more reflective of spread for this species.

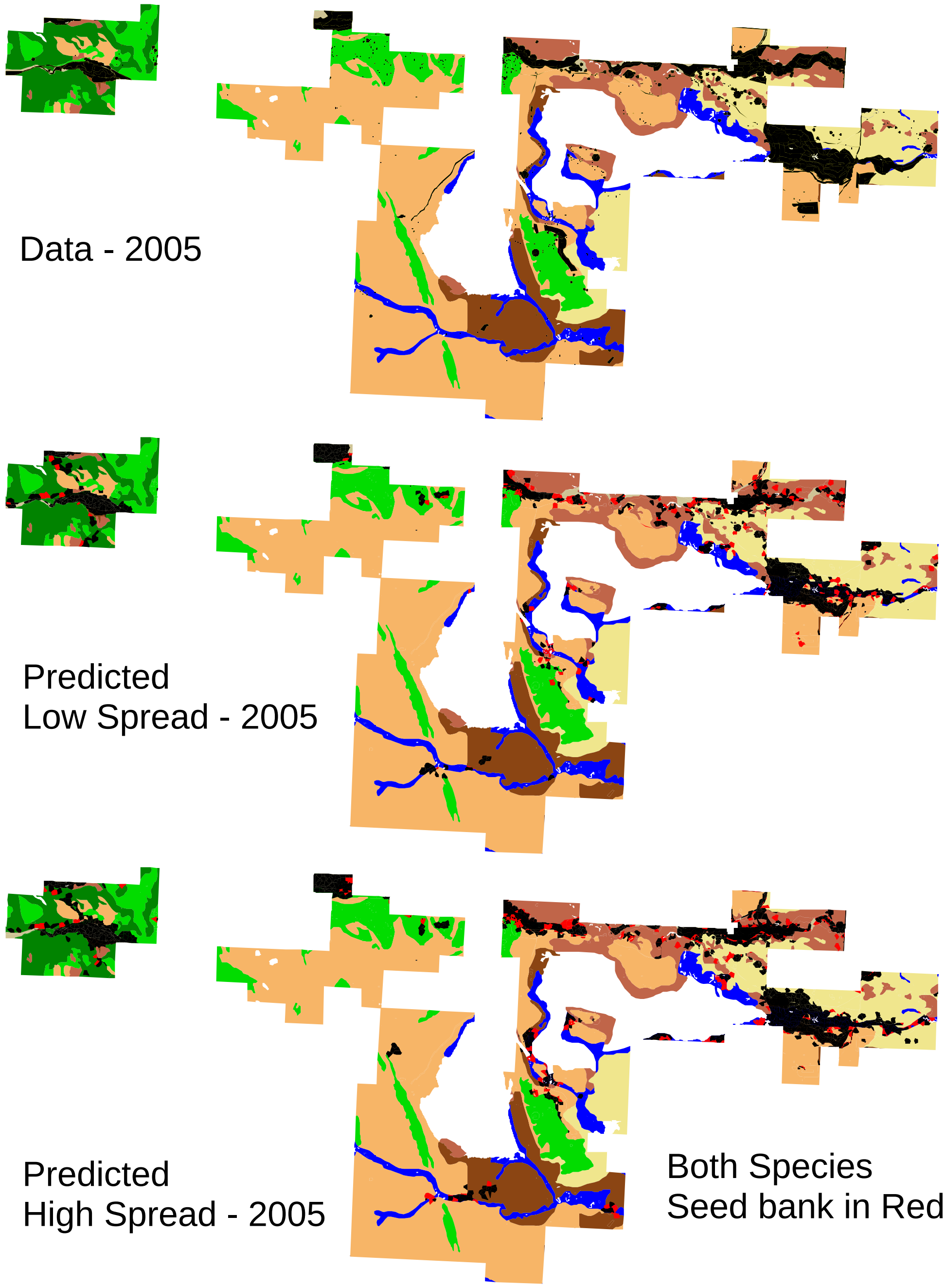

Figure 6. Actual area invaded in 2005 by knapweed and spurge (top) and area predicted by our Pine Butte retrospective analysis for two spread rate hypotheses: slow (middle) and fast (bottom). The black shows initial and established *C. maculosa* and *E. esula*. The red shows the simulated seed-bank. Seed-bank polygons are not shown for the data because these are unknown.

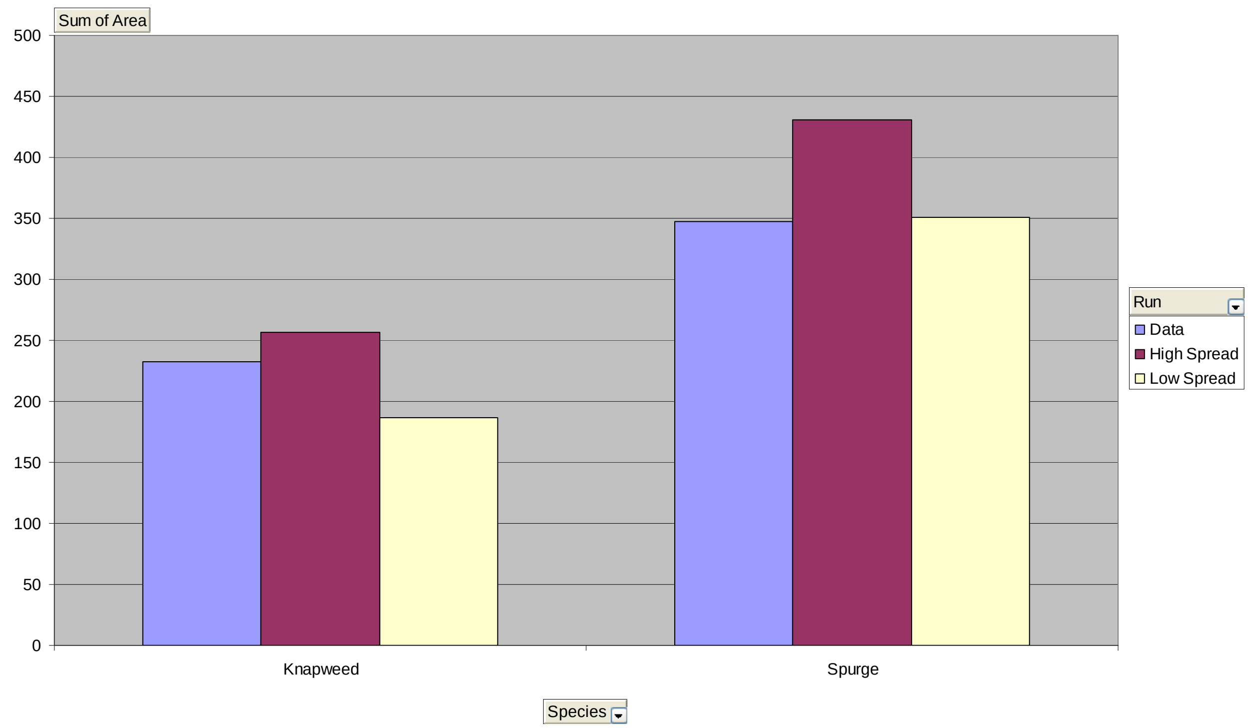

Figure 7. Total area invaded by knapweed and spurge at Pine Butte Swamp Preserve in 2005 compared to fast and slow spread hypothesis predictions for our retrospective analysis.

4.2 Landscape simulations

Regardless of landscape or invasive plant species modeled, simulations demonstrated that without treatment, noxious weeds substantially increase in area occupied. Depending on spread rate, *E. esula* and *C. maculosa* increased approximately 5 to 8 fold on the RMF from the initial condition by the end of the simulations (13,000 to 22,000 ha infested at the end of the simulations). Similar, although less pronounced increases in leafy spurge and spotted knapweed were modeled to occur in the MGP. In the CV, no treatment resulted in approximately 6,000 to 13,000 ha infested by *C. maculosa* at the end of the simulations. In the MGP, infested acres increased from the current area of less than 10 ha to 1849 ha under the high spread scenario.

In the Glaciated Plains, early detection and control kept total area of *C. maculosa* and *E. esula* to approximately 185 to 354 ha, or less than 1% of the landscape (Table 6). In terms of treatment cost, model results suggest that 4500 to 7500 ha in the Glaciated Plains will be treated over a 40 year period of time. Mean treatment acres per year was 150, compared to approximately 14 ha treated the first year, suggesting that treatment area will need to increase at least ten-fold over time to match mean treatment area.

Table 6. Area invaded and cumulative area treated (ha) after year 40 on the Montana Glaciated Plains landscape. Results are shown by strategy, spread and control rates.

Strategy	Area Invaded (ha)		Area Treated (ha)	
Spread Control	Fast Low	Slow High	Fast Low	Slow High
No Management	1849	1165	0	0
Unlimited Management	354	185	7425	4595

Early detection and control was the most effective strategy in the CV (Figures 8-10, Tables 7 and 8). This strategy resulted in the lowest infested area of *C. maculosa* under both high and low budget scenarios, with total area infested ranging from <50 ha to 3500 ha. In contrast, the large patch edge priority strategy resulted in 6500 and 1300 infested hectares for the 200 ha and 400 ha control ceiling limitations, respectively. In the CV there was little difference in the total area treated between each of the 400 ha treatment strategies. However, effectiveness of treatment in terms of total ha infested was substantially less for the 400 ha ceiling of early detection and control when compared to the other three strategies. There was only a small difference in the area of infestation between the 200 ha ceiling for early detection and control and the 400 ha ceiling for large patch edge priority, although cost of the latter was approximately 50% more. The 200 ha ceiling for large patch edge priority had the greatest amount of infested ha, while being the third most expensive to implement.

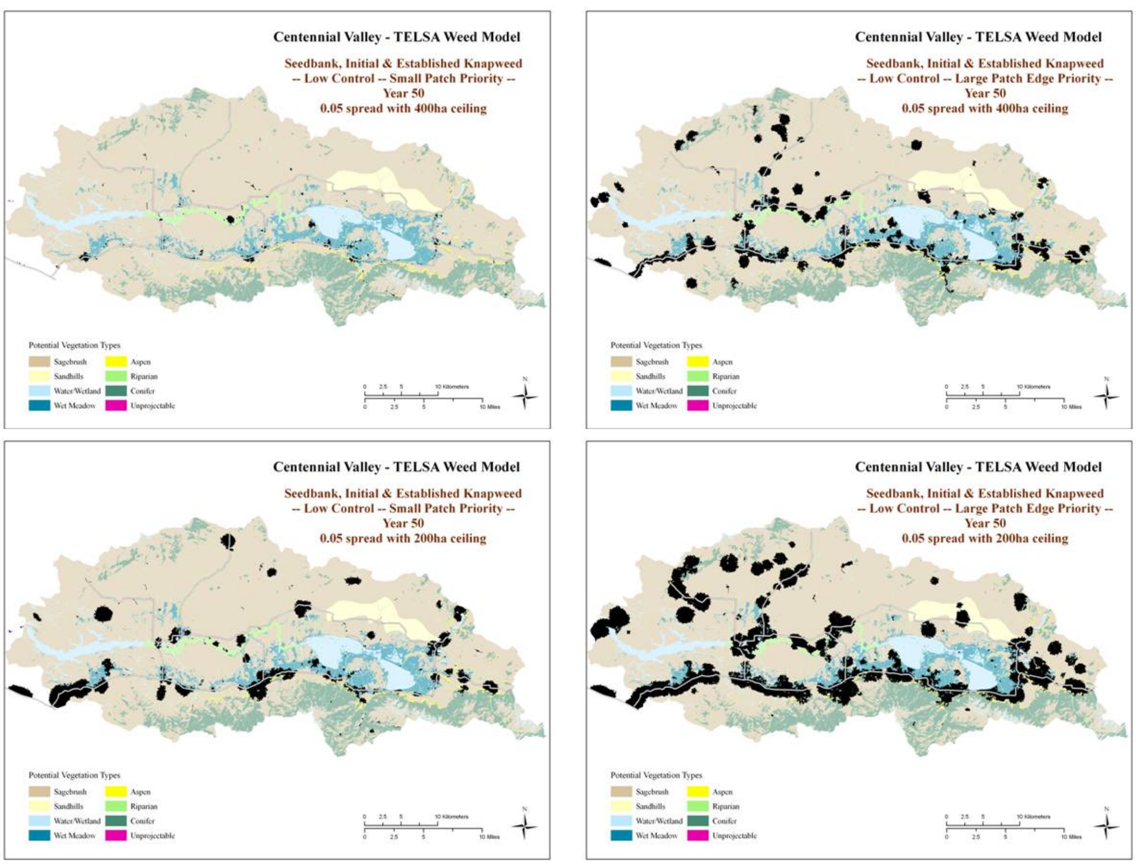

Figure 8. Sample spatial outputs for four management strategies for the fast spread and ineffective control hypotheses on the Centennial Valley.

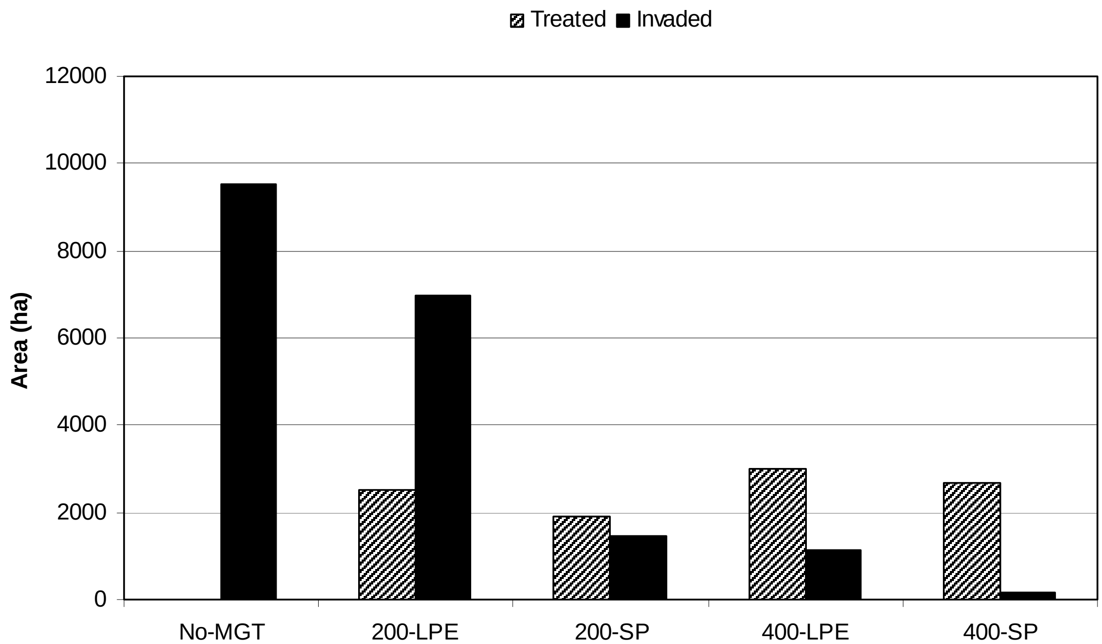

Figure 9. Expected outcomes for alternative budgets and strategies after fifty years for Centennial Valley simulations. For each strategy the expected outcome is the sum of the products of simulation outcomes by alternative hypothesis probabilities. In this example, equal probabilities are assumed for each alternative hypothesis. Strategies are inaction (No-MGT), prioritize large patch edges (LPE), or prioritize small patches (SP). Budgets were either high (400) or low (200) polygon hectares of treatment per year.

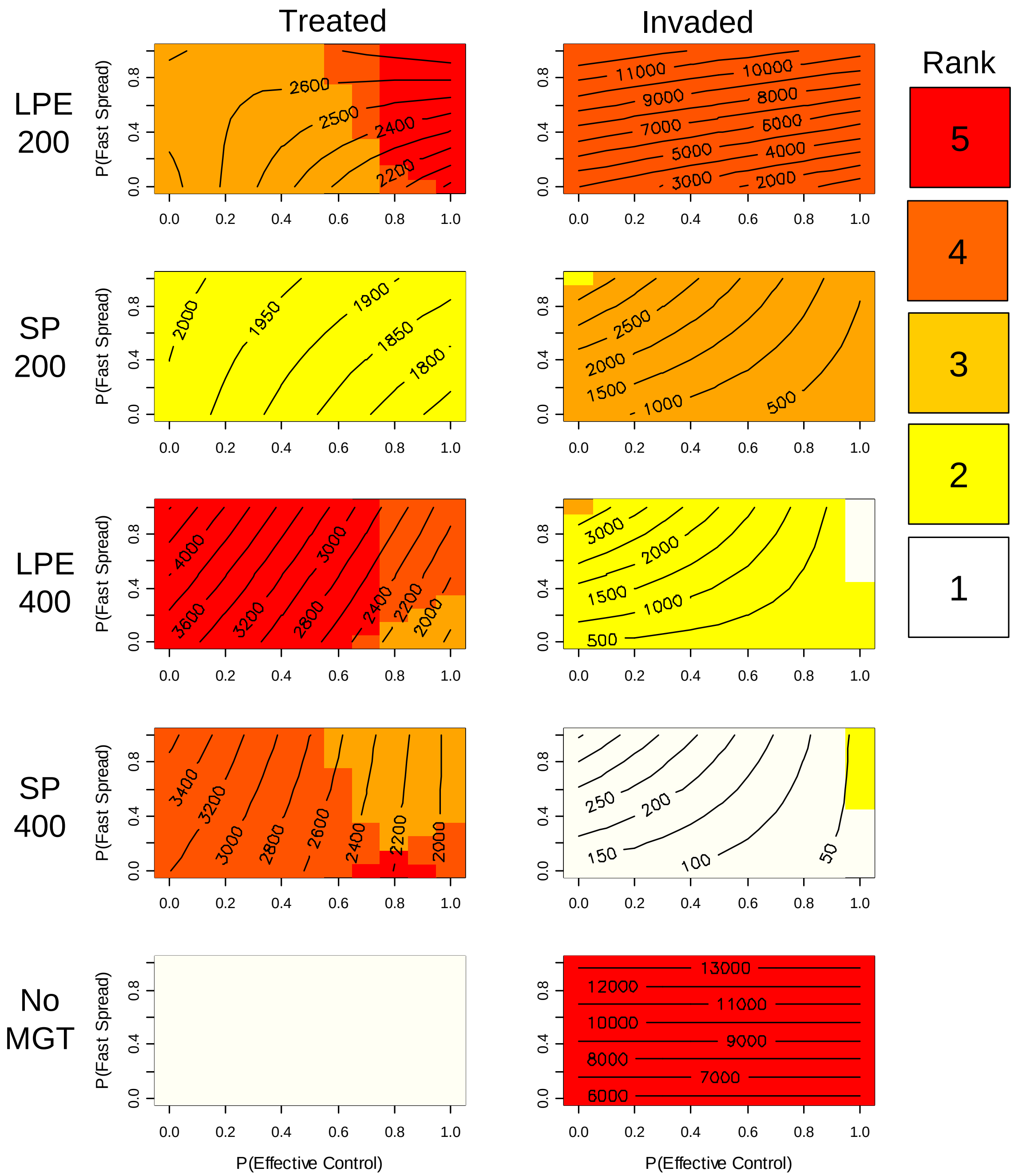

Figure 10. This figure shows both the cumulative area treated and the area invaded by knapweed in the Centennial Valley after fifty years as a function of management strategy and the probability space for alternate hypotheses representing the effectiveness of control and the rate of knapweed spread. Contour lines represent area (ha) treated or invaded. Colors represent ranks for each strategy from lowest to highest. Strategies are inaction (No-MGT), prioritize large patch edges (LPE), or prioritize small patches (SP). Budgets were either high (400ha) or low (200ha) for area of treatment per year.

Table 7. Area invaded (ha) by knapweed in the Centennial Valley at year 50 as a function of the input spread and control rates and management strategy

Strategy	Spread and Control			
	Slow High	Slow Low	Fast High	Fast Low
No Management	5833		13253	
200 Large Patchy Edges	484	4021	10446	12971
200 Small Patches	122	1197	574	3927
400 Large Patch Edges	41	488	32	3952
400 Small Patches	37	132	36	405

Table 8. Cumulative area treated (ha) in the Centennial Valley at year 50 as a function of the input spread and control rates and management strategy

Strategy	Spread and Control			
	Slow High	Slow Low	Fast High	Fast Low
No Management	0		0	
200 Large Patchy Edges	1982	2737	2769	2589
200 Small Patches	1725	1988	1873	2019
400 Large Patch Edges	1754	3602	2273	4414
400 Small Patches	1942	3209	1946	3658

For the RMF, early detection and control combined with treatment of the edges of large patches was the best performing strategy, and kept the total area of both species combined to 3,485 to 6,637 ha (low spread/high control vs. high spread/low control scenarios, Table 9). This outcome was similar to the unlimited treatment scenario (3,057 to 6,150 ha) while treating an average of 30% less acreage (Figure 11). The scenario with 20% of the landscape blocked to treatment resulted in 6,034 to 10,457 ha total area infested, approximately double that of the unlimited treatment scenario. The various remaining strategies with treatment ceilings (large patch priority, small patch priority, knapweed priority, and biological control) were not substantially different from each other in terms of total area invaded, with a range of 6,175 to 8,407 ha (low spread/high control scenarios) and 11,847 to 15,933 ha infested (high spread/low control scenarios). Among these ceiling strategies, the early detection and control strategy performed the best, and the large patch strategies the worst. In addition to strategy and cost, timing was also a major variable in assessing success. Among the strategies with treatment ceilings, those where treatment was delayed until the established state resulted in 50% more acreage being treated.

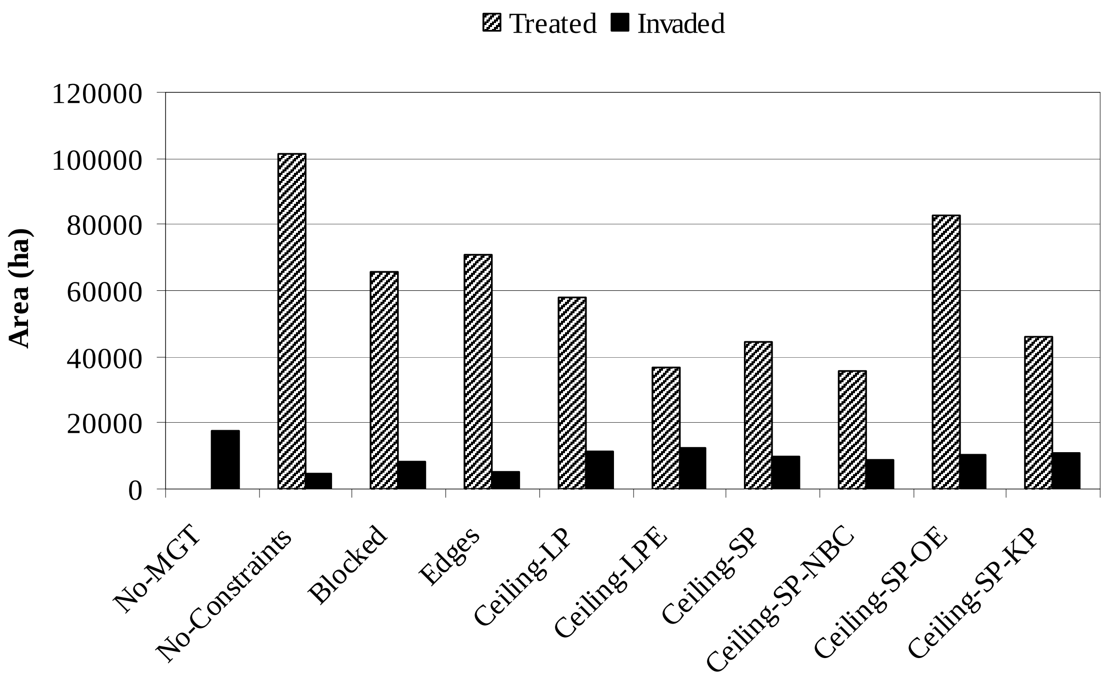

Figure 11. Expected outcomes for alternative budgets and strategies after forty years for Rocky Mountain Front. For each strategy the expected outcome is the sum of the products of simulation outcomes by alternative hypothesis probabilities. In this example, equal probabilities are assumed for each alternative hypothesis. Strategies without a treatment ceiling are inaction (No-MGT), no constraints on treatments (No-Constraints), no constraints on treatment except 22% of landscape blocked from treatment (Blocked), prioritize small patches and large patch edges (Edge). Patches with a treatment ceiling (3400 - 4500 ha) are prioritize large patches (Ceiling-LP), prioritize small patches and large patch edges (Ceiling-LPE), prioritize small patches (Ceiling-SP), prioritize small patches plus no biocontrol (Ceiling-SP-NBC), prioritize small patches but treat only those in the established state (Ceiling-SP-OE), and prioritize small patches with knapweed a priority over spurge (Ceiling-SP-KP). Treatment ceilings in polygon ha were determined by setting the ceiling at 90% of the area treated in the first time-step of the corresponding unlimited treatment scenario.

Table 9. Area invaded and cumulative area treated (ha) after year 40 on the Rocky Mountain Front landscape. Results are shown by strategy, spread and control rates.

Strategy		Area Invaded (ha)		Area Treated (ha)	
	Spread Control	Fast Low	Slow High	Fast Low	Slow High
No Management		22099	13134	0	0
Unconstrained		6150	3057	128230	74281
Blocked		10457	6034	80685	50433
All Edges		6637	3485	87469	54487
Ceiling Large Patches		14689	7821	69323	46667
Ceiling Large Patch Edge		15933	8407	40790	32362
Ceiling Small Patches		12633	6774	50288	38486
Ceiling No Biocontrol		11847	6175	42016	29139
Ceiling Only Established		13506	7269	94412	70619
Ceiling Knapweed Priority		14209	7662	52749	39206

5. Discussion

5.1 Model performance

Our retrospective analysis of Spurge and knapweed spread at Pine Butte shows that our chosen range of spread rates for *C. maculosa* is reasonable and that our spread rates may be slightly high for *E. esula*. These results do not validate our model as 'true'. We may be getting the right results for the wrong reasons. However, they do increase our confidence about the range of spread parameters chosen for alternative hypotheses and provide a 'partial confirmation' of our model (Oreskes et al. 1994). While these spread rates are likely reasonable for the RMF, we are not as confident in their application to other landscapes. Because of this, absolute areas of infestations are not directly comparable among our landscapes.

5.2 Evaluating strategies among landscapes

We considered the strategy with the most robust performance in controlling spread at the lowest cost as having the greatest value for long-term management. The early detection and control strategies (i.e. small patch priority) outperformed the large patch strategies under nearly all conditions. These results are consistent with the predictions made by Moody and Mack (1988). For landscapes with relatively few existing infestations of noxious weeds (CV and MGP), managers can focus resources on detecting and controlling new infestations, which prevents the development of large or new source populations. For the RMF, where some large noxious weed infestations already exist, the early detection and early control strategy was most effective when combined with efforts to control the edges of large patches. Treating only the edges of these large patches was just as effective as treating the entire patch, while requiring less total area to be treated. Prioritizing large existing infestations for treatment is only effective if a large annual treatment budget exists and if control efforts are highly effective (Wadsworth et al. 2000). Treating large source populations can be more effective than prioritizing small patches for plants with long-distance dispersal mechanisms (Cacho et al. 2004). In the CV and RMF, we found that maintaining patches at an initial infestation state, where seed production and dispersal are less than established patches, was crucial for success. We found that under our constrained scenarios where treatment prioritized large patches over small patches, there was neither a sufficient budget nor effective methods to control large patch spread, which expanded and overwhelmed any management efforts. In the RMF, prioritized treatment of large patches increased the required treatment area by 50%. Despite recommendations for early detection and rapid response programs, managers are often mandated to focus on large infestations where weeds are established and problematic. Small infestations early in their invasion do not present an immediate loss of productivity and are often more remote, so resources are directed toward locations where, based on these model results, treatment is less beneficial. The reallocation of resources that are requisite for an effective early detection and rapid response strategy will require justification, such as the results of these models.

Adequately funding a strategy can have substantially different results than the same strategy with an inadequate budget or when constrained strategies are compared. Model results for early detection and control for the CV suggest that doubling the annual budget decreases the area invaded by tenfold. In the RMF, when there were constraints on the total area that could be treated, the outcomes of the differing strategies where not sharply differentiated. This may be a result of the uneven distribution of existing large patches influencing generalized results on the RMF. We did not test multiple, locally unique strategies to address the uneven infestations that may occur in large landscapes, such as the RMF. The results from the CV may be viewed as pilot runs for sub-areas with similar levels of infestations. The model suggests that, given the current weed distribution in the 140,000 ha CV, weeds can be maintained at less than 1% of the landscape over the long term at the cost of treating less than 400 ha. It may be that different strategies perform better under different infestation levels within a landscape. Applying the same strategy over an entire landscape could obscure any value of a combination of locally superior strategies. Future simulations will compare results of different combinations of strategies at the watershed or sub-watershed level in an effort to provide a better understanding of this issue.

Variation in area invaded and treated within each strategy was primarily driven by the probability of ineffective control (Figure 10), although spread rate had a strong influence on the area infested when the probability of effective control was high (i.e. EC>0.80). The range of spread rates may have been overestimated for two landscapes. Sagebrush grasslands in the CV and CRP in the MGP were calibrated with the same maximum spread rate as gravel riparian zones in the RMF, which in retrospect is most likely substantially more susceptible than any other PVT in our landscapes as a result of the highly disturbed condition.

5.3 Biological control

Our results did not show significant benefits of bio-control agents against leafy spurge. This counterintuitive conclusion led us to re-examine our model formulation for biological control. We concluded that the six year, post-introduction time lag for establishment should only apply to an initial introduction event and not to subsequent neighbor-to-neighbor spread events from an established point. We tested the removal of this time lag on a small study area around Pine-Butte and found that without this lag bio-control is predicted to be effective at both reducing the total area invaded by leafy spurge as well as the amount of conventional treatments required. Future simulations will apply this refined bio-control model.

5.4 General trends

Our results are consistent with the conclusion that allocating a larger treatment budget in the short term can have a great benefit in terms of the ultimate outcome in area invaded (Higgins et al. 2000). For the CV, a doubling of the annual treatment budget for early detection and eradication resulted in a tenfold decrease in the area invaded by *C. maculosa* after 50 years. Most cost-benefit comparisons of invasive species control focus on thresholds where the most optimal strategy changes among prevention, eradication, containment, control, and do nothing approaches (Sharov and Liebhold 1998; Born et al. 2005; Leung et al. 2005; Cacho et al. 2004, Buhle et al. 2005). Our model suggests that the optimal management strategy for spotted knapweed and leafy spurge in these three landscapes is sensitive to the proportion of the landscape infested, weed spread rates, and control effectiveness.

While our two performance measures (total area infested and cumulative area treated) provide a good understanding of the relative efficacy of alternative strategies, the cumulative area treated represents a simple cost metric that is not easily translated into actual costs. In the future, a more robust cost analysis will be critical to assign monetary expense to each strategy, in an effort to more accurately identify optimal management objectives. Factors to consider in control costs will include distance from roads, distance from base of operations, and terrain. The costs associated with production loss, disruption of ecosystem processes, and biodiversity loss can introduce another level of complexity in our decision analysis, but will be important to consider in any economic evaluation.

Our conclusions are only valid under conditions in which our underlying assumptions are true. These underlying assumptions include the parameter ranges chosen for alternative hypotheses of control effectiveness and spread rates. In terms of control effectiveness, every effort should be made to monitor the results of control efforts, both to improve model predictions and to improve the control efforts themselves. Clark et al. (1998) have shown that long-tailed distributions can have dramatically higher spread rates for plants than exponential distributions with the same mean dispersal distance. Neubert and Caswell (2000) demonstrated that even rare events of long-distance dispersal can overwhelm the effects of more common short-distance spread mechanisms for some plants. Therefore, in the future it would be prudent to further explore the range of parameters for control effectiveness alternatives, as well as, the distribution shape of dispersal kernels. While it is unlikely that we will ever discern the exact distribution curve for spread rates and establishment of the dispersal kernels for the weed species modeled here, future exploration of parameter space should consider alternative distributions.

One major assumption made by our model is that of complete knowledge about the location of weeds on the landscape and prioritization of action based on this assumption. In reality this is never the case, and managers are much more likely to have information about large existing infestations than about nascent foci. Our performance measures do not allow us to explicitly asses the added cost in monitoring that would be incurred by the strategy that prioritizes early detection and eradication. Some of this cost is captured implicitly by our simulations because of our use of polygon area ceilings. An educated group of public and private land managers may be highly effective at identifying new infestations if they are familiar with the weed species and the relative susceptibility of natural communities to infestation. Further, the increased probability of invasion along roads and other human disturbances may offset detection costs. The most effective method for detection may be through education efforts among diverse stakeholders including landowners, sportsmen, recreationalists, and agency staff.

In the future it is important to explicitly examine tradeoffs between monitoring and treatment by including monitoring cost in our models. It may also be valuable to test monitoring strategies to evaluate their effectiveness in locating infestations. Ultimately, it would be most useful to provide managers with limited recourses answers to the following: (1) How much area should be monitored on an annual basis? (2) Where should monitoring take place? (3) How much area should be treated on an annual basis? and (4) Where should those treatments take place?

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