

Viewpoint**Integrating landscape simulation models with economic and decision tools for invasive species control**Catherine M. Cullinane Thomas^{1,*}, Helen R. Sofaer¹, Sarah A. Cline^{2,3} and Catherine S. Jarnevich¹¹U.S. Geological Survey, 2150 Center Ave. Bldg. C, Fort Collins, CO 80526, USA²U.S. Department of the Interior, 1849 C Street, NW, Mail Stop 3530 Washington, DC 20240, USA³Present address: U.S. Department of Agriculture, 1400 Independence Ave. SW Washington, DC 20250, USAAuthor e-mails: ccullinanethomas@usgs.gov (CCT), hsofaer@usgs.gov (HS), sarah.cline@wdc.usda.gov (SC), jarnevichc@usgs.gov (CJ)

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Received: 9 January 2018**Accepted:** 8 October 2018**Published:** 6 November 2018**Handling editor:** Vadim E. Panov**Copyright:** © Cullinane Thomas et al.This is an open access article distributed under terms of the Creative Commons Attribution License ([Attribution 4.0 International - CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)).**OPEN ACCESS****Abstract**

In managing invasive species, land managers and policy makers need information to help allocate scarce resources as efficiently and effectively as possible. Decisions regarding treatment methods, locations, effort, and timing can be informed by the integration of landscape simulation models with economic tools. State and transition simulation models align with conceptual models of ecosystem change often used by practitioners and have been used to characterize the potential consequences of invasions. Outputs of these simulations are typically summarized to describe landscape changes (e.g., infested area), which may provide sufficient information for managers to make informed decisions. However, it is sometimes helpful or necessary to go a step further to consider the social and economic values associated with treating (or not treating) invasions. Here, we describe when and how to integrate state and transition simulation models with economic and decision tools to aid in the control of emerging and established populations of invasive species. The paper provides an overview of three types of questions that can be addressed: 1) how big is the problem? 2) which management strategy is most appropriate? and 3) what are key sources of uncertainty? For each question, we describe aspects that can be addressed by landscape simulation models alone, and outstanding questions that can be evaluated by integrating economic and decision tools. Through a series of example applications from the literature, we reinforce how the integration of these tools, and the interdisciplinary perspective such an integration requires, can increase relevance and utility of modeling efforts for resource managers and decision makers.

Key words: co-production, cost-benefit analysis, economic valuation, multi-criteria decision analysis, state and transition simulation modeling, value of information

Introduction

Invasive species can alter the state of an ecological system, the dynamics of disturbance (e.g., D'Antonio and Vitousek 1992) and succession (Meiners et al. 2002), and the services an ecosystem provides (Pejchar and Mooney 2009). Decisions about the management and control of invasive species are often complicated by competing values and tradeoffs, and by the dynamic nature of processes by which current actions—or inaction—affect future

conditions. Control of emerging and established invasions is a central challenge, as efforts to control invasive species after establishment and spread represent a large portion of management investments, and because ecological consequences increase during the latter stages of an invasion as impacts scale positively with invader distribution and abundance (Parker et al. 1999). Economic and ecological models and decision tools can help managers and policymakers make informed decisions amidst the uncertainties, risks, and tradeoffs associated with invasive species control.

There is a broad field of ecological and bioeconomic modeling aimed at aiding in invasive control decision making (see Jongejans et al. 2008; Crone et al. 2011; Caplat et al. 2012 for reviews of ecological simulation models; see Olson 2006; Epanchin-Niell and Hastings 2010; Marbuah et al. 2014 for reviews of bioeconomic models). Much of the bioeconomic literature develops optimization-based analyses of invasive species management; though there are also many examples of studies that develop simulation-based bioeconomic models. Our goal is to highlight the potential uses of landscape simulation models and to offer a synthesis that provides ideas and examples of how landscape simulation models can be integrated with economic and decision tools to inform invasive species control decisions. We specifically describe and emphasize state and transition simulation models (STSMs); however, the ideas presented are relevant to other types of landscape-scale simulation models. Examples presented throughout the paper include applications of STSM models as well as other types of simulations including spatio-temporal grid-based and population-based models.

