Decision analysis to evaluate control strategies for crested wheatgrass in Grasslands National Park of Canada

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June 26, 2007

Citation: **Frid, L.** 2006. Decision analysis to evaluate control strategies for crested wheatgrass in Grasslands National Park of Canada. Prepared by ESSA Technologies Ltd., Vancouver, B.C. for Parks Canada, Winnipeg, MB. 21 pp.

Executive Summary

Crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.) has been a popular forage crop in the Great Plains since the 1930s. It is, however, an aggressive invader of native grassland and a problem in Grasslands National Park where seeded roadsides and abandoned fields are encroaching into the native mixed grass prairie. To tackle the crested wheatgrass problem park managers need to determine the best strategy at reducing the cover of crested wheatgrass given limited resources. However, there is a high degree of uncertainty associated with the dynamics of crested wheatgrass spread and control

To compare alternative management strategies against crested wheatgrass in the face of uncertainty we conducted a decision analysis. Our decision analysis consists of the following components: (1) alternative actions, (2) performance measures, (3) uncertainties related to the dynamics of crested wheatgrass spread and control, (4) a model to predict outcomes, (5) a decision tree, and (6) sensitivity analyses.

We identified three strategies and two budget levels for tackling the crested wheatgrass problem in the park. The strategies were: inaction (a benchmark), directing control efforts at known large infestations or early detection and control of new infestations. The budget levels we considered were either current capacity for treatments or a doubling of that. Our performance measures to evaluate these strategies were the total area treated over a 50 year simulation as well as the cumulative area covered by crested wheatgrass over the same time period. Uncertainties relate to the rate of spread of crested wheatgrass patches, the rate at which new patches appear on the landscape and the effectiveness of site specific control measures. For each of these components we formulated two alternative hypotheses spanning a range of parameters thought to encompass our level of uncertainty. To asses the consequences of proposed management actions we developed a spatially explicit simulation model to predict the response of our performance measures for each combination of alternative action and hypotheses for uncertain components of crested wheatgrass dynamics. Using a decision tree and assigning probabilities to our alternative hypotheses we then calculated the expected outcome of each management alternative and ranked these alternatives. Because the probabilities assigned to alternative hypotheses are also uncertain we conducted a sensitivity analysis to the full probability space and present our results in the context of this sensitivity analysis.

Our results show that under current funding levels it is best to prioritize the early detection and control of new infestations. Increasing funding levels to double the current capacity can shift the rankings of strategies such that prioritizing large existing infestations is better. However, this is only the case when site specific control efforts are effective, or patch spread is low and the rate of increase in new infestations is high. Increasing funding levels can greatly reduce the total coverage of crested wheatgrass in the park but will only result in a reduction in treatments over a fifty year period if control efforts are highly effective. We identify key assumptions in our analysis and provide suggestions both for monitoring and further analysis to improve confidence in our conclusions.

Table of Contents

List of Tables

List of Figures

Introduction

Crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.) was introduced into the North American great plains from Eurasia in the 1800s and gained importance as a forage crop for grazing and hay in the 1930s (Dillman 1946; Henderson 2005; Rogler & Lorenz 1983). While the popularity of crested wheatgrass as a forage crop continues, its propensity to invade undisturbed native rangeland (Hull & Klomp 1967; Marlette & Anderson 1986), particularly east of the continental divide (Henderson 2005), makes it an undesirable species in communities where the preservation of native grassland is a management objective. This is the case in Grasslands National Park of Canada where abandoned hay fields and road right-of ways that have been seeded to crested wheatgrass are encroaching onto the surrounding native mixed-grass prairie.

Because of crested wheatgrass' invasiveness, park managers and researchers have worked for years to determine the best methods to stop its encroachment and restore invaded areas (Ambrose & Wilson 2003; Bakker & Wilson 2001; Bakker et al. 1997; Bakker & Wilson 2004; Christian & Wilson 1999; Henderson 2005; Parks Canada Agency 2002; Sturch 2005; Wilson et al. 2004). These research efforts have provided valuable information on the invasion biology of crested wheatgrass and have resulted in methods of control and restoration that have proven effective in the short (Sturch 2005) and long (Bakker & Wilson 2004) term. However, understanding how to eradicate crested wheatgrass in small patches, and restore those patches to native prairie is only the first step in managing this ecosystem. What is needed is a long-term strategy that would control crested wheatgrass for the entire park.

Given limited financial resources that managers face, crested wheatgrass control in Grasslands National Park will take years, and likely decades, so a strategy that maximizes the long-term returns is required. Our objective is to determine how the park can best allocate its limited funds for crested wheatgrass control and restoration to provide the greatest and fastest reduction in crested wheatgrass cover over the next 50 years.

One of the decisions that must be made when allocating resources to the control of invasive plants is whether to focus limited resources on attacking known existing large infestations or on finding and controlling unknown small nascent foci. Moody and Mack (1988) showed that under certain conditions it is more effective to prioritize small nascent foci for management but Wadsworth et al. (2000) showed that this is not the case for plants that spread mainly by long distance dispersal.

Managers must also decide on allocations of resources to devote on an annual basis to invasive management. Various studies have shown that spending less in the short term can be more costly in the long term (Higgins et al. 2000; Pimentel et al. 2000). However, allocating more resources to invasive plants is often at the expense of other park priorities reinforcing the need for an ecological cost-benefit analysis to justify significant expenditures. It is therefore important to evaluate the relative long-term benefits of making these short-term sacrifices.

The park is currently considering various alternative actions in its crested wheatgrass control program. Three decisions, common in invasive species management, need to be made: Should an investment be made in extraordinary short-term control efforts to achieve greater benefits in the long term; should control and restoration focus on emergent or established infestations; and how should effort be partitioned between monitoring and control? Currently, these decisions must be made in the face of uncertainty in three key components of the system: (1) the effectiveness of restoration and control efforts, (2) the rate of spread of existing patches, and (3) the rate of increase in newly infested initially small patches. Here we present a decision analysis (Clemen 1996; Peterman & Peters 1998, Peterman and Anderson 1999) to rank management alternatives for crested wheatgrass given a high degree of uncertainty. To aid in this process we developed simulation models to reflect both management actions and alternative hypotheses about the dynamics of crested wheatgrass spread and control.

Methods

Study Area

Grasslands National Park of Canada (42,368 ha in area, 49°15’N, 107°0’W) was established in 1988 to preserve a representative portion of the Canadian mixed grass prairie ecosystem (Figure 1). The climate is considered sub-humid; winters are long, cold and dry while summers are short and hot. Mean daily temperature ranges from 15ºC below zero in January to 20ºC in July. Total annual precipitation averages 325 mm with most falling as rain in the spring months and approximately one third of this falling as snow in the winter. The growing season in the park is relatively short, averaging 170 days between killing frosts, but low moisture availability often reduces its length further (Davidson et al. 2006; Loveridge & Potyondi 1983).

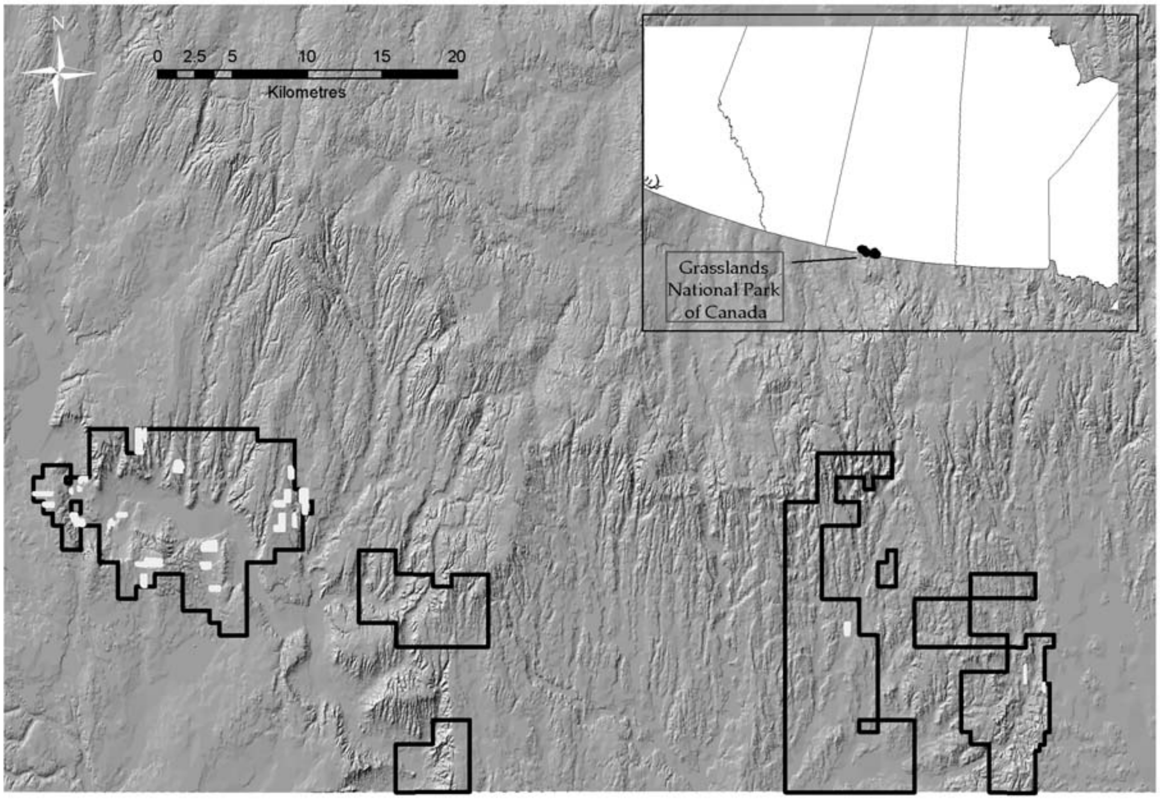

Figure 1: Location of Grasslands National Park of Canada. Solid lines on the insert show the current park land holdings for which the model was parameterized and run. Areas in white represent old fields seeded with crested wheatgrass mapped in 1994.

We categorized the park into 5 biophysical units based upon the vegetation inventory of the park (Michalsky & Ellis 1994): upland grassland, sloped grassland, valley grassland, shrub communities and eroded communities. Crested wheatgrass can be found in all of these biophysical units. While it has been seeded as a hay crop in the upland and valley grasslands, and in some cases the shrub community (the riparian zone in the park) it has spread into the sloped grasslands and eroded communities.

Decision Analysis Framework

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

Alternative Actions

We considered alternative management strategies based on combinations of two components: the annual budget allocated to crested wheatgrass 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 (50 polygon hectares),[1] or a doubling of current capacity (100 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.

Performance Measures

The performance measures we used to evaluate each strategy were: (1) the cumulative area treated over a fifty year period as an indicator of the total cost of each treatment strategy, and (2) the cumulative area covered by crested wheatgrass over that period, as an indicator of the outcome of each management strategy. We chose the cumulative area covered by crested wheatgrass rather than simply the final area at year fifty in order to capture both the magnitude and rate of change in crested wheatgrass cover over time. Model results are reported in terms of polygon areas treated over the entire simulation period and polygon areas covered by crested wheatgrass over the simulation time period. These results were converted to absolute area values by multiplying polygon areas against the average percent cover of weeds for the state (see model below) of the polygon (30% for initial and 90% for established). For each management strategy these performance indicators were probability weighted by alternative hypothesis and summed.

Uncertainties

We focused our analysis of uncertainty on what are perceived to be three key uncertainties in crested wheatgrass dynamics. These key uncertainties are: (1) the rate at which patches spread across the landscape over time, (2) the rate at which new patches appear in the park via long distance dispersal, and (3) the effectiveness of site-specific control efforts.

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[1] Our simulations were conducted at a resolution of 1 ha polygons. Budget ceilings were set at 50 or 100 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.

The invasion of crested wheatgrass follows two distinct patterns. The first is the expansion of hay field margins. Fields of crested wheatgrass spread into the native prairie generally along their windward margin via seed dispersal (Hansen 2006). Crested wheatgrass produces prodigious amounts of seed (Cook et al. 1958; Pyke 1990) and the seed establishes readily, accounting for its popularity as a hay crop (Rogler 1954). This seed is wind dispersed short distances by rolling over hard ground or snow resulting in a field that can creep upwards of 1m per year from a seeded field margin (Ambrose & Wilson 2003; Henderson 2005). However, the exact shape of the dispersal kernel is unknown. This is a key uncertainty because what is most important about a dispersal kernel is not its mean distance but the shape of its tail. Plant species with a fat tailed dispersal kernel have been shown to move across landscapes at very fast and even accelerating rates over time (Clark et al. 1998).

The second form of spread is the long distance dispersal of crested wheatgrass seed likely in herbivore dung. This form manifests itself as scattered crested wheatgrass plants appearing far distances from the nearest seed source. These plants, which can be found in every vegetation community in the park, become a seed source for short-distance dispersal. As a result, unexpected patches of crested wheatgrass can appear in otherwise undisturbed areas of the park that, left unmanaged, can grow to become large invaded areas. While these are routinely observed in the park, we only have limited information about the rate at which these new patches of crested wheatgrass appear.

