Manuscript submitted to: Volume 2, Issue 2, 427-447.

AIMS Environmental Science DOI: 10.3934/environsci.2015.2.427

Received date 30 January 2015, Accepted date 28 April 2015, Published date 14 May 2015

Research article

Simulating long-term effectiveness and efficiency of management scenarios for an invasive grass

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Abstract: Resource managers are often faced with trade-offs in allocating limited resources to manage plant invasions. These decisions must often be made with uncertainty about the location of infestations, their rate of spread and effectiveness of management actions. Landscape level simulation tools such as state-and-transition simulation models (STSMs) can be used to evaluate the potential long term consequences of alternative management strategies and help identify those strategies that make efficient use of resources. We analyzed alternative management scenarios for African buffelgrass (*Pennisetum ciliare* syn. *Cenchrus ciliaris*) at Ironwood Forest National Monument, Arizona using a spatially explicit STSM implemented in the Tool for Exploratory Landscape Scenario Analyses (TELSA). Buffelgrass is an invasive grass that is spreading rapidly in the Sonoran Desert, affecting multiple habitats and jurisdictions. This invasion is creating a novel fire risk and transforming natural ecosystems. The model used in this application incorporates buffelgrass dispersal and establishment and management actions and effectiveness including inventory, treatment and post-treatment maintenance. We simulated 11 alternative scenarios developed in consultation with buffelgrass managers and other stakeholders. The scenarios vary according to the total budget allocated for management and the allocation of that budget between different kinds of management actions. Scenario results suggest that to achieve an actual reduction and stabilization of buffelgrass populations, management unconstrained by fiscal restrictions and across all jurisdictions and private lands is required; without broad and aggressive management, buffelgrass populations are expected to increase over time. However, results also suggest that large upfront investments can achieve control results that require relatively minimal spending in the future.

Investing the necessary funds upfront to control the invasion results in the most efficient use of resources to achieve lowest invaded acreage in the long-term.

Keywords: buffelgrass; *Pennisetum ciliare*; fire, invasive species; state and transition simulation modeling; Tool for Exploratory Landscape Scenario Analysis (TELSA); decision support; Ironwood Forest National Monument; Sonoran Desert

1. Introduction

Invasive species are a recognized problem, impacting native systems, human health, and economies. Management of invasive species is a high priority in many agencies, but limited funds often dictate that management is conducted without a rigorous, quantitative assessment of alternatives and without a clear long-term plan. Managing for invasive species is a complex decision problem which involves determining if control or mitigation are possible; determining the potential impacts of an invasion and the resources required for addressing the invasion; and determining which actions to spend limited resources on (e.g., control versus inventory), which control methods to use, and where and when to use them. These decisions are further complicated by exogenous management decisions made by neighboring land owners and managers whose decisions affect propagule sources [1]. There are relatively few published studies that include a cost-benefit or multi-criteria analysis to aid decision making for management of biological invasions [2]. The majority of invasive species decision tools are focused on risk analysis (i.e., assessing the risk or impact of an invasion that has not yet occurred), or on the decision to try to eradicate, contain or control an existing invasion [2]. Many of these models examine the trade-offs in resource allocation between inventory efforts to locate a species and management efforts to eradicate or contain a species [e.g., 3,4,5]; and many attempt to model how to optimally control invasive species [e.g., 6,7]. Models considering the optimal control of invasive species require relatively reductionist management alternatives (e.g., do nothing, contain, or eradicate), and most of these studies have developed their own models rather than using existing frameworks. Thus, these types of models can have limited practical applications for managers who need to consider a more complicated set of management alternatives and who need to be able to interact with the decision tool to test assumptions and alternatives as new information is learned and as circumstances change. State and transition simulation modeling (STSM) offers a pre-existing framework and a standalone tool that can be used to integrate many of the important components of an invasion: habitat suitability, population dynamics, local dispersal and management activities. STSMs allow for a wide variety of management scenarios to be considered, including the ability to allow differing management strategies and effort levels across different land ownerships. STSM decision support tools can be used to simulate and explore how an invasion may progress over time, and how implementing a variety of potential management alternatives may affect long-term outcomes on the landscape. These simulations can point to important scientific uncertainties and can inform managers of how to most effectively and efficiently allocate scarce resources. Several examples of applications of STSM can be found in this special issue, ranging from modeling the ecosystem carbon implications of land use and land cover change across an entire state [8] to a climate sensitive retrospective and prospective model of whitebark pine in the Greater Yellowstone Ecosystem [9].

This study develops a STSM for buffelgrass in the Ironwood Forest National Monument near Tucson, Arizona. Buffelgrass (*Pennisetum ciliare* syn. *Cenchrus ciliaris*) is an invasive African bunchgrass introduced to the Southwestern United States by the Soil Conservation Service in the early 1940s to improve degraded rangelands [10]. The grass has since been identified as an invasive species; it spreads into both disturbed and undisturbed areas in the Sonoran desert, displacing native species [11]. In addition to outcompeting native vegetation, buffelgrass has created a grass-fire cycle in many parts of the world where it has established with less fire tolerant native species [10]. It is creating an unprecedented fire risk to a Sonoran Desert flora largely composed of fire-sensitive species as it develops a continuous fuel load where none previously existed [12,13]. At test sites in Saguaro National Park near Tucson, Arizona, soil conditions and native seed banks remained viable following control of greater than 10-year-old buffelgrass patches [14]. Thus, control of buffelgrass can result in a return to pre-invasion conditions without additional restoration steps, and buffelgrass is therefore considered to be a good candidate for control.

While buffelgrass has been recognized as a harmful invader in the desert southwest, there are limited resources available to reduce the spread of the plant. Managers must allocate limited budgets and volunteer resources between treatment, monitoring, and control, and they must choose between a variety of possible control methods. Furthermore, managers must make these decisions amidst uncertainties about future climate conditions and about how buffelgrass management may be affected by climatic extremes. We worked with resource managers and species experts to identify buffelgrass management scenarios and climate-related management uncertainties. We then used the Ironwood Forest National Monument STSM decision support tool to explore these scenarios and to determine long-term effectiveness and efficiency tradeoffs between management alternatives.

2. Materials and methods

2.1. Study area

Ironwood Forest National Monument is located approximately 30 km west of Tucson, AZ (Figure 1). While the Monument is managed by the Bureau of Land Management (BLM), there is a matrix of land ownership within the Monument boundaries. The BLM owns 52,400 ha of the 118,600 ha encompassed by the Monument. The remaining land in the Monument is under military, state, private, and tribal ownership. Elevation within the Monument ranges from 550 to 1280 m above sea level. The landscape is located on the northern edge of the Sonoran Desert, which is characterized by sparse, non-fire adapted vegetation [15]. The vegetation communities within the Monument include the transition between Arizona upland and Lower Colorado River Valley, capturing a rich diversity of biological species. The Monument was chosen because it gets very little rainfall, providing a good contrast to similar research done in the relatively wetter Santa Catalina Mountains just northeast of Tucson (average annual precipitation between 1971 and 2000 of 71 cm and 176 cm, respectively) [5,16].