Landscape simulations are primarily focused on forecasting landscape change and may not explicitly account for the values of decision-makers or of the broader public. We describe how economic valuation, cost-benefit analysis, multi-criteria decision analysis, and value of information analysis can be integrated with landscape simulation models to support decision making. The paper begins with brief overviews of STSM models, economic costs and benefits, and multi-criteria decision analysis. The remainder of the paper is organized around three types of questions that STSMs and landscape simulation models are well-suited to address: 1) how big is the problem? 2) which management strategy is most appropriate? and 3) what are key sources of uncertainty? We describe how STSMs can be used to address each of these questions, and the outstanding questions that may motivate the addition or utilization of economic or decision analytic tools. Throughout the paper we provide example applications and highlight how ecological modelers, economists, decision analysts, and lands managers can combine tools to co-produce models and simulation scenarios. Our hope is that the three-question framework provides a useful construct for model-developers to give forethought to the social and policy questions (in addition to the science questions) that landscape simulation models may be called on to answer, and to produce models that can answer both types of questions.

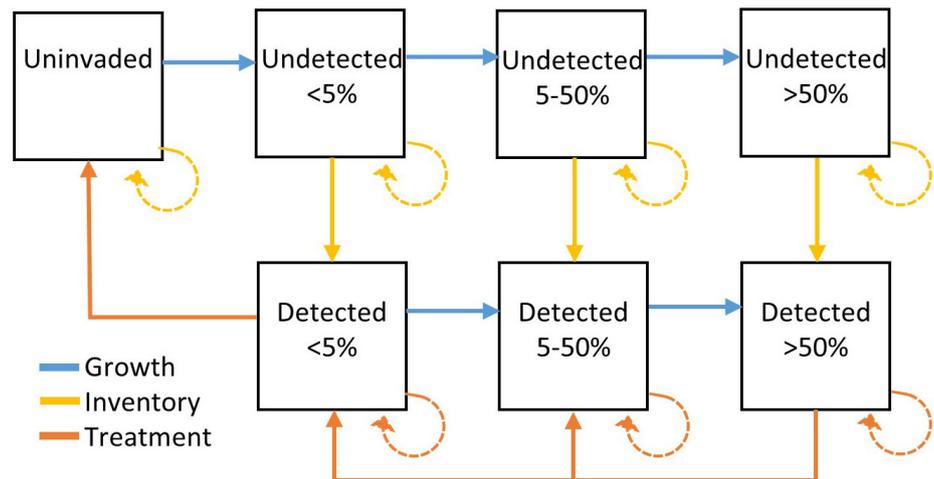


Figure 1. Example state and transition simulation model for an invasive species. Landscape change is captured by defining the processes (transitions) that can move a cell from one state to another. These include both natural transitions (e.g., species dispersal, establishment, growth, fire, disturbance) and management transitions (e.g., inventory, treatment, and other activities related to invasion control). In this example, modified from Jarnevich et al. (2015), each box represents the state of a simulation cell with respect to invasive species cover (uninvaded, < 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), detection (failure and success), and management (treatment and maintenance failure and success). Solid lines represent success; dotted lines represent failure.

State and Transition Simulation models

Spatially explicit state and transition simulation models partition a landscape into a set of discrete spatial units (cells) and describe the conditions (states) of each cell within the landscape. States can be used to describe a variety of vegetation cover and landscape dynamics; for example, states could represent cover levels of an invasive species or the stages of forest succession. Landscape change is modeled by defining the processes (transitions) that can move a cell from one state to another. Future states of the landscape are modeled by simulating state transitions over discrete time steps (Daniel et al. 2016).

There are three main components of a STSM: (1) a conceptual state and transition model that describes how cells transition through the possible states; (2) data to parameterize the model, for example transition probabilities, rates of spread and fire return intervals; and (3) initialization data, including a map of the initial state of the landscape. Figure 1 provides a simple example of a conceptual state and transition model. The conceptual model is a set of box and arrow diagrams describing the dynamics of a vegetation community. In the case of invasive species, states might describe the absence, presence, or abundance of the invader. Because states represent discrete classes of the landscape at a given location, the model is most applicable to sessile organisms such as plant species. Transitions can include both natural transitions (e.g., species dispersal, establishment, and growth) and management transitions (e.g., inventory,

treatment, and other activities related to invasion control). Conceptual models can be developed for a specific project or derived by modifying pre-existing state and transition models such as Natural Resource Conservation Service's ecological site descriptions, which are reports created for different major land resource areas to classify and describe rangeland and forestland vegetation and soil (Natural Resource Conservation Service 2013). Practitioners quantify and parameterize STSMs through literature review, elicitation from experts, and analyses of existing data such as determination of spread rates from aerial imagery. Initialization data can come from existing data such as weed surveys, models such as habitat suitability models that can determine regions of the landscape where a species could establish, and various existing sources such as land cover layers.