The effectiveness of control efforts is another factor that is considered highly uncertain. While recent restoration research has provided the park with effective tools for eliminating crested wheatgrass (Bakker & Wilson 2004; Hansen & Wilson 2006; Sturch 2005; Wilson & Gerry 1995; Wilson & Pärtel 2003), there is still variability in the effectiveness and longevity of these techniques. Our alternative hypotheses for the effectiveness of control efforts ranged from 75%-95% in the initial state and 60% to 90% in the established state. Parameters for alternative hypotheses relating to the spread of patches, the appearance of new patches and the effectiveness of control are shown in Table 1.

Table 1: Parameters used to simulate alternative hypotheses characterizing three components of crested wheatgrass spread and control dynamics: Control effectiveness, Patch Spread and Long Distance Spread.

Component	Hypothesis	Control Ratio Initial[1]: C:S:F	Control Ratio Established[2]: C:S:F	Setback Time[3]	Time to Establish[4]	Pareto Shape	Spread Ratio I:E[5]	Satellite Mean[6]
Control	**High Control**	70:20:05	50:40:10	5	-	-	-	-
Effectiveness	**Low Control**	50:25:05	10:50:40	2	-	-	-	-
Patch	**Slow Spread**	-	-	-	15	3	0.05	-
Spread	**Fast Spread**	-	-	-	10	2.01	0.1	-
Long Dist.	**Few Satellites**	-	-	-	-	-	-	1
Spread	**Many Satellites**	-	-	-	-	-	-	2

[1] Control ratios in the initial state where C represents the proportion of the time that there is a ‘control’ transition to the un-invaded state, S represents the proportion of the time that there is a ‘set-back’ transition that reduces the density of crested wheatgrass but the polygon remains in the initial state, and F represents the proportion of the time that the treatment ‘fails’ to have any effect.

[2] Control ratios in the established state, in this case S represents the proportion of the time that there is a ‘set-back’ transition that reduces the density of crested wheatgrass and the polygon transitions to the initial state.

[3] The number of years that crested wheatgrass is set back on its population growth curve by a set-back transition.

[4] Number of years it takes for a polygon to transition into the established state after invasion.

[5] Relative spread distances from polygons that are in the initial state relative to those that are in the established state.

[6] Mean of the Poisson distribution used to determine the number of new patches appearing from outside the landscape each time-step.

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 crested wheatgrass. 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 Ltd. 2005). 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 (http://www.landfire.gov/ModelsPage2.html) and others (Merzenich and Frid 2005, Merzenich et al. 2005, Hemstrom et al. 2001 and Arbaugh et al. 2000).[2]

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.

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

The model we developed for crested wheatgrass consists of three possible states: un-invaded, initial and established (Figure 2). The un-invaded state represents a polygon in which crested wheatgrass is absent. A polygon in the un-invaded state can transition to the invaded state through the process of invasion either via spread from a neighbour that is invaded or via long distance dispersal. The invaded state represents a polygon that has detectable levels of created wheatgrass, but in which other plant species are still dominant. Polygons in the invaded state act as weak sources of crested wheatgrass to neighbouring polygons. Management efforts applied to crested wheatgrass in invaded polygons frequently result in control, sending the polygon back to the un-invaded state. Occasionally management efforts may reduce the cover of crested wheatgrass in a polygon without accomplishing a control transition back to the un-invaded state. It is also possible that if management is applied incorrectly or under the wrong environmental conditions there will be no effect on the state of the polygon. If enough time elapses in the invaded state without effective management a polygon will transition into the established state.

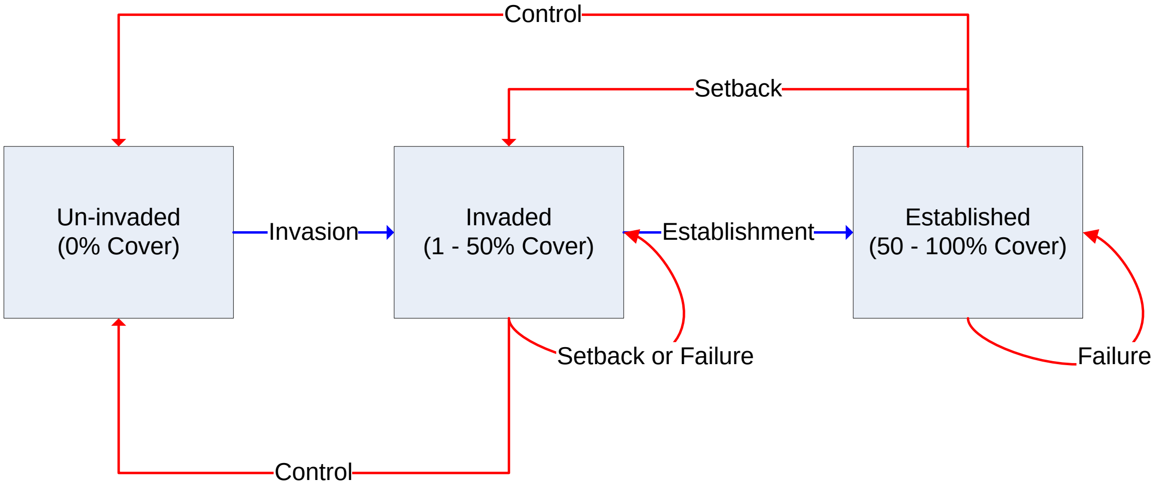

Figure 2: State and transition model for crested wheatgrass dynamics. Invasion is a stochastic process influenced by proximity to neighbouring infestations and vegetation community. Escape to an established infestation occurs after 10 to 15 years of inaction. Control efforts set-back population densities of crested wheatgrass, eradicate the population or fail to have any effect.

The established state represents a polygon in which crested wheatgrass is the dominant vegetation type. Polygons in the established state act as strong sources of crested wheatgrass to neighbouring polygons. Management efforts applied to crested wheatgrass in the established state rarely result in control back to the un-invaded state. Management efforts may frequently result in the reduction of enough cover to transition a polygon from the established to the invaded state. However, the failure of management efforts to have any impact in the established state is also relatively frequent.

The state and transition model described above is not spatially explicit and describes the dynamics of crested wheatgrass only within each 1 ha polygon. 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).[3]

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

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 2).
2. Spatial, GIS data layers representing: vegetation types and current crested wheatgrass distribution of the landscape.
3. Parameters governing the spatial spread and control of crested wheatgrass. These parameters include: the distribution of neighbour-to-neighbour 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 1).

Input polygons defining the initial state and vegetation community of the landscape are subdivided into simulation polygons through a process called ‘tessellation’ (Lee and Li 1998). 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 3. For each time step these events are: (1) ageing, (2) age dependent succession, (3) new infestations, (4) expansion of existing infestations, (5) treatment of infestations, and (6) output.

