TOOLS FOR CONSERVATION PLANNING IN CHANGING FOREST LANDSCAPES: COLLABORATIVE LANDSCAPE SCENARIO MODELING IN MICHIGAN'S TWO HEARTED RIVER WATERSHED

By

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A dissertation submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy
(Environment & Resources)

at the
UNIVERSITY OF WISCONSIN-MADISON
2016

Date of final oral examination: 12/18/2015

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS

Graduate school has been as much about the journey as the destination, a journey that was made possible by the love and support of family, friends, and mentors. With the end in sight, I realize the beginning goes back much further than my first day at the University of Wisconsin–Madison. Thank you to my parents, James and Alice, for making me believe I could grow up to be anything I wanted and giving me the confidence to reach for the stars. I am inexpressibly grateful for all you have done to support my education and aspirations.

Thank you to my husband, Michael, for your unwavering confidence in me. Having you by my side for this trek has made all the difference. You’ve given me joy and inspiration during the uphill climbs, balance and perspective when both the beginning and the end felt far away, and raspberry crumble at every peak.

Thank you to my advisor, Janet, for your intellectual, professional, and personal guidance. Your quiet leadership and dedication to conservation science have been and will continue to be an inspiration. Thank you to our colleagues in the Forest Scenarios Project—Randy, Nick, Kristi, and Amanda. Our partnership so quickly turned to friendship, and our work together has been the most rewarding and sustaining element of my graduate education. Thank you to Rob for years of mentorship, encouragement, and Fenway. And thank you to Adena, Chris, and David for their guidance as members of my dissertation advisory committee.

Thank you to the many mentors that have encouraged and inspired me during the course of my education at the Arkansas School for Mathematics and Sciences (and the Arts) and Lake Forest College, especially George West, Shane Willbanks, Caleb Gordon, Lynn Westley, Shubhik DebBurman, and Ann Roberts.

And finally, thank you to all of the amazing friends both old and new who have celebrated and commiserated with me along the way. To my friends who are not in graduate school, thank you for understanding my inexplicable need to take the hard road. To my friends who have graduated, thank you for showing me that the hard road is navigable. To my friends who have yet to graduate, remember to enjoy the journey.

ABSTRACT

The Two Hearted River watershed has been the focus of collaborative conservation and forest management efforts by The Nature Conservancy, the State of Michigan, local timber management organizations, and private landowners since 2006. Conservation practitioners and land managers in this watershed and other landscapes are faced with the challenge of developing and applying cross-boundary conservation and management strategies in the face of uncertain changing climate and ecosystem dynamics. The Forest Scenarios Project was created to provide insight into which strategies best achieved watershed conservation goals under current and potential future climate conditions. Rather than a traditional research approach where scientists conceptualize, plan, and carry out research independently, the Forest Scenarios Project applied a collaborative scenario modeling approach in which stakeholders collaboratively develop and model scenarios representing a range of alternative conditions. Collaborative scenario modeling and other transdisciplinary approaches have the potential to improve conservation and natural resource management by expanding stakeholder knowledge about the socio-ecological dynamics of the system and enhancing their ability to collaboratively make decisions.

The primary goal of this research was to apply and examine a collaborative scenario modeling approach to provide insight into the possible consequences of management actions and climate change impacts in the Two Hearted River watershed. First, I examine the process of developing alternative landscape scenarios with the input of local stakeholders and identify the various approaches to knowledge sharing most appropriate for eliciting stakeholder knowledge at each stage. Next, I describe the modeling process and analyze results of simulations of alternative landscape scenarios to compare their ability to achieve conservation goals of maintaining landscape spatial heterogeneity and conserving mature forests and wetlands in the

Two Hearted River watershed. Finally, I suggest a framework for the design, implementation, and evaluation of social objectives for collaborative scenario modeling projects when continued collaboration among stakeholders is a desired outcome. I use these three studies to draw conclusions about the ability of specific management and conservation tools to maintain landscape spatial heterogeneity and conserve mature forests and wetlands and the broader applicability of the collaborative scenario modeling approach in other natural resource management contexts.

INTRODUCTION

Forest ecosystems are ecologically and economically critical, providing biodiversity and ecosystem services that support local economies. These systems rely on processes that span large areas and change over time in response to natural and anthropogenic disturbances (Turner et al. 2001). As a result, successful management and conservation efforts must be large in scope, broad in scale (10^3–10^6 ha), and capable of adapting to changing conditions to ensure the integrity of important ecosystem dynamics (Boutin and Herbert 2002). Such broad-scale conservation often requires innovative governance, ownership, and management strategies that cross multiple geographic and institutional boundaries.

Forest conservation practitioners and land managers are using more distributed conservation strategies—efforts to spread limited financial and human resources available for management and conservation over large areas and wide ranges of ownerships (Silbernagel et al. 2011; Price et al. 2012). As a result, rights and responsibilities for the use and management of forest resources are distributed among many individuals, groups, and institutions, blending public and private resources (Merenlender et al. 2004; Fairfax et al. 2005). These diverse stakeholders may have different knowledge and values concerning the ecosystem, and they may differ in their capacity to access and manage the resource (Hurley et al. 2002; Adams et al. 2003; Kabii and Horwitz 2006). These relatively new approaches, such as payments for ecosystem services or working forest conservation easements (WFCEs), are based on the premise that blending resource use, such as sustainable timber harvest, with conservation should yield socioeconomic benefits without significantly compromising biodiversity conservation or provisioning of ecosystem services (Price et al. 2015).

However, understanding the potential long term, cumulative consequences of conservation actions at broad scales remains difficult given interactions between natural and anthropogenic disturbances as well as potentially rapid ecosystem changes resulting from climate change. Shifts in climate variables and seasonal patterns are likely to influence the species composition and dynamics in northern temperate forests (Opdam and Wascher 2004; Scheller and Mladenoff 2008; Mladenoff and Hotchkiss 2009), as well as their management and ability to provide ecosystem services. Ideally, all managed areas are monitored over time and management actions are adapted to remain flexible and effective in light of new information, disturbances, and unanticipated dynamics (Gregory et al. 2006). However, monitoring efforts often span decades, likely exceeding the timeframe for effective climate change mitigation or adaptation. Furthermore, assessing the effects of disturbances through field experiments is difficult at broad spatial extents (10^3 – 10^6 ha) and long time periods (decades to centuries) (He 2008).

In addition, the success of broad-scale management actions depends largely on their social context (Gibson et al. 2000; Baker and Kusel 2003; Dietz et al. 2003; Ostrom and Nagendra 2006) and the informal personal relationships among stakeholders (Rissman and Sayre 2012). When persons that may be affected by or are responsible for management actions have a voice in the decision-making process, that process and its outcomes are often viewed as more legitimate and are more likely to be used in practice (Daniels and Walker 2001). This trust and social capital can be established through information sharing, dialogue, collaborative learning, and analytic deliberation about local resources (Dietz et al. 2003; Pretty 2003; Plummer and FitzGibbon 2007).

Therefore, there is a clear need for approaches that facilitate and inform collaborative, adaptive forest management planning by comparing the potential outcomes of different conservation, management, and natural disturbance alternatives (Opdam and Wascher, 2004). To address this need, the Forest Scenarios Project (FSP) developed and applied a collaborative scenario modeling (CSM) approach to generate, model, and analyze alternative scenarios of forest management and climate change impacts in the Two Hearted River (THR) watershed, a 53,653 ha landscape located in the Upper Peninsula of Michigan, USA. This landscape has been the focus of collaborative conservation and forest management by The Nature Conservancy (TNC), the State of Michigan, local timber investment management organizations, and private landowners since 2006. The landscape contains a complex mosaic of ownership and management strategies typical of landscape-scale conservation efforts in the United States today (Fairfax et al. 2005). For example, WFCEs have been established in this landscape in an effort to provide ecological and socioeconomic benefits to a wide variety of stakeholders. Conservation practitioners and land managers in the THR watershed and many other landscapes are faced with the challenge of developing and applying cross-boundary conservation strategies in the face of uncertain changing climate and ecosystem dynamics.

In addition to improving natural resource management decision-making by enhancing stakeholder knowledge about the dynamics of the system, CSM projects may also aim to create the social conditions necessary for continued collaboration among stakeholders as they work to formulate adaptive, resilient natural resource management strategies. This approach recognizes that decision-making is a social process. While there are notable exceptions (Schneider and Rist 2014), collaborative scenario analyses rarely consider such social effects during project design and implementation. Therefore, CSM provides little theoretical grounding or practical guidance for articulating and achieving social objectives. Adaptive co-management (ACM) is an emerging approach to natural resource management in which stakeholders collaboratively formulate, test, and revise management strategies and institutional arrangements to remain resilient under changing conditions (Folke et al. 2002; Olsson et al. 2004; Armitage et al. 2009). ACM theory has begun to identify the social conditions necessary for the emergence of collaboration among stakeholders (Plummer 2009; Berkes 2009; Plummer et al. 2012). This body of research and practice can guide CSM practitioners in articulating social objectives and understanding how they facilitate the emergence of collaboration in natural resource management settings.

The primary goals of this research were to: 1) examine the CSM process and outcomes to understand the possible consequences of management actions and climate change impacts in the Two Hearted River watershed, and 2) provide a framework for integrating social objectives into the design, implementation, and evaluation of collaborative scenario modeling projects that aim to facilitate collaboration among stakeholders. From this pragmatic foundation, I applied an approach grounded in the theories of landscape ecology, conservation biology, and adaptive co-management. Forest landscape ecology provides a strong foundation for examining the relationships between disturbances and landscape patterns and processes. Conservation biology supports the supposition that a dialog between scientists, natural resource managers, and policy makers can improve long term conservation outcomes (Agrawal and Ostrom 2006; Groom et al. 2006; Meine et al. 2006)And adaptive co-management theory articulates the social conditions necessary for the emergence of collaboration between stakeholders in natural resource management settings. The interdisciplinary nature of these bodies of theory and the practical nature of this study necessitates a mixed methods research design (Creswell 2008).

Chapter Summary

This dissertation is composed of three chapters; supplemental material for each chapter is provided in the Appendix. The first step of collaborative scenario modelling is developing alternative landscape scenarios by local stakeholders. In Chapter 1, “Eliciting Expert Knowledge to Inform Landscape Modeling of Conservation Scenarios,” I examine the process of eliciting and integrating the knowledge of stakeholders, experts in their landscapes, to develop, model, and analyze scenarios of landscape change. I describe the four alternative landscape scenarios developed for the THR watershed: 1) continuation of current management, 2) industrial forestry, 3) expanded area under working forest conservation easement, and 4) cooperative ecological forestry.

In addition, I articulate how stakeholder knowledge was integrated into the CSM process, detail the stages of the process at which various approaches to knowledge sharing—in-person workshops, web-based workshops, one-on-one interviews, and an online collaboration tool—are most appropriate, and explain the considerations that should be made when using each method. I also examine the challenges and benefits of incorporating expert knowledge and collaborative learning into landscape scenario modeling.

This work provides an example of collaborative scenario development and integrating expert knowledge into landscape modeling. By examining how and why I used specific elicitation methods, discussing the direct and indirect benefits of each method, and conveying the many considerations associated with using expert knowledge, this research enables others seeking to apply CSM to choose techniques appropriate for their project’s unique goals, timeline, budget, and stakeholder pool.

In the second stage of CSM, alternative landscape scenarios are simulated using an ecological model tailored to the focal area through stakeholder input and feedback. In Chapter 2, "Collaborative Scenario Modeling Reveals Potential Advantages of Blending Strategies to Achieve Conservation Goals in a Working Forest Landscape," I examine the modeling process and results of the four scenarios presented in Chapter 1. I compare the ability of the alternative scenarios to achieve conservation goals of maintaining landscape spatial heterogeneity and conserving mature forests and wetlands in the THR watershed. Results indicate that blending conservation strategies, such as applying fee simple acquisition and WFCEs in targeted areas of the landscape, may better achieve these goals than applying a single strategy across the same area. However, strategies that best achieve these conservation goals may increase the sensitivity of the landscape to potential changes in wildfire and windthrow disturbance regimes associated with climate change.

By comparing the amount and configuration of forests and wetlands under each scenario over time, these results contribute to a larger effort to help land managers and conservation practitioners understand and effectively address the potential interactions between management and climate change impacts in the THR watershed. This approach enables participants to compare the ability of alternative strategies to achieve specific management goals, identify the trade-offs between goals, and explicitly consider the potential conflicts and synergies of multiple agencies and landowners working across boundaries in this landscape.

In addition to providing insight into the potential future ecological conditions of a focal area, CSM may also facilitate the emergence of ongoing collaboration between stakeholders. In Chapter 3, "A Framework for Integrating Social Objectives into Collaborative Scenario Modeling Projects Informed by Adaptive Co-management," I suggest a framework for design, implementation, and evaluation of social objectives for CSM projects when continued collaboration among stakeholders is a desired outcome. First, I define clear objectives for CSM projects that aim to facilitate collaboration among stakeholders based on ACM theory. Second, I describe how the CSM process can be designed to achieve these objectives using my experience applying this approach in the FSP as an example. Finally, I identify indicators that can be used to measure progress toward these objectives. I discuss the limitations of CSM as a pre-cursor to ACM and suggest directions for future research at the intersection of CSM and adaptive natural resource management to shed light on how the results of such interdisciplinary projects are incorporated into future decision-making.

This research furthers CSM by providing a practical approach for advancing the social outcomes implicitly included in CSM projects and identified as pre-cursors for stakeholder collaboration and ACM. CSM projects will be most effective when the social and ecological components of the approach receive equal weight in project planning, execution, and analysis. Second, it provides a starting point for evaluating progress toward achieving these social outcomes and, therefore, the emergence of collaboration or ACM. Without these advances in theory, the social outcomes, i.e. societal effects, of CSM projects cannot be held to the same standards and evaluated with the same rigor as the natural science outcomes, i.e. scientific effects (Walter et al. 2007).

A conclusion provides an overall critique of the FSP and the CSM approach, lessons learned from the scenario modeling results, an examination of the broader usefulness of these results in informing collaborative natural resource management decision-making, and directions for future research.

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CHAPTER 1

Eliciting expert knowledge to inform landscape modeling of conservation scenarios[1]

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ABSTRACT

Conservation and land management organizations such as The Nature Conservancy are developing strategies to distribute conservation efforts over larger areas. Relative to fee-simple protection efforts, strategies that allow ecologically sustainable timber harvest and recreation activities, such as working forest conservation easements, should yield greater socioeconomic benefits (ecosystem services) with less investment per area without significantly compromising the conservation of biodiversity (ecological targets). At the same time, climate change may profoundly influence forest resilience to management strategies in the coming century. As a result, there are many possible scenarios for the future of our forests and significant uncertainty for practitioners and decision makers. Yet, monitoring efforts aimed at evaluating the effectiveness of conservation strategies span decades or longer, leading to a lag in knowledge transfer and delayed adaptive management.

To explore potential outcomes for biodiversity, provisioning of ecosystem services, and resilience of our forests resulting from various management strategies and climate change projections, we developed an approach that integrates quantitative, spatially explicit landscape modeling with scenario-building informed by expert knowledge. In this paper, we present our

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[1] This chapter was previously published in *Ecological Modelling*. Citation:
Price J, Silbernagel J, Miller N, et al (2012) Eliciting expert knowledge to inform landscape modeling of conservation scenarios. Ecol Modell 229:76–87.

experiences applying this approach to two conservation project areas in the western Great Lakes region of the U.S.

For each project area, spatially explicit landscape simulations were performed using the VDDT©/TELSA© software suite. At key points in the process, we infused the modeling efforts with expert knowledge via interactive in-person or web-based workshops and an online collaborative tool. Here, we capture our experiences applying the scenario building and modeling approach to forests in the western Great Lakes region and our efforts to make the process transparent and responsive to local and regional experts. It is our intent that this approach be transferable and implemented in future landscape scale conservation projects.

INTRODUCTION

Conservation strategies are shifting to distribute protection efforts over larger areas and a broader range of ownerships and management techniques. These ‘distributed conservation strategies,’ such as working forest conservation easements, are based on the premise that blending resource extraction and conservation should provide socioeconomic benefits without significantly compromising the conservation of biodiversity or the provisioning of ecosystem services (Silbernagel et al. 2011). While initially less costly per acre than fee simple ownership of land, these strategies are often complex to negotiate and implement and can be expensive to maintain over time (Merenlender et al. 2004).

At the same time, changes in some climate variables and their seasonal patterns are likely to influence the composition and dynamics of northern temperate forests (Opdam and Wascher 2004; Scheller and Mladenoff 2008; Mladenoff and Hotchkiss 2009). While emerging conservation strategies are aimed at addressing development pressures and potential climate change impacts, the efficacy of these strategies compared to traditional, fee simple protection remains unclear, particularly in light of resource demand pressures over the coming centuries. political, social, and economic situations further complicate conservation decision-making, where financial opportunities and public support often drive conservation actions in addition to ecological considerations (Pergams et al.2004). Conservation planning could be greatly facilitated by the ability to compare strategies and understand the spatial aspects of strategy effectiveness.

Scenario analysis provides a way to visualize and compare the potential outcomes of a variety of conservation strategies and to develop more resilient conservation policies when faced with the irreducible uncertainty associated with applying new strategies under changing climate, ecosystem, and socioeconomic conditions (Peterson et al. 2003b). Rather than relying on predictions, which are quite uncertain under complex, dynamic conditions, scenarios "enable a creative, flexible approach to preparing for an uncertain future," and recognize that several potential futures are feasible from any particular point in time (Mahmoud et al. 2009). Landscape scenario analysis specifically refers to examination of the different possible conditions and factors that underlie landscape change (Nassauer and Corry 2004). Development of landscape scenarios must incorporate the multidimensional drivers of landscape change, such as socioeconomic factors influencing the demand for natural resources, and site-specific ecological responses to these drivers. Inputs from a variety of disciplines and professional fields are required to capture these local dynamics. Such inputs are difficult to acquire from existing academic studies, because the scale and setting of previous studies are often not transferable to the scale and location of interest. In addition, the complex interactions of human and natural systems cannot be reliably anticipated by extrapolations from past trends (Coreau et al. 2009). Therefore, some degree of creative thinking is an asset when forming scenarios, especially when trying to capture rare but plausible events.