Conceptual state and transition models have a long history in fields such as rangeland management (Bestelmeyer et al. 2017). Quantification of conceptual models into STSMs and other landscape simulation models enables the exploration of uncertain ecological processes and of management alternatives through comparisons of simulation outputs across a set of simulation scenarios. Scenarios correspond to different assumptions and decision rules, and are ideally developed via stakeholder-driven scenario planning to represent divergent, plausible system conditions (Peterson et al. 2003; Mahmoud et al. 2009; Symstad et al. 2017). STSMs can explore the implications of management alternatives or resource and budget levels, as well as spatial variation in critical attributes such as habitat suitability, propagule pressure, spread rates, inventory and control costs, and control efficacy. Spatially-explicit landscape simulation models are particularly suited to addressing questions about the dynamics of specific species on a specific landscape (Jongejans et al. 2008). STSMs can capture realistic spatial variation within the scope and scale of land management units (e.g., a National Park or protected area unit), which make them especially relevant for on-the-ground management decisions. Examples of STSMs applied to invasive species control include Frid and Wilmshurst (2009), Frid et al. 2013a, Grechi et al. 2014, and Jarnevich et al. 2015. STSMs provide a flexible framework for modeling landscape dynamics (Daniel et al. 2016) and can therefore be used to model interactions of invasive species spread and control with other ecological processes such as drought, fire, and climate change (see for example Miller et al. 2015, 2017).

Measuring the Costs and Benefits of Invasion Control

Economic value is defined in terms of the trade-offs that individuals are willing to make, i.e., what an individual is willing to trade to see an improvement (or prevent a loss) in the quantity or quality of an ecosystem

good or service. Although not required, these tradeoffs are typically described in terms of monetary value (individual or societal willingness to pay) because money provides a common measure by which to assess tradeoffs. By comparing the costs and benefits of invasive species control, analysts and decision-makers are assessing the overall net benefits, or value, that society or relevant stakeholders will gain through management.

The primary costs of invasive species control are direct treatment and inventory costs such as labor and chemical costs. Costs can also include unintended damages from control, for example damages to non-target species (Epanchin-Niell and Hastings 2010). Information on control costs are typically easier to obtain than information on benefits, as control costs are often available from previous studies or from individuals who are managing invasive species at a specific location. To incorporate control costs into a STSM, cost data needs to be partitioned in a way that matches management transitions in the model (e.g., inventory costs and treatment costs corresponding to different levels of invader cover). Cost data typically needs to be expressed on a per unit area basis (e.g., cost to treat per acre or per hectare). It is important to consider whether control costs vary over time or space, such as across different terrains or in different seasons. In addition, control costs may not be linear as they may be dependent on the density of the invasive species or they may vary based on economies of scale (Olson 2006).

The benefits of invasive species control are the avoided damages that could have been imposed by the invader if left unchecked. Damages could include losses to agricultural production, biodiversity, or other ecosystem services such as flood control, pollination, water purification, recreation, aesthetics, and spiritual values (Pejchar and Mooney 2009). Outside of lost agricultural production and damages to infrastructure, the potential value of damages from invasive species are often non-market in nature. Estimates of damages to non-market goods and services require non-market valuation methods. Non-market valuation is a field of study aimed at defining and measuring the values that individuals and society assign to goods and services provided by natural systems. There are a variety of well-accepted methods for assessing these values (Champ et al. 2017); society's willingness to pay to prevent damages from invasive species can be quantified via stated preference methods such as choice experiments or contingent valuation surveys (Boyle 2017; Holmes et al. 2017), or through the method of benefit transfer which relies on secondary valuation data (Rosenberger and Loomis 2017). Stated preference valuation methods utilize carefully worded survey instruments to rank or value respondents preferences for a change in the quantity or quality of a good or service; statistical models are then used to scale individual responses to estimate the value of the change to a relevant population. As an example, Meldrum et al. (2011) developed a

contingent valuation survey to estimate the non-market benefits of preserving high elevation forests in the Western United States from the threat of white pine blister rust, a disease caused by an invasive fungus (*Cronartium ribicola*). Although high elevation forests are not an important source of timber or any other market products, the study found that the public values the existence of this unique ecosystem at over \$2.8 billion.

The most common application of economic analyses to invasive species modeling is through bioeconomic optimal control models. Optimal control models often combine invasive spread models with per unit area information on costs of control and invasion damages to find the control strategy that maximizes net benefits, accounting for trade-offs across time and space (Olson 2006; Epanchin-Niell and Hastings 2010). With the inclusion of per unit area cost and benefit information, simulation models can be used in a similar way to estimate net benefits for a discrete set of control strategies, though this approach cannot fully account for intertemporal trade-offs resulting from control choices (Epanchin-Niell and Hastings 2010). Yemshanov et al. (2009) developed a simulation-based cost-benefit model that integrates a spatially explicit spread model with a forest harvest model to estimate the market value of potential timber losses from an invasive insect in eastern Canada. Another example is Frid et al. (2013b)'s simulation model that incorporates both per unit control costs and damage estimates to compare cost-benefit ratios for a set of management interventions for control of three invasive weeds in Canada. To estimate benefits of control, they use the method of benefit transfer to approximate per hectare damages for each species based on valuations of comparable species and land uses; damages from the species included a combination of market and non-market services including grazing, forestry, agricultural, recreation, and food sources for wildlife.

Because data on control costs are typically much easier to obtain than data on the economic value of damages, it is most common for simulation models to only incorporate control costs. When per unit area control-cost data is incorporated, simulation models are well suited for cost-effectiveness analyses. Cost-effectiveness analyses quantify the costs of invasion control in monetary terms, but the benefits of control remain in terms of the original units of performance measurement (e.g., area invaded, biodiversity lost, probability of eradication, years-to-eradicate) (e.g., Higgins et al. 2000; Cacho et al. 2006; Cacho and Hester 2011; Jarnevich et al. 2015). If the benefits of control can be reasonably compared across alternatives, cost-effectiveness analysis may be sufficient to select the best course of action.

Multi-Criteria Decision Analysis

Invasive species problems can involve conflicting objectives, and different stakeholders may hold differing preferences for control outcomes. Cost-

benefit approaches condense individual preferences into a single aggregated net benefit value which can mask the complexity of stakeholders values (Saarikoski et al. 2016). Further, cost-benefit methods typically require monetary valuation of invasion damages, which can be difficult or costly to obtain. Multi-criteria decision analysis (MCDA) is an alternative value-based approach to address complex decisions with multiple, possibly competing, objectives (Keeney 1982). Related, structured decision-making is an application of MCDA that is often applied to environmental management and public policy problems (Gregory et al. 2012). MCDA and structured decision-making do not require monetary valuation of invasion damages.

MCDA and structured decision-making are relevant for invasive species problems for which there is uncertainty about the outcomes of management alternatives, there are multiple management objectives, and there are multiple stakeholders interested in the management decision (Maguire 2004). The MCDA and structured decision-making methods provide a transparent process to clarify decision-maker and stakeholder objectives and values and to integrate these into the model building and assessment process. The process involves clearly identifying the decision problem, eliciting measurable objectives and associated performance measures, identifying alternative actions that could be taken to meet those objectives, and using formal or informal models to assess how alternative actions perform across objectives (Gregory et al. 2012). Performance measures can be compared directly across alternatives, or a variety of MCDA methods can be used to reduce and combine multiple objectives to select a preferred alternative (Kiker et al. 2005; Gregory et al. 2012). Aggregation methods involve weighting and/or ranking objectives to develop an overall score for each management alternative, and thereby incorporate relative values for each objective (Kiker et al. 2005; Gregory et al. 2012).