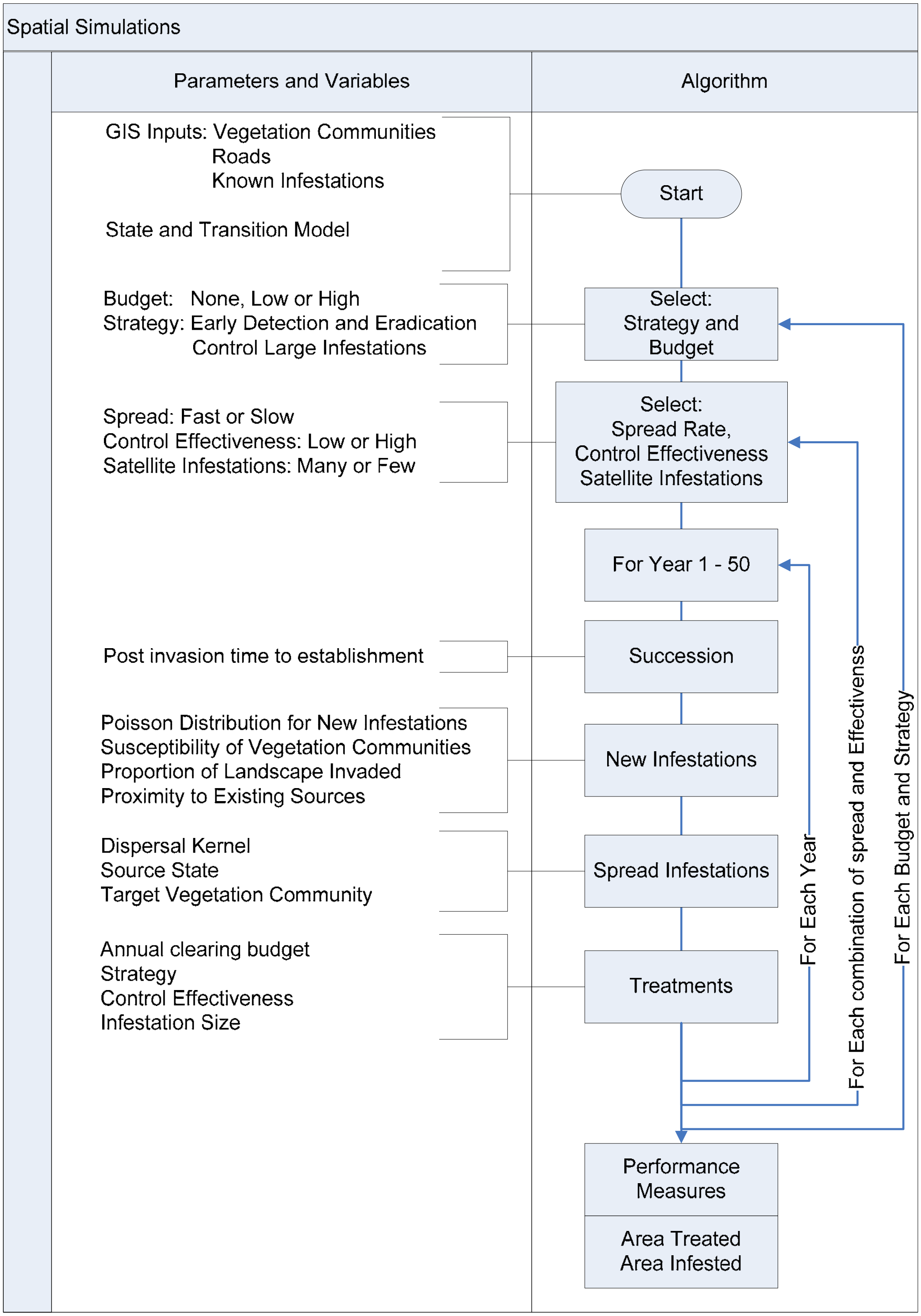

Figure 3: Flowchart depicting the spatially explicit model algorithm used to asses the consequences of different management strategies under different hypotheses of spread, control effectiveness and satellite populations.

The probability that any site in the park could be invaded by crested wheatgrass is a function of the biophysical unit the polygon is in. There are few data available on the susceptibility to invasion by crested wheatgrass into vegetation communities defined by composition. However Henderson (2005) and Henderson and Naeth (2005) provide some correlates that we useful for relative rankings. Based on these rankings the relative susceptibility of each of these communities to crested wheatgrass invasion is: valley grassland 1, sloped grassland 0.68, shrub community 0.68, upland grassland 0.59, and eroded community 0.18. This relative susceptibility affects both the rate at which crested wheatgrass spreads along a moving front as well as the likelihood of long distance dispersal in our model.

Ageing is the process of incrementing the effective time since invasion on every polygon that has crested wheatgrass. After ageing, 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. For simulating long distance dispersal we used the Poisson distribution to describe the number of new patches of crested wheatgrass appearing in the park on an annual basis. Our alternative hypotheses for long distance dispersal were mean numbers of new patches being equal to one or two per year. The model loops over potential target polygons in a random sequence. Potential target polygons consist of all polygons that are not invaded by crested wheatgrass. While the number of polygons being looped over remains lower than the number of new infestations drawn from the Poisson distribution for that time step, the model determines the relative probability of invasion of each target based on a random draw to determine if the target will be invaded or not. The relative probability of invasion for a target is based on its vegetation community. Once the 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-neighbour spread) by drawing a random source polygon for each target. If the source polygon contains crested wheatgrass, the model draws a random spread distance from the Pareto spread distance distribution. 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 target. This process continues until all potential targets have been examined, thus making non-neighbour, long-distance dispersal within the landscape a consequence of the proportion of the landscape currently infested.

After the simulation of new infestations, the model simulates the expansion of existing infestations (i.e. neighbour-to-neighbour spread). For each invasive species and each polygon that is contagious, the model loops over each neighbour of that polygon. Neighbours include polygons whose edge-to-edge distance is < 100m. For each target neighbour 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 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=0.05 or 0.1, Established=1.0) and by the relative vulnerability of the target polygon vegetation community. Spread distances from established polygons are greater than those from initial polygons. Spread distances into the most vulnerable vegetation communities are greater than spread distances into the least vulnerable communities. If the spread distance is greater than the centroid-to-centroid distance between source and target polygons, the target polygon is invaded and transitions to an initial infestation.

We used a Pareto distribution (equation 1) of annual spread distances for modeling short and intermediate spread distances (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. Our decision analysis considered two alternative hypotheses for spread rates by varying the shape parameter (a) for the

Pareto distribution between the values of 2.01 and 3. Spread distributions were reduced for initial infestations. Seed production and successful establishment of each species vary with the vegetation type, so spread distributions were also modified to reflect the relative competitiveness and success of the weeds across habitat classes.

$$P(Spread < x) = 1 - \left(\frac{0.5}{x} \right)^{a} ; x > 0.5 - meters \qquad [1]$$

The final step in the simulation process is the simulation of management actions and transitions. For 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 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 2).

For specific time step intervals, the state of every polygon at the end of the time-step 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, 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.

Decision Tree

Our five management strategies and the three uncertain components of weed spread dynamics resulted in 36 possible simulations of the model (Figure 4). 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.

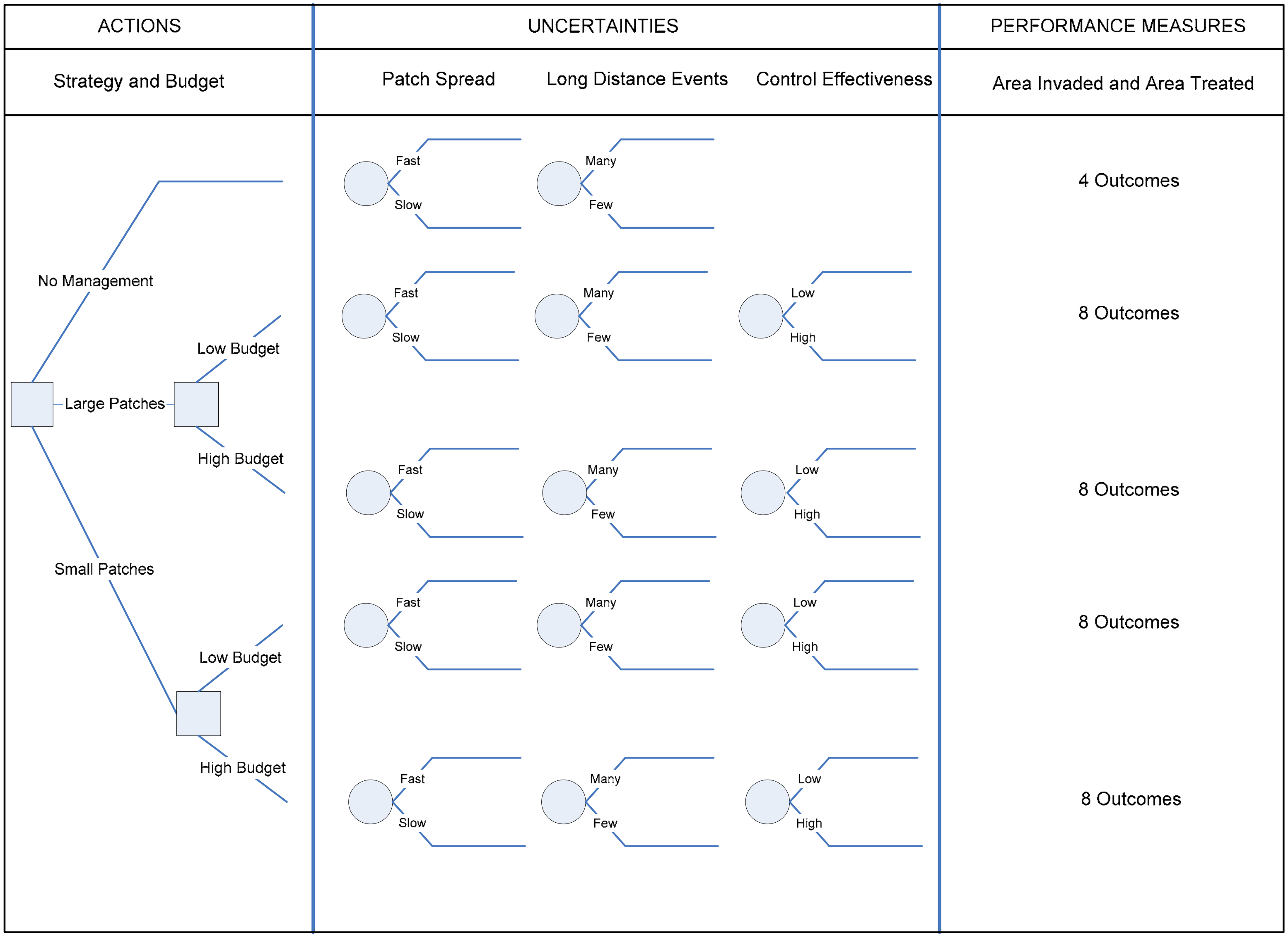

Figure 4: Decision tree depicting simulation scenario's for alternative decisions about annual clearing budgets and management strategies given alternative hypotheses about spread, control effectiveness and satellite populations.

Sensitivity Analyses

We conducted a sensitivity analysis to the probabilities assigned to alternative hypotheses across the full three dimensional probability space for patch spread, long distance dispersal 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.

Model output post processing

We examined two model outputs from each simulation that were relevant for our questions: the cumulative area treated in the invaded and established states over a fifty year period and the integral of the area invaded over time in each state. Because the state of every polygon was only printed every ten time steps; the area invaded over time was interpolated. Areas for initial and established states can be normalized to a common scale by assuming an average percent cover of crested wheatgrass by state (I = 0.3 E = 0.9).

Results

Figure 5 shows sample output maps for 3 of the simulations at year fifty. The scenario’s shown under the most pessimistic assumptions (fast spread, many satellites, low control) are: inaction, early detection and control with current capacity and controlling large existing infestations with current capacity. Differences in outcomes between the two management strategies are shown clearly. The early detection and control scenario eliminates all small patches and reduces the total number of patches but leaves a few very large patches on the landscape. The strategy that prioritizes the largest patches reduces the over size of patches on the landscape but results in many more patches overall.