To form landscape scenarios that are plausible both ecologically and socio-politically, a collaborative process among various experts, practitioners, and stakeholders can be used (Peterson et al. 2003a; Hulse et al. 2004). Though the term plausible is not well defined in the literature, here it describes possible or believable, though not equally likely, alternative futures (Mahmoud et al. 2009). In the case of landscape scenarios, local experts, including foresters, business people (e.g. paper mill managers), land managers, wildlife biologists, and ecologists, can identify and define various potential drivers of landscape change and consider the contrasting, plausible alternative futures that might result.

To further strengthen this approach, landscape scenarios can be combined with quantitative landscape models. For example, in regional environmental applications, landscape scenario analysis is often integrated with landscape modeling to create spatially explicit landscape futures resulting from various land management, policy, climate change, and resource or energy demand conditions (Baker et al. 2004; Santelmann et al. 2004; Provencher et al. 2007; Sturtevant et al. 2007; Wilhere et al. 2007; Zollner et al. 2008; Low et al. 2010). However, limited guidance is available on the process of eliciting and integrating expert knowledge into scenario building and modeling efforts.

Here, we demonstrate the elicitation and integration of expert knowledge to develop, model, and analyze scenarios of landscape change in a collaborative project by the Wisconsin and Michigan Chapters of The Nature Conservancy (TNC) and landscape ecologists at the University of Wisconsin at Madison. This project aims to evaluate the effectiveness of various conservation strategies under conditions of climate change and demand for woody biomass for energy production. Expert knowledge was infused into the overall scenario-building and modeling process (Figure 1) in three key stages – (1) scenario development, (2) model parameterization, and (3) spatial narrative building. We discuss how a variety of methods was utilized at each of these stages, including in-person workshops with local experts, web-based workshops with regional experts, one-on-one interviews, and an online collaborative tool. We articulate the direct and indirect benefits of each method as well as the many considerations associated with using expert knowledge in such instances. By providing examples of how and why we used these four elicitation methods, we enable readers to choose techniques appropriate for their project’s unique goals, timeline, budget, and expert pool.

Such integration of scenario analysis and landscape modeling enables scientists and conservation practitioners to better understand the potential outcomes of the complex and simultaneous interactions of the diverse milieu of processes that influence landscape change, including ecological processes, climate change, and interactions of humans and the environment (Seidl et al. 2011). Ideally, this approach can be applied more broadly to consider new, high-risk strategies seeking to balance cost-effectiveness, biodiversity conservation, and maintenance of ecosystem services in other forest settings. By bringing together diverse experts such as landowners, foresters, and ecologists this approach aims to foster cooperation and yield more robust simulations and subsequent conservation adaptation.

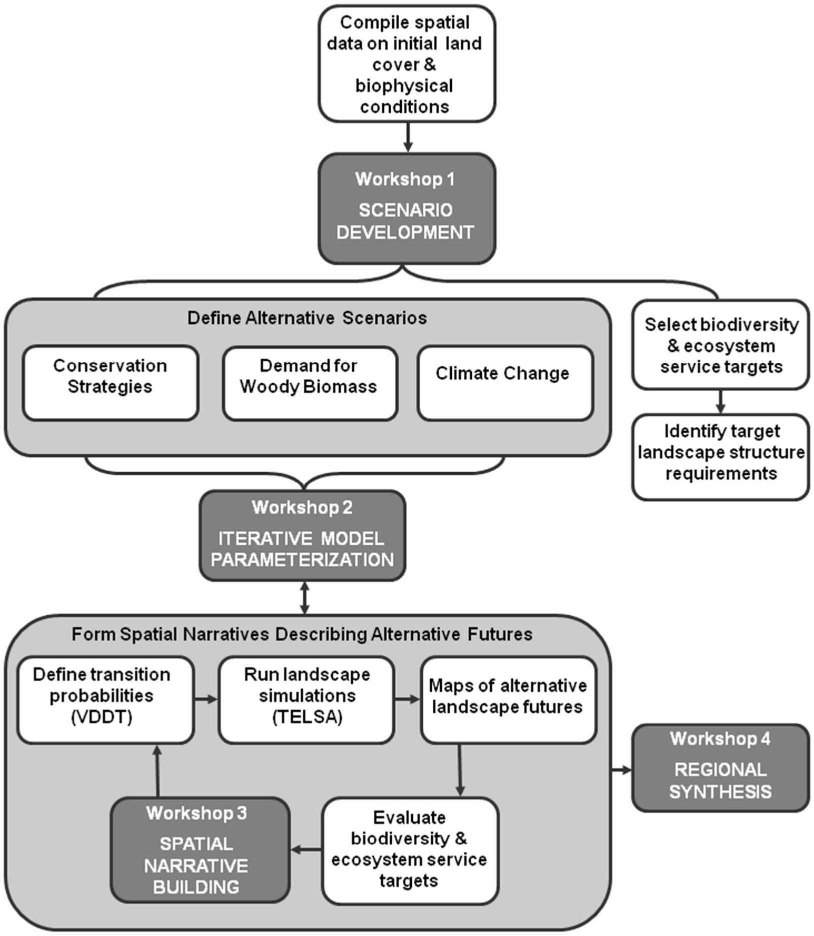


Figure 1. Flow chart illustrating the collaborative process used to develop and model landscape scenarios. Expert input was elicited and integrated into the project via four workshops, indicated by the dark grey boxes.

ELICITATION METHODS AND OUTCOMES

Study Areas

This project focused on two study areas – the Wild Rivers Legacy Forest in northeastern Wisconsin and the Two Hearted River watershed in Michigan's Upper Peninsula (Figure 2). The Wild Rivers Legacy Forest study area spans 218,792 ha of northern hardwood and hemlock-hardwood forests, interspersed with a complex of lakes, cedar swamps and other wetlands, rivers, and streams. Current ownership and conservation of this area results from collaboration between TNC, the Wisconsin Department of Natural Resources (DNR), and two timber management investment organizations (TIMOs). As a result, the area contains national forest; state forest lands managed by the Wisconsin DNR; county forests; lands owned by TIMOs under a state-held working forest conservation easement restricting subdivision, development, and forest management practices; and lands owned by the TIMOs without easement restrictions (Figure 2a).

The Two Hearted River watershed (Figure 2b) encompasses 53,653 ha and contains a mixture of forest types, including upland hardwood forests, pine stands, and coniferous forests, interspersed with a variety of wetland systems, including muskeg, bogs, and swamps (Swaty and Hall 2009). Together, the Michigan DNR, a TIMO, and TNC own 80% of the watershed. All of the land controlled by the TIMO is managed under a working forest conservation easement. In both study areas, diverse owners have multiple management objectives, ranging from a focus on conservation of biodiversity (TNC) and improvement of forest condition for investors (TIMOs) to recreation, forest products, and reduction of fire risk (DNR). These areas exemplify the complex mosaic of ownership and management (Fairfax et al. 2005) and environmental pressures that must be considered in typical landscape scale conservation efforts in the U.S. today.

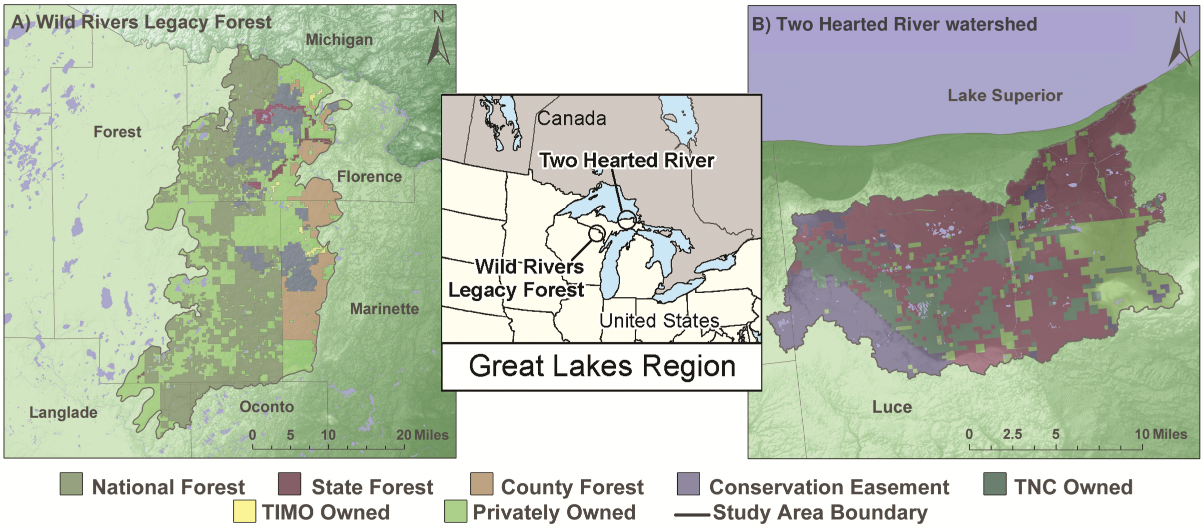


Figure 2. Maps of the study areas – the Wild Rivers Legacy Forest in northeastern Wisconsin (A) and the Two Hearted River watershed in Michigan's Upper Peninsula (B).

Selection of Expert Pool

In general, experts involved in scenario development and modeling can be divided into stakeholders, practitioners, and academic and agency scientists, separable by the scale at which they understand the study landscape and the level of their management responsibility (Figure 3). We aimed to develop and model landscape scenarios composed of a set of three drivers of landscape change identified a priori by the project team – a conservation strategy, a level of demand for woody biomass for energy production, and selected climate change variables.

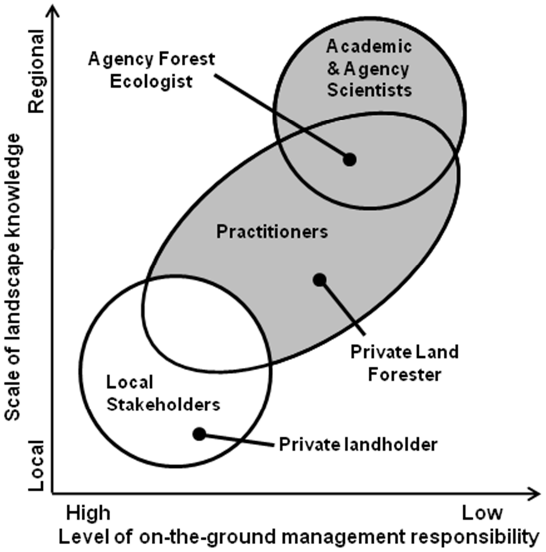


Figure 3. A conceptual diagram of the different types of experts – local stakeholders, practitioners, and academic or agency scientists – who can provide input for scenario-building and modeling approaches. The project team fell within the academic or agency scientists bubble, having broader scale expertise and little or no on-the-ground management responsibility. Experts fell within the shaded area, ranging from forestry practitioners to agency scientists with local and regional knowledge.

Development and modeling of these scenarios required local and regional knowledge, including the previous and current conditions of each study area, the local biotic and abiotic processes affecting these areas, and their broader socioeconomic setting. Knowledge of forest succession often stems from forestry practitioners and is not formally documented in peer-reviewed literature (Drescher et al. 2008). Local experts were primarily practitioners (Figure 3), chosen for both their knowledge base and their affiliation with the agencies and organizations responsible for the management of the study areas, including the Wisconsin and Michigan DNRs, TNC, and TIMOs. Regional experts were primarily academic and agency scientists

(Figure 3) capable of considering the project within the context of broad-scale forest management and monitoring in the western Great Lakes region. Stakeholders, in this study, refer to local landowners or others with a local, non-professional land interest.

This composition (1) increased the likelihood that experts would view the resulting scenarios and simulations as valid and incorporate them into their management decisions and (2) decreased the likelihood that the resulting scenarios would be biased toward a particular point of view or set of goals or values. While selecting broadly across agencies, it was also necessary to ensure knowledge gaps identified by the project team could be addressed by at least one participating expert. For example, local experts were selected to achieve a representation of subject-specific expertise, such as wildlife biology, forestry, recreation management, landscape modeling, and the effects of disturbance processes in the western Great Lakes region.

Scenario Development

In-person workshops

In-person workshops with local experts, one near each study area, were used to facilitate collaborative development of locally tailored landscape scenarios (Figure 1, Workshop 1). This format enabled gathering information from many experts simultaneously and provided a venue for expert discussion, crucial for capturing the uncertainty and variability inherent in scenario analysis. In advance of the workshop, experts were provided with descriptions of the project's motivation, aims, and approach. By considering the experts' prior experiences with conservation planning, the project team clearly communicated the utility of the scenario building and modeling approach, discussed how the approach and its results can complement conservation planning efforts, and anticipated and answered questions.

Workshops began with an introduction to the project designed to complement and elaborate upon the pre-workshop materials. This introduction emphasized the anticipated outcomes of the project, including resources to pre-assess and compare conservation strategies, complement long-term monitoring, adjust strategies to anticipate future conditions, and inform ongoing and future conservation opportunities. The necessity of expert input and the role of experts in the scenario building and modeling process were also explicitly addressed to both inform experts of what to expect and encourage them to develop a sense of ownership and value their personal investment in the project.

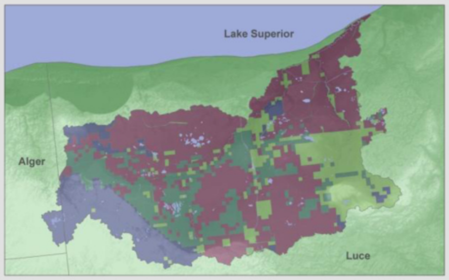
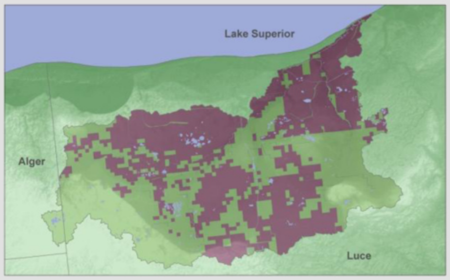
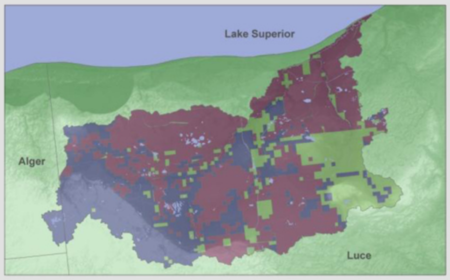
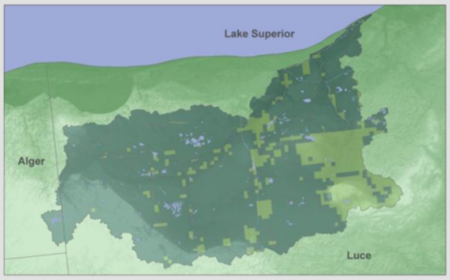
Because no prior landscape scale modeling efforts existed for these study areas, experts were first asked to characterize the current state and functioning of local forest ecosystems. Next, experts were assembled into a single group, and discussion time was devoted to each of the three scenario components in turn – climate change, demand for woody biomass for energy production, and possible conservation strategies.

To start the discussion, the project team presented climate change projections for the study area (TNC 2009b; WICCI 2010), and experts discussed the climate variables they thought were the most important drivers of local landscape change. Second, experts were asked to describe the potential future of woody biomass harvest for energy production in the study area. The future of woody biomass harvest will be determined by a complex interaction of ecological, economic, and sociopolitical factors, and it is expected that these factors will be highly dependent on location. Therefore, local impressions of this market and its future are crucial for informing scenarios. Third, to elicit current and possible future conservation strategies and their geographic distribution in the study area, experts reviewed current, ground-truthed land cover maps of the study areas. These initial landscape maps provided the baseline from which alternative future landscapes diverge during the modeling process.

The full elicitation process was conducted separately with Wisconsin and then Michigan experts. The project team then reviewed the two sets of information to identify common alternatives for each of the three scenario components to formulate a single set applicable to both study sites (Table 1). To build complete scenarios, one alternative from each of the three components – a conservation strategy, a level of harvest of woody biomass, and climate change – were combined to generate a set of 10 landscape scenarios.

Table 1. Landscape scenario descriptions and illustrative maps developed through collaboration with local experts for the Two Hearted River Watershed. The same resource demand and climate change conditions and similar alternative management strategies were simulated for the Wild Rivers Legacy Forest.

Scenario components

1. Management strategies	**Alternative Management Areas**
a. Current Management. Landscape dynamics are simulated under today's management boundaries and regimes. In maps of alternative management areas, lands managed by the Department of Natural Resources (DNR) are shown in maroon (🟥), under a working forest conservation easement in blue (🟦), by The Nature Conservancy as a forest preserve in dark green (🟩), and by private owners in light green (🟩).	
b. No Conservation Action. Lands unowned by the state's Department of Natural Resources (DNR) are acquired by private, industrial timber interests and managed for maximum timber productivity (green). To simulate timber harvest by multiple, private owners acting independently, management activities are not spatially aggregated within the privately owned zone. Current management is simulated on state DNR owned lands (maroon).	
c. Easement. In this alternative landscape, area originally purchased by TNC is placed under an easement instead. Today's management strategies are applied in this larger easement area (blue) and the DNR management area (maroon). Management in the easement area is spatially aggregated to reduce fragmentation.	
d. Ecological Forestry. This scenario simulates cooperative, ecological forestry across the whole study area except privately owned lands. TNC management (dark green) is expanded to include the current easement and DNR management areas, including restoration forestry to reduce the area of uncharacteristic land cover and promote old growth characteristics. Management was spatially aggregated.	

2. Resource Demand

a. No harvest of woody biomass.
b. Harvest of woody biomass for energy production on a 25 year time horizon.

3. Climate Change

a. A gradual increase in the probability of fire over the duration of the simulation, culminating in a 50% increase over today's conditions at year 100.
b. A gradual increase in the probability of both fire and wind over the duration of the simulation, culminating in a 50% increase over today's conditions at year 100.

Scenario development

32 landscape scenarios were constructed by combining one alternative of each component—one management strategy, one resource demand condition, and one climate change condition. For example, one scenario combines current management, harvest of woody biomass for energy production on a 25 year time horizon with an increase in only fire under climate change conditions.

Model parameterization

Landscape scenarios were modeled using the VDDT®/TELSA® software suite developed by ESSA technologies Ltd. (Kurz et al. 2000; Beukema et al. 2003; Provencher et al. 2007). Non-spatial, state and transition models of probabilistic disturbance, succession, and management in each land cover type in the study areas were developed in VDDT (Vegetation Dynamics Development Tool) by modifying vegetation models previously developed by LANDFIRE, the Landscape Fire and Resource Management and Planning Tools Project (LANDFIRE 2007; TNC 2009a). VDDT models, along with spatial data, serve as an input for TELSA (Tool for Exploratory Landscape Analysis) to simulate land cover change at multiple time steps under each scenario. We refer the reader to Forbis et al. (2006) and Provencher et al. (2007) for a full description of VDDT and TELSA methodology.

Table 2. Model parameters incorporated into each component of the modeling interface.

Parameters	VDDT	TELSA	Source
Stand development			
Seral stages—defines ecological succession in each modeled cover type	Define age and structural characteristics; Assign deterministic succession pathway		Existing LANDFIRE models (LANDFIRE, 2007b), current land cover maps
Natural disturbances			
Fire, wind, flooding, and insect infestation	Define intensity and transition pathways; Assign return interval through a combination of probability and proportion	Define size and spatial distribution	Existing LANDFIRE models (LANDFIRE, 2007b), state records, scientific literature, local and regional experts
Management			
Timber harvest—thinning, selection cutting, clear cutting, plantation	Define transition pathways	Define stand age and size limits, return interval, and spatial	Local experts

management		distribution for each cover type and management unit	
Restoration forestry	Define transition pathways	Define stand age and size limits, return interval, and spatial distribution for each cover type and management unit	Local and regional experts

Model parameters, including ecological pathways of disturbance and succession, influences of projected climate variables and resource demand, and conservation strategies, were defined and incorporated into the model interface by the project team (Table 2). Though these parameters are based on the principles of forest and landscape ecology, expert knowledge of local and regional dynamics was crucial to define and refine model parameters, ensuring that model results were plausible (Figure 1, Workshop 2). This input was gathered through two web-based workshops and a series of one-on-one interactions.

Web-based workshops

The first web-based workshop (Figure 1, Workshop 2) began with an explanation of the modeling process, carefully prepared to match the level of technical detail to the experience and knowledge of the participating experts. For example, to overcome the potential barrier of experts' unfamiliarity with the modeling platform, the project team provided a simple conceptual diagram of each VDDT model and explained how expert knowledge would be integrated into that model as specific parameters. Figure 4 shows a VDDT 'box' diagram and a corresponding conceptual diagram of the Alkaline Conifer Hardwood Swamp land cover model. Such conceptual diagrams make the dynamics of succession, disturbance, and management easier to visualize, communicate, and discuss.

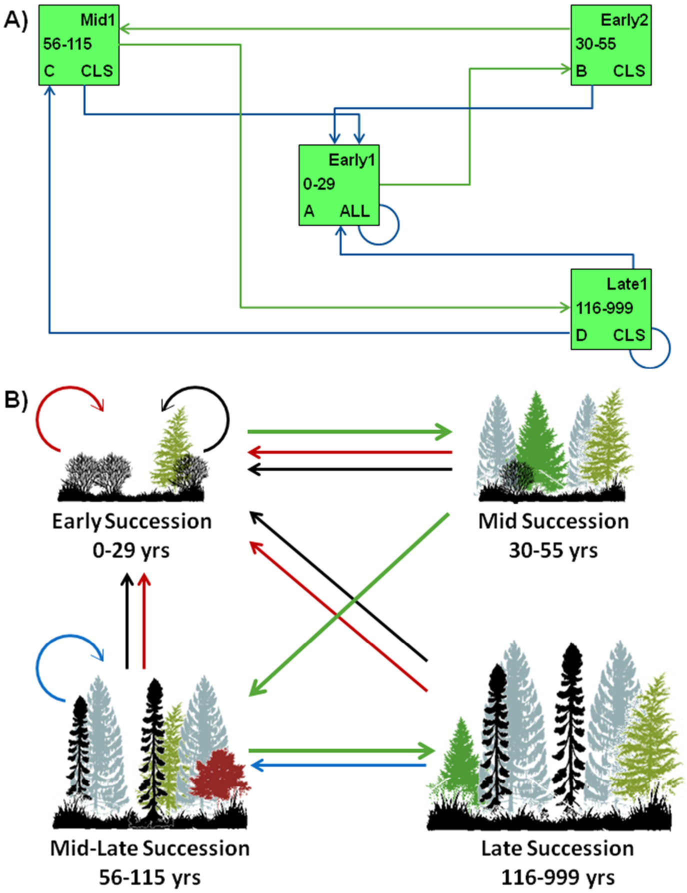


Figure 4. A 'box' diagram of the state and transition model developed in VDDT to simulate the dynamics of the Alkaline Conifer Hardwood Swamp ecosystem (A) and the corresponding conceptual diagram developed to explain the same model to experts (B).

To target expert discussions and narrow the potentially overwhelming set of possible model variables and parameters, the project team defined the information needed from experts in two ways. First, we developed very specific questions that were manageable in breadth, each phrased as relevant to only one of the many modeled cover types, e.g. how well can forestry practices restore species and structural diversity to northern hardwood forests? Second, we provided initial parameter approximations for each scenario to serve as a starting point.

Importantly, information not useful for model parameterization may be useful for forming spatial narratives to explain model outputs. For example, experts may provide information pertinent to stand-level dynamics, such as the potential loss of tree or herbaceous species currently at the northern edge of their range due to climate change. However, the VDDT and TELSA modeling captures dynamics at a landscape scale. While such stand-level details cannot be captured within the model, spatial narratives can synthesize spatial model outputs with expert input and previous research to illuminate the characteristics within and between stands in possible future landscapes. Expert input elicited during this workshop was integrated into models after the workshop, and each scenario was modeled with this set of initial parameters.

After initial modeling runs, a second web-based workshop (Figure 1, Workshop 2) was held to gather local and regional expert input on the maps of possible future landscapes resulting from the current conservation scenario. During the workshop, maps of possible land cover resulting from each scenario 25, 50, 75, and 100 years into the future were presented. Maps of natural disturbances and of management activities over this time period were also presented (Figure 5). Output maps were also available to experts through an online collaborative tool described in below. For each set of maps, experts were asked if the outputs were reasonable and, if not, how the models could be improved to more accurately capture the landscape dynamics in the study areas. Specifically, experts were asked to comment on the location and magnitude of each disturbance type and management activity while considering both the land cover type and ownership.

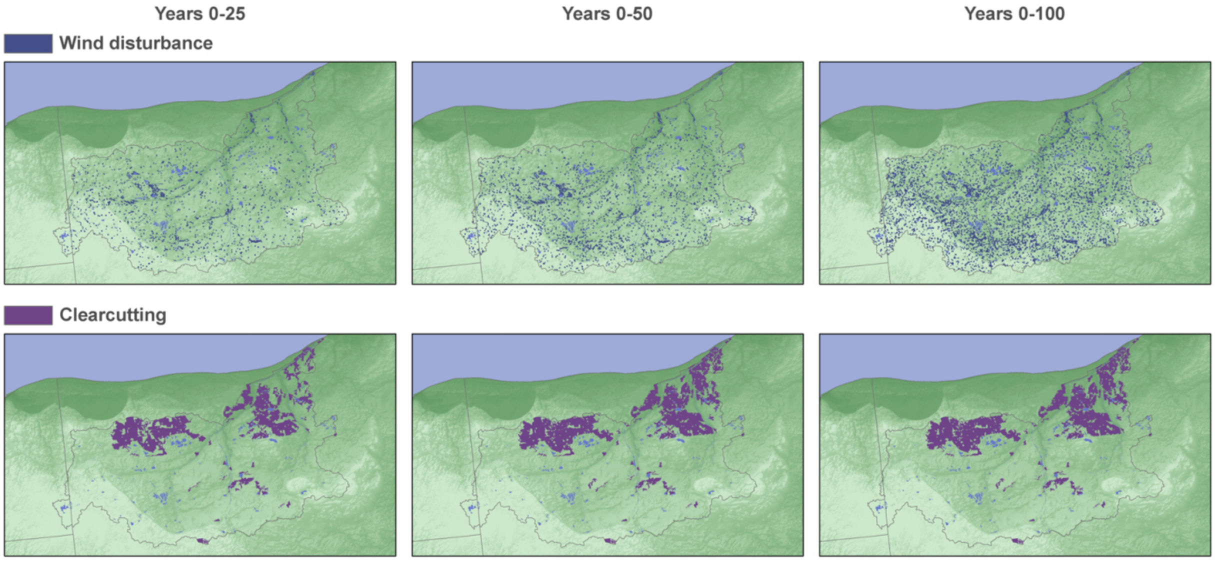


Figure 5. Time series maps of simulated wind disturbance and clearcutting in the Two Hearted River watershed under the "Current Management" scenario. For each scenario, time series maps of land cover and management as well as fire, wind, flooding, and insect and disease pathogens were generated.

One-on-one interactions with experts

Because refinement of model parameters requires detailed and often quantitative inputs too narrow or technical to be adequately addressed in workshop format, expert input was also elicited through one-on-one interactions. These interactions consisted primarily of informal phone conversations and email exchanges with experts individually. In general, these questions focused on defining specific model parameters necessary to accurately simulate the spatially and technically varied management regimes employed in different scenarios.

Remote one-on-one interactions were often supplemented by the use of information sharing technology. Online meeting technology (e.g. WebEx, www.webex.com) allows sharing of visuals during a phone conversation. For example, during these meetings we viewed and demonstrated VDDT models, inspected spatial data, and opened websites. While it is often possible to share documents ahead of time via e-mail, this method is more interactive and flexible.

Data Basin as an online collaborative tool and data repository

To supplement workshop and one-on-one interactions, expert input on modeling results and parameters was also elicited using Data Basin, an online collaboration tool developed by the Conservation Biology Institute (www.databasin.org). Data Basin enables remote workgroup communication and feedback, sharing of spatial and non-spatial data, and interactive mapping without the need for GIS experience or software. Conceptual diagrams and descriptions of ecosystem models were posted to enable experts to review and comment on model parameterization. We encouraged use of discussion space for comments, textual discussions, and "at your leisure" review of materials.

Narrative building

Spatial scenario output alone, in the form of classified maps and summary statistics, can still be abstract and difficult to interpret, particularly by those working on the ground. For example, end users may want to explore how projected land cover change will affect target conservation species, or what compounding factors may or may not lead to changes in the pattern of wetland ecosystems. Thus, a second set of in-person workshops (Figure 1, Workshop 3) were held for each study area, in which experts worked with the project team to build spatial narratives, or storylines, around the projected landscape futures. These narratives describe hypothesized human-ecological dynamics behind the simulated landscape change and impart place-specific meaning to otherwise neutral map outputs (Silbernagel 2005).

The format and contents of spatial narratives should be tailored to both the project and target audience. While the narratives resulting from this project will be reported in a future publication, they follow a general sequence beginning with a socio-ecological description of the study landscape from pre-European settlement through present day, answering the question ‘how and why did today’s landscape come to be?’ For example, previous forest managers perceived mixed northern hardwood stands on sandy soils as unproductive for sugar maple (*Acer saccharum*), a historically highly valued timber species, and chose to liquidate sugar maple from those areas to capture its economic value, leaving lower value American beech (*Fagus grandifolia*) and red maple (*Acer rubrum*). This historical management has left two important legacies on today’s landscape – (1) areas of mixed northern hardwoods in which sugar maple was removed now have an unusually high beech component, increasing their susceptibility to beech bark disease, and (2) tree biodiversity has been lost in areas previously targeted for sugar maple production as the species grew to dominate these stands by repressing regeneration of shade-intolerant northern hardwood species. This portion of the narrative is shared by all scenarios and explicitly acknowledges that present day forest conditions and patterns, the starting point for modeling future scenarios, is a result of the area’s land use legacy and underlying geologic history. As one expert explained during Workshop 3, “You have to think about where we’ve been to figure out where we’re going.”

Next, the narratives of alternative future scenarios diverge to explain the landscapes resulting from differing scenario conditions. Here, the question ‘how and why did this landscape come to be?’ is answered from a future vantage point. By way of example, we can continue to focus on specific areas dominated by an unnaturally high proportion of sugar maple. Under the No Conservation Action scenario, the market value for timber and pulp are assumed to drive management decisions, and the stumpage price for sugar maple is expected to remain high. Model results show areas of sugar maple dominated forest expanding, causing a loss of diverse mixed northern hardwood. Under the Ecological Forestry scenario, management is aimed at restoring diverse or characteristic structure and composition, with economic gains a secondary concern, and model results show a reduction in the total area of sugar maple dominated forest. The narrative focuses on explaining the economic, social, and small-scale ecological repercussions of these mapped, spatially explicit differences, and highlights tradeoffs. For example, the higher level of harvest under the No Conservation Action scenario may provide more forestry-related jobs and income to the area and increase habitat suitable for game species such as deer. However, production oriented harvest may also lead to a loss of biodiversity and increase the vulnerability of the forest to insect and disease pathogens. Also, private, industrial ownership of forested areas may limit public access to recreation, hunting, and non-timber forest products, all of which are culturally significant to the residents of the area. In contrast, the Ecological Forestry scenario may increase forest biodiversity and provide more habitat for species sensitive to anthropogenic disturbance while providing fewer forestry-related economic benefits. Importantly, the increased expense of restoration forestry practices may inhibit its application over time.

As the simplified example above illustrates, spatial narratives provide a multi-disciplinary and locally relevant analysis of scenario results, bringing in economic, social, and ecological drivers and consequences. They also provide an opportunity to capture important landscape dynamics not handled by the modeling software, such as changes in species composition and nutrient cycling. In our case, we supplemented stand level model results with information from the Tree Atlas (Prasad et al. 2007-ongoing; Iverson et al. 2008), other modeling efforts (Scheller and Mladenoff 2008), and analyses (Swanston et al. 2011; WICCI 2011a,b; Birdsey et al. unpublished report) to explain possible future changes in tree species composition and its influence on biodiversity and ecosystem service targets. Experts are key sources of information regarding the past, present, and future human-ecological dynamics on these landscapes. With expert input and spatial narratives, we can more fully capture the feedbacks between management decisions, economic drivers, natural disturbance dynamics, and the possible effects of climate change.

Also during this stage, experts helped distinguish plausible from implausible scenarios and helped identify the most likely origin of implausible results by considering such contributing factors as human error, poor input data, poor match of software to issues, and technical difficulties. In this way, expert input from Workshop 3 guided model revisions to produce more realistic simulations of possible future landscapes.

INSIGHTS AND IMPLICATIONS

Recommendations for selection of experts

Experts should represent the agencies and organizations involved in the management of the study area and provide insights into subject areas identified by the project team. To widen the expert pool, experts can recommend peers who could contribute to the project. While there is no ideal number of experts or spatial scale of information, consultation of multiple experts and sources of quantitative data at both local and regional scales increases the likelihood of compatibility and provides insight into the range of variation across the landscape. Whether one or many experts are consulted, project teams should be cognizant of expert uncertainty and quantitatively evaluate within and between expert uncertainties when possible. Differences in expert opinion may be the result of differing professional experience, and sub-sampling of expert groups representing many fields may be necessary (Czembor et al. 2011).

Importantly, the locally tailored scenarios and modeling outcomes resulting from expert input are only applicable to the study areas under consideration. Therefore, the scenario-building and modeling process, including selection of an expert pool, must be repeated for each area of interest. Such specificity can be seen as an advantage or a disadvantage depending on time and funding constraints as well as the availability and willingness of local experts and practitioners to participate in the process.

Recommendations for utilizing each mode of expert input

Below we describe the benefits and considerations associated with each method of expert knowledge elicitation employed at each stage of the project (Table 3). Given the varied types of expert input required for collaborative scenario-building and modeling, we anticipate a hybrid approach that employs multiple modes of interaction in concert will be most effective. While the need for effective mediation of expert discussions seems obvious, the open-ended nature of both workshops and one-on-one interactions and the need for elicitation of unanticipated knowledge makes this point worth emphasizing. The basic tenets of good meeting facilitation apply in all interactions (e.g., advance preparation, facilitator impartiality, conflict resolution, and solicitation of input from all attendees). In workshop settings, facilitators should be cautious to avoid forcing consensus among experts, especially with regard to model parameters, and take precautions to avoid dominance by one or a few group members as well as groupthink (Janis 1972), as both can result in over-confidence and biased models (Czembor et al. 2011). For example, all experts involved in this study were given the opportunity to review alternative scenarios, model parameters, and results independently during one-on-one interactions and using the online collaborative tool.

Table 3. Benefits and considerations associated with each method of expert knowledge elicitation.

Project stage and elicitation methods	Benefits	Considerations
Scenario development		
In-person workshop	Gathers input from many experts at once; Establishes rapport among researchers and experts; Provides opportunity to visit study areas.	Supports multi-media presentations; Time consuming and expensive to plan and host; May require travel by project team and participants resulting in a larger carbon footprint.
Model parameterization		
Web-based workshops	Easier to schedule than in-person workshops; Gathers input from many experts at once; Inexpensive; Good for gathering general or 'ballpark' figures for parameters; Ideal for presenting results, such as model outputs, that are easily conveyed in digital format.	May need to hold multiple workshops for model parameterization; Participation is limited; Requires access to and comfort with web conferencing technology; Should follow in-person interactions if possible.
One-on-one interactions	Greater flexibility in scheduling, location, and discussion topics; Facilitates gathering detailed information for parameterization, especially capturing specifics not included in peer-reviewed or agency publications; Lack of formal agenda is conducive to gathering unanticipated input; Builds rapport with experts.	Time consuming; Relies on a single expert as the source of reliable information.
Spatial narrative building		
In-person workshop	Conducive to sharing map outputs; Enables discussion	See above.

	and debate among experts.	
Data Basin	Facilitates continued expert participation; Allows experts access to project information and results; No need for access to or experience with expensive, complicated GIS software.	Requires time investment for startup and maintenance, perhaps third-party help; Maintaining expert interest and participation is challenging; Best used as supplement to other elicitation modes.

It is essential to clearly define the expectations of the project team at the start of each meeting to minimize misunderstandings and maximize the amount and quality of information received. While advanced preparation on the part of the project team can ensure that discussions stay on-topic, care should be taken to remain flexible, as unanticipated input may alter how the interaction, a particular stage, or the entire project proceeds. Flexibility can also give the experts a sense of ownership and further engage them in the project.

In-person workshops

In-person workshops provide input from multiple experts on several topics in a setting conducive to discussion and interaction. Situating in-person workshops near study sites provides the opportunity for field visits in which experts can familiarize the project team with the study area and provide examples of different landscape features, management regimes, and ecosystem responses to specific drivers of landscape change. This is especially helpful when local experts and practitioners use local references and language during the workshop. In-person interactions promote familiarity and trust between project team members and local experts, and increase the likelihood of continued expert involvement and support. Therefore, we suggest planning in-person workshops early in the project timeline if possible. However, in-person workshops require significant planning, demand a greater time commitment from both planners and participants, have a greater carbon footprint, and are more costly than remote communication.

Web-based workshops

Alternatively, web-based workshops excel when time is tight, travel budgets are slim, and experts are geographically distributed. A variety of web-based and telecommunications software are available to host remote workshops, and project teams should consider the clarity in which they are able to present information and the ease in which expert participants are able to log on, view project information, and provide feedback. Special consideration should be given to the types of visual information to be shared and the accessibility and ease of use of sharing technologies to experts. In our experience, web-based workshops are more successful once rapport with experts and familiarity with project study areas have been established. Therefore, we recommend holding web-based workshops after in-person interactions with experts and field visits, if possible.

One-on-one interactions

While in-person and web-based workshops offer a format for efficient and focused discussion among a group of experts, one-on-one interactions can delve more deeply into specific questions or detailed information. Here, specificity is gained while the ability to brainstorm or collaborate with a group is lost, and there can be a tendency to rely on one expert for reliable information, though the project team can subsequently check facts as needed. However, one-on-one interactions provided greater flexibility in scheduling, location, and discussion topics, as well as a more relaxed setting, than in-person or web-based workshops. In the absence of a formal agenda, experts are more likely to provide unanticipated but useful information. In our experience, a personal relationship with the expert increases the odds of a successful one-on-one interaction and subsequent interest in project outputs. The project team can build trust and rapport with experts by meeting in a location and atmosphere that is comfortable for the expert.

Online collaborative tool

A major challenge to collaborative projects is obtaining continued involvement of participants. Data Basin is one of several online, GIS-based tools available to display two dimensional maps or three dimensional landscape visualizations of alternative landscape futures (Lovett 2005) to aid in both urban and natural resource planning. When choosing and employing such tools, project teams must be cognizant of the strengths and weakness of the approach (Pettit et al. 2011) and should clearly communicate the assumptions underlying each alternative landscape and the limitations of the visual material (Monmonier 1996; Sheppard 2001).

These tools allow continued review and discussion of project materials at experts' convenience outside of scheduled workshops or meetings. The Data Basin project gallery was effectively used during and after web-based workshops and to supplement one-on-one interactions. However, the natural resources experts we engaged tended to prefer discussing forest conservation issues in the field, and efforts were made to engage these experts through one-on-one interactions. The project team may need to regularly send announcements and project updates to keep experts involved in the online collaboration. At this time, access to this project on Data Basin is still 'by invitation only' to workgroup members but will be publically accessible.

Implications

Integrating expert knowledge into scenario analysis and landscape modeling provides a mechanism for managing uncertain futures, allowing us to imagine future landscapes for which there may be no past analogues. This approach presents unique challenges – coupling technology with experts' imagination and creativity to produce useful outcomes can be difficult and sometimes infeasible with the available modeling tools. Some limitations are unavoidable; some situations simply cannot be modeled. Alternatively, software capable of modeling such situations may be available, but its use could be prohibitive due to intensive input requirements, platform limitations, applicability to end-users, or other constraints. Project teams should explicitly communicate with experts the rational for their choice of approach and modeling platform as well as the strengths and weaknesses of these tools (c.f. Scheller and Mladenoff 2007; Sturtevant et al. 2007).

In addition, there can be a conflict between model complexity and expert input. As model programming and parameters become more complex, more effort may be needed to frame issues, questions, and processes for experts. Many practitioners do not think in terms of parameterization, disturbance probabilities, or algorithms. Therefore, model transparency is paramount (Mendoza and Prabhu 2005; Sturtevant et al. 2007). From our experience, it was worth our time to produce schematics, visuals, and explanations of our modeling concept at the front end of an expert workshop so that professional, non-modeling experts are on the same page. This allowed the project team to collect expert knowledge in formats more familiar and accessible to local experts (e.g. fire return interval) and convert to another format required by the model (e.g. annual probability of fire).

Furthermore, spatial modeling outputs (e.g. maps and indices) of landscape futures alone do not explain why conditions changed from time step to time step. Instead, spatial narratives derived through collaborative interactions with experts with place-based knowledge (Silbernagel 2005) provide a richer, more complete understanding of the drivers underlying landscape change.

With so many variables in a natural system, there will be important drivers or responses of landscape dynamics that cannot be addressed by the quantitative modeling process as well as they can in qualitative spatial narratives. Thus, a spatial narrative approach can be a way of filling in gaps and making the project useful to a wider audience (Carpenter et al. 2006).

However, a project team may be tempted to push difficult modeling questions to the spatial narratives for convenience, especially in the face of a challenging effort to learn modeling software, select parameters, and adapt spatial data. Construction of a valid and insightful narrative involves equivalent effort by the project team and experts. Relevant spatial narratives result from a rigorous collaborative effort to search notes, recordings, and output, and to think about and discuss the plausible stories that led to the futures indicated by the modeling output.

Our approach recognizes and handles an uncertain future but does not reduce such uncertainty. The likelihood of one scenario over another cannot be measured, and results should not be considered predictions. As Scheller and Mladenoff (2008) explain, scenarios should be regarded as experiments and interpreted in context with and comparison to the alternative scenarios examined.

Landscape models informed by expert opinion are also uncertain. While a complete discussion of model uncertainty is beyond the scope of this work, we provide a brief overview below to summarize current thought. Uncertainty in these models is commonly divided into three components – modeled ecosystem stochasticity, uncertainty of an individual expert, and between expert uncertainty (Czembor et al. 2011). Natural ecosystem stochasticity is often captured by multiple Monte Carlo simulations or similar methods in which values are sampled from distributions for specific parameters, which can be based on historical data or future projections.

The uncertainty of individual experts can be estimated through self-assessment techniques (Drescher et al. 2008), bounded sensitivity analysis (Czembor et al. 2011), and other statistical methods. Kuhnert et al. (2010) suggest eliciting a quantitative confidence interval or probability distribution rather than a single parameter value from single experts. However, individual confidence intervals are often overestimated, and the degree of overestimation is influenced by the format of questions used to elicit the interval (Speirs-Bridge et al. 2010).

Between expert uncertainty results from disagreement between experts and is often overlooked by methods that reduce the opinions of many experts to a singular parameter value, such as forced consensus among experts, Delphi methods, or averaging expert responses. However, between-expert uncertainty should be explicitly considered when parameterizing models and interpreting results. Drescher et al. (2008) suggest that uncertainty of expert knowledge of forest succession is generally high, especially for systems with high species diversity and moderate site conditions, implying that an acute awareness of uncertainty is necessary when modeling these systems. Failure to consider model uncertainty may result in overconfidence in model results and undermine the reliability of decisions based on those results.

While the use of expert knowledge introduces additional sources of model uncertainty, published research alone often does not provide the detailed, site-specific information necessary to develop alternative landscape scenarios or to fully parameterize spatially explicit landscape models. As noted previously, forestry practitioners are often the only source of information about forest succession and dynamics, especially at local scales (Drescher et al. 2008). In addition, experts are the only source of information regarding the current and future management strategies employed on these landscapes, especially on private lands. As a result these models are, by necessity, a synthesis of previous research (e.g. LANDFIRE and peer reviewed literature), empirical data (e.g. fire data from the DNR), and expert knowledge. The iterative process of eliciting expert feedback on model results is crucial for refining models and scenarios and producing reasonable results. In addition, failure to engage experts affiliated with the agencies and organizations responsible for the management of the study areas could reduce the perceived credibility and subsequent utilization of project results.

CONCLUSIONS

To be effective, the conservation community must constantly seek innovative means to protect lands and waters, manage natural resources, and match public policy with conservation goals. The working forest conservation easements described here provide one example of such innovation, allowing for the distribution of limited conservation funds across larger landscapes (i.e., “distributed conservation,” Silbernagel et al. 2011) than would be possible with more traditional, fee-simple protection. Careful planning, rooted in scientific literature, generally precedes such conservation work. However, because the pace of conservation is driven by ephemeral alignments of opportunity and funding, the development and application of conservation strategies is rapid and often outpaces the availability of supporting information from peer-reviewed publications. While outcomes of these strategies will certainly become evident over time and through long-term monitoring efforts, the ability to envision possible futures resulting from untested strategies provided by this approach is crucial to evaluate, adapt, and inform ongoing and future conservation efforts. Furthermore, cost–benefit analysis similar to the approach described by Low et al. (2010) can be used to capture the budgetary considerations that also underlay decisions about how conservation strategies are arranged on the landscape.

Where conservation practices step beyond the support of peer-reviewed publications, information from experts can provide helpful data and insights that have not yet been published. In addition, a wealth of information can be gained from those experts whose knowledge base is not typically found in publications. Likewise, if the insights resulting from collaborative scenario building and modeling efforts are to be considered and adopted by decision-makers, researchers must reach beyond academic publications to present their findings in outlets focused on practitioners and decision-makers. For example, the results from this study will be presented at a regional conference focused on sharing tools for sustaining western Great Lakes forests. Ideally, conservation practitioners, land managers, and scientists in attendance at the conference can integrate this and other techniques into their own forest management efforts. Careful planning and preparation for interactions with experts, as examined in this study, combined with a spirit of adaptability and a willingness to follow unexpected leads and insights, can lead to a more thorough understanding of the implications of conservation actions. Indeed, successful collaboration increases the validity and transfer of results to those involved in making management and policy decisions affecting landscape conservation.

ACKNOWLEDGEMENTS

We appreciate the opportunity to develop ideas and structure for this paper through invitation and early reviews by A. Perera, C. Ashton Drew, and C. Johnson. The work presented has been funded with support from The Nature Conservancy’s Rodney Johnson/Katherine Ordway Stewardship Endowment grant, USDA Forest Service State and Private Forestry Redesign, the Doris Duke Conservation Fellowship Program sponsored by the Doris Duke

Charitable Foundation, the NSF IGERT Fellowship Program (DGE- 0549407), and the University of Wisconsin at Madison.

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CHAPTER 2

Collaborative scenario modeling reveals potential advantages of blending strategies to achieve conservation goals in a working forest landscape[1]

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ABSTRACT

Context. Broad-scale land conservation and management often involve applying multiple strategies in a single landscape. However, the potential outcomes of such arrangements remain difficult to evaluate given the interactions of ecosystem dynamics, resource extraction, and natural disturbances. The costs and potential risks of implementing these strategies make robust evaluation critical.

Objectives. We used collaborative scenario modeling to compare the potential outcomes of alternative management strategies in the Two Hearted River watershed in Michigan's Upper Peninsula to answer key questions: Which management strategies best achieve conservation goals of maintaining landscape spatial heterogeneity and conserving mature forests and wetlands? And how does an increase in wildfire and windthrow disturbances influence these outcomes?

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[1] This chapter was previously published in *Landscape Ecology*. Citation:
Price J, Silbernagel J, Nixon K, et al (2015) Collaborative scenario modeling reveals potential advantages of blending strategies to achieve conservation goals in a working forest landscape. Landscape Ecology 31(5): 1093-1115

Methods. Scenarios were modeled using the VDDT/TELSA state-and-transition modeling suite, and resulting land cover maps were analyzed using ArcGIS, Fragstats, and R statistical software.

Results. Results indicate that blending conservation strategies, such as single-ownership forest reserves and working forest conservation easements in targeted areas of the landscape, may better achieve these goals than applying a single strategy across the same area. However, strategies that best achieve these conservation goals may increase the sensitivity of the landscape to changes in wildfire and windthrow disturbance regimes.

Conclusions. These results inform decision-making about which conservation strategy or combination of strategies to apply in specific locations on the landscape to achieve optimum conservation outcomes, how to best utilize scarce financial resources, and how to reduce the financial and ecological risks associated with the application of innovative strategies in an uncertain future.

INTRODUCTION

Forest ecosystems are ecologically and economically critical, providing biodiversity and ecosystem services that support local economies. These systems rely on processes that span large areas and change over time in response to both natural and anthropogenic disturbances (Turner et al. 2001). As a result, successful management and conservation efforts must be broad in scale (10^3–10^6 ha) and capable of adapting to changing conditions to ensure the integrity of ecosystem dynamics (Boutin and Herbert 2002). These efforts often require multiple governance, ownership, and management strategies that span geographic and institutional boundaries.

In response, forest land managers and conservation practitioners are increasingly implementing distributed conservation strategies—efforts to spread limited financial and human resources over large areas and wide ranges of ownerships (Silbernagel et al. 2011; Price et al. 2012). As a result, rights and responsibilities to use and manage forest resources are distributed among many individuals, groups, and institutions, blending public and private resources and responsibilities. These relatively new strategies are based on the premise that combining resource use and conservation efforts should yield greater socio-economic benefits without significantly compromising biodiversity or provisioning of ecosystem services (Merenlender et al. 2004; Fairfax et al. 2005). Working forest conservation easements (WFCEs) are one such strategy. These legally binding, voluntary agreements between a landowner and an easement holder, often a government or non-profit organization, aim to protect the conservation values of a property while promoting sustainable forest management by restricting specific land uses and providing forest management guidelines (Block et al. 2004; Rissman et al. 2013). Similarly, functional zoning (or TRIAD) has also been proposed as strategy for balancing conservation values and timber extraction by dividing an area into three distinct zones managed for different values—

timber production, ecological management, and conservation—and has been applied in single, large ownerships (Seymour and Hunter 1992; Côté et al. 2010). However, functional zoning does not distribute management rights or responsibilities among multiple entities.

Understanding the potential long term, cumulative consequences of management actions at broad scales remains difficult given uncertain interactions between natural and anthropogenic disturbances (Gustafson et al. 2011). In addition, changes in climate variables and seasonal patterns are likely to influence northern temperate forests in myriad ways including shifts in natural disturbance regimes (Scheller and Mladenoff 2008; Mladenoff and Hotchkiss 2009; Janowiak et al. 2014; Duveneck et al. 2014b). Management actions must be adapted to such changes to remain responsive and effective (Gregory et al. 2006). Ideally, all managed areas are monitored over time, but monitoring efforts must often span decades to be meaningful. As a result, detection of and effective management responses to rapid environmental change are challenging. Furthermore, assessing the effects of disturbances through field experiments is difficult at broad spatial extents (He 2008; Gustafson et al. 2011).

Landscape modeling has been used previously to simulate management, policy, climate change, and resource or energy demand alternatives. In most forest landscape modeling examples, scenarios represent systematic variations in specific model variables designed by researchers to test hypotheses about the influence of each variable on landscape characteristics and processes (Radeloff et al. 2006; Hemstrom et al. 2007; Costanza et al. 2012; Duveneck et al. 2014a; Halofsky et al. 2014; Costanza et al. 2015b). In other cases, scenarios represent management alternatives for single-owner landscapes defined by the research team or a government agency (Gustafson et al. 2006b; Zollner et al. 2008; Côté et al. 2010; Gustafson et al. 2011). Rarely has landscape modeling been combined with collaborative scenario development involving local natural resource managers and other stakeholders (Provencher et al. 2007; Low et al. 2010; Meyer et al. 2014). Further, these tools have not been applied previously to investigate new approaches to conservation, such as WFCEs or cooperative ecological forestry, or the cumulative effects of management by multiple landowners and agencies on the broader landscape.

We advanced ecological modeling to inform cross-boundary natural resource management by engaging multiple natural resource managers working in a landscape to collaboratively develop and model scenarios representing a range of management alternatives. Involving land managers and conservation practitioners in the scenario development and modeling process has several advantages. First, the knowledge and experience of individuals working on the landscape, combined with peer reviewed literature and other field data, allows models to be tailored to specific locations. This approach recognizes that knowledge of forest succession and other processes often stems from land managers and is not always formally documented in peer-reviewed literature (Drescher et al. 2008). Second, the scenario modeling process and its outcomes are more likely to be utilized in practice when the individuals responsible for planning and implementing management actions are included (Daniels and Walker 2001; Hulse et al. 2004; Gustafson et al. 2006a). Finally, the collaborative process can build trust, social capital, and informal relationships among local resource managers, which have been identified as important to the success of broad-scale management actions (Gibson et al. 2000; Baker and Kusel 2003; Dietz et al. 2003; Pretty 2003; Ostrom and Nagendra 2006; Plummer and FitzGibbon 2007; Rissman and Sayre 2012). Exploring alternative scenarios may better equip citizens and practitioners to develop resilient management and conservation practices when faced with the irreducible uncertainty associated with changing climate, ecosystem dynamics, and socioeconomic conditions (Peterson et al. 2003; Hulse et al. 2004; Nassauer and Corry 2004; Coreau et al. 2009; Mahmoud et al. 2009; National Research Council 2014). When multiple landowners and agencies are involved in the scenario development and modeling process, as described here, collaborative scenario modeling may help identify the potential conflicts and synergies of these entities in managing a single landscape.

A landscape modeling framework that is rapid, transparent, and transferable to land managers and conservation practitioners is critical to achieving this goal. We chose spatial state-and-transition modeling (STM) using the VDDT/TELSA modeling suite. This stochastic, empirical simulation model was designed to project the spatial interactions of succession, natural disturbances, and management at broad spatial scales (up to 250,000 ha) over decades to centuries (Kurz et al. 2000; ESSA Technologies Ltd. 2007; ESSA Technologies Ltd. 2008). STMs and VDDT/TELSA in particular have been widely employed to simulate the effects of management in other landscapes of conservation interest (Forbis et al. 2006; Provencher et al. 2007; Hemstrom et al. 2007; Costanza et al. 2012; Costanza et al. 2015a; Costanza et al. 2015b).

STMs are well-suited for collaboratively simulating alternative landscape scenarios for several reasons. STMs explicitly consider the spatial interactions of management and disturbances at large spatial extents, capturing the scale and processes relevant to natural resource management and planning. Vegetation communities, ecological succession, and the impacts of management and natural disturbances are distinct components of the model and their behavior is explicitly represented (Costanza et al. 2015a). This intuitive, transparent representation of ecosystems can be more easily communicated, explored, and refined through a collaborative process with stakeholders than digital global vegetation models or other mechanistic models that represent vegetation as plant physiognomic types, an abstract view of vegetation that is more difficult to use for management planning (Scheller and Mladenoff 2007; Daniel and Frid 2012; Kerns et al. 2012). STMs can be parameterized using expert knowledge to capture the dynamics of local ecosystems, and parameters can be easily adjusted to explore alternative management scenarios and plausible changes in natural disturbance regimes. Also, while many simulation models capture only forested ecosystems, STMs can be parameterized to simulate any vegetation type or land use, making them ideal for applications in landscapes with multiple ecological communities such as forests and wetlands (Daniel and Frid 2012; Costanza et al. 2015a). The VDDT/TELSA modeling suite was specifically chosen for its potential for rapid deployment owing to its open-source, freely available software platform and its compatibility with LANDFIRE data products, including Vegetation Dynamics Models and land cover data (LANDFIRE 2007a; LANDFIRE 2007b). Importantly, the availability of nation-wide LANDFIRE land cover maps and accompanying STMs facilitates the application of this approach here and transferability to other areas in the U.S.

We applied this approach in the Two Hearted River watershed (THR) located in the Upper Peninsula of Michigan, USA. The watershed is a complex mosaic of forest and wetland patches interspersed on the landscape, displaying an inherently fragmented, patchy pattern due to the underlying land form and surficial geology. This landscape remains relatively intact and spatially heterogeneous, though historic land use and management practices have homogenized and simplified the species, age, and structural composition of this landscape and the region (Karamanski 1989; Beyer et al. 1997; Zhang et al. 1999; Schulte et al. 2007; Michigan-DNR 2012; Wisconsin-DNR 2012). As a result, the THR was included in the Northern Great Lakes Forest Project, a collaborative effort among natural resource management agencies, conservation organizations, and local resource users to protect the ecological integrity of the watershed and the Upper Peninsula more broadly (TNC 2005; McGowan 2010; TNC 2010). Central to achieving this conservation goal is developing management strategies that maintain or enhance its characteristic spatial heterogeneity and the mature forests and wetlands that support biodiversity, ecosystem services, and timber harvesting. Local foresters, ecologists, and land managers collaboratively developed four alternative management scenarios for the watershed: 1) continuation of current management, 2) industrial forestry, 3) expanded area under working forest conservation easement, and 4) cooperative ecological forestry. These experts also identified possible changes in the natural disturbance regime, specifically increased probability of wildfire and windthrow, as an issue of concern due to potential interactions with management activities (Price et al. 2012). Collaborative landscape scenario modeling allowed us to answer three sets of questions relating to the management and conservation of this landscape (Table 1):

1. How do these management scenarios differ in their ability to maintain characteristic landscape spatial heterogeneity, and which land cover classes are responsible for this pattern in each?
2. How do these management scenarios differ in their ability to conserve mature forests and wetlands?
3. How does an increase in wildfire and windthrow disturbances influence these outcomes?

These results will inform whether different management strategies are likely to achieve watershed conservation goals, information critical to natural resource management in the THR watershed and other similar landscapes. This research demonstrates how collaborative scenario modeling and STMs can serve as resources for management planning by bringing natural resource managers together to develop a shared understanding of the local ecological system and conservation goals and by serving as tools to assess a variety of management strategies under a range of future conditions.

Table 1. Experimental design for simulating alternative management scenarios and natural disturbance regimes as well as the response variables measured for each scenario. Each management strategy was simulated under the current natural disturbance regime and under increased probability of wildfire and windthrow for a total of eight model runs. Each response variable was measured using multiple landscape metrics or measures.

Treatment Factors	**Levels**	**Response variables**
Management strategy	1. Current management 2. Industrial forestry 3. Expanded easement 4. Ecological forestry	1. Landscape spatial heterogeneity—measured by number of patches, mean patch size, contagion 2. Area of mature forest and wetland—measured by average age of land cover, proportion of the landscape occupied by mature vegetation
Natural disturbance regime	1. Current 2. Increased probability of wildfire and windthrow	

METHODS

Study area and land cover data

The Two Hearted River watershed encompasses 53,653 ha of Michigan's Upper Peninsula (46°-42'06" N and 085°-24'52" W) and is situated in the northeastern portion of Ecological Province 212R, the Eastern Upper Peninsula Section of the Laurentian Mixed Forest Province (Cleland et al. 1997; McNab et al. 2007). Land cover was mapped in the year 2000 at 30m resolution and classified according to NatureServe's Ecological Classification used by LANDFIRE (Comer et al. 1995; LANDFIRE 2007a). Using this classification, land cover in the Two Hearted River watershed falls into eight types—boreal acid peatland (9,546 ha, 18% of the watershed), alkaline conifer hardwood swamp (8,565 ha, 16%), jack pine barrens (3,834 ha, 7%), northern pine oak forest (10,758 ha, 20%), northern hardwood hemlock forest (8,122 ha, 15%), northern hardwood forest (8,600 ha, 16%), pine hemlock hardwood forest (2,615 ha, 5%), and shrub herbaceous wetland (1,494 ha, 3%; Figure 1, Appendix 1). Mapping using the same classification system as LANDFIRE allowed us to use LANDFIRE Vegetation Dynamics Models as described below.

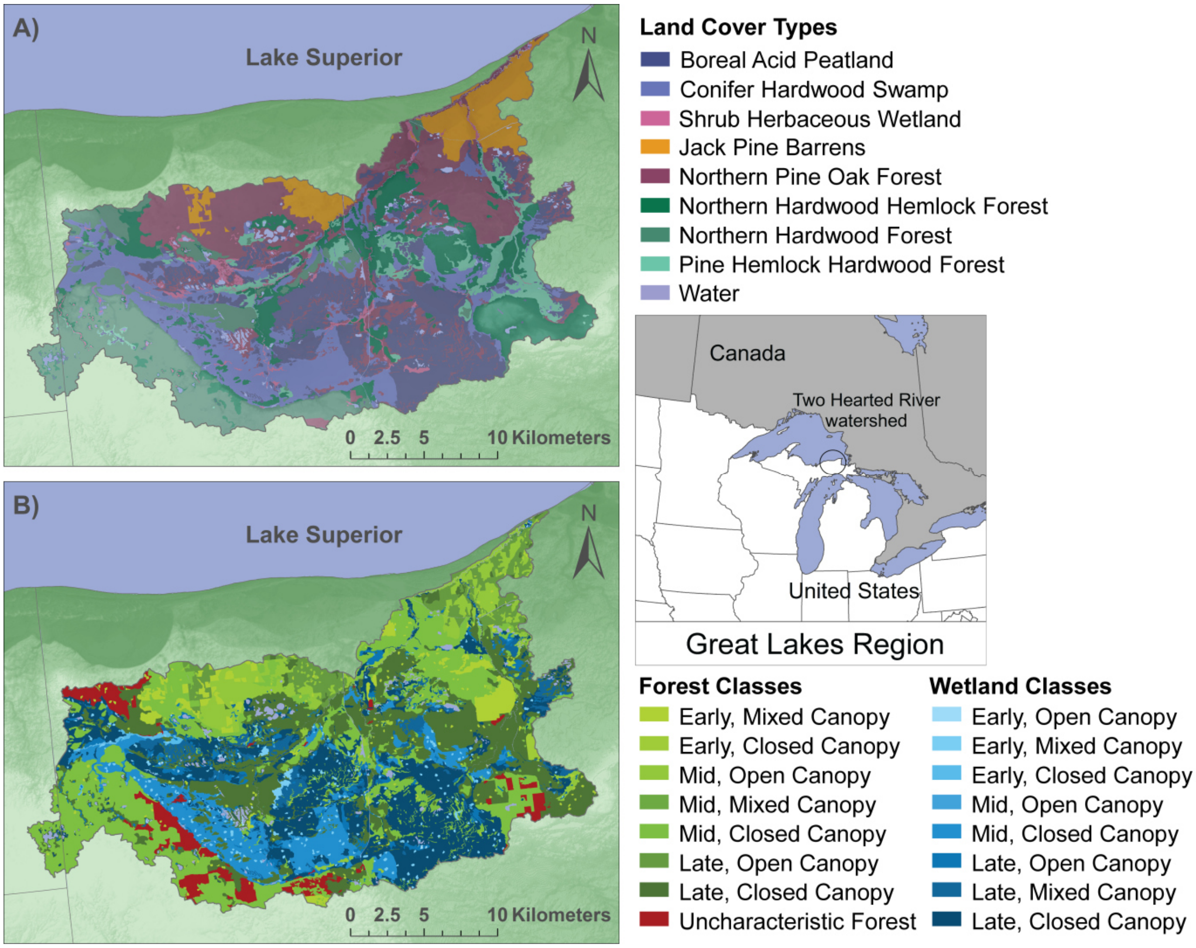


Figure 1. A map of the Two Hearted River watershed showing current land cover (A) classified according to the NatureServe's Ecological Systems classification (Appendix 1) and (B) reclassified more generally as forest and wetland of a specific age and canopy closure (Appendix 3). Inset shows the location of the study area within the Great Lakes Region.

Expert engagement

To develop landscape scenarios and models tailored to the management concerns and ecological conditions of the THR watershed, we assembled a team of local and regional experts that consisted of scientists and land management practitioners that work on this landscape. The process of assembling an expert team and utilizing expert knowledge in the scenario development and collaborative modeling process was fully described by Price and colleagues (2012). Briefly, local experts were chosen for their knowledge base and their affiliation with the agencies and organizations responsible for the management of the study area, including the Michigan Department of Natural Resources (DNR), The Nature Conservancy (TNC), and timber investment management organizations (TIMOs). Regional experts were primarily academic and agency scientists capable of considering the project within the context of broad-scale forest management and monitoring in the western Great Lakes region. Experts were selected to achieve a representation of subject-specific expertise to ensure that gaps in the literature could be addressed by a member of the team. Expert knowledge was integrated into the scenario-building and modeling process in three stages – (1) scenario development, (2) model parameterization and validation, and (3) results review.

Alternative management scenarios

Experts identified four plausible management scenarios for the THR watershed described in more detail below: 1) continuation of current management, 2) industrial forestry, 3) increased area under working forest conservation easement, and 4) cooperative ecological forestry. Each scenario represents a unique spatial arrangement of hypothetical ownership boundaries, each with a specific management regime, on the landscape (Figure 2). In the case of the Ecological Forestry scenario, a single management unit was established across ownership boundaries as detailed in the scenario description below. For each management strategy – selection cutting, clearcutting, thinning, and restoration forestry - the entry size, return interval, total annual harvest goal, and spatial arrangement of management activities in each land cover class were defined by experts (Table 2).

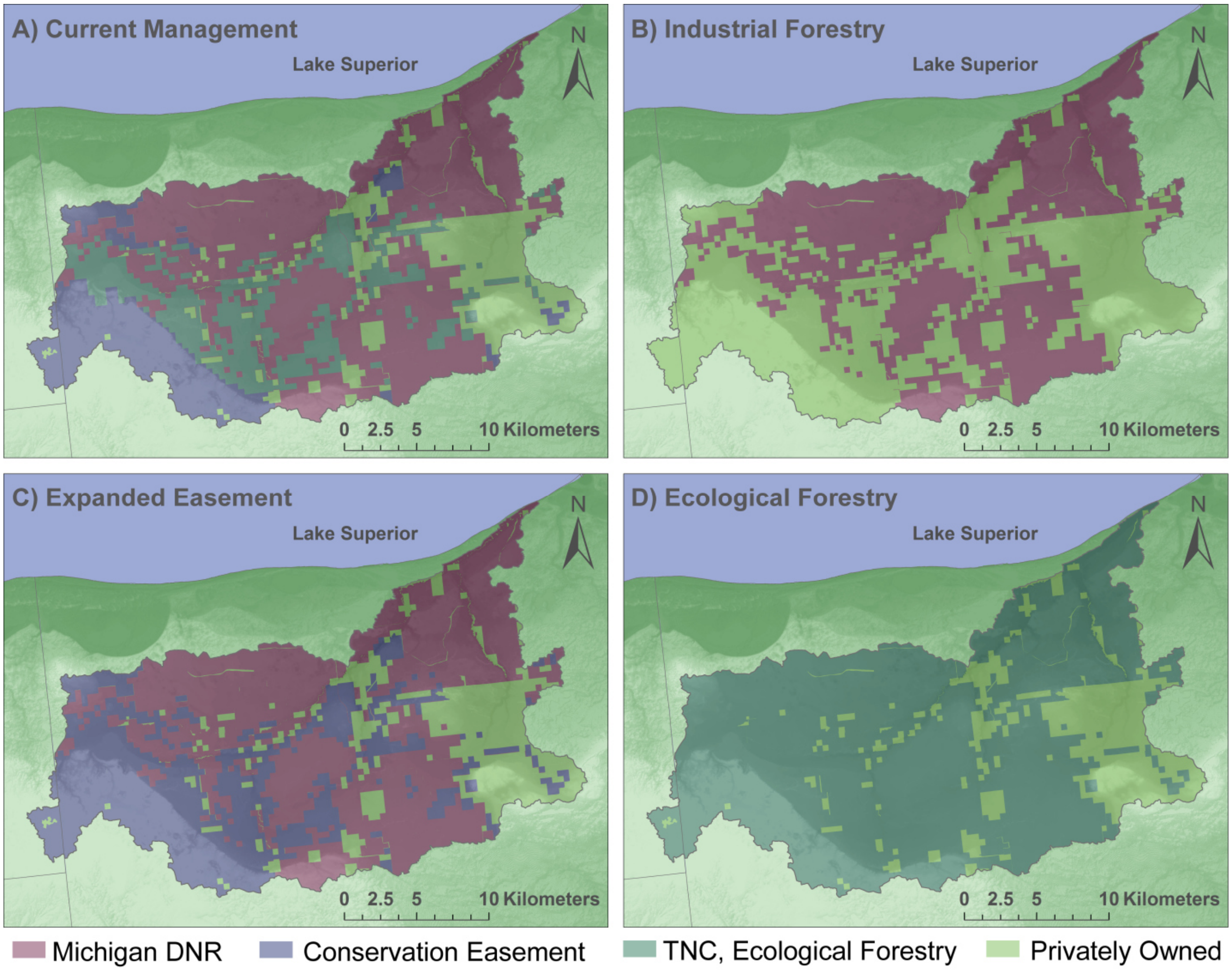


Figure 2. Maps showing management boundaries under four alternative landscape scenarios for the Two Hearted River watershed.

Table 2. Management parameters for the four different management scenarios aggregated to the landscape level to show total annual area targets for each management activity. Table adapted from Nixon et al. (2014).

	Management activity area (ha/yr)				
Management strategy	**Selection cutting**	**Thinning**	**Clearcutting**	**Restoration**	**Total harvest goal (ha)**
Current Management	171, years 1-20 789, years 21-100	923, years 1-25 819, years 26-50 715, years 51-100	429	60	2129, years 1-20 2210, years 21-25 2106, years 26-50 2002, years 51-100
Industrial Forestry	871	1119	476	0	2466
Expanded Easement	803	1089	452	57	2401
Ecological Forestry	1006	208	249	202	1665

Current Management

This scenario simulated the current spatial arrangement of ownership on the landscape and a continuation of current management practices that resulted from the Northern Great Lakes Forest Project (TNC 2005; McGowan 2010; TNC 2010). Under this scenario, 50% of the landscape was managed by the Michigan DNR to provide habitat for wildlife, enable a variety of recreational activities, and support sustainable timber harvest. Fifteen percent was managed under WFCE restrictions by a TIMO with the goal of conducting sustainable timber harvesting while maintaining the ecological integrity of the forest. TNC managed 18% of the landscape as a reserve with the management goal of protecting wetland ecosystems and restoring forest species, age, and structural diversity through management activities. The remaining 17% was held in many, relatively small, private ownerships (Figure 2A). While the individual goals of private non-industrial forest landowners vary, we assume that these individuals are enrolled in either Michigan's Commercial Forest Program or Qualified Forest Programs, which are forest tax programs that encourage sustainable forest management on private lands by providing property tax incentives to landowners (Michigan-DNR 2014a; Michigan-DNR 2014b). Under the Current Management scenario, the total area managed annually was larger than under the Ecological Forestry scenario but smaller than under the other two scenarios (Table 2). The majority of wetlands were located in the TNC management zone, where they were treated as a reserve with no timber harvest.

Industrial Forestry

This scenario simulated an alternative future in which private industrial timber interests owned all lands not currently owned by the Michigan DNR (50% of the landscape) and managed this area for maximum timber productivity (Figure 2B). To simulate timber harvest by multiple, private owners acting independently, conventional forestry techniques were applied in privately-owned areas, and the location of management disturbances were not spatially aggregated. Current management techniques were applied on Michigan DNR lands. The minimum size of individual management disturbance events was larger in the privately-owned area in this scenario than in any area in the Current Management or Expanded Easement scenarios. With the singular goal of maximum timber production, industrial timber interests were assumed to maximize harvest per entry, while entry sizes in the DNR, TNC, and easement areas were limited to accommodate the ecological conservation goals of these ownerships. The Industrial Forestry scenario had the largest annual harvest goal of all four scenarios and the largest annual area of even-aged management, but only slightly more than Current Management and Expanded Easement scenarios (Table 2). Under this scenario, alkaline conifer hardwood swamp in the privately owned area was managed for timber harvest.

Expanded Easement

In this alternative future, the area currently owned by TNC was placed under a WFCE instead. Current management strategies were applied in this larger easement area (33% of the landscape), in the Michigan DNR management area (50% of the landscape), and in the privately-owned area (17% of the landscape, Figure 2C). Management activities in the easement area were spatially aggregated to reduce fragmentation. Under this scenario, forested portions of boreal acid peatland and alkaline conifer hardwood swamp in the easement area were managed for timber harvest as allowed by the Michigan DNR's best management practices for forestry (Michigan-DNR 2009).

Ecological Forestry

This scenario simulated cooperative, ecological forestry across the whole THR watershed, excluding privately-owned areas (Figure 2D). Ecological forestry is a silvicultural approach in which management activities mimic natural disturbances and stand dynamics with the goal of maintaining the heterogeneous stand structure, biological legacies, and spatial patterning that are responsible for biodiversity, ecosystem functions, and resilience to disturbance (Franklin et al. 2007; Hanson et al. 2012). Lands in the current TNC, Michigan DNR, and easement areas were managed as a single unit comprising 83% of the landscape using ecological forestry practices—management activities were spatially aggregated to reduce fragmentation, and maximum entry sizes were smaller than in any other scenario. Restoration forestry was included to reduce maple monoculture and achieve old growth characteristics. Red and sugar maple are natural components of these forest types, but a combination of deer herbivory, fire suppression, and a legacy of harvesting more desirable timber species ('high grading') has resulted in maple dominance in stands that were historically more diverse (Beyer et al. 1997; Crow et al. 2002; Schulte et al. 2007; Wisconsin-DNR 2012). Current management was applied in privately-owned areas (17% of the landscape). The Ecological Forestry scenario had the smallest area managed under even-aged management and the smallest total annual harvest goal of all scenarios. On the other hand, this scenario had the largest annual area of selection harvest and restoration (Table 2). No wetland cover types were managed for timber harvest in the Ecological Forestry scenario.

Landscape modeling

We used a two factor experimental design for landscape modeling, simulating each of the four forest management scenarios described above under two natural disturbance regimes—current natural disturbances and the increased probability of wildfire and windthrow (Table 1).

Spatial state-and-transition modeling framework

Landscape scenarios were simulated using the VDDT/TELSA modeling suite (ESSA Technologies Ltd. 2007; ESSA Technologies Ltd. 2008). A STM for each land cover type was developed in Vegetation Dynamics Development Tool (VDDT). In each model, successional stages were defined as 'state classes' with a specific age range, species composition, and stand structure. Transitions between states resulted from natural succession (aging), natural disturbances (including wildfire, windthrow, flooding, insects and diseases), and management activities and were simulated with an annual time step in a semi-Markov process. Figure 3 shows an example STM for Northern Hardwood Forest. Transitions via natural succession were deterministic and were defined by the age range of the state class. Natural disturbance transitions were probabilistic (Table 3), and management transitions were based on area targets (Table 2).

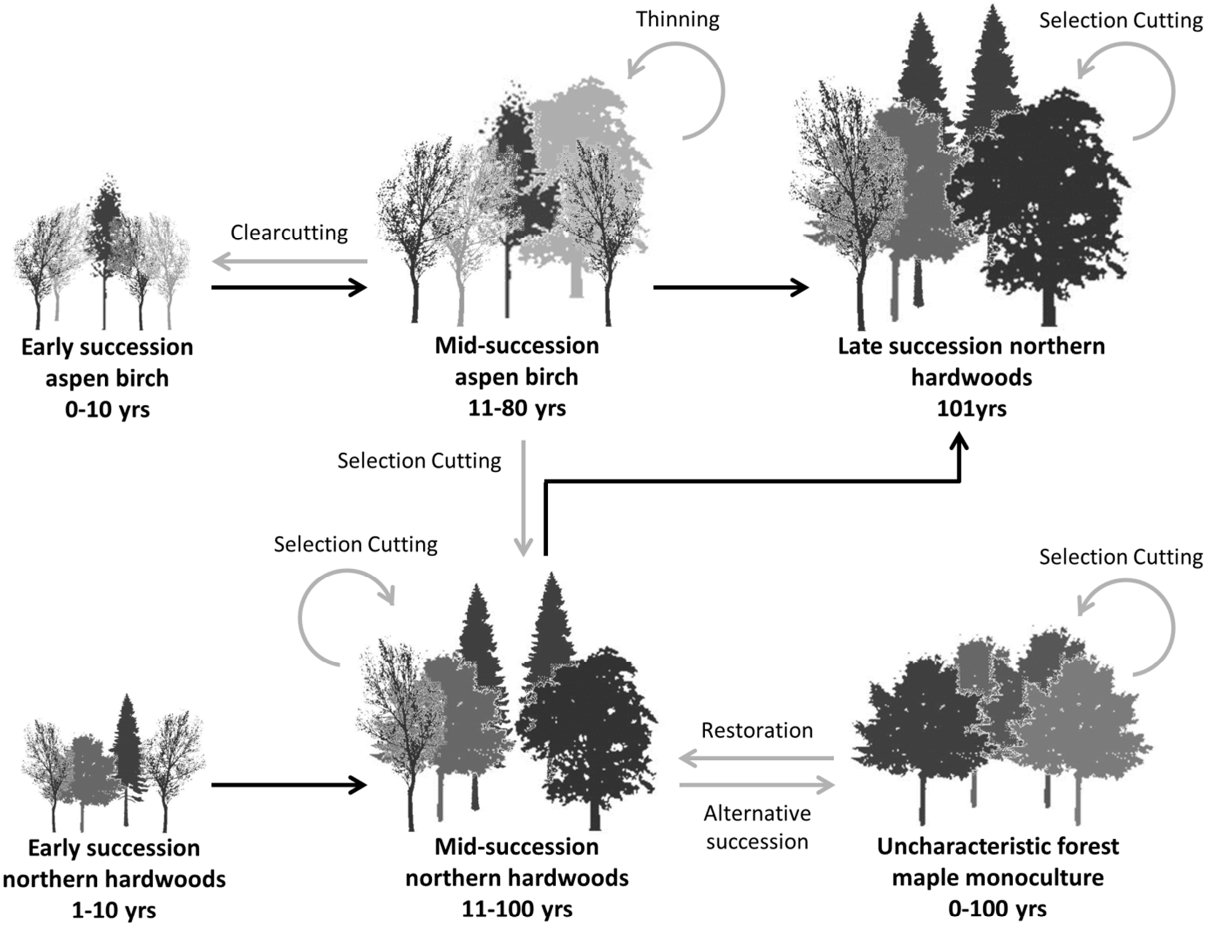


Figure 3. Example VDDT state-and-transition model pathway for Northern Hardwood Forest. This model was adapted from LANDFIRE base model 5113021. Transitions shown in black represent natural succession from one state to the next. Transitions shown in grey represent management activities and alternative succession. All state classes may experience replacement fire resulting in a transition to early succession aspen birch. Mid and late succession classes may experience wind disturbance resulting in a transition to early succession northern hardwoods. See Table 3 for transition probabilities.

Table 3. Succession, natural disturbance, and example management transitions for the Northern Hardwood Forest model parameterized in VDDT.

From state class	Transition	To state class	Prob	Propn[c]	Min Age	Max Age	TSD[d]
Early succession aspen birch	Succession	Mid-succession aspen birch	–	–	0	10	–
	Replacement fire[a]	Early aspen birch	0.0025	1	0	10	0
Mid-succession aspen birch	Succession	Late-succession northern hardwoods	–	–	11	80	–
	Replacement fire[a]	Early succession aspen birch	0.004	1	11	80	0
	Wind	Early succession northern hardwoods	0.002	1	40	80	0
	Thinning[b]	Mid-succession aspen birch	1	1	40	100	>10
	Clearcutting[b]	Early succession aspen birch	1	1	40	100	>10
	Selection cutting[b]	Mid-succession northern hardwoods	1	1	40	80	>20
Early succession northern hardwoods	Succession	Mid-succession northern hardwoods	–	–	1	10	–
	Replacement fire[a]	Early aspen birch	0.0004	1	1	10	0
Mid-succession northern hardwoods	Succession	Late succession northern hardwoods	–	–	11	100	–
	Replacement fire[a]	Early succession aspen birch	0.0006	1	11	100	0
	Wind	Early succession northern hardwoods	0.002	0.2	40	100	0
	Selection cutting[b]	Mid-succession northern hardwoods	1	1	40	100	>20
	Alternative succession	Uncharacteristic forest – maple monoculture	1	0.07	11	100	–
Late succession northern hardwoods	Succession	Late succession northern hardwoods	–	–	101	999	–
	Replacement fire[a]	Early succession aspen birch	0.0002	1	101	999	0
	Wind	Early succession northern hardwoods	0.002	1	101	999	0
	Selection cutting[b]	Late succession northern hardwoods	1	1	101	999	>20
Uncharacteristic forest – maple monoculture	Succession	Uncharacteristic forest – maple monoculture	–	–	0	150	–
	Replacement fire[a]	Early succession aspen birch	0.0006	1	0	150	0
	Wind	Early succession northern hardwoods	0.002	1	40	150	0

	Selection cutting[b]	Uncharacteristic forest - maple monoculture	1	1	40	150	>20
	Restoration[b]	Mid-succession northern hardwoods	1	1	20	150	>10

[a] LANDFIRE wildfire probabilities in all models were adjusted to reflect current probabilities of wildfire in the region (Cleland et al. 2004).

[b] Management transitions shown here are typical of management in this forest type. All management transitions – thinning, clearcutting, selection cutting, and restoration – were modeled using an area target specific to reach scenario rather than a probability.

[c] Propn is the proportion of time that the transition leads to the specified class within the specified region.

[d] Time since disturbance, or TSD, is the minimum number of years (time steps) that must pass after a disturbance before another disturbance event can occur.

The STM for each land cover type along with vector based maps of land cover and management boundaries served as input for TELSA. For each simulation year, TELSA first simulated natural succession for every polygon based on the rate and direction of succession defined in the STMs. Next, natural disturbances were simulated in a random order. For each natural disturbance type, the model calculated the expected area affected annually by the disturbance as the sum of the products of the area of all polygons with a non-zero probability of that disturbance and the probability of the disturbance multiplied by the annual variation and long term trend for the disturbance. The size distribution for the disturbance was used to distribute the total area affected annually into multiple, discrete disturbance events. Then, disturbance events were applied to the landscape—a target disturbance size was drawn from the size distribution; initiated in a random, eligible polygon; and spread to neighboring eligible polygons until the target size was met or no adjacent polygons were eligible. Simulation of a disturbance type was complete when the expected area affected annually was met or no eligible polygons remained. Lastly, TESLA simulated management activities by generating a list of randomly ordered management units (groups of neighboring polygons under the same management system) based on their current state class. Management activities were applied until the area limit for each activity was reached or all eligible units were managed (Kurz et al. 2000).

State-and-transition model development and parameterization

We created STMs for each land cover type in VDDT by modifying Vegetation Dynamics Models previously created by LANDFIRE (LANDFIRE 2007b, Appendix 1). The accuracy of these models and the final TELSA model were validated in several stages (Table 4). The LANDFIRE Vegetation Dynamics Models included the state classes, succession pathways, and natural disturbances to represent ecosystem dynamics of each land cover type before major

European Settlement and were previously validated by the LANDFIRE team (Table 4, Stage 1). We adapted these models to capture current ecosystem dynamics in three ways. First, the probabilities of wildfire disturbances were modified using a temporal multiplier to represent current conditions based on previous research (Cleland et al. 2004), observations by the Michigan Department of Natural Resources (Paul Kollmeyer, personal communication), and input from experts. Here, we applied a temporal multiplier of 0.1 to all fire disturbances, as fire suppression has decreased the fire frequency ten-fold relative to pre-settlement conditions (Cleland et al. 2004).

Table 4. Stages of validating the spatial STM used to simulate succession, natural disturbances, and management activities in the THR watershed.

Validation Stage	**Model Setup**	**Output examined**	**Validation Source**
1. Succession and historical natural disturbance dynamics	Aspatial VDDT simulation of succession and historical natural disturbances using the baseline LANDFIRE BpS STM for each land cover type	a. Area occupied by each succession state/cover type b. Area affected by each natural disturbance annually	Literature and empirical data on ecosystem composition and natural disturbance dynamics of the study region and reviewed by experts as described in the LANDFIRE Biophysical Setting Model Descriptions (LANDFIRE 2007b)
2. Spatial characteristics of current succession and natural disturbance dynamics	Spatial TELSA simulation of succession and current natural disturbances only using updated STM for each land cover type	a. Area occupied by each succession state/cover type b. Area affected by each natural disturbance annually c. Size distribution of each natural disturbance type	Reviewed by modeling team and experts based on literature and empirical data on natural disturbance dynamics of the study region, specifically the historic size distribution of

			windthrow, insect outbreaks, and flooding events (e.g. (Schulte and Mladenoff 2005) and data on the current size distribution of wildfire events (e.g. Cleland et al. 2004).
3. Spatial characteristics of management activities	Spatial TELSA simulation of succession and management using updated STM for each land cover type	a. Area affected annually by each management activity in each management area b. Size distribution of each management activity in each management area	Review by modeling team and experts to ensure the model reasonably simulated the management regime in each management area.

Second, we added an ‘uncharacteristic’ state class to three of the models – Northern Hardwood Forest, Northern Hardwood Hemlock Forest, and Pine Oak Forest – to represent forest stands dominated by maple species (*Acer spp.*). In each model, transition to this uncharacteristic class was represented as alternative succession from a characteristic mid-succession state, such as from mid-succession northern hardwoods (Figure 3). Transition out of this class was represented as restoration back to an early succession stage, such as early succession northern hardwoods (Figure 3), as described below. The accuracy of simulated current succession and natural disturbance dynamics was validated based on primary literature and expert review (Table 4, Stage 2).

Third, we added transitions to represent management activities based on input from local land managers (Figure 3, Table 3). Thinning, clearcutting, selection cutting, and restoration transitions were used to simulate the three primary silvicultural systems applied on this landscape—even-aged management, uneven-aged management, and restoration forestry. Clearcutting was applied to represent even-aged management and changed the state class of a stand to the youngest class in the cover type. Selection cutting was applied to represent uneven-aged management, where the stand remained in the same state class and continued to age. Once a stand was selectively harvested, no other management activity could be applied for a specified number of subsequent time steps, referred to as a time since disturbance (TSD), to represent the management return interval. Depending on the cover type, thinning could be applied to a stand prior to clearcutting or selection cutting. Similar to selection cutting, a stand remained in the same state class after thinning and continued to age without further management activities until the TSD had passed. Restoration forestry was represented by the restoration transition which captured a range of management activities aimed at maintaining or improving the ecological conditions of a stand, such as gap creation, removal of undesirable species, and planting (Fassnacht et al. 2015). Restoration resulted in the transition of a stand to an early or mid-succession state class characteristic of the land cover type represented by the model. Because the success of restoration activities varies in practice, we included a probability that a stand would remain in the uncharacteristic state in the event of restoration.

Simulating changes in the natural disturbance regime

Experts identified potential changes in the natural disturbance regime due to climate change as a major management concern in this landscape, especially an increase in the frequency of stand-replacing wildfire and windthrow events. Historically, wildfire and windthrow were the major natural disturbances shaping forests of the Upper Peninsula and continue to be so today (Zhang et al. 1999; Cleland et al. 2004; Schulte and Mladenoff 2005; Schulte et al. 2007; Stueve et al. 2011; Janowiak et al. 2014). Projected increased temperature in fall and spring combined with drier summer months are expected to increase the length of the fire season as well as the susceptibility of this landscape to ignition from natural sources (Drever et al. 2009; Flannigan et al. 2009; Drobyshev et al. 2012), though precipitation projections remain uncertain (Winkler et al. 2012). The probability of fire in the eastern Upper Peninsula of Michigan is estimated to increase by 40 to 60% by 2100 based on two global climate models (Guyette et al. 2014). Windthrow events are extremely localized and the result of conditions that change on a relatively short timescale, including soil saturation and wind gusts (Peterson 2000). The continued increase in the frequency of extreme precipitation events and severe thunderstorms and their associated high wind and saturated soil conditions (WICCI 2011; Diffenbaugh et al. 2013; Janowiak et al. 2014) combined with the geographical predisposition of the upper Great Lakes region to the development of intense convective thunderstorms and damaging wind conditions (Stueve et al. 2011) may lead to an increase in the frequency of windthrow events. The annual mean frequency of hourly high wind events (> 70km/hr) in the region of Canada bordering Lake Superior is estimated to increase by approximately 60% by 2100 with wind gusts > 90km/hr showing an even greater increase based on projections from an ensemble of eight global climate models (Cheng et al. 2014). Wildfire and windthrow disturbances may be some of the first and most intense climate change impacts to affect forest management in the short term, and these stand-replacing disturbances may be major drivers of landscape change in the long term (Kerns et al. 2012; Janowiak et al. 2014). Though efforts are underway to relate wildfire and windthrow events with climate variables (Dale et al. 2001; Guyette et al. 2014), researchers assert that projections of future frequency or severity of these disturbances are highly uncertain (Peterson 2000; Dale et al. 2001; Coniglio and Stensrud 2004; Cushman et al. 2007; Janowiak et al. 2014).

Several state-and-transition modeling efforts have utilized temporal multipliers derived from historic data (Provencher and Anderson 2011), developed through statistical modeling (Costanza et al. 2015a), or chosen heuristically (Keane et al. 2008) to simulate changes in natural disturbances associated with climate change. Here, we used a temporal multiplier to linearly and gradually increase the probability of wildfire and windthrow by 50% above today's probability over the course of the simulation. A 50% increase in the probability of these disturbances by 2100 is within the range of future projections (Cheng et al. 2014; Guyette et al. 2014). In addition, since probabilities of disturbances represent an average, this relatively conservative increase in the probability of these disturbances is well within the historical disturbance regime and ecosystem dynamics that these STMs were designed to simulate. Modeling each scenario under the current and an alternative natural disturbance regime allows conservation practitioners and land managers to explore the potential effects of a range of natural disturbance regimes in an uncertain future.

Spatial model parameterization and input

For each scenario, the land cover map of the THR watershed classified according to LANDFIRE's Biophysical Settings (BpS) and state class scheme (LANDFIRE 2007a) and corresponding map management boundaries were input into TELSA. Current management boundaries were the result of Northern Great Lakes Forest Project, and spatial data was provided by TNC. We created maps of alternative management boundaries in ArcMap 9.3 (ESRI 2008) based on scenario descriptions (Figure 2). The size distribution of each natural disturbance type was specified for each land cover type based on primary literature and expert input. Constraints on the size of individual management events, on the total area affected by each management activity per annual time step, and the spatial arrangement of activities (clumped to dispersed) were specified for each management area based on input from local land managers. These spatial attributes of management activities were unique to each scenario. All model inputs and their sources are summarized in Appendix 2.

Model output

All four management scenarios were simulated for 100 yearly time steps under the current natural disturbance regime and under increased probability of wildfire and windthrow. Since initial land cover conditions corresponded to the year 2010, final model outputs represent the year 2110. One hundred years was considered a reasonable time horizon for management planning and long enough for the consequences of management activities to become apparent on the landscape (Kimmins et al. 2008). Ten Monte Carlo runs were performed for each scenario to capture variability of stochastic natural disturbance events. Modeling results were reviewed and validated by experts, including the amount and location of areas affected by each natural disturbance and management activity for each scenario (Table 4, Stage 3). Qualitative model validation by experts is a widely used approach for validating results in forest landscape models (He 2008), especially when traditional comparisons of model results to empirical land cover data are not possible.

Spatial and statistical analysis

Using ArcGIS 9.3 (ESRI 2008), we generalized land cover in the current and simulated output maps by reclassifying the 39 LANDFIRE land cover and successional stage classes used by the VDDT/TELSA model as 16 forest or wetland classes of a specific succession stage and canopy closure (Figure 1, Appendix 3).

To answer our first and third questions, we calculated landscape and class metrics under each scenario using FRAGSTATS (McGarigal et al. 2002). Landscape level contagion, number of patches, and mean patch area were used to quantify the spatial heterogeneity of the watershed. Contagion is a measure of the spatial distribution of land cover classes on the landscape, with values ranging from zero to 100. Low values indicate a dispersed or disaggregated spatial arrangement of land cover classes, while high values indicate a clumped or aggregated arrangement. When considered together, these metrics characterize landscape spatial heterogeneity, where a large number of patches, small mean patch area, and a low contagion value indicate a highly heterogeneous, patchy pattern (Turner et al. 2001). At the class level, the total area of each cover class was expressed as a percentage of the landscape (PLAND). Mean patch area and percentage of like adjacencies (PLADJ) were used to characterize the spatial configuration of each class. PLADJ is a measure of contagion for a single land cover class and ranges from zero when a class is maximally dispersed to 100 when a class is maximally aggregated. Patch metrics were calculated using the 4 neighbor rule, because we wished to capture and compare the relatively fine-scale landscape heterogeneity characteristic of the THR watershed. Here, we examined class metrics to shed light on the specific land cover classes and dynamics responsible for overall landscape characteristics.

‘R’ statistical analysis software was used to calculate the mean and standard deviation of each landscape and class metric at the beginning of the simulation (year 2010) and 100 years in the future to characterize variability within the models (R Core Team 2015). Analysis of variance (ANOVA) and Tukey’s HSD post hoc test were used to test for significant differences in each metric between pairs of scenarios 100 years in the future using a significance level of 0.05.

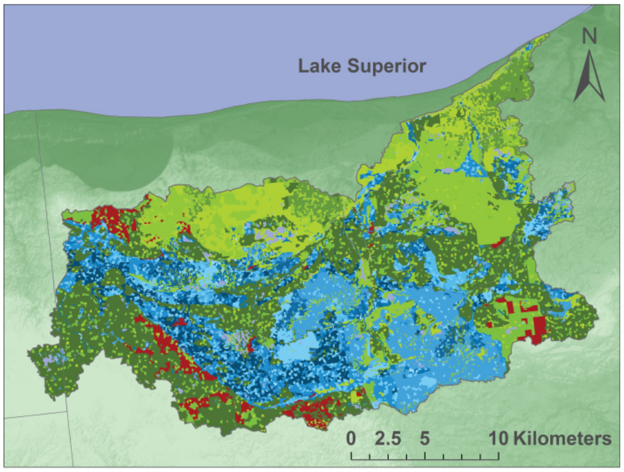
To answer our second and third questions, we calculated the average age of land cover and the total area of land cover ages 0-25, 26-50, 51-75, 76-100, 101-125, 126-150, and 151-999 years old at the beginning of the simulation (year 2010) and 100 years in the future under each scenario and both natural disturbance regimes. The total area of late succession forest and wetland cover classes also informed our analysis of the ability of each management scenario to maintain mature forests and wetlands.

RESULTS

Each scenario resulted in unique patterns of potential land cover in the THR watershed. The number of patches and mean patch area were significantly different between all scenarios under both natural disturbance regimes ($p < 0.05$, Figure 4, Appendicies 3 and 4). Contagion was also significantly different between all scenarios under both natural disturbance regimes except between the Current Management and Industrial Forestry scenarios under the current natural disturbance regime and between the Industrial Forestry and Ecological Forestry scenarios under increased probability of wildfire and windthrow ($p > 0.05$, Figure 4, Appendicies 3 and 4).

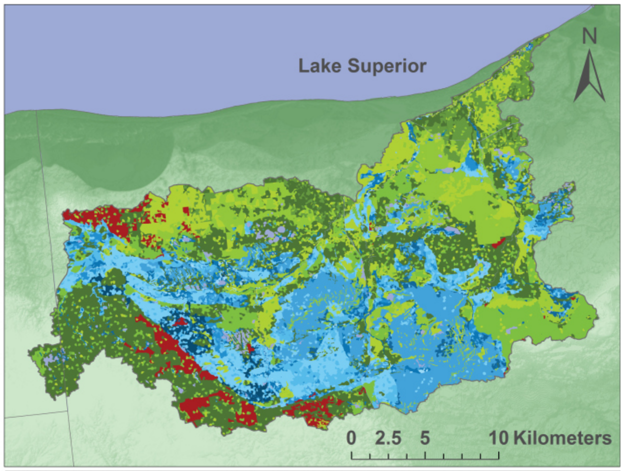
In all scenarios, the number of patches was greater, mean patch area was smaller, and contagion was lower under increased probability of wildfire and windthrow than under the current natural disturbance regime (Figure 4). The Ecological Forestry scenario showed the greatest and the Industrial Forestry scenario showed the smallest magnitude of difference in both the number of patches and contagion between natural disturbance regimes of all scenarios. The magnitude of difference in mean patch area between natural disturbance regimes was smallest under the Industrial Forestry scenarios.

A) Current Management



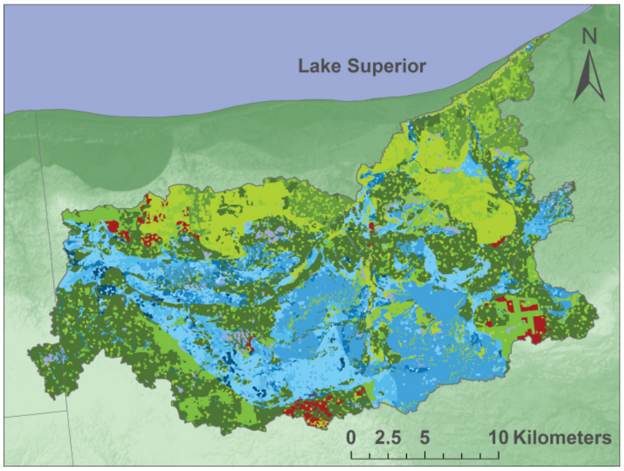
Current Natural Disturbance Regime	Metric	SE
Number of patches	8,966.9	28.1
Mean patch size (ha)	5.9	0.019
Contagion	48.9*	0.0469
Increased Wildfire and Windthrow		
Number of patches	10,240.5	35.3
Mean patch size (ha)	5.1	0.018
Contagion	48.0	0.0387

B) Industrial Forestry



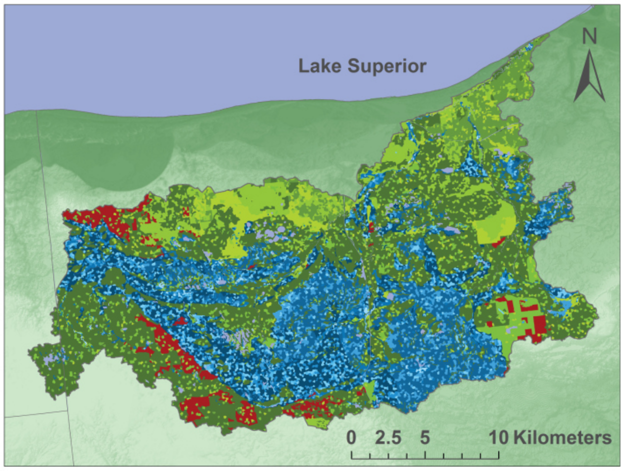
Current Natural Disturbance Regime	Metric	SE
Number of patches	8,611.0	26.6
Mean patch size (ha)	6.1	0.019
Contagion	49.0*	0.0468
Increased Wildfire and Windthrow		
Number of patches	9,753.5	42.9
Mean patch size (ha)	5.4	0.024
Contagion	48.6**	0.0769

C) Expanded Easement



Current Natural Disturbance Regime	Metric	SE
Number of patches	7,449.2	27.8
Mean patch size (ha)	7.1	0.026
Contagion	52.6	0.173
Increased Wildfire and Windthrow		
Number of patches	8,698.5	31.7
Mean patch size (ha)	6.1	0.022
Contagion	51.8	0.165

D) Ecological Forestry



Current Natural Disturbance Regime	Metric	SE
Number of patches	10,412.7	22.1
Mean patch size (ha)	5.1	0.011
Contagion	51.2	0.0367
Increased Wildfire and Windthrow		
Number of patches	12,637.3	41.8
Mean patch size (ha)	4.2	0.014
Contagion	48.6**	0.0305

Figure 4. Land cover maps and landscape metrics for the Two Hearted River watershed 100 years in the future under each of the four alternative scenarios. Maps use the same symbology as Figure 1B and show land cover resulting from the first Monte Carlo run of each scenario under the current natural disturbance regime. Metrics are reported as the average of 10 Monte Carlo runs for each scenario. Asterisks indicate scenarios for which a metric is not significantly different ($p > 0.05$).

The THR watershed was most heterogeneous under the Ecological Forestry scenario under both natural disturbance regimes, having the greatest number of patches, smallest mean patch area, and the second highest contagion value of all scenarios (Figure 4D). These land cover patterns were the result of the transition of mid-succession closed canopy forest and wetland primarily to late succession stands via natural succession. To a lesser degree, late succession forest also transitioned to early succession stands through forest management activities and natural disturbances, while late succession wetland transitioned to early succession wetland via natural disturbances only. Both expanding and shrinking cover classes were composed of a greater number of patches with a smaller mean patch area that were more spatially dispersed than under initial conditions, resulting in a more heterogeneous landscape (Appendix 6).

Landscape heterogeneity was similar under the Current Management and Industrial Forestry scenarios under both natural disturbance regimes, lower than under the Ecological Forestry scenario, and higher than under the Expanded Easement scenario. The Current Management scenario showed the second highest number of patches and the second smallest mean patch area of all scenarios (Figure 4A), while the Industrial Forestry scenario showed the second lowest number of patches and the second largest mean patch area under both natural disturbance regimes (Figure 4B). Contagion was not significantly different between these scenarios under the current natural disturbance regime (Figure 4A and B). This intermediate level of landscape heterogeneity was driven primarily by the transition of mid-succession closed canopy forest to early and mid-succession open canopy forest and the transition of late succession closed canopy wetland to early succession open canopy wetland via management. In all forest classes and most wetlands classes, large patches were split into many smaller patches, decreasing the aggregation of each class. However, patches of early succession and mid-succession open canopy wetland became larger and more aggregated than under initial conditions (Appendix 4).

Outcomes for late succession closed canopy forest differed between the Current Management and Industrial Forestry scenarios. Under the Current Management scenario, total area of late succession closed canopy forest increased from initial conditions to a greater degree than under the Industrial Forestry scenario under both natural disturbance regimes (Appendix 6). Under the Industrial Forestry scenario, late succession closed canopy forest was one of the few classes in which total area changed in different directions under the two natural disturbance regimes—increasing by 6.6% under the current natural disturbance regime and decreasing slightly under increased probability of wildfire and windthrow (Appendix 6).

The THR watershed was least heterogeneous under the Expanded Easement scenario under both natural disturbance regimes (Figure 4C), having the fewest patches, the largest mean patch area, and highest contagion value of all scenarios. Landscape patterns were primarily the result of the transition of mid-succession closed canopy forest and late succession wetlands to form a greater number of larger, more aggregated patches of early and mid-succession forest and wetland classes via management activities. To a lesser degree, mid-succession closed canopy forest also transitioned to late succession closed canopy forest through natural succession. Late succession wetland cover classes experienced the greatest declines in total area under the Expanded Easement scenario than any other, shrinking from 24.9% to just 3.64% of the landscape (Appendix 6).

The average age of land cover in the THR watershed was 146 years old (± 0.1 years SD) under initial conditions (year 2010). At the end of the 100 year simulation, the average age of land cover remained approximately the same under the Current Management scenario—143 years (± 0.3 SD) under the current natural disturbance regime and 139 years (± 0.5) under increased probability of wildfire and windthrow—and 33-31% of the landscape was occupied by mature vegetation (greater than 150 years old, Figure 5). The average age of land cover was reduced under the Industrial Forestry scenario to 123 years (± 8.2 SD) under the current natural disturbance regime and 115 years (± 0.9 SD) under increased probability of wildfire and windthrow, and 28-24% of the landscape was occupied by mature vegetation (Figure 5). The Expanded Easement scenario also resulted in younger average age of vegetation—124 years (± 0.5 SD) under the current natural disturbance regime and 119 (± 0.5 SD) under increased probability of wildfire and windthrow—and just 27-25% of the landscape was occupied by mature vegetation (Figure 5). The Ecological Forestry scenario was the only scenario in which the average age of the landscape increased, reaching 191 years (± 15.7 SD) under the current natural disturbance regime and 187 years (± 0.5 SD) under increased probability of wildfire and windthrow, and 55-52% of the landscape was occupied by mature vegetation (Figure 5).

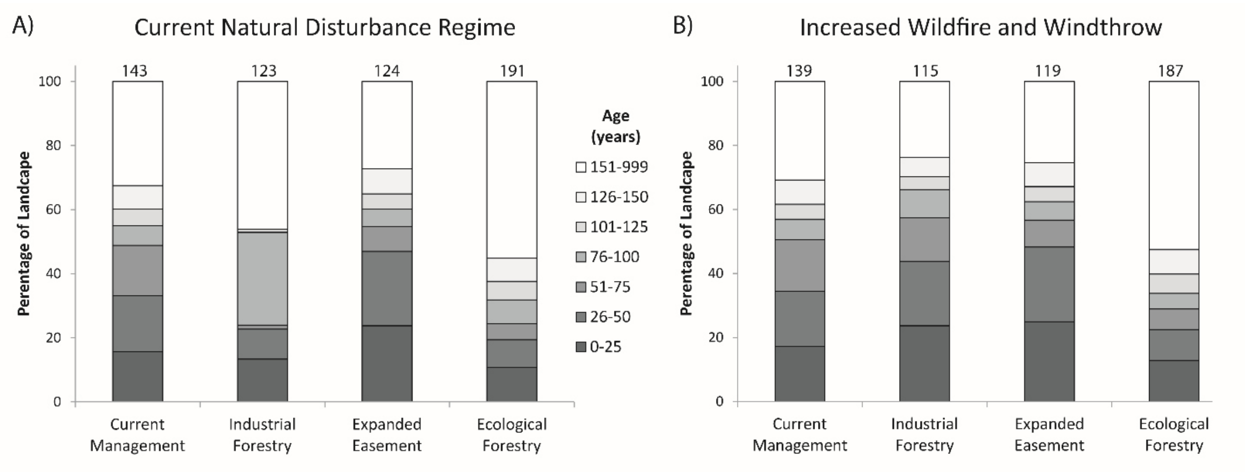


Figure 5. Graphs showing the distribution of average land cover age (years) for the Two Hearted River watershed 100 years in the future under each of the four alternative scenarios under (A) the current natural disturbance regime and (B) with increased probability of wildfire and windthrow (n=10 Monte Carlo runs). The average land cover age of the landscape is shown at the top of each column.

DISCUSSION

The four alternative management scenarios modeled for the THR watershed resulted in possible future landscapes that differed in their ability to meet watershed conservation goals of maintaining landscape spatial heterogeneity and conserving mature forests and wetlands. To answer our first and third questions, landscape spatial heterogeneity was highest under the Ecological Forestry scenario, lowest under the Expanded Easement scenario, and intermediate under the Current Management and Industrial Forestry scenarios due to differences in management activities and their interactions with natural disturbances under each scenario (Figure 4). To answer our second and third questions, the average age of the landscape and proportion of the landscape occupied by mature vegetation was highest under the Ecological Forestry scenario, intermediate under the Current Management scenario, and lowest under the

Industrial Forestry and Expanded Easement scenarios (Figure 5). Lastly, increased probability of wildfire and windthrow did not change the overall trends in the differences between scenarios but affected the outcomes of each scenario to different degrees.

Current Management and Industrial Forestry scenarios had similar outcomes for landscape spatial heterogeneity (Figure 4A and B), with landscape metrics having median values among the scenarios. However, differences in management between these scenarios manifest as differences in the age and spatial distribution of land cover. The annual timber harvest goal and area of even-aged management were larger in the Industrial Forestry scenario than all other scenarios, and entry sizes were larger in the private, industrial management area in this scenario than in the same locations on the landscape under the Current Management or Expanded Easement scenarios. In contrast to the Current Management and Ecological Forestry scenarios, some wetlands were managed for timber harvest under the Industrial Forestry scenario. The Industrial Forestry scenario resulted in a landscape composed of larger patches of early succession vegetation, especially in wetlands, and the youngest average land cover age of any scenario (Figure 5). The Current Management scenario, on the other hand, resulted in an increase in the area of late succession forest (Appendix 6).

Therefore, both the age and spatial heterogeneity of the landscape, especially in wetlands, were better promoted by the Current Management scenario than the Industrial Forestry scenario. The greater age diversity and spatial heterogeneity of the Current Management scenario may support a greater diversity of habitats and, consequently, wildlife species (Nixon et al. 2014). That is, today’s management strategies, which included WFCE and reserve, more effectively achieved conservation goals of maintaining landscape spatial heterogeneity and conserving mature forest and wetlands relative to an alternative future in which the landscape was managed for industrial timber production without traditional or distributed conservation.

The Expanded Easement scenario produced a less heterogeneous landscape with fewer patches and a larger mean patch area than in any other scenario (Figure 4C). Again, these differences are the result of the spatial arrangement of management activities. Forest management activities within the expanded easement management area were spatially aggregated, whereas they were randomly distributed in the corresponding area under the Current Management and Industrial Forestry scenarios, and the total annual area target for restoration forestry was greater. As a result, the configuration of the landscape remained relatively stable, with contagion decreasing only 4% over the course of the century.

However, this scenario had starkly different outcomes for forests and wetlands. Stands of late succession forest remained larger and more spatially aggregated than in any other scenario (Appendix 6). These results indicate that WFCE restrictions can support both natural resource extraction and conservation of late succession forest. In contrast, the area of late succession wetland classes declined more than in any other scenario due to timber harvesting in a larger area of boreal acid peatland and alkaline conifer hardwood swamp cover types (Appendix 6). These results suggest that WFCE restrictions, which are accompanied by a sustainable forestry management plan in this context, may not be sufficient to ensure conservation of cover types with long successional trajectories or that are slow to recover from disturbance.

The Ecological Forestry scenario was the only scenario in which the average age of the landscape increased, resulting in a larger area of mature forests and wetlands (Figure 5, Appendix 6). Here, larger, contiguous forest stands were perforated by numerous, small natural disturbance events, including wildfire and windthrow. Forest management, most notably even-aged management, had a smaller footprint under the Ecological Forestry scenario than any other. These small, spatially dispersed disturbance events resulted in a larger number of patches of a smaller mean size than in any other scenario. While this scenario conserved the largest, most contiguous area of late succession cover types (Appendix 6), spatial heterogeneity was the highest among all the scenarios (Figure 4). As a result, this alternative future provided the most available habitat for a suite of avian species selected of conservation concern in this landscape (Nixon et al. 2014).

There were large differences in landscape metrics between natural disturbance regimes under the Ecological Forestry scenario (Figure 4D). Mature forest and wetlands have higher susceptibility to wildfire and windthrow disturbances than younger age classes. Therefore, an increase in the proportion of mature forests and wetland through cooperative ecological forestry also increased the sensitivity of the landscape to changes in these stand-replacing disturbances. Landscape metrics differed the least between natural disturbance regimes under the Industrial Forestry scenario. These results indicate an interaction between management and stand-replacing natural disturbances—management can reduce the area of the landscape most susceptible to stand-replacing disturbances, in this case wildfire and windthrow events, and lessen the overall impact of those events on the landscape. However, this may be at the expense of maintaining older, more structurally diverse stands, which may provide habitat for focal species (Nixon et al. 2014).

Based on these results, combining conservation strategies, such as single-ownership forest reserves and WFCEs in targeted areas of the landscape as in the Current Management scenario, resulted in a larger proportion of mature forests and wetlands and effectively promoted spatial heterogeneity of land cover than when a single strategy was used in the same area as in the Expanded Easement scenario. Essentially, multiple strategies can be utilized to better tailor conservation to local land cover and management contexts. Increasing the area of the landscape under cooperative ecological forestry most effectively maintained spatial heterogeneity, conserved mature (late succession) land cover, and provided the largest area of available habitat for a suite of target species (Nixon et al. 2014), yet this conservation strategy may increase the sensitivity of the landscape to an increase in the probability of wildfire and windthrow. While WFCEs effectively promoted similar benefits in forest ecosystems, the age and spatial heterogeneity of wetland ecosystems declined substantially.

It is important to note that not all of the impacts of various conservation strategies are best quantified by landscape modeling and metrics. The protections offered by conservation actions may not be realized in the form of changes in land cover or lack thereof. Conservation easements perpetually protect lands against subdivision and alternative land uses, which is not captured in these scenarios. Landscape conservation actions are often in response to perceived threats to the ecological values of the landscape from land use and land change. However, such changes are difficult to project into the future in areas that have a history of boom and bust cycles of development and resource extraction, such as the Upper Peninsula of Michigan (Karamanski 1989).

This model reflects the current understanding of this ecosystem's dynamics and management and can further serve as a tool for rapidly assessing the potential outcomes of alternative management strategies. STMs like the one used here are based on empirically derived data describing current ecological dynamics. As future climate conditions diverge from the past, process-based landscape models that mechanistically simulate the influence of climate variables on ecosystem dynamics are necessary to capture the full range of ecosystem responses to novel climate conditions (Cuddington et al. 2013; Gustafson 2013). This is especially critical for simulations of very long time scales (>100 years), in areas where changes in climate are expected to be rapid and pronounced, and in studies where fine-scale ecosystem attributes, such as species composition, are of primary concern. However, the extensive data, time, and manpower necessary to create and parameterize these models currently limits their applicability for informing management decisions (Cushman et al. 2007; Cuddington et al. 2013). Researchers are working to develop an integrated modelling approach where multiple models representing different ecosystem components are linked (Cushman et al. 2007; Gustafson 2013; Halofsky et al. 2013; Halofsky et al. 2014). The STM developed here could be linked with mechanistic models to serve as a starting point for mechanistically simulating the impacts of climate change in this area.

The scenarios and models used here were tailored to the specific ecological conditions and management concerns of this landscape and group of experts. Therefore, these scenario results do not represent the full range of possible future outcomes for this landscape. The rate and magnitude of changes in the natural disturbance regime due to changing climate conditions remains uncertain (Peterson 2000; Cardille et al. 2001; Dale et al. 2001; Coniglio and Stensrud 2004; Janowiak et al. 2014). The future socioeconomic opportunities and constraints influencing land management decisions and their interaction with the ecosystem are inherently unpredictable. (Coreau et al. 2009; National Research Council 2014). Scalar complexity, ordering complexity, historical contingency, legacy effects, and temporal nonstationarity of ecological processes make it impossible for models to predict exactly how, when, and where something will occur (Taylor 2005; Pilkey and Pilkey-Jarvis 2007; Scheller and Mladenoff 2007; Cuddington et al. 2013; National Research Council 2014). Nonetheless, land managers in this landscape and others are faced with the challenge of developing management strategies resilient to possible future conditions. Collaborative scenario modeling can provide insight into a range of plausible alternative scenarios to inform land management planning and cope with uncertainty.

CONCLUSIONS

This research shows that blending conservation strategies, such as single-ownership forest reserves and WFCEs in targeted areas of the landscape, may better achieve conservation goals than applying a single strategy across the same area. However, WFCEs and other distributed conservation strategies may be less effective at protecting wetlands and other ecosystems with long successional trajectories. Finally, conservation strategies that most effectively maintain landscape spatial heterogeneity and conserve mature forests and wetlands, such as cooperative ecological forestry, may increase the sensitivity of the landscape to changes in windthrow and wildfire disturbances.

The collaborative scenario modeling approach described here advances the application of scenario modeling to inform cross-boundary natural resource management. This approach brings together known science, existing data, and the knowledge of land management and conservation practitioners to tailor the scenario modeling process and outcomes to the local ecosystem and management context. These participants are the best source of information regarding the current natural resource management and conservation strategies as well as the potential application of new approaches in a focal landscape. Modeling scenarios developed by these individuals and agencies can directly inform their local management planning and implementation. This approach enables participants to compare the ability of alternative strategies to achieve specific management goals, identify the potential trade-offs between goals, and explicitly consider the potential conflicts and synergies of multiple agencies and landowners working across boundaries in a landscape. As a result, managers have more information to make decisions about which conservation strategy or combination of strategies to apply in specific locations on the landscape to achieve optimum conservation outcomes, how to best utilize scarce financial resources, and how to reduce the financial and ecological risks associated with the application of innovative strategies in an uncertain future.

ACKNOWLEDGEMENTS

This research was funded with support from The Nature Conservancy's Rodney Johnson/Katherine Ordway Stewardship Endowment grant, USDA Forest Service State and Private Forestry Redesign, the Doris Duke Conservation Fellowship Program sponsored by the Doris Duke Charitable Foundation, the NSF IGERT Fellowship Program (DGE- 0549407), and the University of Wisconsin at Madison. Special thanks to Melissa Motew for help with climate data analysis, to all of the experts that contributed to this project, and to Eric Gustafson and four anonymous reviewers for critical feedback that improved this manuscript.

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CHAPTER 3

A Framework for Integrating Social Objectives into Collaborative Scenario Modeling Projects Informed by Adaptive Co-management[1]

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ABSTRACT

In addition to improving natural resource management decision-making by enhancing stakeholder knowledge about the dynamics of the system, collaborative scenario modeling projects may also aim to create the social conditions necessary for continued collaboration among stakeholders as they work to formulate adaptive, resilient natural resource management strategies. This approach recognizes that decision-making is a social process. However, collaborative scenario analyses rarely consider such social effects during project design and implementation. Adaptive co-management, an emerging approach to natural resource management, has begun to identify the social conditions necessary for the emergence of collaboration among stakeholders. Here, I provide a framework for integrating social objectives into the design, implementation, and evaluation of collaborative scenario modeling projects that aim to create the social conditions necessary for continued collaboration among stakeholders. This framework defines clear social objectives for collaborative scenario modeling projects, describes how the collaborative scenario modeling process can be designed to achieve these objectives, and identifies indicators that can be used to measure progress toward these objectives. This research can guide collaborative scenario modeling practitioners in articulating social

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[1] This chapter will be submitted to *Environmental Management.*

objectives and understanding how they facilitate the emergence of collaboration in natural resource management settings.

INTRODUCTION

Scenario analysis, also called alternative futures analysis, is a useful and increasingly popular tool for conservation and natural resource management planning. Scenarios are stories that describe plausible alternative futures that could arise from the present (Nassauer and Corry 2004; Mahmoud et al. 2009; Carpenter et al. 2015). While scenarios can be purely illustrative and examined from a qualitative perspective, scenarios are most commonly paired with computational modeling to produce quantitative output. Scenario modeling has been used to compare the outcomes of alternative natural resource management strategies (Radeloff et al. 2006; Duveneck et al. 2014), potential effects of invasive species (Costanza et al. 2012), multiple landscape policy and development options (Van Berkel and Verburg 2012; Meyer et al. 2014; Wu et al. 2015), wildlife habitat availability (Wilhere et al. 2007), and climate change (IPCC 2014).

Collaborative, or participatory, approaches for scenario development and modeling have been used to engage stakeholders in the scenario analysis process (Provencher et al. 2007; Low et al. 2010; Meyer et al. 2014; Carpenter et al. 2015; Price et al. 2016). Involving stakeholders has several advantages (Price et al. 2016). First, the knowledge and experience of individuals working on the landscape, combined with peer reviewed literature and other field data, enables development of scenarios and models tailored to the ecological and management context of a focal landscape. Second, many assert that the scenario modeling process and its outcomes are more likely to be utilized in practice when decision-makers and other stakeholders are involved (Daniels and Walker 2001; Hulse et al. 2004; Gustafson et al. 2006a). Collaborative scenario modeling (CSM) is an example of transdisciplinary research, “characterized by a process of collaboration between scientists and non-scientists on a specific real-world problem” (Walter et al. 2007). CSM and other transdisciplinary approaches aim to improve conservation and natural resource decision-making through both scientific effects and social, or societal, effects (Walter et al. 2007). Scientific effects are new insights into the dynamics of the study system that can inform decision-making and are most often explicitly addressed as an intended outcome of such projects. Social effects “include changes in the knowledge and the decision making capacity of the stakeholders, as well as decision support for these stakeholders in the form of robust future development orientations” (Walter et al. 2007).

As a way to improve decision-making, CSM projects may aim to create the social conditions necessary for continued cooperation and collaboration among stakeholders as they work to formulate adaptive, resilient natural resource management strategies. This approach recognizes that decision-making is a social process. In contrast to scientific effects, social effects are a result of the collaborative *process* rather than a final outcome. While there are notable exceptions (Schneider and Rist 2014), collaborative scenario analyses rarely consider social effects during project design and implementation. Some studies refer to the social ‘benefits’ of engaging stakeholders in the scenario analysis process with no quantification of such benefits (Priess and Hauck 2014), treat a single social effect, such as social learning, as an objective (Van Berkel and Verburg 2012), or only provide post hoc evaluations of the social effects of collaborative processes (Walter et al. 2007). When CSM projects aim to create or enhance the social conditions necessary for collaboration among stakeholders, social objectives should be clearly formulated and integrated into project design. However, there is little theoretical grounding or practical guidance for articulating and achieving social objectives within the field.

Adaptive co-management (ACM), also called collaborative adaptive management or adaptive governance, is an emerging approach to natural resource management and governance that provides concepts for formulating the social objectives of such collaborative processes.

Under ACM, stakeholders collaboratively formulate, implement, test, and revise management strategies and institutional arrangements to remain resilient under changing conditions (Folke et al. 2002; Armitage et al. 2009). ACM theory has begun to identify the social conditions necessary for the emergence of ongoing collaboration between stakeholders. Therefore, ACM theory can guide CSM practitioners in articulating social objectives and understanding how they facilitate the emergence of collaboration in natural resource management settings. The current ACM theory is largely a mix of social learning and co-management scholarship alongside post-hoc descriptions of circumstances in which collaborative, adaptive management arose (Olsson et al. 2004b; Charles 2007; Plummer 2009; Lundmark et al. 2014). As a result, there is little guidance or agreement on available methods or approaches to apply ACM theory in practice to achieve these social goals. Another major shortcoming is the lack of agreed upon indicators that can be used to measure progress toward achieving these social objectives.

Here, I suggest a theoretical framework for the design, application, and evaluation of CSM projects to achieve social objectives by building on ACM theory. The framework was developed based on existing scientific literature and critical reflections emerging from the application of collaborative scenario modeling in the Forest Scenarios Project which evaluated forest conservation and management planning in a cross-boundary context. First, I define clear objectives for collaborative scenario modeling projects that aim to facilitate collaboration among stakeholders based on the adaptive co-management literature. