Application of Structured Decision Making and Rapid Prototyping to Plan a Management Response to Invasive Species: Hemlock Woolly Adelgid on the Cumberland Plateau in Tennessee, USA.

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Abstract

We designed an adaptive management framework for responding to invasion of hemlock woolly adelgid on the Cumberland Plateau of northern Tennessee. Hemlock woolly adelgid, an invasive forest pest, was first detected in this area in 2007. We used a structured decision making process to identify and refine the management problem, objectives, and alternative management actions, and assess consequences and trade-offs among selected management alternatives. We identified four fundamental objectives: 1) conserve the aquatic and terrestrial riparian conservation targets, 2) protect and preserve hemlock, 3) develop and maintain adequate budget, and 4) address public concerns. We designed two prototype responses. By rapidly prototyping responses, insights were gained and shortcomings were identified, which were incorporated and corrected in subsequent prototypes. We found that objectives were best met when management focused on early treatment of lightly infested but relatively healthy hemlock stands with predator beetles. Also, depending on the cost constraint, early treatment should be coupled with silvicultural management of moderately to severely-infested and declining hemlock stands to accelerate conversion to non-hemlock mature forest cover. The two most valuable contributions of the structured decision making process were 1) clarification and expansion of our objectives and 2) application of tools used to assess tradeoffs and predicting consequences of alternative actions. Predicting consequences allowed us to evaluate the importance of uncertainty on the decision. For example, we found that uncertainty regarding predator beetle effectiveness was not an impediment to good decision making. The adaptive management framework that we designed requires further development including identifying and evaluating uncertainty, designing a monitoring program to update the predictive models, and generating support for planning and implementation.

Introduction

Successfully reducing populations of invasive species requires complex decisions and coordinated action across multiple spatial scales, temporal scales, and scales of governance (Pimentel et al. 2005; Graham et al. 2008). Decisions occur on short temporal scales (e.g., daily to annually) by individuals who manage a single area to organizations and government agencies making continent-wide policy that is implemented for decades. For example, response to spread of invasive quagga (*Dreissena rostriformis bugensis*) and zebra (*Dreissena polymorpha*) mussels beyond the North American Great Lakes required massive planning and coordination among state and provincial agencies, United States and Canadian federal agencies, and many other organizations (Drake and Bossenbroek 2004). Inaction or delayed responses to invasive species can result in high economic costs and loss of biodiversity (e.g., Leung et al. 2002; Rohr et al. 2009).

Structured decision making and adaptive management are decision analysis techniques that can provide transparency to decision-making under uncertainty and an approach to learn from management actions (Keeney and Raiffa 1993; Nichols and Williams 2006; Gregory and Long 2009). The techniques incorporate an integrative process for framing the management problem, identifying objectives, choosing feasible management alternatives, modeling system dynamics, and monitoring system response to management and updating predictive models (e.g., Johnson et al. 1997; Hammond et al.1999). These decision techniques can be extremely useful by providing efficient, targeted responses to conservation and management problems (Gregory and Keeney 2002). Although portions of these decision tools are routine in pest management (e.g., integrated pest management by the United States' Environmental Protection Agency), they have rarely been used to design and implement management strategies for invasive species (e.g., Bogich and Shea 2008).

Hemlock woolly adelgid (*Adeleges tsugae*) is native to Asia and was introduced to the eastern United States from Japan in the early 1950s (Havill et al. 2006). It has since spread throughout the eastern United States in eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*Tsuga caroliniana*) forests at a rate of > 15 km per year and, consequently, become a forest pest of management concern (McClure et al. 2001; Evans and Gregoire 2007). Hemlock woolly adelgid can cause > 60% mortality of hemlocks in infested stands in < 12 years, which results in a series of subsequent ecosystem-level effects including decreased soil moisture, uptake of water, and uptake of nitrogen and increased decomposition and nitrogen content in throughfall (e.g., Orwig et al. 2002, 2008). Hemlock woolly adelgid invaded eastern Tennessee and has been detected in several counties on the Cumberland Plateau (Costa and Onken 2006; USFS 2009).

The forest management and conservation community (e.g., Tennessee state land management agencies, The Nature Conservancy) is concerned about the potential spread of the pest in the state because hemlocks are a major component of riparian ecosystems on the Cumberland Plateau in Tennessee. Tennessee Wildlife Resources Agency (TWRA) owns and manages approximately 89,000 ha (220,000 acres) on the Cumberland Plateau. Hemlock-containing communities comprise approximately 20,600 ha (51,000 acres) or 23% of TWRA-owned lands in the region. As part of forest management practices, TWRA uses riparian buffers to protect streams from possible effects of timber harvesting and provide forested corridors for wildlife in areas harvested for timber. Because the overstory canopy of many riparian areas on the Cumberland Plateau is dominated by hemlock trees, invasion of hemlock woolly adelgid could compromise the effectiveness of these riparian buffers as forested corridors for federally listed forest-dependent species (e.g., Indiana bat, *Myotis sodalis*) and for protecting aquatic habitat for federally listed aquatic species (e.g., blackside dace, *Phonixus cumberlandensis*) as well as affect other riparian-dependent conservation targets (e.g., Swainson's warbler, *Limnothlypis swainsonii*, and Alleghany woodrat, *Neotoma magister*).

The state land management agencies (TWRA, Department of Environment and Conservation Divisions of Parks, Natural Heritage, and State Natural Areas; Department of Agriculture Division of Forestry) and US Forest Service formed the Tennessee Interagency Hemlock Woolly Adelgid Task Force (TNIHWATF) and developed a strategic response plan for detecting and managing the spread of this pest (Kirksey et al. 2004). As part of this task force, TWRA has invested in development of biological control agents including two predator beetles: *Sasajiscymnus tsugae* and *Laricobius nigrinus*.

We formed a team of biologists and foresters from TWRA, USFWS, and the Northern Cumberlands Forest Resources Habitat Conservation Plan (NCFRHCP) to plan management in response to invasion of hemlock woolly adelgid on the northern Cumberland Plateau in Tennessee. The team included the decision makers: nongame biologists (MT) and foresters (BM) from TWRA and an endangered species biologist (GC) from the US Fish and Wildlife Service (USFWS). The USFWS must approve the amount of take allowed under the incidental take permit issued to TWRA under the Endangered Species Act and hence also influences the decision. Two conservation coordinator (SB, TJ) from the NCFRHCP comprised the remainder of the team. This team attended a USFWS and US Geological Survey- (USGS) sponsored workshop that provided technical assistance on structured decision making and rapid prototyping. With assistance of structured decision making experts from the USFWS (MP, SB), USGS (DS), and University of Nebraska (JM), we planned a response for management of hemlock stands when hemlock woolly adelgid is detected on TWRA-managed lands. Here, we report on the process we used to plan a management response to hemlock woolly adelgid invasion. We present the prototyped management frameworks that resulted from the process, and we discuss the value and limitations of the process and propose further development that we feel is required to apply the framework.

The PrOACT Process

During the workshop, the team iterated through a structured decision making process (Hammond et al. 1999; Gregory and Long 2009) and developed two prototype management responses to invasion of hemlock woolly adelgid. The steps of the process can be summarized as identifying the problem, clarifying the objectives, generating alternative actions, predicting consequences of the actions in terms of the objectives, and evaluating tradeoffs. Hammond et al. (1999) used PrOACT as short hand for the steps in the process. For each of the iterations, the team reframed the problem to focus on different aspects, which subsequently led to a distinct problem statement and solutions (Table 1). The primary difference between the problem statements is that the second iteration focused on the single fundamental objective to maintain mature riparian forest cover and explicitly defined the spatial and temporal framework for the decision. This refinement allowed us to make progress on building a mathematical model to predict likely consequences of alternative management responses and evaluate which responses best meet our objectives.

Following the PrOACT steps, we 1) articulated a set of fundamental objectives and built an objective hierarchy from which we ultimately chose a single fundamental objective to focus our decision analysis, i.e., hemlock protection and preservation; 2) defined a range of treatment alternatives and ecological conditions under which each alternative might be considered appropriate for a given stand; 3) developed a conceptual model (e.g., an influence diagram) and mathematical model incorporating assumptions and uncertainties to describe how the treatment alternatives interact with ecological processes to affect hemlock woolly adelgid invasion at the stand and landscape levels; and 4) used the models to explore likely outcomes at a landscape scale that would result from annually implementing a given management strategy at the stand level. As we worked through the process, we identified key elements including the spatial scale at which to treat for hemlock woolly adelgid, the type of treatments to apply, ecological condition of hemlock stands and its relationship to treatment, and the proximity of the stands to known occurrences and habitat of covered species.