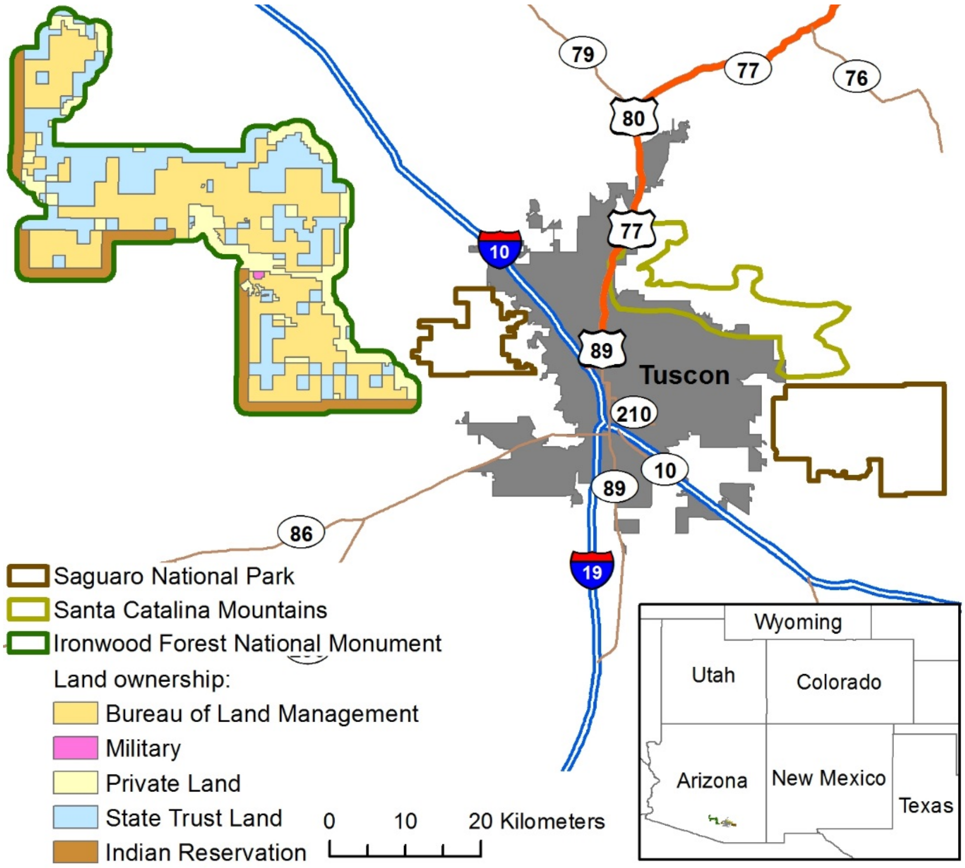


Figure 1. Location of Ironwood Forest National Monument in relation to other landmarks in Southwestern Arizona and the land ownership within the Monument boundaries.

2.2. State and transition simulation modeling

We used a spatially-explicit STSM implemented in the Tool for Exploratory Landscape Scenario Analyses (TELSA) software developed by ESSA Technologies Ltd. to simulate terrestrial ecosystem dynamics [17]. The STSM model describes the possible condition of locations in the Monument with respect to buffelgrass occurrence and cover, and can be used to simulate how the condition of the landscape may change over time. Simulations are conducted using a tessellated version of the landscape in which the landscape is divided into a spatially-explicit set of polygons. The state in each polygon describes the condition of the landscape within that polygon at a given time. Figure 2 provides a conceptual diagram of the STSM developed for Ironwood Forest National Monument. At each time-step, polygons are classified as being in one of nine possible states (boxes in Figure 2). The simulated state of each polygon changes over time based on a set of probabilistic and deterministic transitions including both natural transitions and transitions resulting from management activities (arrows in Figure 2). Natural transitions include dispersal, establishment and spread of buffelgrass, and drought induced mortality (more details in Supplementary Table 1). Management transitions include detection, treatment, and maintenance of buffelgrass patches. Dispersal from polygons where buffelgrass is present to neighboring polygons is simulated with a probability distribution of annual spread, known as a dispersal kernel (described further in the model initialization section below).

Establishment success and the maximum density of buffelgrass in a polygon is influenced by the polygon's suitability (based on a habitat suitability model described below). Once a polygon has become infested, without management intervention, the state of the polygon follows a deterministic growth pattern, transitioning to the next higher level of cover every 10 years.

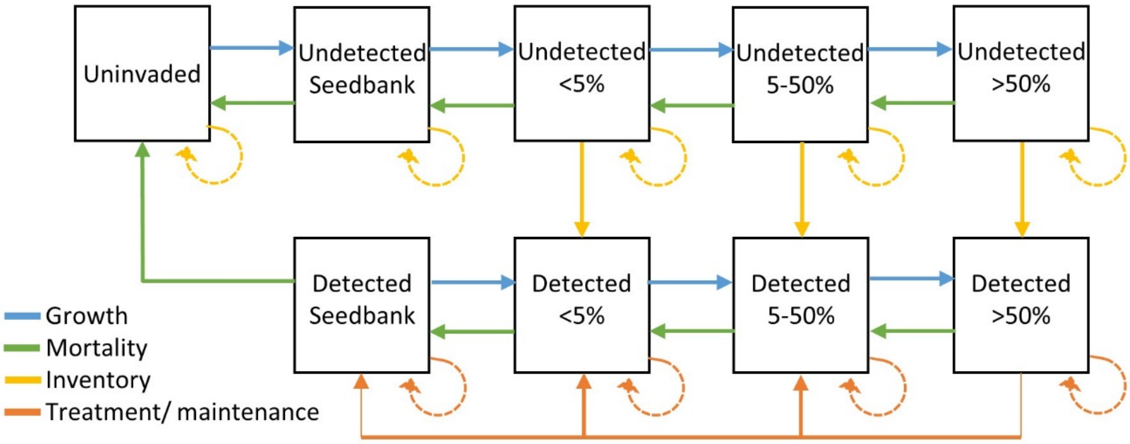


Figure 2. State and transition simulation model for buffelgrass, where each box represents the state with regards to buffelgrass cover (uninvaded, seedbank, < 5% cover, 5–50% cover, or > 50% cover; left to right) and detection (undetected or detected; top to bottom). The different color coded arrows represent different types of transitions including growth (invasion, establishment, spread), climate induced mortality (decrease in density or failure to germinate), inventory (failure or success), and management (treatment and maintenance failure or success). Solid lines represent success; dotted lines represent failure.

The model distinguishes between locations where buffelgrass is present but undetected and locations where it has already been detected. Detection requires an investment of resources in the form of mapping and inventory activities. As buffelgrass cover increases, so does the probability of detection (Table 1). Management activities can only occur at sites where buffelgrass has been detected. The effectiveness of manual and herbicide treatments determines the amount of reduction in buffelgrass cover for the polygon. If a polygon has a high density of buffelgrass present, several consecutive treatments are required in order to eliminate live plants. Once live plants have been eliminated, follow-up maintenance is required to prevent re-establishment of the soil seed bank.

The spatially-explicit function of the model simulates spread of buffelgrass between polygons and determines where management activities occur. The likelihood of spread is influenced by propagule pressure, and propagule pressure increases with buffelgrass density in the source polygon. Treatment and inventory activities can be allocated on the landscape according to patch size and other factors including land ownership and remoteness. Incidental inventory was allocated at random whereas intensive inventory occurred across the entire landscape at periodic time intervals depending on which scenario was being simulated (see section on Management Scenarios). We prioritized small patches for treatment and maintenance following the findings of several studies [5,18,19]. To implement small patch management, TELSA sorts eligible patches according to size and at each timestep the model allocates treatment budgets from smallest to largest patches until either all patches are treated or the budget is exhausted. Different management scenarios allocated different treatment budgets by activity according to land ownership (BLM owned or not) to allow for different levels of management effort across ownerships. The costs and feasibility of management activities within a polygon are also affected by remoteness. Areas within one mile of a road are more accessible and less costly to treat, so polygons were classified as accessible or remote.

Table 1. Management activities and their estimated success (i.e., detection probability for inventory activities and transition to a lower cover class for treatment activities) for each of the states defined by buffelgrass cover. Partial success indicates that the treatment resulted in a movement to the 5 to 50% cover state rather than the < 5% cover state. The last column also includes estimated cost of treating a hectare of land invaded by buffelgrass, based on values provided by Ironwood National Monument for 2011 activities. A value of 'NA' indicates that management activity never occurred for that cover state.