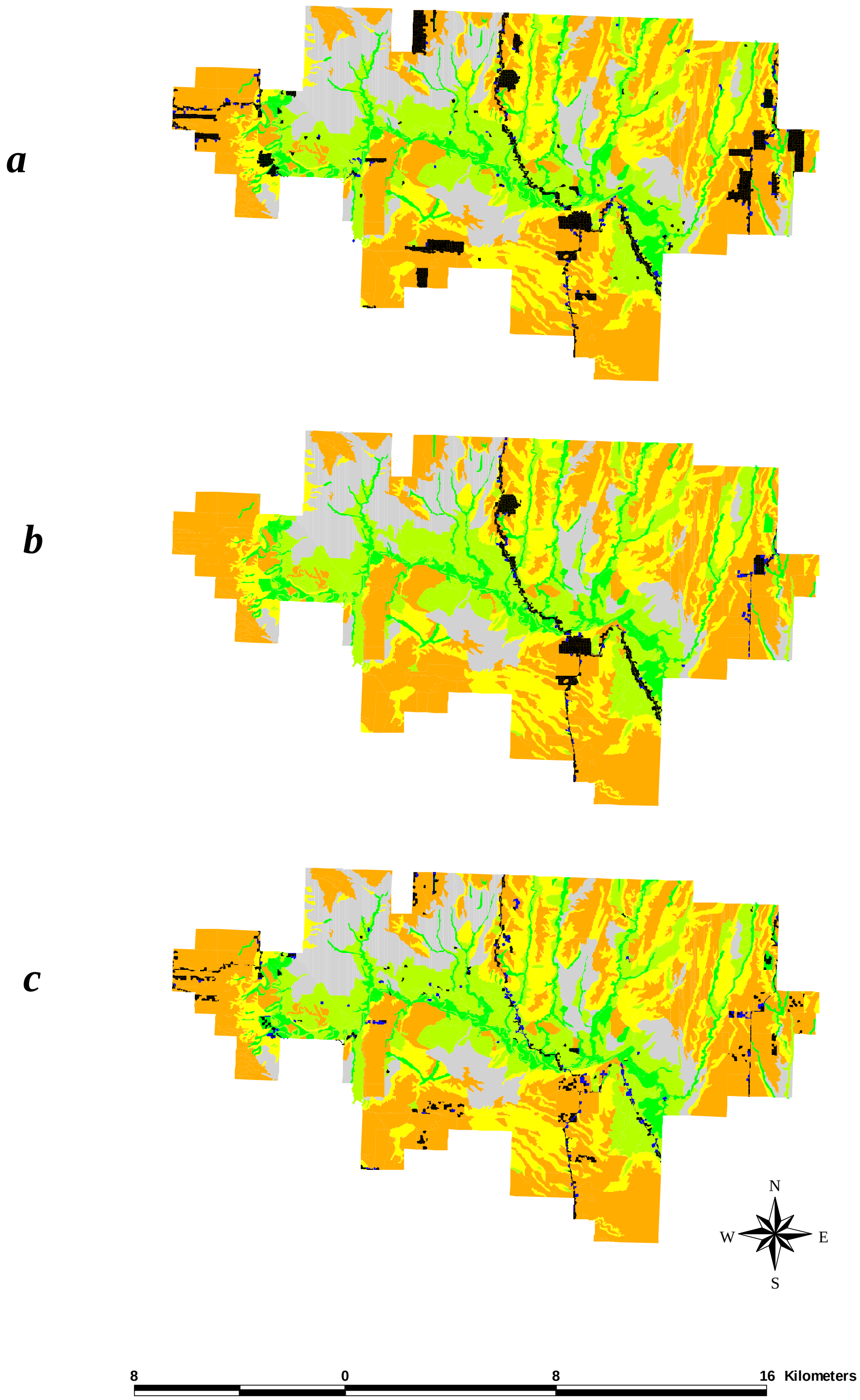

Figure 5: Sample spatial outputs for a portion of the park known as Larson Block in year fifty of three simulations. Crested wheatgrass is shown in blue (initial) and black (established). Results shown are for the most pessimistic assumptions (fast spread, many satellites and low control effectiveness). Strategies shown are: (a) inaction, (b) current capacity prioritizing early detection and control of new patches and (c) current capacity prioritizing the control of large existing infestations.

Figure 6 shows the performance of the five strategies in terms of total area treated and average crested wheatgrass coverage over a fifty year period assuming equal probabilities assigned to our alternative hypotheses for patch spread, long distance spread and control effectiveness. To understand the implications of uncertainty with respect to the probability assigned to these hypotheses we conducted a sensitivity analysis to the full three dimensional probability spaces for the inaction simulations (Figure 7) and for the four simulations in which treatments were applied (Figure 8). In the absence of any treatments the average annual coverage of crested wheatgrass in the park over a fifty year period ranges from 920 to 1060 ha (Figure 7). Most of the variation in this range is explained by the probability assigned to the Fast vs. Slow Patch spread hypothesis.

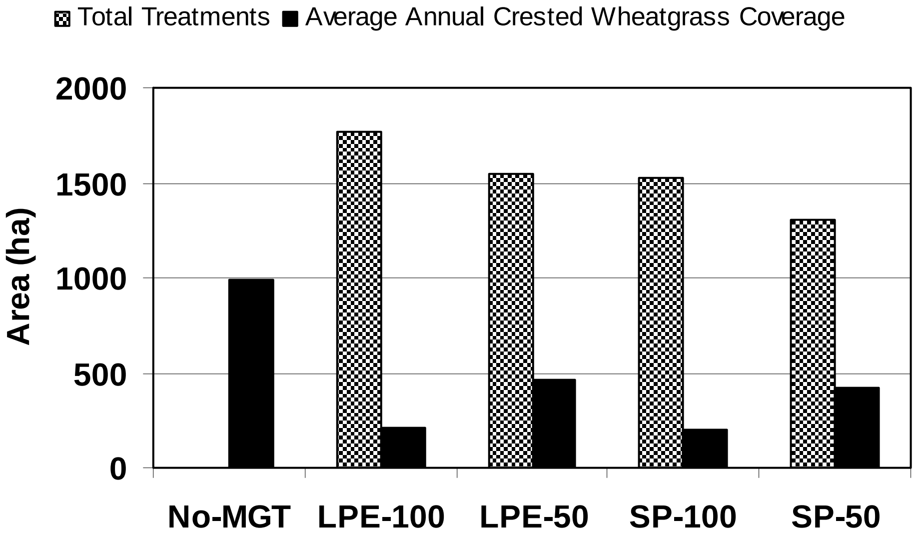

Figure 6: Expected outcomes of average crested wheatgrass coverage, and total treatments over fifty years for Grasslands National Park assuming equal probabilities for all alternative hypotheses about spread rates, control effectiveness and satellites. Strategies are: inaction (No-MGT), prioritize large patch edges (LPE) and prioritize the smallest patches (SP). Annual clearing budgets are either 50 or 100 polygon ha.