Using a MCDA or structured decision-making process to guide STSM development can help to ensure that the model will produce outputs that can be used to measure the extent to which objectives of decision-makers and stakeholders are met across alternatives. The process can also help to ensure that simulated management alternatives and scenarios address important management questions. Participants in the process could include a relatively small group of managers, scientists, and decision-makers who are closest to the problem, or the process could include a wider group of stakeholders (e.g., Liu et al. (2011) describe a deliberative multi-criteria evaluation approach that incorporates public involvement). One of the most important pieces for participants to co-produce are a set of primary objectives that succinctly encapsulate the values and concerns associated with management or policy decisions. Objectives can be ecological and/or social in nature; they may be associated with the desired

states of the landscape (e.g., maximize acres of uninvaded or restored landscape, or minimize acres of invaded landscape), with natural transitions (e.g., minimize new invasions), with management actions (e.g., minimize treatment and inventory costs), or with social outcomes (e.g., minimize predicted effects on aesthetic values, biodiversity, or agricultural losses). Measurable primary objectives (performance measures) determine the outputs that should be produced by the STSM. These model outputs become the performance measures to assess simulated management alternatives.

Questions that can be addressed with simulation models AND Economic and Decision Tools:

Here we describe three invasive species management questions that STSMs are well suited to address: 1) how big is the problem? 2) which management strategy is most appropriate? and 3) what are key sources of uncertainty? Table 1 summarizes how these questions can be approached using STSMs and other landscape simulation models and how economic and decision tools can be used to address outstanding value-based questions. The framework can help to identify the goals of the model and to ensure that simulation output can be integrated with economic and decision tools, if desired.

How big is the problem?

“How big is the problem” encompasses questions about the potential extent of the spread of an invasion, the amount of funds required to treat an invasion, and the value of the damages that may result from the invasion.

STSM models have been used to explore landscape change, often in terms of possible area invaded. To do this, simulation scenarios with no management actions can be used as a baseline to assess the potential magnitude of an unmanaged invasion, and unconstrained management scenarios (i.e., scenarios for which management actions are applied until specific cover-level targets are met) can be used to test the bounds of management potential. For example, Frid et al. (2013a) used a STSM to assess the potential spread of buffelgrass (*Pennisetum ciliare*) within a protected area near Tucson, Arizona, USA. Their no-management simulation showed that, without treatment, buffelgrass infestations could grow from 80 ha to more than 6,000 ha within 50 years, whereas unconstrained management could reduce and maintain buffelgrass levels to 50 ha.

By incorporating information on control costs, simulations can be used to estimate budgets required to meet specific landscape targets. Krug et al. (2010) used this approach to put bounds on the critical budgets required to control invasive species in protected areas in South Africa’s Cape Floristic Region; they estimated a lower critical limit budget below which their modeled

Table 1. Questions that can be addressed with simulation models and outstanding questions that can be addressed using economic and decision tools. For each question, examples are provided for how an STSM can address the question, including the scenarios that may be explored and the outputs that may be relevant. Economic and decision-support tools can in turn integrate these outputs with additional information to consider values and trade-offs central to the decision.

Questions that can be addressed with simulation models:	How big is the problem?	Which management strategy is most appropriate?	What are key sources of uncertainty?
Scenarios: Simulation outputs: Example:	Compare unconstrained management actions to a baseline of invasive spread under no management Estimated extent of invasion and treatment/control costs associated with no management and unconstrained management Without treatment, buffelgrass invasion in the Catalina Mountains could grow from 80 to 6000 ha over 50 years of simulation, whereas unconstrained management resulted in 50 ha (Frid et al. 2013a)	Compare alternative resource-constrained management scenarios Scenario-specific values for performance measures associated with multiple management objectives Evaluation of alternative vegetation management strategies in Badlands National Park highlight tradeoffs between grazing and vegetation composition, and between the short- and long-term costs of invasive species management (Miller et al. 2017)	Sensitivity analysis of model parameters/assumptions and explorations of major ecological uncertainties Range of performance measures associated with sensitivity analyses Targeting large patches of crested wheatgrass was expected to be efficient only if budget and control effectiveness were high – suggesting research on control effectiveness could aid in management decisions (Frid and Wilmshurst 2009)
Additional questions that can be addressed by integrating economic and decision tools:	What benefits are gained from management? Do the benefits gained justify the costs?	How do we choose the most appropriate management alternative given competing objectives?	Is it important to reduce the uncertainty associated with specific parameters or assumptions? What is the value of additional information?
Economic and decision tools: Outcomes: Examples:	Economic valuation (e.g., contingent valuation, choice experiments); Cost-benefit analysis Determine whether the societal benefits of control efforts outweigh the costs of control Willingness to pay for invasive species control demonstrated social support for an increased budget for invasive alien species management in Doñana Natural Protected Area, Spain (García-Llorente et al. 2011)	Multi-Criteria Decision Analysis (MCDA) Transparent selection of management alternatives that considers multiple objectives and multiple values MCDA was used to evaluate alternative management strategies for crested wheatgrass in Canada’s Grasslands National Park including different budget levels and patch size prioritization (Frid and Wilmshurst 2009)	Multi-Criteria Decision Analysis; Value of Information Analysis Identify key decision-relevant research needs and the value of new information Reducing uncertainty related to effects of fire frequency, demography, and management effectiveness in control of the invasive <i>Salix cinerea</i> in alpine Australia would not change which management strategy was identified as the best unless budgets increased substantially (Moore and Runge 2012)

invasion continued to expand, and an upper critical limit budget above which there was no substantial change in the time needed to reach the target cover level.

Estimates of required budgets for management targets can be combined with information from baseline no-management scenarios to put upper and lower bounds on the costs (in terms of control costs) and benefits (in terms of reduction in possible area invaded) of management. While these

scenarios are generally not realistic in terms of management strategies (unconstrained management is unlikely to be economically feasible and no-action management scenarios may be unlikely for invaders that are the focus of detailed modeling), they do provide information to communicate the potential damages of the invasion and the range of resources required for control. Highlighting information about the potential magnitude of the invasion can help secure funding, and information about the estimated resources required to meet landscape goals can help determine whether allocated funding is sufficient to be effective. Hester et al. (2010) developed a matrix population simulation and estimated control funds required to achieve eradication of *Miconia calvescens*, an invasive tree that is displacing native plants in the rainforests in Australia. They found that the current annual investment for control in the region is similar to what their model suggests is needed to achieve eradication, suggesting that the program is on track to achieve eradication (if no new infestations are found).

Results from unconstrained management scenarios may predict that control is possible but expensive. In these cases, monetary valuation of the benefits of control may be justified to determine whether the investment of public funding is worthwhile (McIntosh et al. 2009; Saarikoski et al. 2016). For example, Plank et al. (2016) used simulation output from unconstrained and no-management scenarios to estimate the potential costs and benefits of control for three alien species that affect agricultural production and human health. For invasions that affect non-market goods and services, non-market studies could be undertaken to estimate willingness to pay for invasion control. An idea that we have not yet seen implemented in the literature is the possibility of using simulation output developed through a STSM as a basis to develop contingent valuation surveys or economic choice experiments. There are, however, several studies that estimate willingness to pay for invasion control (e.g., McIntosh et al. 2009; García-Llorente et al. 2011; Meldrum et al. 2011; Walsh et al. 2016). García-Llorente et al. (2011) illustrated how societal willingness to pay can be compared to current control budgets; they used a contingent valuation survey to estimate willingness to pay for invasive alien species control in Doñana Natural Protected Area, Spain, and found that total willingness to pay for control was greater than the government's current control budget, suggesting that the government has sufficient social support to justify a budget increase.

If one of the goals of the STSM is to answer the question “how big is the problem?”, then the modeling exercise can be designed to be relevant for an economic valuation analysis. The STSM will output measures of ecological change and management effort, and these outputs will need to be able to be linked to measurable indicators of changes in human welfare, called bridging indicators or benefit-relevant indicators (Olander et al. 2015). To ensure this, it is important to identify how the ecological changes

that could result from the invasion and its management are relevant to the ecosystem services that people care about (U.S. Environmental Protection Agency Science Advisory Board 2009; Segerson 2017). Simulation outputs do not need to be direct indicators of human welfare, they just need to be able to be linked and translated into benefit-relevant indicators. These connections can be explored and articulated through the development of a causal chain or means-end diagram, a logical model that maps how management actions are expected to effect ecosystems and the provision of ecosystem services, explicitly linking ecological indicators to benefit-relevant indicators (Olander et al. 2015).

Which management strategy is most appropriate?

A common motivation for developing an STSM model is to enable decision-makers to envision what the future might look like and how their actions could affect the progression of an invasion. Identifying when, where, how, and how much control to apply to a landscape is primarily the realm of bioeconomic optimal control models (for examples see Epanchin-Niell and Hastings 2010). Although simulation models can only be used to compare a discrete set of management alternatives rather than finding an optimal strategy, STSM models are nevertheless useful for this question because they offer an opportunity to explore a wide range of “what ifs” while incorporating spatial variation in important model elements.

Decision-makers face a variety of uncertainties when making control decisions, including uncertainties about:

- the system and the invasion – such as the model describing the biological system, parameters of that model, the current state of the system, and efficacy of control;
- management strategies – such as questions about the quantity and distribution of resources, the most effective spatial strategies, and explorations of new or emergent control technologies;
- policy decisions – such as allowable control methods and available budgets;
- external human systems – such as the effects of human spread vectors and the effects of control actions (or inactions) made on neighboring landscapes; and
- external forces – such as climate change and land use change.

STSMs provide a modeling framework that enables the exploration of scenarios that combine elements from all of these types of uncertainties (Daniel et al. 2016). Scenarios can be developed that describe combinations of management alternatives, model parameters and model structure, as well as scenarios of possible divergent futures. Scenarios of possible futures are useful when there is a high level of uncertainty about system elements

that are out of the control of the decision-maker (Peterson et al. 2003; Mahmoud et al. 2009), for example actions of neighbors, exogenous policy decisions, land use change, and climate change. Although there are many scenarios that can be explored, each scenario requires time and data and therefore a focused set of scenarios that best address the questions and concerns of stakeholders and decision-makers needs to be developed. Helpful questions to consider as part of scenario development include:

- What management actions are currently being taken?
- What management options are you considering?
- What questions and uncertainties do you have about management?
- What questions and uncertainties do you have about the system?
- What ecological uncertainties are you concerned about?; and
- What policy uncertainties are you concerned about?

Miller et al. (2017) used a scenario planning process to co-produce a STSM and a set of scenarios to project changes in landscape vegetation in Badlands National Park, South Dakota, USA. They modeled a set of scenarios that combined four future climate scenarios with four vegetation management alternatives. Model outputs highlighted tradeoffs between bison/cattle grazing and vegetation composition, and between the short- and long-term costs of invasive species management.

Amidst uncertainty, decision-makers must still select among management alternatives for invasion control, or lack thereof. The MCDA and structured decision-making processes provide a framework that enables management alternatives to be compared. STSM models developed through a MCDA process produce model outputs that are performance measures of primary management objectives. These outputs are generally multi-dimensional, and for spatial simulations, outputs of interest can include attributes of both the composition and configuration of the invaded area. Simulation outputs must be carefully examined to understand potential trade-offs. The simulation output on its own may provide sufficient information for decision-makers, or MCDA weighting and ranking tools can be used to rank alternatives. Or, if scenarios represent divergent futures, management alternatives could be selected for robustness across uncertain futures (Maier et al. 2016). Frid and Wilmshurst (2009) provide an example of an STSM for crested wheatgrass (*Agropyron cristatum*) control developed and evaluated using a MCDA process. They considered scenarios to explore combinations of management budgets with prioritization strategies for treating large existing patches of crested wheatgrass versus small new populations. Grechi et al. (2014) provide another example of an STSM developed through a MCDA process. Their model is focused on tradeoffs in managing for buffelgrass, a species that is beneficial for some stakeholders (provides forage for grazing) and damaging for others (negatively effects

biodiversity). They develop utility functions to measure the relative values of different levels of buffelgrass cover in terms of biodiversity conservation and forage production and use this to search for the optimal biodiversity/production strategy.

What are key sources of uncertainty?

Information about system dynamics and underlying parameter values can be scarce, and STSM conceptual models and parameter values are often developed using expert elicitation and secondary data sources, such as values from similar species or studies from different locations. Simulation model results from a range of simulation scenarios and sensitivity analyses can provide information on the effects of epistemic uncertainties in parameters (parameter uncertainty) and processes (model uncertainty) on model outcomes (Regan et al. 2002; Walker et al. 2003). In the context of plant invasions, parameter uncertainty is often explored through sensitivity analyses that run combinations of alternative specifications (e.g., low, medium, and high) for each parameter; these parameters can be part of either a deterministic (e.g., time needed to reach the next cover class) or a stochastic (e.g., probability of long-distance dispersal) portion of the model (Miller et al. 2015). Model uncertainty in STSMs can be explored by running analyses with differing underlying conceptual state and transition models. Scenarios and sensitivity analyses that explore ecological and budget uncertainties can help to assess whether the choice between alternative management strategies is likely to be sensitive to aspects such as current or future variation in habitat suitability for the focal invader, future funding levels for control efforts, and the effectiveness of different types of control. For example, Miller et al. (2017) faced substantial uncertainty in the effect of drought on Canada thistle (*Cirsium arvense*) establishment in their STSM for Badlands National Park, but sensitivity analysis of this variable did not result in a significant change in modeled outcomes – suggesting that further research on this variable may not help to improve management decisions. Frid and Wilmschurst (2009) faced uncertainty about the efficacy of control in their study of crested wheatgrass, and found that the interaction of control efficacy and budget levels affected the choice of best management strategy. Specifically, targeting large patches was expected to be efficient only if budgets for control were high and control was effective; otherwise, spread from large patches overwhelmed control and it was more effective to target emerging infestations. They concluded that research to better measure and to improve control effectiveness could result in a clearer choice for how to manage the invasion.

Value-of-information analysis provides a formal approach for deciding if additional research and knowledge will improve the outcome of a decision, and can be used to identify those uncertainties that would be most valuable to resolve (Runge et al. 2011; Maxwell et al. 2015). By estimating the value

of resolving uncertainties, researchers can determine if the benefits of acquiring improved information outweigh research costs and can help to ensure that scarce project and research budgets are focused on obtaining information most valuable for decision-making. The expected value of new information is the expected value of the best alternative given new information minus the expected value of the best alternative without the new information (Runge et al. 2011). The return on investment for learning is typically expressed in terms of improvement in management objectives (e.g., reduced area invaded, or increased probability of meeting a target cover level); if model outcomes are measured in monetary values, then the return on investment can be expressed in dollars (Runge et al. 2011).

Value of information analyses require: a set of alternative models of system behavior (e.g., sets of uncertain parameter/structure combinations), a prediction of the outcomes/performance measures for each of the models, and *a priori* weights of the probability of each of the models (Runge et al. 2011). For STSMs developed through a MCDA process, the models of system behavior would be the set of scenarios and sensitivity analyses, and the simulated outcomes for the model would be aggregated scores of performance measures for each scenario. Weights of scenario probabilities could be obtained through expert elicitation (Runge et al. 2011).

Johnson et al. (2017) and Moore and Runge (2012) provide examples of value of information analyses applied to invasive species decision problems. Johnson et al. (2017) developed a simulation to assess the effects of removal strategies on tegu lizard (*Salvator merianae*) populations in south Florida, USA. They found that the expected value of resolving model parameter uncertainty varied based on the relative weights assigned to the primary management objectives (minimize tegu abundance and control costs), with the greatest potential for improved outcomes achieved when decision-makers value the two objectives equally (i.e., weights are near 50% for both objectives). Moore and Runge (2012) developed a model to simulate the effects of management of invasive gray willow (*Salix cinerea*) in Victoria, Australia. They found that there would be little value in reducing uncertainty about the system unless management budgets were substantially increased.

Conclusions

The goal of any applied modeling effort is to develop a model that will ultimately increase understanding of a system and that will be useful in some way for land managers and other decision makers. STSMs and similar landscape simulation models can provide valuable information to managers about how an invasion might progress across a landscape and how management actions could affect an invasion. Alone, models of landscape change may not explicitly address questions of social values that are often important considerations in land management decisions. STSMs

and economic and decision tools can be used together to inform decision-making and enhance the efficacy and efficiency of invasive species control decisions. The three types of questions outlined here encompass a variety of motivations for undertaking an analysis centered on invasive species impacts and control. The delineation among types of questions that can be answered using integrated STSM models provides a framework that can help determine which value-based tools might be most useful. By collaboratively developing model goals, simulation scenarios, and conceptual models, stake-holders can help to ensure that models and scenarios target simulations of greatest management interest and produce outputs that can be incorporated into economic valuation or decision analysis ranking methods. It is critical that the economic and decision analysis methods are part of the forethought and development of the ecological model, such that output from the ecological model is set up to serve as inputs into value-based analyses.

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