Management Activity	Effectiveness by % cover					
	Seedbank	< 5%	5 to 50%	> 50%	> 50% partial success	Average Cost per Hectare (US$ for 2011)
Incidental inventory	NA	1%	50%	90%	NA	$0.15
Intensive field surveys	NA	90%	90%	100%	NA	$0.25
Vehicle mounted spraying	NA	75%	75%	75%	25%	$988.00
Backpack spraying (accessible)	NA	50%	65%	50%	45%	$308.75
Volunteer hand pulling	NA	90%	90%	90%	9%	$169.54
Contract hand pulling	NA	90%	90%	90%	9%	$988.00
Helicopter spraying	NA	NA	NA	NA	80%	$123.50
Follow-up maintenance (remote)	100%	NA	NA	NA	NA	$169.54
Follow-up maintenance (accessible)	100%	NA	NA	NA	NA	$276.64

The Ironwood Forest National Monument STSM is based on the STSM developed by Frid et al. [5] for buffelgrass in the Santa Catalina Mountains. We modified the Santa Catalina STSM by inserting a seedbank state between the uninvaded state and the established <5% buffelgrass state. This modification allows the dispersal kernel to be independent of habitat, whereby seeds can disperse across the landscape and the subsequent establishment rates of those seeds can vary with the habitat suitability at the dispersal site.

2.3. Model initialization

The Monument landscape was divided into 161,630 tessellated polygons ranging from 0.0001 hectares to 2.18 hectares, with a mean size of 0.73 hectares with 0.44 standard deviation. Initial polygon states were based on intensive surveys conducted in the Monument in 2001–2002 and again in 2010. The surveyors believed they captured all buffelgrass in 2001–2002 due to drought conditions making it easy to spot on the landscape; it was harder to see in 2010. Thus, we followed the methods of Frid et al. [5] to classify 10 percent of polygons as being in the Undetected < 5% state to match the distribution of different sized patches found in Saguaro National Park. The total initial invaded area was 30.4 ha, with 0.4 ha in the Undetected < 5% state, 25.6 ha in the Detected 5–50% state, and 4.4 ha in the Detected > 50% state.

Each polygon was classified into one of three susceptibility strata (low, medium, and high). To classify polygons, we created a habitat suitability model using the Random Forest algorithm [20] based on observations from the Pima Association of Governments' buffelgrass database and the Monument with 10,000 random pseudo-absence locations. Predictor variables included Landsat 5 TM reflectance from August 2009 (all six bands), NDVI derived from the Landsat data, slope, cosine of aspect, sin of aspect, and topographic ruggedness index. Following Frid et al. [5] we classified the habitat suitability model into low, medium and high classes that correspond to the geographic location of the three different strata in the model.

Spread of buffelgrass from polygons where it is present to neighboring polygons was simulated using a probability distribution of annual spread distances (i.e., dispersal kernel) with a Weibull distribution. We calibrated the dispersal kernel with time series spread data from the nearby Santa Catalina Mountains from Olsson et al. [21], because no time series data was available within the Monument. For calibration we varied the Weibull scale parameter (alpha; 0.04 to 0.2) and shape parameter (beta; 0.3 to 0.5), selecting the closest match to the observed data (alpha 0.05 and beta 0.33).

2.4. Precipitation mortality threshold assessment

Buffelgrass surveyors in the Monument noted that there was buffelgrass die-back in untreated areas in the northern part of the Monument during the 2010 survey. This region is the driest part of the Monument, and they hypothesized the die-back was due to moisture deficit. We wanted to explore the potential effect of moisture driven buffelgrass die-back on our simulations.

To estimate the rainfall levels associated with the observed die-back events, we obtained monthly precipitation data from PRISM [22]. In 2010, surveyors flagged two untreated buffelgrass patches as mostly dead, and three untreated buffelgrass patches as half dead. Based on 2010 PRSIM data, the mostly dead patches had summer monsoon season (June through September) precipitation values of 43 and 45 mm, and the half dead patches had summer precipitation values of 49, 55 and 60 mm. Based on these values we chose to test two different precipitation thresholds for die-back events: 45 mm and 60 mm. We obtained 20 years of summer precipitation values from PRISM time series data for 1989 to 2008 (covering a 20 year period such as that in our simulation). Using the PRISM time-series data, we calculated the number of years within the 20-year period in which summer precipitation fell below the 45 mm and 60 mm thresholds; precipitation amounts less than 60 mm occurred in six years, while amounts less than 45 mm occurred in three years. To incorporate precipitation values into the STSM, we randomly assigned the PRISM time-series precipitation values to each of the simulation time steps over the 20-year simulation time horizon. To account for random variability in rainfall patterns over time, we replicated the random assignment of precipitation values to time steps in two separate draws (termed draw 1 and draw 2) such that the die-back events would occur during different years within the simulation. Spatially, the probability of a die back event was initiated based on the 20-year average summer rainfall for each of the polygons within the Monument, with polygons with higher average annual rainfall having a lower probability of experiencing a die-back event.

We ran scenarios for combinations of parameters related to buffelgrass die back from drought including: (1) no die back, (2) die back corresponding to monsoon season rainfall of < 45 mm with timing from draw 1, (3) die back corresponding to monsoon season rainfall of < 45 mm with timing from draw 2, (4) die back corresponding to monsoon season rainfall of < 60 mm with timing from draw 1, and (5) die back corresponding to monsoon season rainfall of < 45 mm with timing from draw 2. To access sensitivity of the model to stochastic processes, we ran the scenarios using five Monte Carlos.

2.5. Management scenarios

We held a workshop in February 2012 to elicit information on management activities and parameterization values for the identified activities. We defined 11 management scenarios, including a baseline scenario with no management actions (Table 2).

Management actions include two inventory actions (intensive inventory from an exhaustive survey of the Monument and incidental inventory), five treatment actions (herbicide spraying from a vehicle, from a backpack, or from a helicopter, and hand pulling by volunteers or contract labor), and two maintenance actions (visiting an accessible or a remote treated site in subsequent years to contain any new seedlings from the seedbank). Each management action has associated success rates and costs (Table 1). Success rates were elicited from workshop participants. Average costs per hectare for each treatment activity are based on actual management costs incurred by the Monument in 2011.

The 11 scenarios consist of different levels, both hectares and frequency, of the management actions (Table 3). In 2011, the Monument had a budget of approximately US$51,000 which was allocated across the management activities (*2011 level*; Table 3). The *2011 level* scenario uses the Monument's 2011 budget and treatment and inventory strategies. Monument managers and workshop participants identified six constrained management alternatives to the implemented 2011 baseline. The *no intensive survey*, *less spray*, and *every other year* scenarios all address different approaches managers could take if they face budget cuts or increased costs of management activities. The *helicopter* scenario replaces backpack spraying with helicopter spraying, trading a higher

Table 2. Management scenarios identified by the Monument to explore the potential outcome of different management implementations.

Scenario name	Short Name	Description
No management	No management	No management actions are taken anywhere within the Monument
2011 level of management	2011 level	Management remains constant at 2011 management level for BLM lands within the Monument
Reduced backpack spraying	Less spray	Maintain 2011 budget for backpack spraying but with reduced acreage treated as a result of increased costs of treatment
No intensive surveys	No intensive survey	A 10% reduction in the 2011 management level that removes intensive surveys and decreases amount of backpack spraying
Treatment and maintenance every other year	Every other year	Maintain 2011 management levels but decrease frequency of management activities to every other year

Current management plus helicopter spraying	Helicopter	Management remains constant at 2011 management level with the addition of helicopter spraying
Increased BLM management	Increased BLM	Increased management of BLM lands (roughly two times 2011 level)
Manage all lands	Manage all	Extend 2011 management level that was limited to BLM lands to the same level of effort on non-BLM lands within the Monument
Containment level management for BLM	Unlimited BLM	Unlimited management to maintain current level of infestation on BLM lands
Containment level management for all lands	Unlimited all	Unlimited management to maintain current level of infestation within the entire Monument (regardless of ownership)
Cost of delay for all lands	Unlimited delay	Unlimited management with a 10 year delay in starting management

Table 3. Maximum hectares allowed to be treated per yearly timestep for the various management activities (rows) under the different management scenarios (columns) with the number of years between treatments in parentheses.

Management Activity	2011 level	Increased BLM	Manage all	No intensive surveys	Helicopter	Less spray	Every other year
Incidental inventory	4858 (1)	4858 (1)	24,300 (1)	4858 (1)	4858 (1)	4858 (1)	4858 (1)
Intensive field surveys	52,227 (7)	52,227 (7)	261,225 (7)	0 (7)	52,227 (7)	52,227 (7)	52,227 (7)
Vehicle mounted spraying	4 (2)	4 (2)	9 (2)	4 (2)	4 (2)	4 (2)	4 (2)
Backpack spraying (accessible)	81 (1)	203 (1)	186 (1)	69 (1)	0 (1)	49 (1)	81 (2)
Hand pulling (accessible)	16 (1)	16 (1)	37 (1)	16 (1)	16 (1)	16 (1)	16 (2)
Hand pulling (remote)	4 (1)	4 (1)	7 (1)	4 (1)	4 (1)	4 (1)	4 (2)
Helicopter spraying	0 (0)	0 (0)	0 (0)	0 (0)	243 (1)	0 (0)	0 (0)
Follow-up maintenance (remote)	4 (1)	4 (1)	7 (1)	4 (1)	4 (1)	4 (1)	4 (2)
Follow-up maintenance (accessible)	32 (1)	69 (1)	74 (1)	32 (1)	32 (2)	32 (1)	32 (2)

probability of effectiveness for the ability to treat a greater number of hectares. The *increased BLM* scenario has roughly twice the budget as the *2011 level* scenario; in this scenario, managers opted to allocate additional funds toward additional backpack spraying and follow-up maintenance. The *manage all* scenario explores how extending the 2011 level that was limited to BLM lands to all of the lands within the Monument affects buffelgrass cover. Three non-constrained scenarios were developed to explore the resources and management actions required to contain buffelgrass in the Monument. The first, *unlimited BLM*, allows unlimited management activities to maintain 2011 levels of infestation on BLM lands. The second, *unlimited all*, extends this to maintain 2011 levels of infestation within the entire Monument. The third, *unlimited delay*, allows unlimited management within the entire Monument, but the start of management is delayed 10 years. This last scenario addresses the question of the cost of delaying treatment.

To compare scenarios we examine predicted hectares invaded at the end of 20 years and the amount of different types of management actions occurring in each year, and we evaluate the efficiency of the scenarios. Efficiency is examined by comparing the hectares invaded after 20 years to the cumulative expenditures for treatment over the 20-year simulation horizon. Cumulative expenditures were calculated in four ways. We calculated cost of treatment by adjusting for the density of buffelgrass within a polygon by adjusting the area of the polygon being treated by multipliers of 0.025 for < 5% cover, 0.25 for 5–50% cover, and 0.75 for > 50% cover. We also calculated costs without adjusting for buffelgrass density. Additionally, volunteers performed hand pulling management in 2011. We wanted to examine how having to pay for hand pulling management would affect overall costs, and so calculated costs using paid contract labor rather than volunteer labor for hand pulling (Table 1).

Due to computer processing time, we only ran the precipitation effect models for the *no management* and *2011 level* scenarios.

3. Results

Without any management actions (*no management* scenario), invaded areas in the Monument are expected to increase from 30 ha at the start of the simulation to a simulated 219 ha after 20 years (Figure 3). After 20 years the rate of increase is still steady, indicating that areas susceptible to invasion remain after the simulation ends.

3.1. Constrained management scenarios

Over time, the area invaded for the *no intensive survey* scenario starts to approach that of the *no management* scenario (Figure 3); this occurs because as the known patches of buffelgrass are treated, no new patches are found. The area invaded for the *helicopter* scenario also approaches that of the *no management* scenario (Figure 3), because, for helicopter spraying to occur, patches must have > 50% cover (Table 3). Patches of this size only existed in years 0 and 1 of the simulation and again in years 10 and 11, so a minimal amount of the landscape was available for aerial spraying over the course of the simulation (Figure 5a). A different spatial configuration, with larger patches of buffelgrass, or a scenario which allows backpack spraying in years where patches are not available for helicopter spraying, would likely produce a different result. Both the *increased BLM* and *manage all* scenarios resulted in relatively less invaded area after 20 years, with only unlimited scenarios performing better.

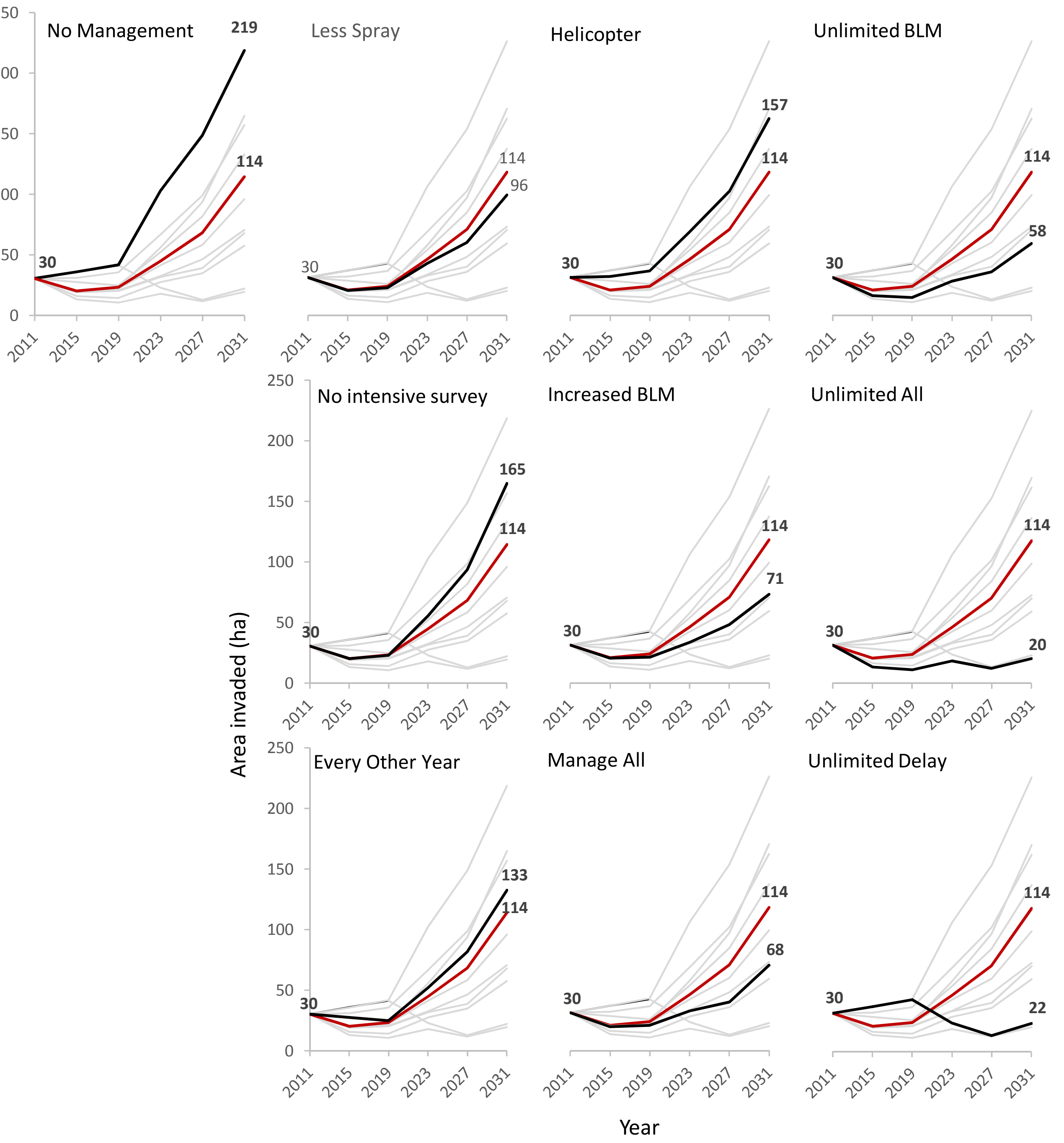


Figure 3. Forecasted area invaded in hectares at four year intervals within the 20 year simulation for the 11 different management scenarios described in Table 2. The 2011 level management scenario is highlighted in red for comparison with the other scenarios, with each labeled one highlighted in black. The beginning area invaded and final area invaded are labeled.

3.2. Unlimited management scenarios

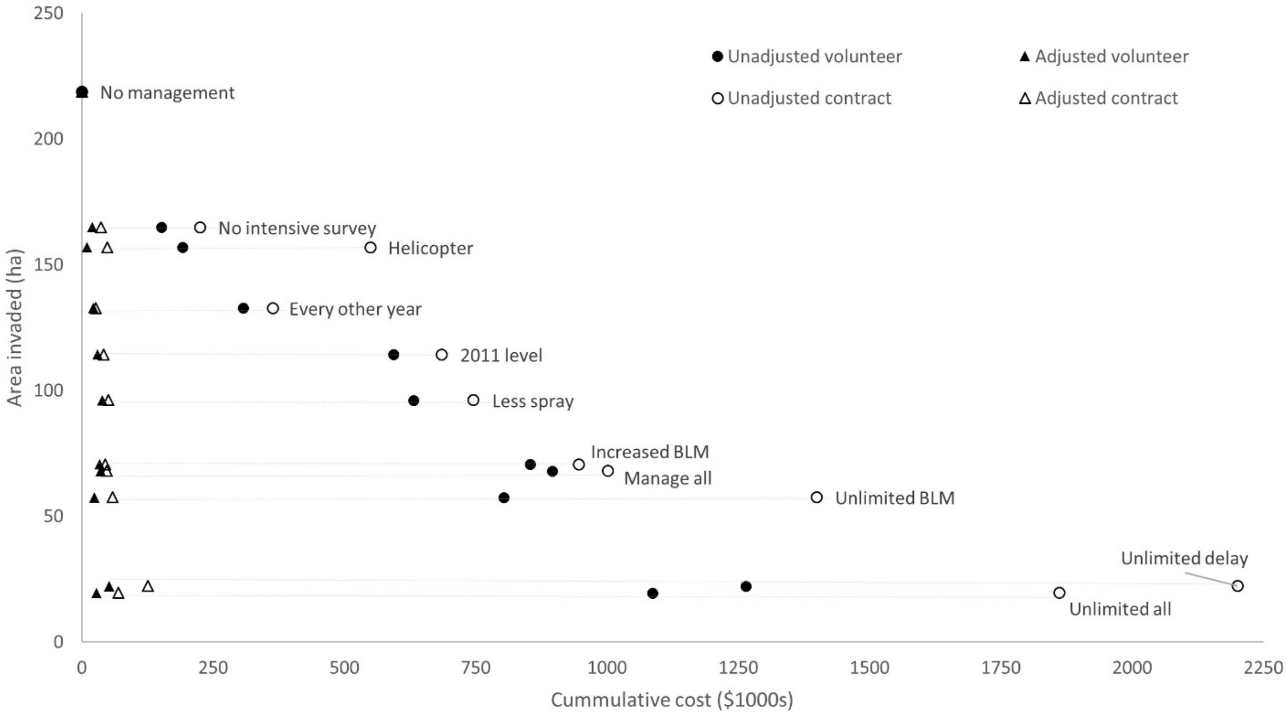
The *unlimited all* and *unlimited delay* scenarios, which involved unconstrained management on all lands regardless of jurisdiction, were the only scenarios with a predicted reduction in area invaded after the 20 years of simulation (30 ha reduced to 20 and 22 ha). Once management begins in the *unlimited delay* scenario, it only takes two years to reduce invasion levels to match the scenario of non-delayed unlimited management (year 12). Scenarios with management limited to BLM lands, even with unlimited treatment resources, result in more invaded acres by the end of 20 years (30 ha increased to 58 ha in the *unlimited BLM* scenario). More than half of these acres were found on non-BLM lands, where we assume no treatment is occurring.

3.3. Cost efficiencies

Figure 4 shows the relative tradeoff between treatment success (indicated by a low area invaded), and cumulative treatment cost. The nearer a scenario falls to the origin, the more efficient the scenario is (i.e., high treatment success and low cost). The general pattern of the efficiency of scenarios is similar with both adjusted and unadjusted cost estimates (Figure 4a). However, the cumulative unadjusted cost estimates are considerably higher than the adjusted cost estimates.

As expected, the unlimited scenarios have the highest treatment success (i.e., the lowest invaded area at the end of the 20-year simulation), and they also have the highest costs. The *unlimited all* and the *unlimited delay* scenarios have the greatest treatment success, with the *unlimited all* scenario resulting in a substantially lower cumulative cost compared to the *unlimited delay* scenario. Regardless of whether cost is adjusted for buffelgrass cover, these results suggest that there is a substantial cost to delaying treatment. .

For the constrained scenarios, the patterns of efficiency are roughly linear, with an increase in amount spent resulting in a similar decrease in invaded area. If the Monument has to pay for hand pulling treatments (contactor cost instead of volunteer cost), the overall cost of all management scenarios increases by relatively small amounts for the constrained scenarios, and by relatively large amounts for the unlimited scenarios.



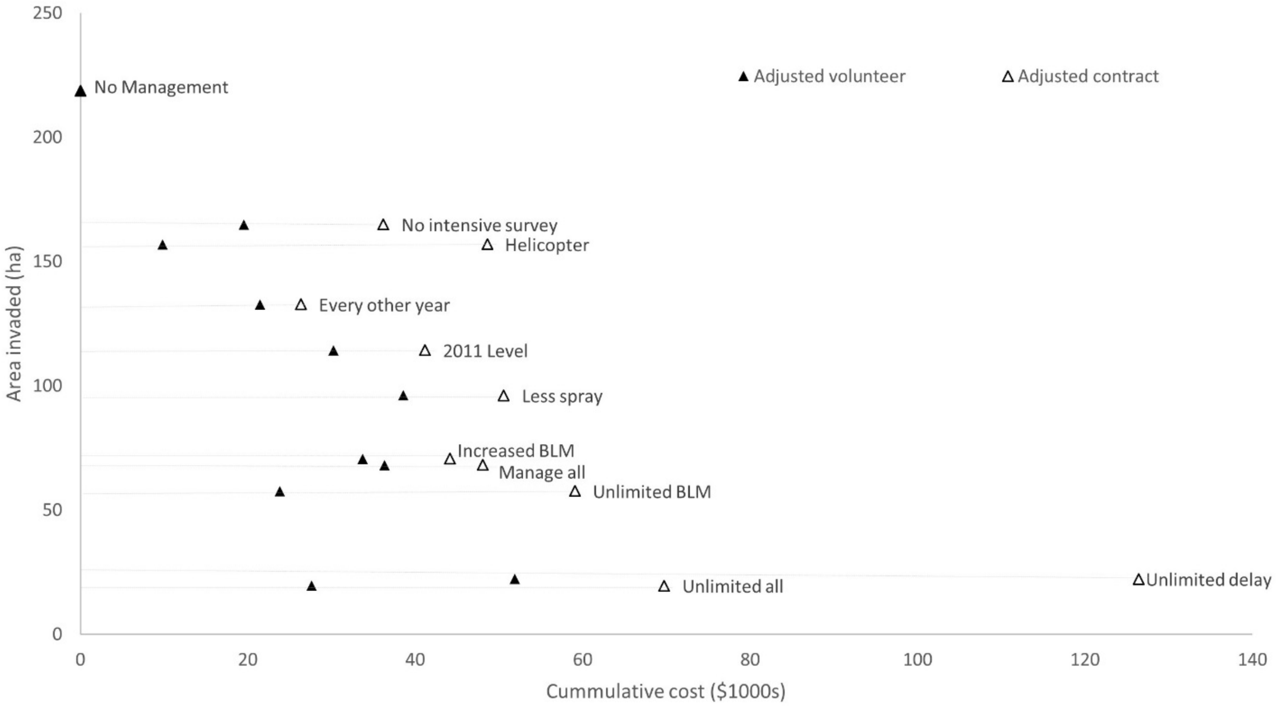
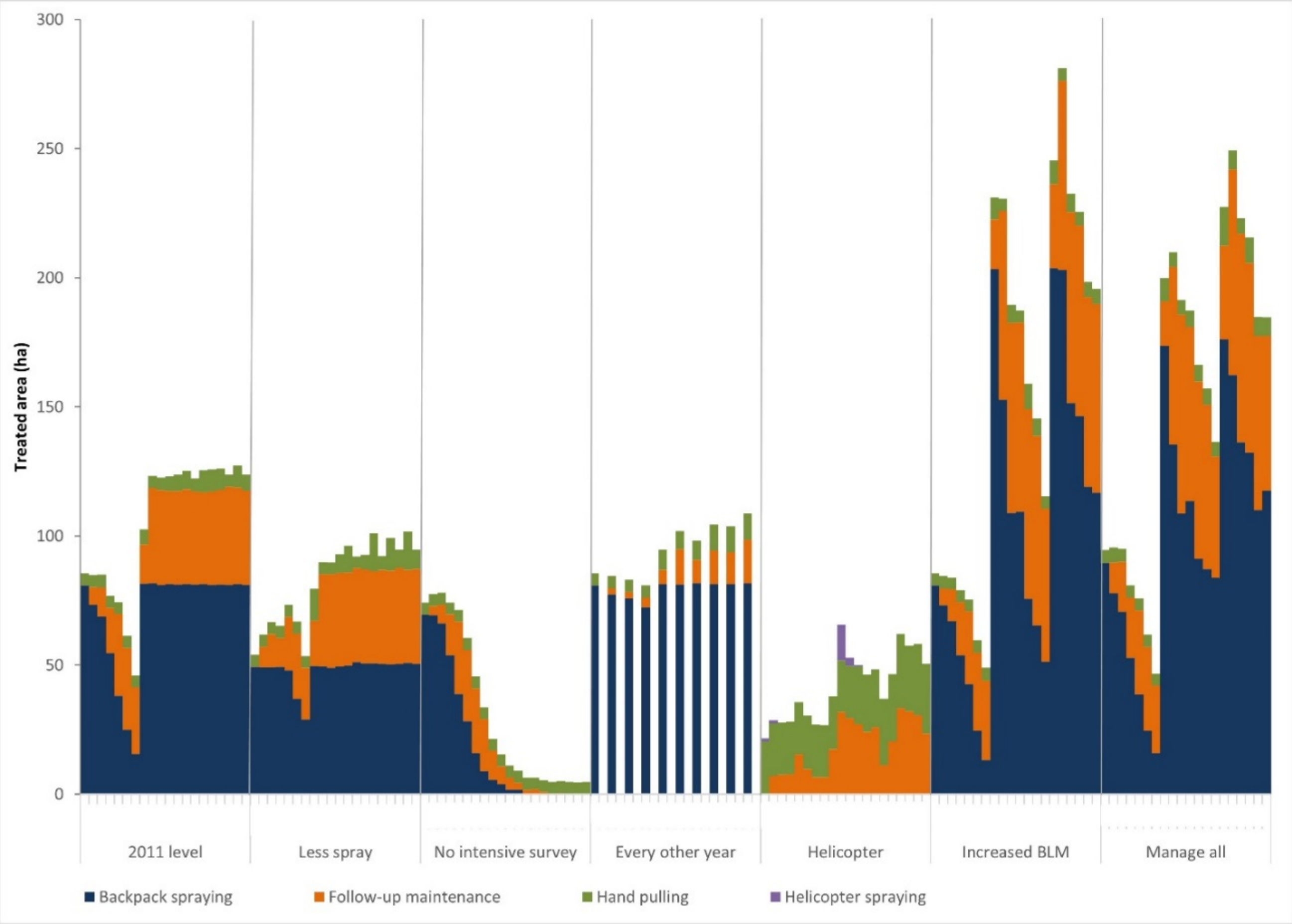


Figure 4. Graph of efficiency of the 11 management scenarios (Table 2) with forecasted number of hectares invaded after 20 years of simulation on the y-axis and the cumulative cost in US$1000s over the 20 year period of simulated management activities on the x-axis. Costs include those adjusted (triangles) and unadjusted (circles) for buffelgrass cover and cost where hand pulling is conducted by volunteers (solid shapes) or by contractors (open shapes), with a) all four calculations for scale comparison (US$0 to $2,250,000), and b) zoomed into the adjusted cost zone (US$0 to $140,000).

3.4 Effects of the inventory cycle

The intensive inventory cycle was set to seven years for all scenarios that include intensive inventories, matching the Monument’s 2011 management strategy. The seven year intensive inventory cycle had a noticeable effect on all of the scenarios in which intensive inventory occurred. During the first seven years there is a decrease in treated hectares through time as detected patches are controlled and new ones are not discovered (Figure 5). After intensive inventory occurs in year 8, there is an increase in treatment activities again. This trend is especially noticeable in the *unlimited all* scenario, where there is a more than 200% increase in treated hectares between years 7 and 8 (3.5 to 683.5 ha treated) and years 14 and 15 (11.7 and 852.9 ha treated). The increase in the detected area available for treatment directly following years with intensive surveys indicates that in the years between intensive inventories buffelgrass is growing undetected and thus untreated on the landscape, suggesting that the seven year inventory cycle is a limiting factor for buffelgrass treatment in these scenarios.

For constrained scenarios, budgets and management options are constrained such that known patches of buffelgrass are increasing on the landscape faster than they can be treated. Therefore, for these scenarios the seven-year inventory cycle does not limit treatment in the long-term. After year seven, many of the scenarios are treating the maximum allowed hectares for the remainder of the simulation (e.g., the *2011 level* scenario treats the maximum allowed (Table 3) of roughly 81 ha with backpack spraying and 36 ha with follow-up maintenance after intensive surveying in year 8; Figure 5a). The *less spray*ing scenario follows a similar pattern. The *no intensive survey* scenario does not have treatments maximized because, although buffelgrass is increasing on the landscape, it is impossible to treat as it remains undetected. Every other year is maximizing spraying the entire time. For these scenarios, budgets and management options are constrained such that known patches of buffelgrass are increasing on the landscape faster than they can be treated after the intensive inventory in year 8. Therefore, for these scenarios the seven-year inventory cycle does not limit treatment in the long-run; only during the initial 8 years of the simulation. The three unlimited scenarios never include spraying as a treatment because it is less effective than hand pulling (Table 1; Figure 5b), and thus rely heavily on hand pulling for buffelgrass control. The *2011 level* scenario includes 16 ha of volunteer hand pulling, and extending this effort to all lands would increase that to 37 ha (Table 3). The *unlimited all* scenario has almost three times that amount of hand pulling occurring in years immediately following intensive inventory: year 1 had 101 ha; year 8 had 341 ha; year 14 had 422 ha (Figure 5b). Again, buffelgrass is increasing undetected on the landscape in between intensive inventory efforts, so even with unlimited treatment resources there is a noticeable effect of the inventory cycle.



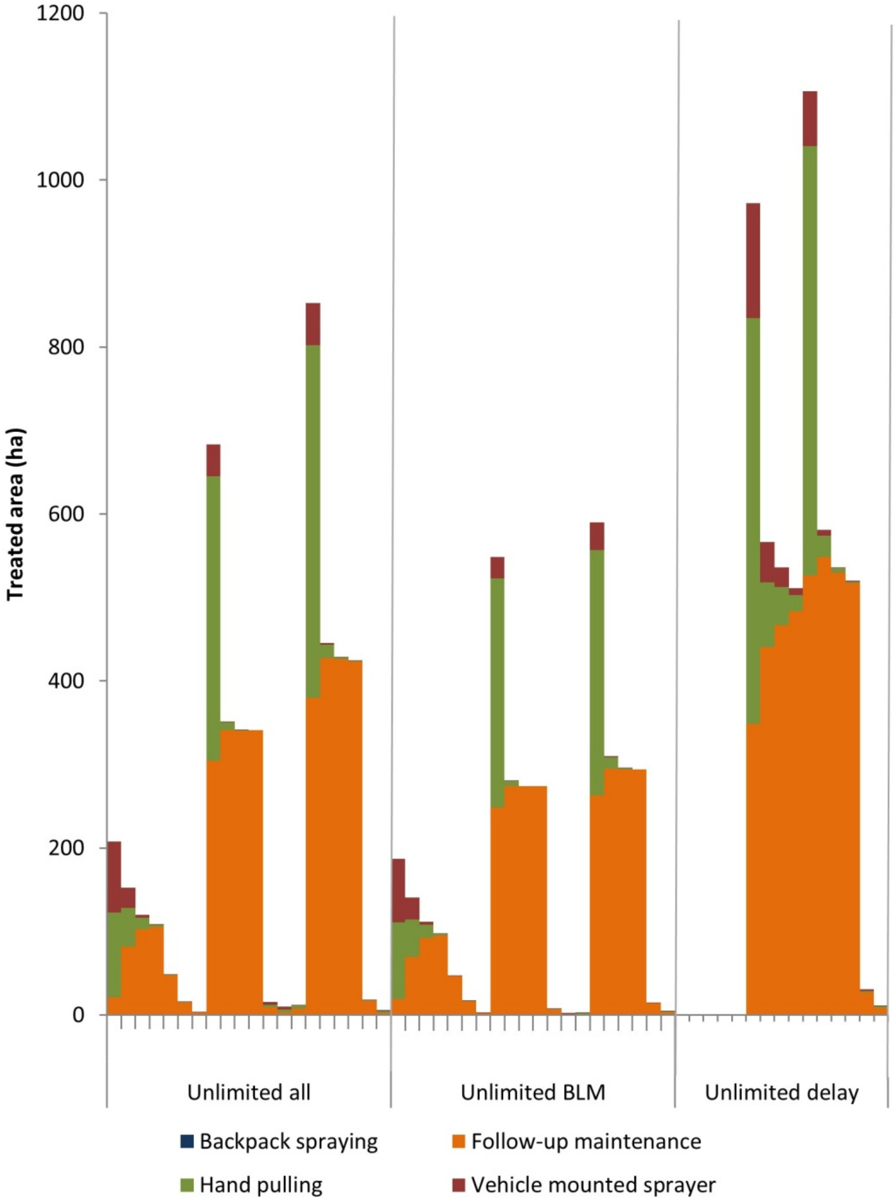


Figure 5. Number of hectares treated by each treatment activity including hand pulling, backpack spraying, helicopter spraying, and follow-up maintenance occurring in each year of the twenty year simulation for a) the seven scenarios with annual caps on management activities and b) the three scenarios without annual caps on management activities.

3.5. Precipitation mortality threshold assessment

Including die-back events at either threshold, 45 mm or 60 mm, did not make a significant difference in the forecasted number of hectares invaded after 20 years of simulation (Figure 5). With the *no management* scenario, there was a wide range in predicted hectares invaded after 20 years among all five Monte Carlo simulations (Figure 6a). For the *2011 level* scenario there was a much smaller range among the Monte Carlo simulation predictions for the run without any die-back events

(Figure 6b). The model runs diverge more with each time step, so greater differences might emerge if the simulations were run beyond 20 years.

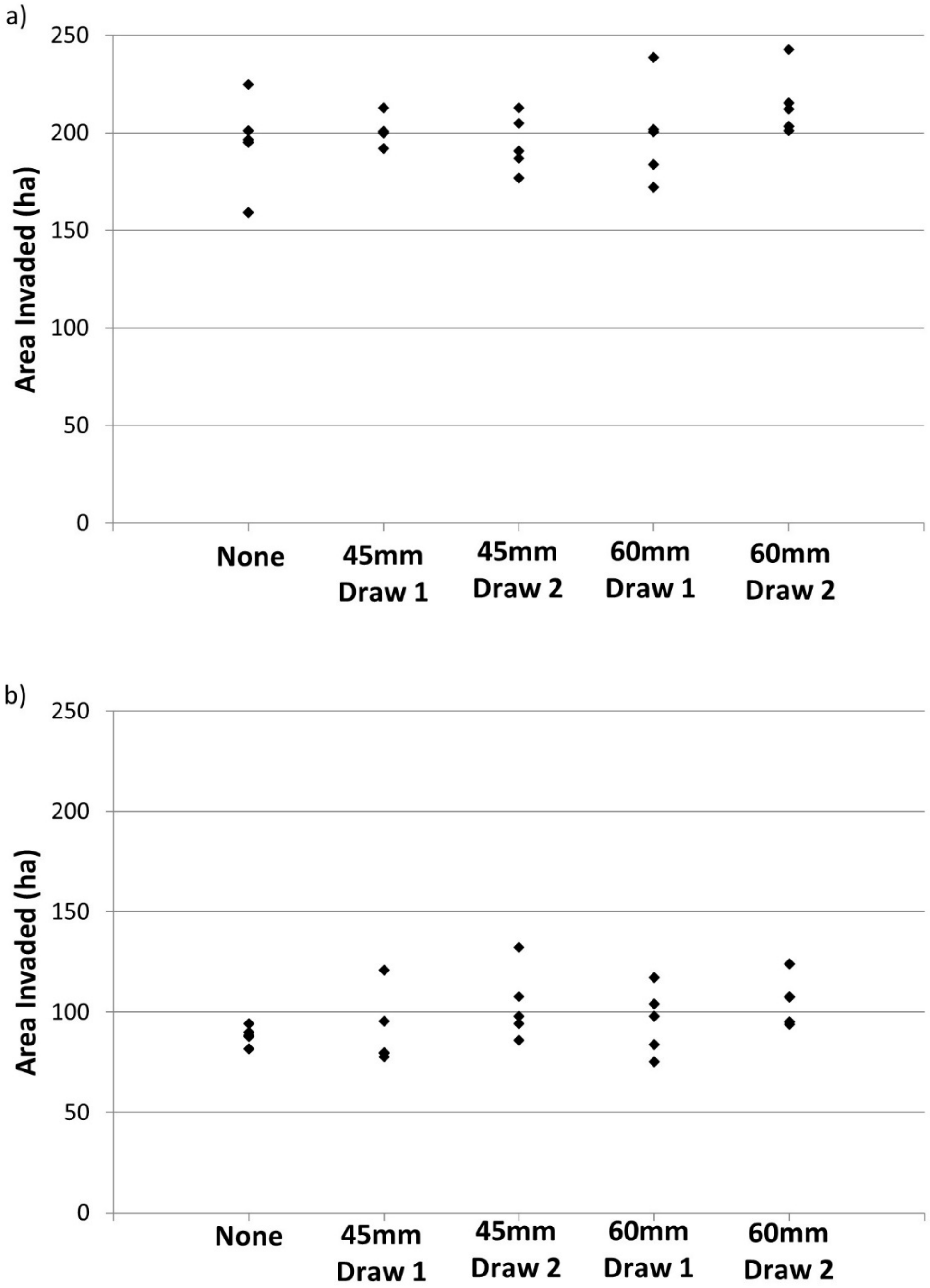


Figure 6. Forecasted number of hectares invaded after 20 years of simulation for two scenarios, a) no management and b) 2011 level, with five different parameters related to buffelgrass die back from drought including no die back, die back corresponding to monsoon season rainfall of < 45 mm or < 60 mm with two different timings of die back rainfall events (draw 1 versus draw 2). Five Monte Carlos were run for each.

4. Discussion

We evaluated the long-term effectiveness of different configurations of management strategies that the Monument is already using. We show that by investing more resources early in the simulation, the overall cost efficiency of buffelgrass management should increase. A key result from the simulations is the importance of inventory, as most scenarios show an impact of undetected nascent populations. Increasing the frequency of inventory could potentially reduce the overall cost and infestation of buffelgrass.

Frid et al. [5] developed a similar simulation model with TELSA for the nearby Santa Catalina Mountains, but focused on the question of allocating resources between inventory and management. Their scenarios were run for 50 years, and the unlimited scenarios became comparable in acres treated towards the end of that time frame. If this trend is consistent in the Monument, we would expect the unlimited scenarios to become more efficient with the longer time frame (i.e., cumulative cost would become more comparable while the difference in area invaded would become larger).

Buyuktahtakin et al. [23] developed a spatial dynamic control model for buffelgrass, determining the optimal locations to spray given labor constraints while considering damage reduction to saguaros, buildings, and ephemeral riparian areas. They were unable to fully optimize the model, but instead evaluated three management rules of thumb identified in the Southern Arizona Buffelgrass Strategic Plan developed in 2008 by the buffelgrass working group [24]. Their methods focus on where to treat as a function of priority resource protection, while our focus was on how to treat. Thus, their conclusions are very specific to the configuration of resources on the landscape. With their small landscape, they ignored the issue of inventory. Our results highlight the importance of knowing where populations are, which is a concern on a landscape the size of our study area.

Optimal control in the Buyuktahtakin et al. model is constrained by the availability of labor. In our scenarios, we considered budget constraints but did not consider the labor constraint with relation to availability of volunteers. Because hand pulling has the highest success rate of all treatment options, hand pulling is heavily utilized in the unlimited management scenarios in our simulations. As suggested by Buyuktahtakin et al., the availability of labor to implement these unlimited treatments may in fact be limiting, and this constraint is something that should be taken into consideration in future scenario analyses. The cost estimates for the unlimited scenarios that include contract labor for hand pulling are probably more realistic than those including volunteers.

A major difference in the literature is the assumption of how treatment costs relate to high and low density locations. Buyuktahtakin et al. [12] assumed that buffelgrass treatment cost increased linearly with population density; Frid et al. [9], working with two different invasive weeds in Montana, calculated costs that decreased with population density. In both approaches, the authors have assumed that treatment cost is dependent on density, but the studies assume opposite directions of dependence. We calculate costs using two different sets of assumptions. Our unadjusted costs are independent of the buffelgrass density of the polygon. This assumption is based on the hypothesis that higher costs associated with increased search times for low density polygons would cancel out higher costs associated with increased herbicide and spraying costs for high density polygons. Our adjusted costs assume an increasing linear relationship between buffelgrass density and treatment cost, similar to Buyuktahtakin et al. [12]. With differences in adjusted and unadjusted cost estimates for the unlimited scenarios of more than US$1,000,000, it is clear that obtaining better estimates of the relationship between treatment cost and buffelgrass density is important to estimate the overall costs required to contain buffelgrass and the relative costs of the different management scenarios.

Scenarios with treatment only occurring on BLM lands had more acres invaded at the end of 20 years, potentially because the non-BLM lands acted as seed sources to the areas being treated. This finding highlights the need for an inter-agency management plan, with the BLM engaging all land owners within the boundaries and adjacent to the boundaries.

All patches started the simulation at age zero, so there was limited opportunity for growth over the 20 year period because 10 years are required to transition to a greater density state class. Varying the age of patches with model initialization would result in a higher initial growth rate of buffelgrass on the landscape.

There is disagreement in predicted changes in monsoonal precipitation among future climate models [25]. Thus, it is difficult to evaluate how the potential sensitivity of buffelgrass to extremely dry summers may affect future populations. Cool season precipitation is expected to decrease, but it is unclear how this may affect buffelgrass.

Future research could involve porting the TELSA model into ST-SIM, the latest STSM software [26,27]. This software moves from a tessellated landscape to a grid, is more computationally efficient, and much more user-friendly. Use of ST-SIM could enable the hand-off of these models to resource managers. It could also enable more in-depth sensitivity analyses. Additional scenarios, including those with more frequent inventory, could be investigated to identify potentially more efficient management strategies.

5. Conclusions

Scenario results suggest that to achieve an actual reduction and stabilization of buffelgrass populations in Ironwood Forest National Monument, management unconstrained by fiscal restrictions and across all jurisdictions and private lands is required; without broad and aggressive management, buffelgrass populations are expected to increase over time. However, results also suggest that large upfront investments can achieve control results that require relatively minimal spending in the future.

Acknowledgements

The authors would like to thank the U.S. Geological Survey Invasive Species program for funding support. They would also like to thank Darrell Tersey, Julio Betancourt, Lindy Brigham, the Southern Arizona Buffelgrass Coordinating Committee, and all attendees of the February 2011 workshop for their assistance. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Conflict of Interest

All authors declare no conflicts of interest in this paper.

Supplementary

Table S1. Natural transition probabilities, including the transition type (growth, invasion, mortality of buffelgrass, mortality of seedbank, and seed establishment. Probabilities can be different depending on the stage of the location, so the current stage and the stage being transitioned to are included as the "From stage" and "To stage".

Transition type	From stage	To stage	Probability
Growth	Invaded-Cover < 5%	Invaded-Cover 5–50%	Deterministic after 10 years without treatment post seed establishment
Growth	Invaded-Cover 5–50%	Invaded-Cover > 50%	Deterministic after 20 years without treatment post seed establishment
Invasion	Uninvaded	Seedbank	Contingent on spread from neighbors or long distance dispersal (0.01)
Mortality	Invaded-Cover < 5%	Seedbank	0.01 (temporal and spatial variability implemented with multipliers)
Mortality	Invaded-Cover > 50%	Invaded-Cover 5–50%	0.01 (temporal and spatial variability implemented with multipliers)
Mortality	Invaded-Cover 5–50%	Invaded-Cover < 5%	0.01 (temporal and spatial variability implemented with multipliers)
Mortality (seedbank)	Seedbank, Detected	Uninvaded, Undetected	0.1(temporal and spatial variability implemented with multipliers)
Mortality (seedbank)	Seedbank, Undetected	Uninvaded, Undetected	0.01(temporal and spatial variability implemented with multipliers)
Seed Establishment	Seedbank, Low susceptibility	Invaded-Cover < 5%, Detected	0.05
Seed Establishment	Seedbank, Medium susceptibility	Invaded-Cover < 5%, Detected	0.5
Seed Establishment	Seedbank, High susceptibility	Invaded-Cover < 5%, Detected	1

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