The two iterations of the PrOACT process enabled us to gain insights and refine the prototype solutions. The second prototype was an adaptive management framework for managing hemlock woolly adelgid invasion on lands within the NCFRHCP project area. The decision framework can be modified as necessary to incorporate new information to guide future decisions.

Prototype Solutions

The first prototype

Objectives. Our first rapid prototype included multiple fundamental objectives: 1) conserve the NCFRHCP covered aquatic and terrestrial riparian species, 2) protect and preserve hemlock, 3) develop and maintain adequate budget, and 4) address public concerns. For each fundamental objective, we developed a measurable attribute or performance criterion to measure success in terms of our objectives (Figure 1).

Alternative management actions. The management actions we initially considered focused solely on treatment of hemlock woolly adelgid. We expanded the management actions to help mitigate possible ecosystem effects due to loss of mature forest canopy surrounding streams. These management options were intended to provide habitat for riparian-dependent covered species (e.g., Swainson's warbler and Alleghany woodrat), maintain stream temperatures, reduce fluctuations in water flows, and decrease sediment input due to loss of mature forest cover for aquatic covered species (e.g., blackside dace). Possible actions were categorized by their treatment of hemlock woolly adelgid, forest cover (i.e, silvicultural treatment), or riparian buffer widths (Table 2). Silvicultural treatments reduced the amount of time a stream lacked mature forest cover. Alternative riparian buffers widths within harvested stands were modified from status quo (e.g., 91.4 m [300 ft] on each side of the stream).

We reduced complexity of the decision framework by focusing on how to manage the hemlock stands possessing the most desirable ecological characteristics, hereafter, a high-quality hemlock stand (Table 3). We defined a high-quality hemlock stand as: > 50% hemlock overstory canopy cover, > 4.0 ha (10 acres) in spatial extent, less advanced understory tree regeneration or a *Rhododendron* spp. dominated understory, and NCFRHCP covered species present. Additionally, the hemlocks in the stand were in healthy condition (< 10% mortality, 11-25% defoliation; Kirksey et al. 2004). We included stands with less advanced understory tree regeneration or a *Rhododendron* spp. dominated understory as a desired ecological characteristic because this characteristic eliminated the silvicultural options from consideration during the first prototype. Criteria to describe hemlock stand health and hemlock woolly adelgid infestation were based on the Hemlock Woolly Adelgid Strategic Plan and Management Plan for State Lands in Tennessee (Kirksey et al. 2004).

Portfolios of alternative actions were developed by choosing from our list of possible management options for hemlock woolly adelgid (Table 2). We created the following three portfolios that could be applied to high-quality hemlock stands: 1) the status quo (i.e., existing TWRA program for applying hemlock woolly adelgid treatment), 2) maximizing hemlock protection, and 3) minimizing take of NCFHCP covered species over a 30-year time horizon (Table 4).

Examining consequences. We created a conceptual model that relates the management actions to our fundamental objectives (Figure 2). The conceptual model helped us think through how alternative actions might affect the fundamental objectives. Predictions were made for each objective's performance criteria based on accessible information and expert opinion. A consequence table was used to arrange the objectives with predictions for each portfolio of actions (Table 5). This allowed us to examine the consequences and compare relative performance of the three portfolios. Most importantly, the portfolio that aimed to maximize hemlock protection performed best for all ecological objectives despite its poor performance for cost and public concern. This exposed inherent tradeoffs among the objectives and indicated that analysis of the tradeoffs would depend on the preference or value place on the objectives.

Tradeoff analysis. We used the consequence table to analyze the trade-offs among our fundamental objectives (Table 5). We used swing weighting to quantify each team member's relative preferences among the fundamental objectives given the expected change in the performance criteria (Keeney and Raiffa 1993). We normalized scores and averaged team member preferences to assign weights to the fundamental objectives for our final tradeoff analysis. Most weight (81%) was assigned to the ecological objectives; 65% was on the fundamental objective to conserve target species. Cost and public concern received only 19% of the weighting. Reflecting the preferences, the portfolio that attempts to maximize hemlock protection was > 1.4 times more effective at meeting the objectives than the status quo management or the portfolio that focuses on minimizing take of covered species.

The second prototype

Objectives. Because the portfolio that aims to maximize hemlock protection was the most effective at meeting the fundamental objectives, the team chose to focus on the ecological objectives (i.e., preserve hemlock and target NCFRHCP species) and consider the remaining fundamental objectives as constraints in the second prototype (Figure 1). The team agreed that none of the current management actions cause an unacceptable public concern. So, cost was the remaining constraint. We also moved towards an adaptive management approach by incorporating time and assessing how management options may change over a 30-year planning horizon. As reflected in the revised problem statement (Table 1), we additionally considered preservation or creation of mature hardwood- and pine-dominated riparian forests because this mature riparian forest type is also an important habitat for the covered species.

Alternative management actions. We continued to consider management actions for high-quality hemlock stands as defined in the first prototype. However, we also considered management of stands with higher levels of hemlock health decline and hemlock woolly adelgid infestation. We incorporated these levels into a stand categorization scheme in which the combined level of decline and infestation influences the likelihood of treatments being effective at restoring stand health (Table 6). We used the monitoring criteria in the Hemlock Woolly Adelgid Strategic Plan and Management Plan for State Lands in Tennessee to develop a matrix to define hemlock stand condition/infestation states (Table 3; Kirksey et al. 2004). We eliminated states that were unlikely to exist in nature or unlikely to be managed. We also included a mature hardwood- or pine-dominated stand as transition after hemlock loss as a fifth state. Thus, there were five states where management might be appropriate (Table 6), and we assessed alternative treatments that might be applied to these five stand states (Table 7) by considering which treatments in the first prototype would be applied depending on stand state (Table 4)

Predicting consequences. We created a state-based predictive model (Figure 3) that illustrated possible transitions among the five hemlock stand condition/infestation states (Table 6). The model provided the basis for predicting consequences of management actions. We used an exponentially increasing colonization rate of uninfested stands to describe the way hemlock woolly adelgid spread across the landscape (Table 7). This nonlinear colonization rate model assumes an exponentially increasing likelihood of a new stand being colonized as the landscape becomes saturated with infested stands. Exponentially increasing population growth rate has been suggested for many terrestrial invasive species (Grosholz 1996), and known rates of hemlock woolly adelgid spread on the landscape in the southern portion of the range in the eastern United States are higher than in the northern US (Evans and Gregoire 2007).

We used available data and opinion to parameterize the model. The parameters reflect how the management actions would change the transition probabilities (Table 8). Hemlock woolly adelgid populations are known to induce mortality of hemlock stands in 12 years in the northern US and at higher rates further south (Orwig et al. 2002). The average time from infestation with hemlock woolly adelgid to hemlock stand mortality was assumed to be 15 years in our model. Survival of adelgids is primarily limited by minimum winter temperatures and the highest predicted survival rates in the eastern US include areas in Tennessee (Trotter and Shields 2009). We used these data to estimate the growth (g) transition probability and assumed hemlock woolly adelgid populations would grow to the next state in five years.

Silvicultural techniques can stimulate regeneration of understory hardwoods and pines if used aggressively (e.g., felling dying hemlocks to increase solar exposure in conjunction with herbicides and/or burning to eliminate competing understory vegetation). We predicted that silvicultural techniques would reduce the amount of time without mature riparian forest cover by one quarter.

The pesticide imidacloprid is highly effective at eliminating hemlock woolly adelgid and is safe in recommended dosages, but is expensive to purchase and apply (Cowles 2009; R. Rhea, personal communication). We determined in what situation we would apply pesticides (Table 7) and its effectiveness (Table 8), but did not consider the pesticide treatment for the trade-off analysis in the second prototype. We did this for four reasons: the prohibitive cost and potential for public concern that were identified in the first prototype, the preference of TWRA to apply predator beetles rather than pesticides to control hemlock woolly adelgid, pesticides and predator beetles treatments would be applied in similar management situations (i.e., states; Table 7), and to reduce complexity in the trade-off analysis.

The effectiveness of predator beetles at landscape-level hemlock woolly adelgid control is poorly known (R. Rhea, personal communication) and represents a source of structure uncertainty in the decision analysis. Single tree experimental evidence indicates predator beetles may reduce hemlock woolly adelgid abundance by > 50% (e.g., *Laricobius nigrinus*, Lamb et al. 2006), and releases of multiple species of predator beetle may be more effective than single species releases (Flowers et al. 2006). We utilized a range of values (i.e., most effective and least effective beetles) for how predator beetles reduce the growth rate of hemlock woolly adelgid populations within treated stands (d, e_h, and e_p) to assess uncertainty in predatory beetle effectiveness.