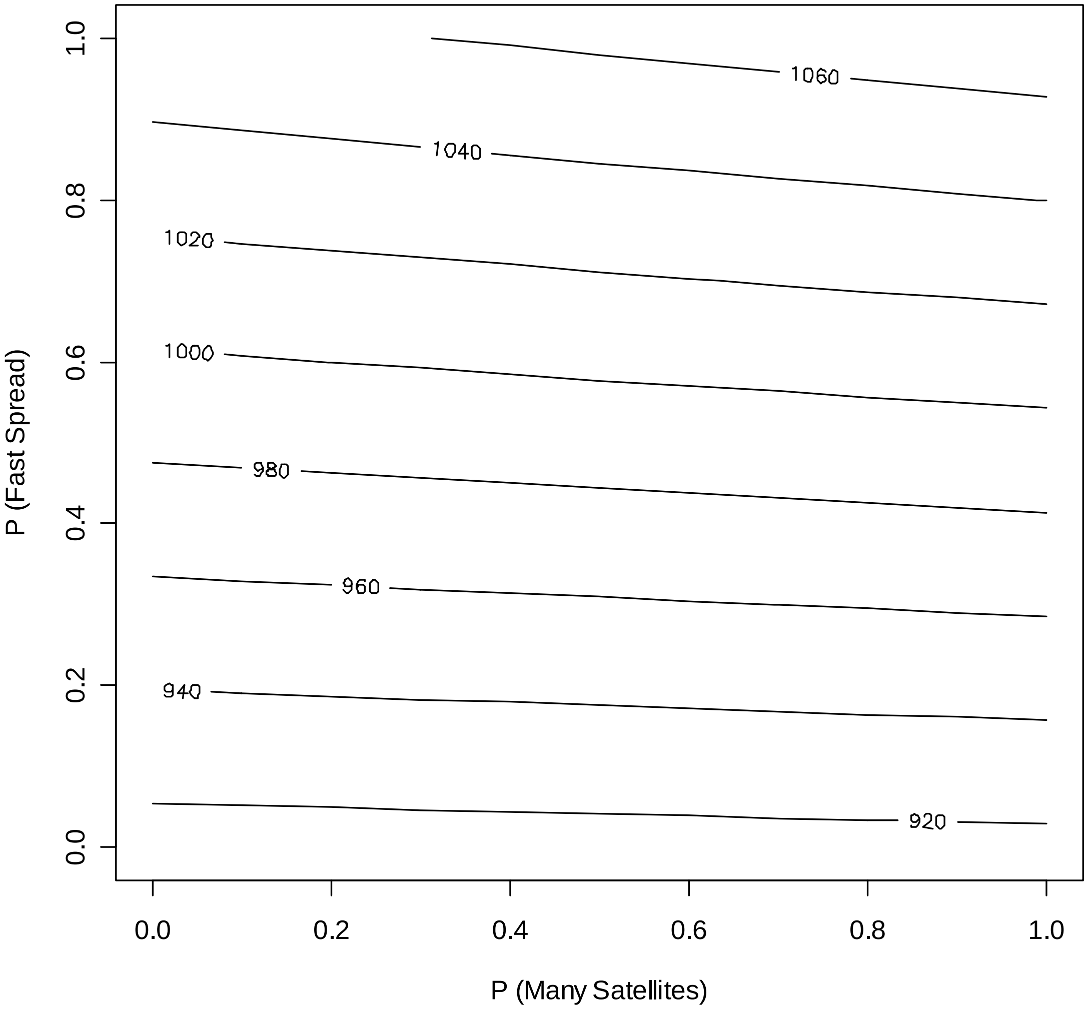

Figure 7: Average crested wheatgrass coverage (hectares) over fifty years with no management as a function of the probability assigned to the fast spread hypothesis and the many satellite hypotheses.

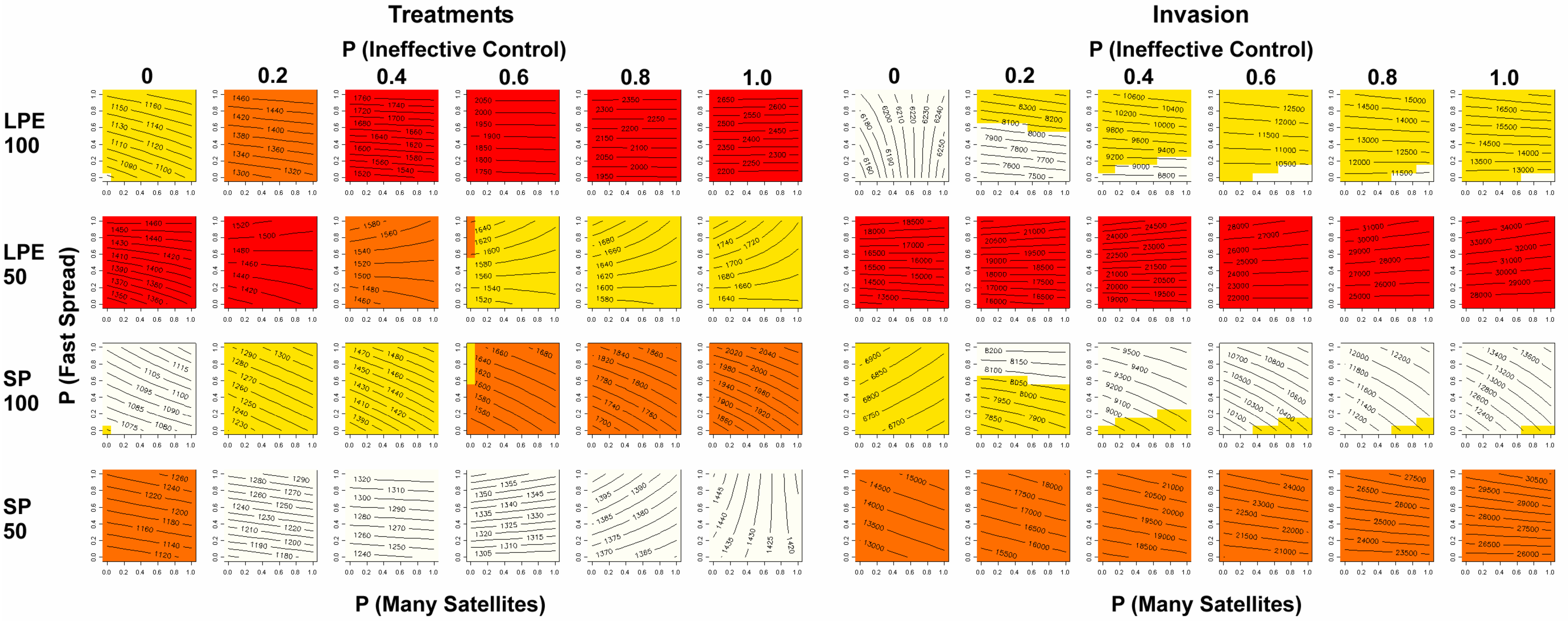

Figure 8: Cumulative area treated (left) and covered by crested wheatgrass (right) as a function of management strategy (rows), the probability assigned to the ineffective control hypothesis (columns), the probability assigned to the many satellite hypothesis (x axis on each graph) (ha) and the probability assigned to the fast spread hypothesis (y axis on each graph). For any one location in probability space, strategies are ranked using a spectrum from white to red (white is best and red it worst). Contours represent cumulative area values for treatments and crested wheatgrass coverage in ha. Strategies use either current capacity (50 polygon ha of treatments per year) or double that. Strategies are either to prioritize early detection and control of new infestations (SP) or reduction in the size of large known infestations (LPE).

Figure 8 shows both rankings and absolute values by strategy for total area treated and cumulative crested wheatgrass coverage over the fifty year period as a function of the probability assigned to the ineffective control, fast spread and many satellite hypotheses. Only under conditions of effective control (P[Ineffective Control] = 0) does allocating a larger annual treatment budget result in overall less area treated than with a lower annual treatment budget. Under these conditions the coverage of crested wheatgrass is reduced rapidly to levels in which fewer subsequent treatments are required.

Under current capacity the strategy that requires lower treatment levels is the one that prioritizes early detection and control of small patches. In terms of the cumulative area covered by crested wheatgrass over a fifty year period control effectiveness also has a big impact. Under conditions of high effectiveness (P[Ineffective Control] = 0) the strategy that ranks first is a high annual budget that prioritizes large existing infestations for treatment. Variation in the absolute area invaded for this strategy under this level of control effectiveness is mainly explained by the probability assigned to the 'many satellite' hypothesis. As the probability of ineffective control increases the proportion of probability space in which the large patch strategy ranks first decreases and allocating more resources to early detection and control of new infestations becomes the better strategy.

When control efforts are more likely to be ineffective P[Ineffective Control] > 0.2) prioritizing treatments for large existing infestations is more effective when the probability of fast spread is low and the probability of many satellites is high. Under current funding levels prioritizing early detection and control always ranks better than prioritizing large existing infestations.

Discussion

Our results show that under current levels of funding and uncertainty the strategy that most often ranks first in terms of reducing the coverage of crested wheatgrass in the park is one of early detection and control of new infestations of crested wheatgrass. This is consistent with the conclusions made by Moody and Mack (1988) that ignoring nascent foci will only result in more large patches to deal with in the future and that focusing treatments on large patches may be ineffective because spread from theses patches tends to overwhelm any treatment efforts.

Doubling of current capacity for treatments can shift the rankings of strategies such that prioritizing large existing infestations ranks first but only under conditions in which control is highly effective or when spread is slow and the rate of increase in new infestations is high. Under conditions of large budgets and effective control patches it is possible that control efforts will not be overwhelmed by spread from large patches. As the effectiveness of control efforts decreases prioritizing large patches can only be more effective if budgets are high, spread is slow and the rate of increase in new infestations is high enough to overwhelm strategies that prioritize early detection and control. Wadsworth et al. (2000) showed that under conditions in which long distance dispersal is the dominant form of dispersal it is better to prioritize larger patches. Our results are in agreement with this conclusion.

Some studies have shown that increasing funding levels in the short term can reduce the overall long-term expenditure of funds for controlling invasive weeds (Higgins et al. 2000). In the case of our simulations this is only true under conditions in which control efforts are highly effective. Under these conditions, increased capacity can reduce levels of crested wheatgrass quickly enough that the level of effort subsequently required decreases to levels below current capacity. Otherwise, under conditions of imperfect control, doubling of current capacity always results in greater expenditures over the fifty year period. Park mangers are therefore faced with a trade-off. Do they allocate more resources to crested wheatgrass control to rapidly reduce coverage and forego other long term priorities or do they maintain levels of treatment at current capacity and tolerate greater levels of crested wheatgrass within the park over the long term?

Given our assumptions about parameter ranges for alternative hypotheses and current funding levels, uncertainties about our three components of crested wheatgrass spread and control dynamics have no influence on the ranking of strategies. Under these conditions allocating resources to early detection and control of new infestations always ranks better, both in terms of total area treated over 50 years and in terms of the average area covered by crested wheatgrass over this time period. If park managers are considering increasing capacity for treatments there are some key uncertainties that must be resolved in order to determine whether treatments should prioritize early detection and control of new infestations or reducing the size of large existing infestations.

The first of these key uncertainties is the effectiveness of control efforts. If control efforts turn out to be highly effective then allocating resources to large existing infestations always ranks better than prioritizing early detection and control of new infestations. Mapping and monitoring of restoration efforts is required to determine the effectiveness of control. If control efforts are not effective then the other key uncertainties are the rates of patch spread and long distance dispersal. Rates of patch spread could be measured by monitoring transects perpendicular to the borders of existing infestations (Hansen 2006). Rates of long distance dispersal could be established by monitoring permanent sample plots that are not adjacent to existing infestations throughout the park.

Our conclusions are only as valid as the key assumptions that make up our analysis. These key assumptions are: (1) the ranges assigned to parameters for alternative hypotheses about spread and controls are representative of the full range of possibility for these parameters, and (2) detection of new patches is relatively inexpensive. If the ranges of these parameters are not valid then rankings of strategies and absolute values for our performance measures may differ from what we predicted. It is therefore important to verify that the values of these parameters are within our ranges even if managers are not considering an increase in current capacity. If detecting new infestations is expensive and requires a great deal of resources it may be more effective to focus on patches that are already known. Using real monitoring costs, an observation model that explicitly considers the tradeoffs between monitoring and treatments could be developed.

The model formulation used in this analysis was developed over a 1 day meeting in Kamloops on September 8th 2006 between John Wilmshurst, Russ Walton and Leonardo Frid. It is a first approximation to our description of the problem. Subsequent to this analysis we have identified the following shortcomings in our model and identified future analyses that would improve the level of confidence in our results. (1) The boundary between the initial and established states is artificial; in reality there is a gradual continuum between a polygon with a single crested wheatgrass plant and one which has 100% cover of crested wheatgrass. (2) It is difficult to relate control effectiveness parameters back to monitoring data on control effectiveness, more measurable effectiveness parameters and formulations would relate to the percent reduction in crested wheatgrass cover on a polygon. (3) Our treatment budgets are written in terms of polygon area, rather than absolute coverage of crested wheatgrass. Coverage of crested wheatgrass varies according to state but we can’t incorporate this into our budget ceilings for treatments. A better approach would incorporate a percent cover relationship per hectare against time since invasion. Treatment ceilings would be applied against total area covered by crested wheatgrass rather than polygon areas. Reductions in cover via different levels of control effectiveness would lead to movement back along the age-cover relationship. (4) We do not explicitly consider costs and limitations on monitoring efforts. This could be incorporated in a state and transition formulation in which crested wheatgrass is present but unknown and present and known to managers. Monitoring efforts could transition polygons from unknown to known states assuming different detection probabilities.

An approach that could be taken to reduce uncertainty and increase learning is to conduct an active adaptive management experiment to determine the most effective strategy for crested wheatgrass management in the park (Shea et al. 2002). Under such an experiment managers would subdivide the park into different experimental units and use different strategies in each. Monitoring of crested wheatgrass population densities and locations within each unit would help determine if our predictions regarding the most effective management strategies really are correct. Measurements of parameters conducted within each unit would enable us to improve our model and increase the accuracy of future predictions.

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