Tradeoff analysis. We compared five possible management strategies that incorporate two treatment options, silviculture and predator beetles (Table 7). The management strategies that resulted are as follows: 1) no treatment; 2) an early intervention strategy that treats lightly infested stands with predator beetles that are most effective at controlling hemlock woolly adelgid; 3) an early intervention strategy that treats lightly infested stands with predator beetles that are least effective at controlling hemlock woolly adelgid; 4) an early intervention strategy that treats lightly infested stands with predator beetles that are most effective at controlling hemlock woolly adelgid and a late intervention strategy that uses silviculture to promote the transition of moderately and severely infested stands to mature hardwood- or pine-dominated stands; and 5) an early intervention strategy that treats lightly infested stands with predator beetles that are least effective at controlling hemlock woolly adelgid and a late intervention strategy that uses silviculture to promote the transition of moderately and severely infested stands to mature hardwood- or pine-dominated stands. We assessed the potential of each of these five management strategies to maximize mature forest cover constrained by cost. We defined mature forest cover as hemlock stands in the healthy, uninfested state (HH) or healthy to light decline and lightly infested state (LH) and mature hardwood- or pine-dominated stands (MHP).

To illustrate the effectiveness of each strategy, we designed a simulation. We started with a set of 50 hypothetical hemlock stands, five of which began in the LH state, and projected the consequences of applying the same management alternative annually for the 30-year planning horizon. During the simulation, we tracked the number of stands in healthy mature forest cover (Figure 4), the habitat value for each of three species covered by the NCFRHCP, and the cost, which was treated as a constraint (Table 8B). The habitat values for the target species were based on proposed habitat relationships (Table 8C). Swainson's warbler is a hemlock canopy specialist, blackside dace is an aquatic species, and Alleghany woodrat is a mature forest species.

In the simulation, the number of stands remaining in mature forest states (HH, LH, or MHP) at the end of the 30-year simulation was maximized by following Strategy 5, which included early intervention with most effective predatory beetles on stands in the LH state and late intervention with silviculture on stands in the MH or SH states (Figure 5). Habitat value for each of the species generally followed the same pattern that mature forest cover did with the species differing only slightly in the degree of change due to the changes in forest cover (Figure 6). However, costs were highest for Strategy 5 (Figure 7). When cost was taken into account by dividing the number of mature stands by the total cost, early intervention without silviculture was the best strategy (Table 9). Thus, the cost constraint was determinative in the decision process.

Expected value of perfect information. The uncertainty in predator beetle effectiveness was potentially important, and we were concerned that the best decision could not be found until the uncertainty was resolved. We calculated the expected value of perfect information (EVPI) to assess how critical the unresolved uncertainty was to finding the best the decision. We performed two expected value of perfect information analyses on the simulation results to assess tradeoffs among the two management alternatives (predator beetles and silviculture) included in our four management strategies (excluding the no treatment option) and determine the value of knowing the effectiveness of the predator beetles at controlling hemlock woolly adelgid populations, the source of structural uncertainty we evaluated in the second prototype. The EVPI in this case is the difference in the number of mature forest stands that would result if the uncertainty in predator beetle effectiveness was resolved before deciding on the strategy compared to the result if the decision was made without first resolving the uncertainty.

The values shown in Table 9 can be used to calculate expected value of perfect information. First, consider the objective of maximizing mature stands regardless of cost. When beetles were least effective, the early intervention with silviculture strategy resulted in 27 mature stands compared to 17 without silviculture. When beetles were most effective, the early intervention with silviculture strategy resulted in 49 mature stands compared to 44 without silviculture. Thus, if uncertainty was resolved before making the decision, the expected number of stands would be 38 (i.e., [27 + 49]/2 = 38), assuming that the level of effectiveness was equally likely. In contrast, if uncertainty was not resolved before making the decision then early intervention without silviculture would be expected to result in 30.5 mature stands, and including silviculture would be expected to resulting 38 mature stands. Because the maximized expected value was 38 stands whether the uncertainty was resolved or not, the EVPI was 0 (i.e., 38 - 38 = 0), and resolving uncertainty about the effectiveness of predator beetles would not help to make a better decision.

Second, consider the objective of maximizing mature stands per unit cost. The expected value of perfect information can be calculated similarly when cost is considered. When the objective is to maximize the number of mature forest stands per $1000 spent per year, the best strategy is early intervention without silviculture, and resolving uncertainty would not lead to a different decision. Thus, based on EVPI uncertainty of predator beetle effectiveness was not determinative. The effectiveness of predator beetles is not an important source of structural uncertainty in the decision framework because it did not affect the best decision given the choice of management strategies considered. There might be epistemic interest in resolving predator beetle effectiveness; however, that uncertainty need not be an impediment to good decision making. Also, the management action itself followed by monitoring will help determine effectiveness of predator beetles.

Discussion

Value of decision structuring

The two most valuable contributions of the structured decision making process were 1) clarification and expansion of our objectives and 2) application of the tools used to assess tradeoffs and consequences of alternative actions. Our initial focus was on minimizing habitat loss for the NCFRHCP covered species. After the first prototype, the team realized that we intrinsically valued hemlocks and that this should be a fundamental objective during the decision making process. Additionally, we considered two other objectives, budget and public acceptance, that had not been incorporated explicitly into our decision framework.

Application of techniques to predict consequences of management actions resulted in valuable insights. Conceptual modeling encouraged clear thinking about decision-relevant process and highlighted aspects of the decision framework that needed careful definition. Defining the possible hemlock stand conditions where management could occur given the health and infestation level of a stand (Table 6) was an important step in refining and modeling our alternative management actions in the second prototype. Predicting consequences allowed us to evaluate the importance of uncertainty on the decisions. Our initial assumption was that uncertainty regarding predatory beetle effectiveness was a significant impediment to good decision making. However, at least for the decision framework that we considered, resolving uncertainty was not a critical first step.

Rapid prototyping process

We worked through the two iterations of the structured decision making prototyping cycle during the workshop. The three largest challenges for the team were defining the spatial scale being considered (e.g., stand- vs. wildlife management area-scale), reducing complexity of the situation to a manageable amount for a 1-week workshop, and proceeding forward using team-member opinions and available, albeit sometimes incomplete, information.

By prototyping two possible solutions, we gained insights and identified shortcomings, which can be incorporated and corrected in future prototypes. For example, we did not adequately define our spatial scale when the decision was framed. We defined our spatial scale of the stand after we started to define our management alternatives and put together our alternative portfolios for the first prototype. This oversight became apparent after we started to define our management alternatives because different alternatives were being suggested that worked at different scales. In our second prototype, we defined spatial scale more carefully from the beginning.

Prototyping requires that some complexity is reduced or ignored. We found it useful to simplify and add complexity as needed. There is a seemingly infinite amount of complexity that could be included in any ecological decision, but it is important to evaluate the sensitivity of decision making to different factors and sources of uncertainty. As a rule, decision analysis should include only those complexities that affect the decision. We reduced the complexity of our management situation by defining a single stand condition and defining a temporal scale to work with for purposes of the prototyping process. For the first prototype, we reduced the range of possible stand conditions by defining a high-quality hemlock stand with a light level of hemlock woolly adelgid infestation after we started to define our alternatives and put together our alternative portfolios. Different alternatives were being proposed based on different stand conditions (e.g., % hemlock composition, understory composition, degree of infestation, and stand health) and this made it difficult to adequately define our alternatives. For the first prototype, we also dealt with a management action carried out at one point in time. For the second prototype, we added two pieces of complexity that were removed for the first prototype;

management actions were carried out over the 30-year plan duration, and a high-quality hemlock stand could become infested at four categorical levels (Table 3; Table 6; Figure 3).

Perhaps the biggest challenge for our team was preceding forward using team-member opinions and available information. We used preliminary habitat models for the covered species (SB, unpublished data) and expert opinion to assign relative effectiveness of alternative treatments and to define associated costs (R. Rhea, personal communication). We largely worked from team-member knowledge, but also relied on literature and made one phone call to an expert on hemlock woolly adelgid. The details associated with individual treatments and the interaction among multiple treatments occasionally created uncertainty that stifled our progress, but the coaches helped us to focus on the process rather than the details.

Further development and recommendations

We proceeded through the rapid prototyping with little spatially explicit information and made many simplifying assumptions during the rapid prototyping process (e.g., working only with high-quality hemlock stands). Our areas for further development focus on identifying and resolving important sources of uncertainty, gathering additional data to parameterize the models, and generating support for planning and implementation.

Uncertainty. We identified 16 sources of uncertainty that apply to both prototypes and acknowledged them by making assumptions in the predictive models or simplifications in the complexity of the decision. Following others (e.g., Williams 1997), we categorize sources of uncertainty into partial observability, partial controllability, epistemic uncertainty, and environmental stochasticity. Partial observability is uncertainty about the effectiveness of management due to an inability to accurately monitor the status of a population. We identified the following sources of partial observability: 1) location of hemlock stands and hemlock stand characteristics (i.e. composition, structure, etc.), 2) presence and level of infestation of hemlock woolly adelgid, 3) availability of beetles, and 4) human perception and reaction to treatment or non-treatment. Partial controllability is uncertainty about the effectiveness of management due to differences between the intended versus the actual ability to deploy the management action. As a special case of partial controllability, institutional uncertainty is the inability to predict how agencies will adapt to the outcome of the structured decision making process. The team will present the results of this workshop to institutions that make up TNIHWATF. We identified the following institutional uncertainties that could influence whether the framework we developed will be implemented: 5) willingness of TNIHWATF to collaborate with the NCFRHCP-based planning, 6) flexibility of TWRA decision-making (e.g., sunk costs with predator beetles), and 7) availability of funding and personnel for surveying, monitoring, and treatments. Additionally, treatment effectiveness is a special case of partial controllability. We identified 8) the relative effectiveness of hemlock woolly adelgid treatments, 9) adverse environmental effects, and 10) cost-effectiveness of treatments at large scales as sources of partial controllability. Epistemic uncertainty is an incomplete understanding about biological mechanisms that limits the effectiveness of management, and we evaluated our 11) poor understanding of predator beetle effectiveness. We identified sources of 12) structural uncertainty represented by more than one underlying model (e.g., one predictive model for less effective beetles and another for more effective beetles) and 13) parametric uncertainty represented by estimates of model parameters (e.g., transition probabilities in the state-based model). Finally, environmental stochasticity includes variation in climate, landscapes, and other unpredictable influences that lead to uncertainty about the effects of management. The following are sources of environmental stochasticity in the NCFRHCP project area identified by the team: 14) climate change, 15) drought, and 16) effects of other stressors, such as elongate hemlock scale, on hemlock forests.

There are many sources of uncertainty to be considered in ecological decisions. The essential challenge is to determine which uncertainties are relevant to decision making. It is our experience, as we found with predator beetle effectiveness, that many uncertainties do not interfere with good decision making. It is important to separate an academic interest in resolving uncertainty from the value of resolving uncertainty before making a decision.

Monitoring and updating predictive models. To gather additional data, we will: 1) contact existing hemlock woolly adelgid control efforts (e.g., Great Smokey Mountains National Park); 2) sample hemlock stands and calibrate remote sensing/aerial photograph data to characterize variation in hemlock stands on wildlife management areas; 3) define stand priorities based on i) range of hemlock composition, ii) proximity/presence of NCFRHCP covered species, iii) degree of infestation, iv) hemlock health, v) understory structure and composition , and vi) location relative to infestation (i.e., model stands other than those we defined as high quality); and 4) develop a framework for monitoring of stand condition relative to range of stand health and infestation categories (including pre- and post- treatment monitoring).

To finish developing the modeling framework, we will: A) develop priorities for treatments and allocating resources at landscape scale with respect to monitoring and hemlock woolly adelgid management; B) develop an optimization model; and C) develop a process for incorporating new information into the adaptive management framework at an appropriate frequency to influence management decisions.

Recommendations and generating support for planning and implementation. We recommend the TNIHWATF and the NCFRHCP utilize the decision process and suite of tools that we developed in moving forward with efforts to control the invasion of hemlock woolly adelgid in the state of Tennessee and the NCFRHCP project area. In two iterations of the rapid structured decision making process, we developed a framework for the decision process and a suite of tools that can be used by TWRA managers to determine hemlock woolly adelgid management strategies that optimize control of this pest based on the control techniques and financial resources available. There are many other details that need to be integrated into future development of a management plan for this pest, but developing the decision framework was a major step in this process and should prove valuable to TWRA's efforts to manage the effects of hemlock woolly adelgid.

Our team had at least five insights during the structured decision making process. First, do not forget the value of having fresh eyes take part in complex decisions and processes. Second, analytically skilled persons are important in structured decision making. Third, devoting time to making smart decisions can lead to substantial cost savings over time. For example, without having this process, we may have been successful at attaining beetles and grant money but not have known how to successfully implement our strategy. Fourth, it is worth the time and effort to gather the best information. Using the structured decision making process we were able to focus in on the most relevant information for the decision from a wide range of information available to us. Finally, rapid prototyping is not the end, it is the beginning of the structured decision making process.

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Table Captions

Table 1. Problem statements for the two rapid prototypes of the structured decision making process for invasion of hemlock woolly adelgid on the Cumberland Plateau of Tennessee.

Table 2. Alternative management actions available for hemlock woolly adelgid invasion on the Cumberland Plateau of Tennessee. The status quo buffer is a 30.5 m (100 ft) no harvest zone on each side of a perennial stream and a 50% partial harvest zone extending 61.0 m (200 ft) beyond the no harvest buffer (i.e., from 30.8 - 91.4 m [101-300 ft]). We only considered one pesticide, imidacloprid, to control hemlock woolly adelgid.

Table 3. Hemlock stand health condition and infestation categories. Descriptions for each category of stand health and infestation are based on categories monitored by Tennessee state foresters (Kirksey et al. 2004).

Table 4. Alternative management portfolios considered during the first prototype. See Table 1 for more details on management options.

Table 5. Raw scores and normalized, weighted scores that were used to assess consequences and tradeoffs among the three alternative management portfolios in the first prototype. We assessed how well each portfolio met the performance criteria for the four fundamental objectives (Table 4).

Table 6. Possible riparian forest stand states based on hemlock stand decline and hemlock woolly adelgid infestation (HWA) categories assessed in the second prototype. The following states helped to build a state-based predictive model of the system: HH = healthy hemlock stand, LH = lightly infested and healthy to lightly declining hemlock stand, MH = moderately to severely infested and moderately declining hemlock stand, SH = moderately to severely infested and severely declining hemlock stand, and MHP = mature hardwood- or pine-dominated stands (Figure 3). Infestation and decline categories except MHP follow Kirksey et al. (2004; Table 3).

Table 7. Alternative management actions assessed in the second prototype based on riparian stand states including decline of hemlock stand health and infestation level of hemlock woolly adelgid. An x indicate where a management option may be used. Management actions are described in Table 2 and riparian stand states are described in Table 6. We only considered predator beetles and silviculture in the trade-off analysis for the second prototype.

Table 8. Initial model parameters including transition probabilities between model states (A), treatment costs for one stand (B), and species habitat preference values (C) for simulation to assess tradeoffs at maximizing healthy mature forest cover based on expected changes due to each of five management strategies in the second prototype. Transitions between stand states are shown in Figure 3. Costs of predator beetles and pesticide treatments were based on stand averages (R. Rhea, US Forest Service, personal communication). Habitat preference scores were based on preliminary habitat models for each species on the Cumberland Plateau and Mountains ecoregion (SB, unpublished data).

Table 9. Number of healthy, mature forest stands and number of stands per $1,000 per year after a management strategy for hemlock woolly adelgid is applied each year for 30 years. Both management strategies included early intervention with predator beetles. The number of stands were predicted under uncertainty regarding predator beetle effectiveness (i.e., assuming either

least or most effective predation). The expected value was calculated assuming equal likelihood for least and most effective predator beetles.

Figure Captions

Figure 1. Fundamental objectives, measureable attributes, and performance criteria for protection of hemlocks and conservation of two conservation targets, blackside dace (*Phoxinus cumberlandensis*) and Swainson's warbler (*Limnothlypis swainsonii*). We added a third conservation target, Alleghany woodrat (*Neotoma magister*), during the second prototype.

Figure 2. Conceptual influence diagram for the first prototype illustrating how treatment for hemlock woolly adelgid (HWA) could affect the performance criteria of our four fundamental objectives (Figure 1). We considered four loss categories in the decision process (none, low, moderate, and high).

Figure 3. Model depicting the stand-level transitions among the five riparian forest stand states that was used to predict the outcome of the treatment alternatives for hemlock woolly adelgid (HWA). Riparian forest states follow Kirksey et al. (2004; Table 3) and are described in Table 6. Transitions between states can occur due to colonization (c), growth (g), and extinction/decline (d, the probability of a moderately infested stand declining to a light infestation; e_h, the probability of a lightly infested stand going extinct; or e_p, the probability of a severely infested stand going extinct).

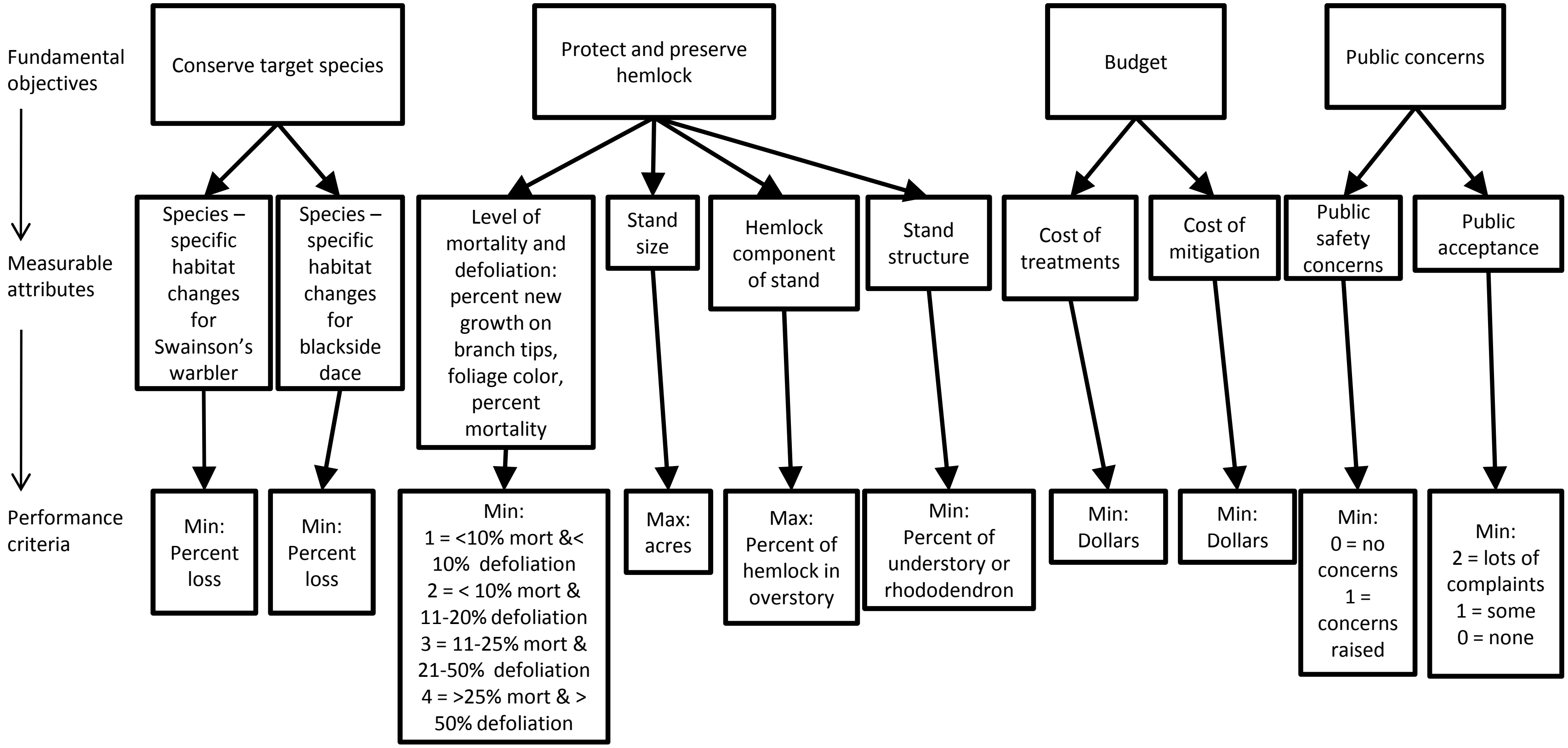
Figure 4. Change in number of stands in each of the five riparian forest states (Table 6) over the 30 years under four management strategies: no treatment (a), early intervention at the LH state with most effective predator beetles (b), early intervention at the LH state with least effective predator beetles (c), and early intervention at the LH state with least effective predator beetles plus late intervention at the MH and SH states with silviculture (d) in the second prototype.

Figure 5. Number of stands remaining in mature forest cover (HH, LH and MHP states) after 30 years under each of the five management strategies in the second prototype.

Figure 6. Habitat value for three conservation targets, Swainson's warbler (black bars), blackside dace (white bars), and Alleghany woodrat (gray bars), after 30 years under each of the five management strategies in the second prototype. Habitat preference values for each species are shown in Table 8.

Figure 7. Total cost after 30 years following each of the five management strategies in the second prototype. Annual costs were calculated by multiplying the number of stands in a given state by the cost of treatment under the given strategy and summed over the 30 years. We assumed the cost of treatment would be incurred in every year (i.e., effectiveness of treatments did not transfer from one year to the next).

Figure 1



Fundamental objectives
Measurable attributes
Performance criteria
Conserve target species
Protect and preserve hemlock
Budget
Public concerns
Species – specific habitat changes for Swainson's warbler
Species – specific habitat changes for blackside dace
Level of mortality and defoliation: percent new growth on branch tips, foliage color, percent mortality
Stand size
Hemlock component of stand
Stand structure
Cost of treatments
Cost of mitigation
Public safety concerns
Public acceptance
Min: Percent loss
Min: Percent loss
Min: 1 = <10% mort &< 10% defoliation 2 = < 10% mort & 11-20% defoliation 3 = 11-25% mort & 21-50% defoliation 4 = >25% mort & > 50% defoliation
Max: acres
Max: Percent of hemlock in overstory
Min: Percent of understory or rhododendron
Min: Dollars
Min: Dollars
Min: 0 = no concerns 1 = concerns raised
Min: 2 = lots of complaints 1 = some 0 = none

Figure 2

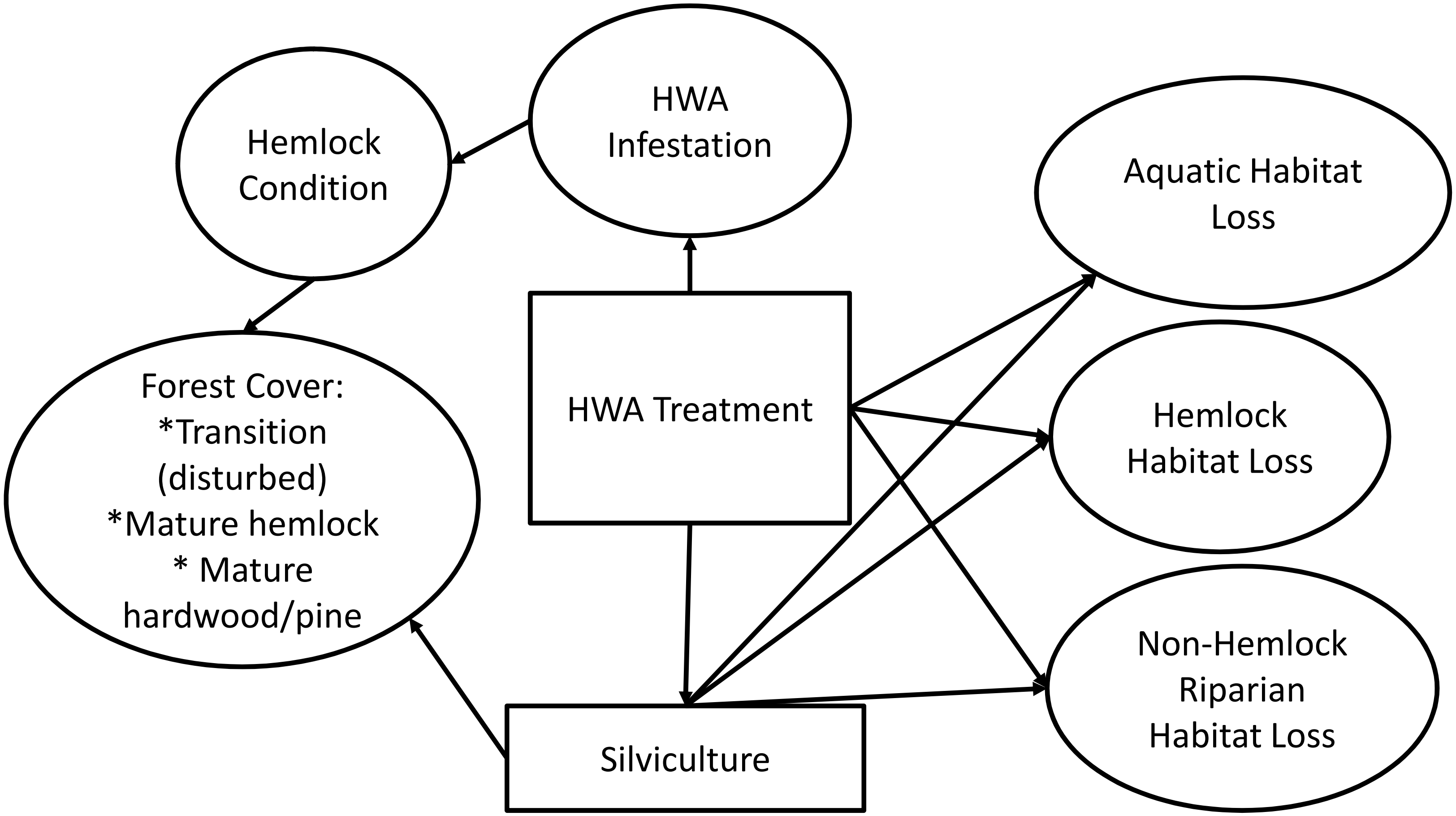

HWA Infestation
Hemlock Condition
Aquatic Habitat Loss
Forest Cover:
*Transition (disturbed)
*Mature hemlock
* Mature hardwood/pine
HWA Treatment
Hemlock Habitat Loss
Non-Hemlock Riparian Habitat Loss
Silviculture

Figure 3

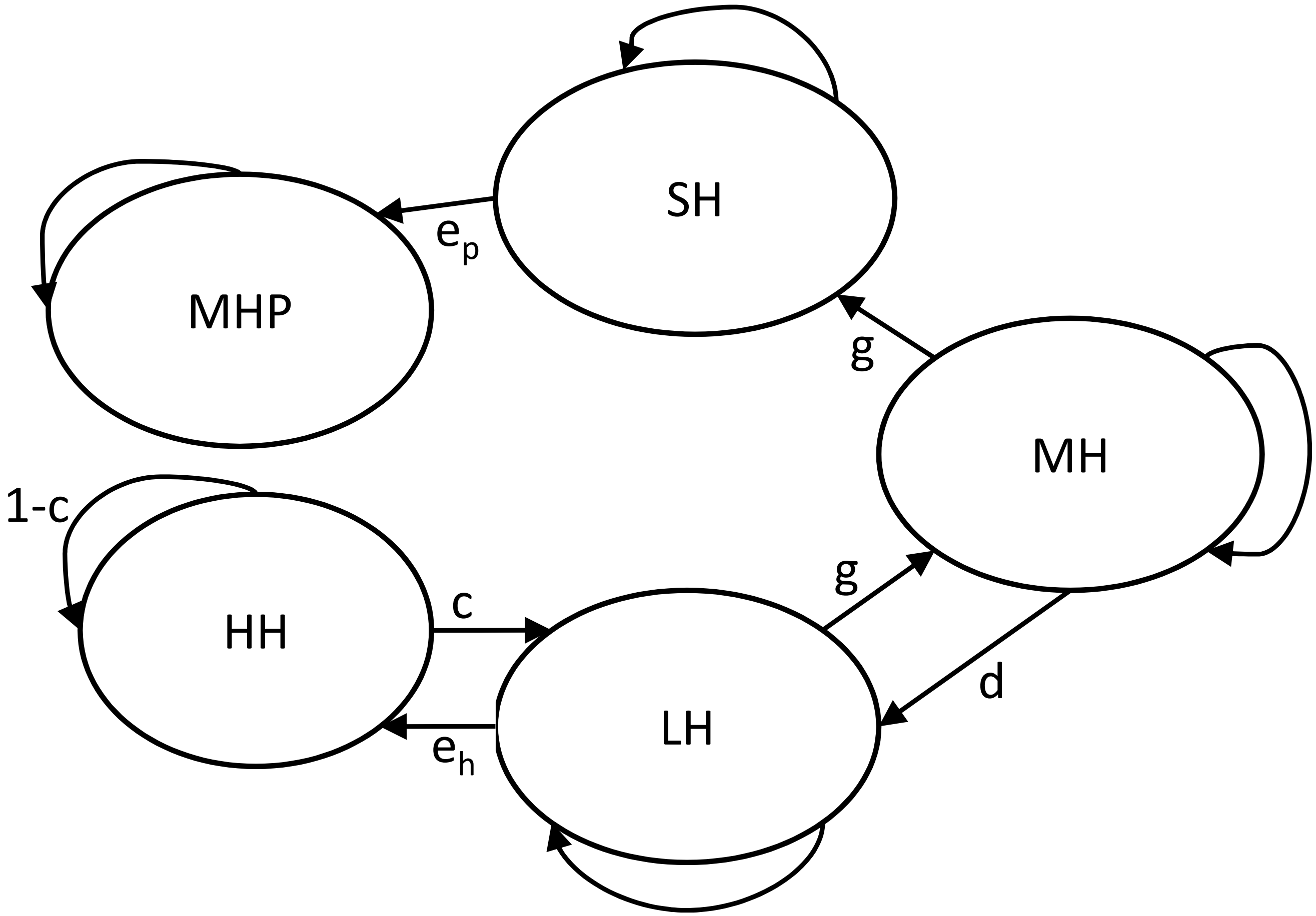
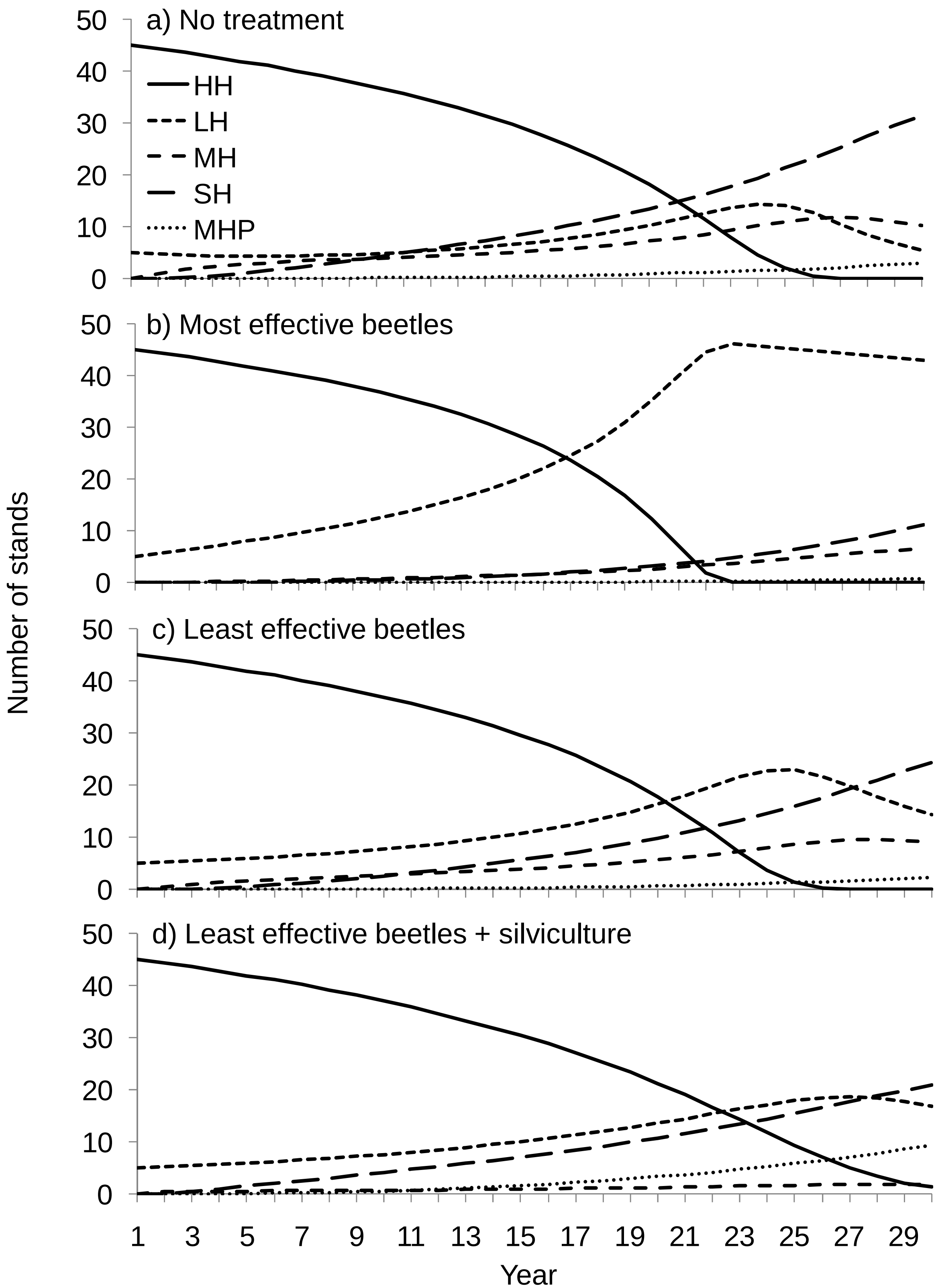


Figure 4



a) No treatment
HH
LH
MH
SH
MHP
b) Most effective beetles
c) Least effective beetles
d) Least effective beetles + silviculture
Number of stands
Year
50
40
30
20
10
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29

Figure 5

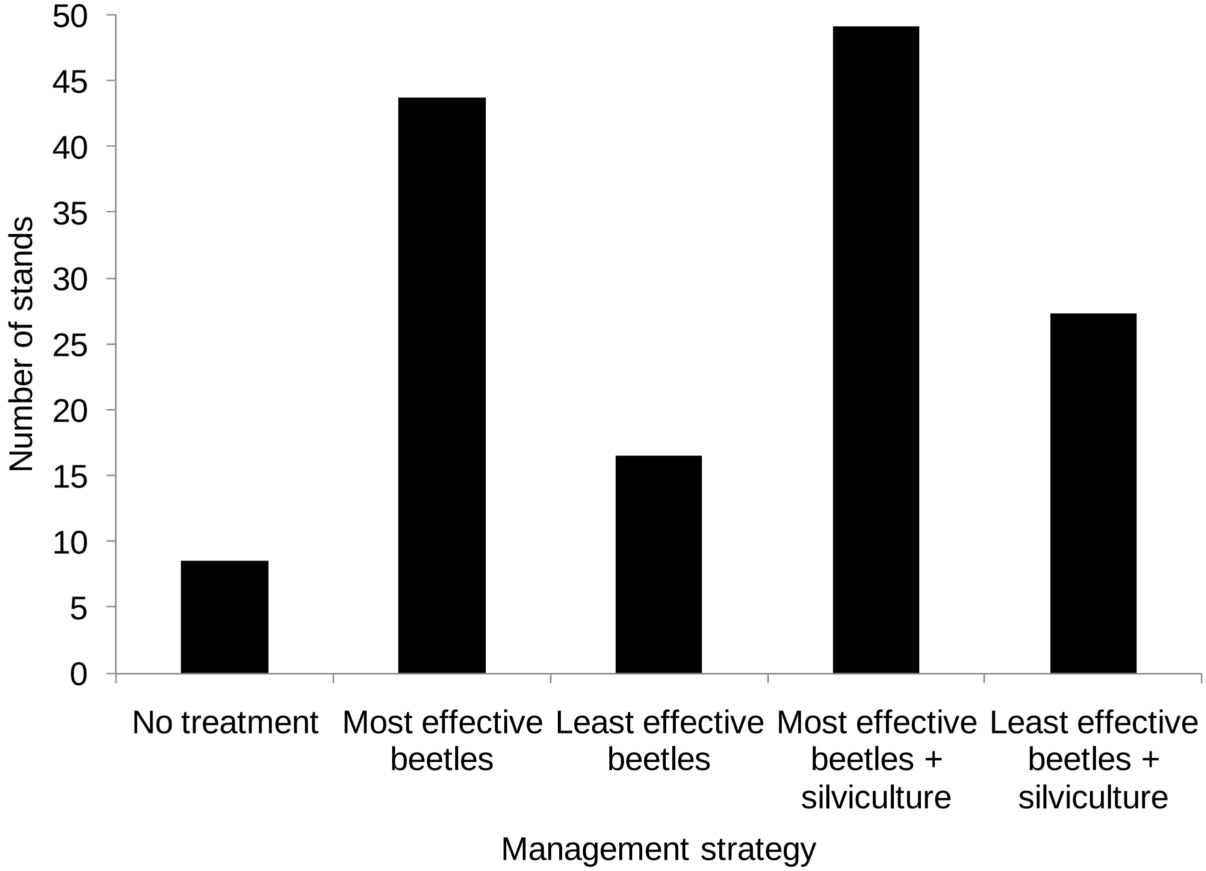

50
45
40
35
30
25
20
15
10
5
0
Number of stands
No treatment
Most effective beetles
Least effective beetles
Most effective beetles + silviculture
Least effective beetles + silviculture
Management strategy

Figure 6

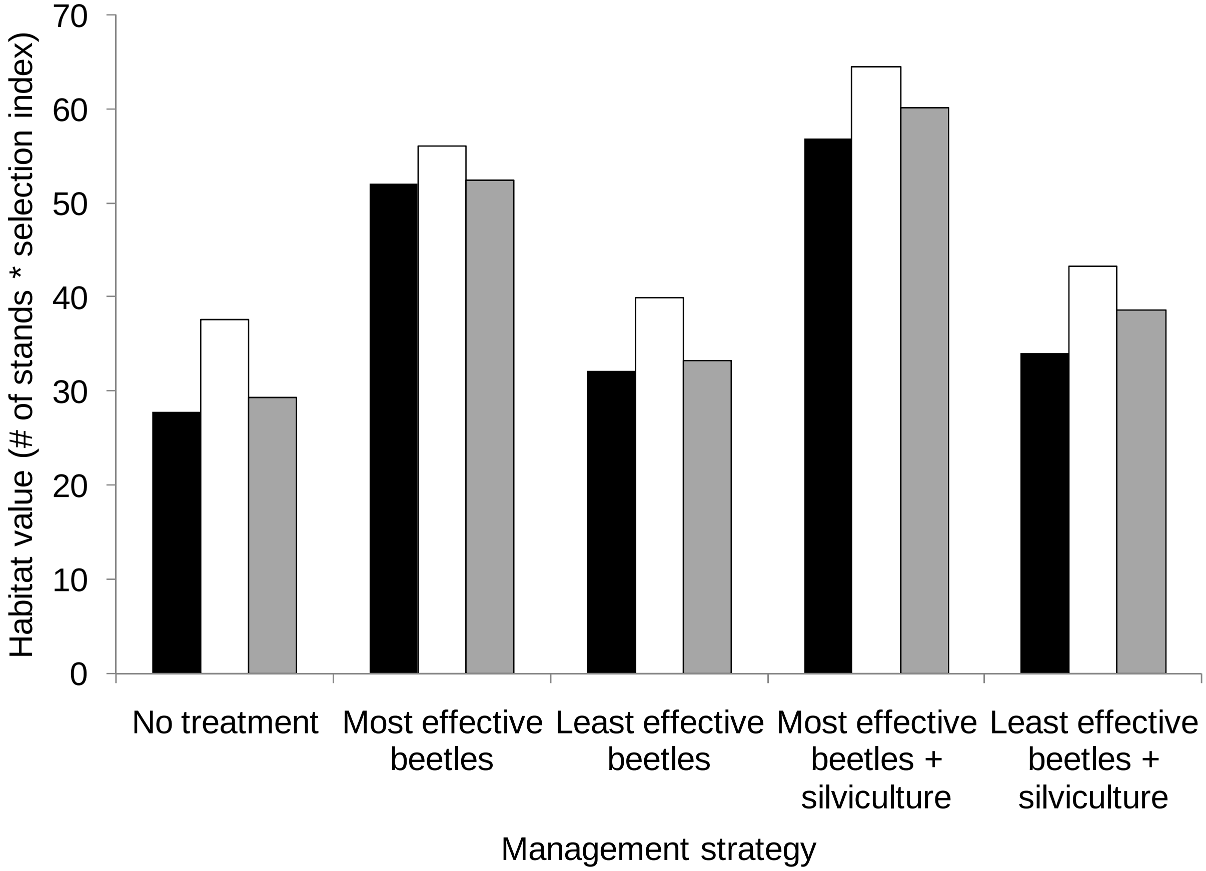
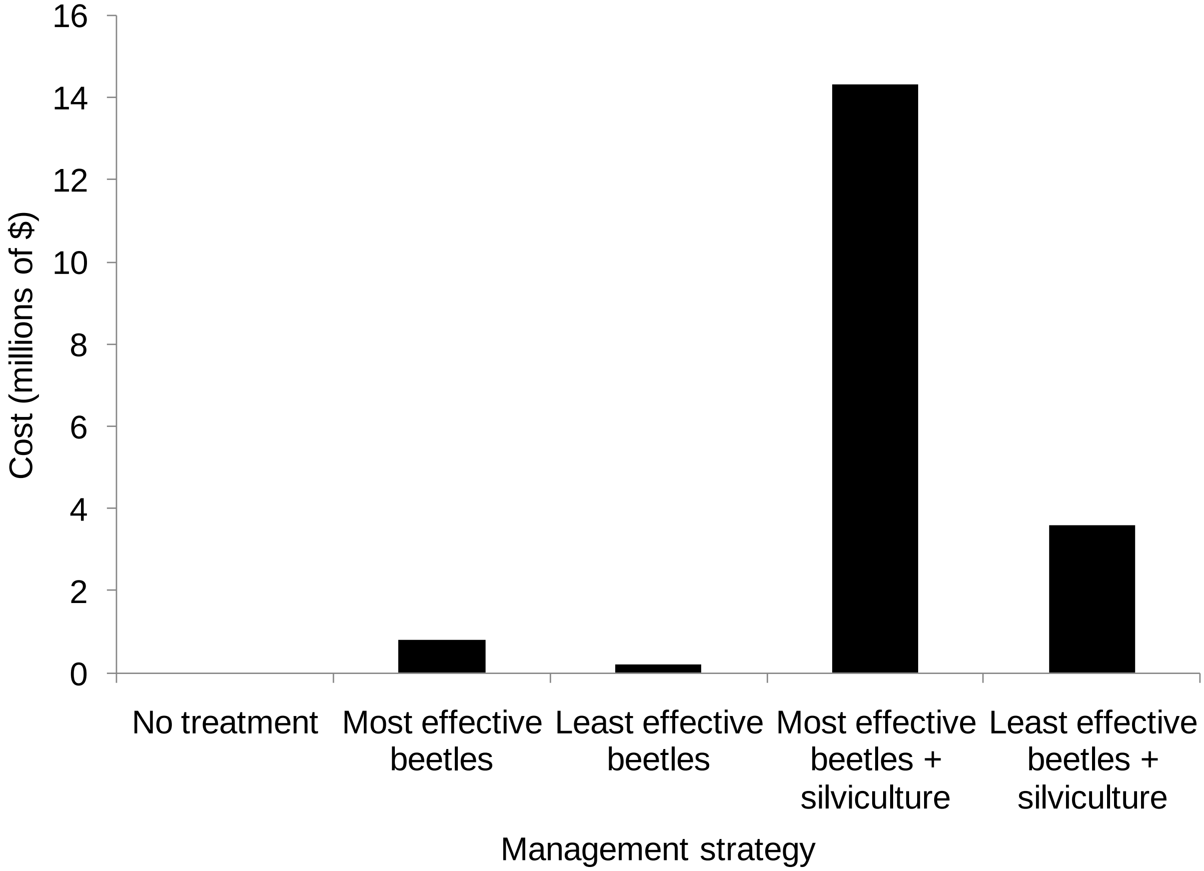

70
60
50
40
30
20
10
0
Habitat value (# of stands * selection index)
No treatment
Most effective beetles
Least effective beetles
Most effective beetles + silviculture
Least effective beetles + silviculture
Management strategy

Figure 7



16
14
12
10
8
6
4
2
0
Cost (millions of $)
No treatment
Most effective beetles
Least effective beetles
Most effective beetles + silviculture
Least effective beetles + silviculture
Management strategy

Table 1.

Prototype	Problem statement
First	Tennessee Wildlife Resources Agency in consultation with the United States Fish and Wildlife Service through a habitat conservation plan and incidental take permitting process will manage state wildlife management areas to maintain mature forest cover and native species composition within riparian buffers. Hemlock woolly adelgid is an acute and present threat to the structure and composition of riparian areas in the Cumberland Plateau and Mountains, where hemlock is a significant component. Because effectiveness of hemlock woolly adelgid control is uncertain, information gained will be incorporated into future decisions.
Second	Tennessee Wildlife Resources Agency, in consultation with the United States Fish and Wildlife Service through the habitat conservation plan and incidental take permitting process, will decide annually where to manage hemlock woolly adelgid infestation 1) to maintain hemlock- and hardwood/pine-dominated mature forest cover within riparian buffers of wildlife management areas totaling 220,000 acres and 2) to avoid or minimize the take of federally listed species over the next 30 years. Because effectiveness of hemlock woolly adelgid control is uncertain, information gained will be incorporated into future decisions through an adaptive management framework.

Table 2.

Management option	Treatment category		
	Hemlock woolly adelgid	Silviculture	Riparian buffer
1	No treatment	No silviculture	Retain as is
2	Predator beetle 1 – *Sasajiscymnus tsugae*	Mechanical site prep	Expand buffer size by 61.0 m (200 ft) on either side where quality hemlock stands are lost
3	Predator beetle 2 – *Laricobius nigrinus*	Chemical site prep	Decrease buffer size
4	Soil injection (pesticide)	Prescribed burns	
5	Tree injection (pesticide)	Understory release - chemical	
6	Fungal sprays	Understory release- mechanical	
7	Horticultural oils/soaps	Planting: pines or hardwoods	
8		Tree removal	

Table 3.

Index	Category	Description
Hemlock woolly adelgid infestation	None	No adelgids observed
	Light	Most trees are uninfested and/or most infested trees have < 10% of infested branches
	Moderate	26% to 50% of the trees appear to be infested and most often individual trees have < 50% of the branches infested
	Heavy	> 50% of the trees are infested and most often the majority of the branches on individual trees are infested
Hemlock stand decline	Healthy	Trees appear to be in reasonably good health with < 10% of the trees showing signs of stress such as defoliation, needle discoloration and/or branch tip dieback. Hemlock mortality < 10% throughout the stand.
	Light decline	Trees appear minimally stressed with many trees showing 11-25% defoliation, needle discoloration and/or branch tip dieback. Larger branch mortality may be present but not frequent on trees within the stand. Hemlock mortality < 10% throughout the stand.
	Moderate decline	Trees generally appear under stress with most trees showing 26-50% defoliation, needle discoloration and/or tip dieback. Larger branch mortality is relatively common throughout the stand. Hemlock mortality 11-25% throughout the stand.
	Severe decline	Trees appear obviously stressed with most trees showing > 50% defoliation, needle discoloration and/or branch tip dieback. Larger branch mortality is common throughout the stand. Hemlock mortality may be > 25% throughout the stand.

Table 4.

Management portfolio	Treatment category	Treatments included
Status quo	Hemlock woolly adelgid	Both predator beetle species
	Silviculture	No silviculture
	Riparian buffer	Retain as is
Maximize hemlock protection	Hemlock woolly adelgid	Both predator beetle species and both pesticide options (soil and tree injection)
	Silviculture	No silviculture
	Riparian buffer	Retain as is
Minimize take of HCP species	Hemlock woolly adelgid	Both predator beetle species
	Silviculture	No silviculture
	Riparian buffer	Expand buffer size by 61.0 m (200 ft) on both sides of stand

Table 5.

Objectives	Goal	Units	Raw scores for portfolios: Status quo	Raw scores for portfolios: Maximize hemlock protection	Raw scores for portfolios: Minimize take of HCP species	Weight	Normalized, weighted scores for portfolios: Status quo	Normalized, weighted scores for portfolios: Maximize hemlock protection	Normalized, weighted scores for portfolios: Minimize take of HCP species
Swainson's warbler habitat loss	Minimize	% decline	32.50	10.00	17.50	0.23	0.00	0.23	0.26
Blackside dace habitat loss	Minimize	% decline	5.00	2.50	4.00	0.21	0.00	0.21	0.08
Hemlock stand health	Minimize	1-4 scale (1 = healthy)	4.00	2.00	3.00	0.22	0.00	0.22	0.11
Hemlock component	Maximize	% of hemlock in overstory	32.50	45.00	40.00	0.16	0.00	0.16	0.10
Cost of treatment (+ opportunity cost)	Minimize	dollars	7.00	30.00	18.00	0.14	0.14	0.00	0.07
Public safety concerns	Minimize	0 = no concern; 1 =	0.00	1.00	0.00	0.05	0.05	0.00	0.50

	concern			
Final score		0.19	0.82	0.57

Table 6.

Degree of hemlock stand infestation	Decline of hemlock stand health: Healthy	Light decline	Moderate decline	Severe decline
None	HH			
Light HWA	LH	LH		
Moderate HWA			MH	SH
Severe HWA			MH	SH
Mature hardwood/pine	MHP			

Table 7.

Stand state	Management actions				
	No treatment	Predator beetles	Pesticide	Predator beetles and pesticide	Silviculture
HH	x				
LH	x	x	x		
MH	x		x	x	x
SH	x				x
MHP	x				

Table 8.

a)

Treatment	Transition probability			
	Growth (g)	Extinction from LH state (e_h)	Decline from MH to LH state (d)	Extinction from SH state (e_p)
No treatment	0.2	0	0	0.01
Predator beetles	0.01-0.1	0	0.3-0.6	0.01
Pesticide	0	0.8	0.8	0.01
Silviculture	1	0	0	0.04

b)

Treatment	Cost (US$)
Predator beetles	9000
Pesticide	30000
Silviculture	2200

c)

Species	Habitat preference score (0-1)		
	HH/LH	MH/SH	MHP
Swainson’s warbler	1	0.5	0.5
Blackside dace	1	0.7	1
Alleghany woodrat	1	0.5	1

Table 9.

Strategy	Number of mature stands after 30 yr			Number of mature stands * $\$1000^{-1} * yr^{-1}$		
	Least effective predator beetles	Most effective predator beetles	Expected value	Least effective predator beetles	Most effective predator beetles	Expected value
Early intervention	17	44	30.5	1.69	2.43	2.06
Early intervention and silviculture	27	49	38	0.41	0.06	0.23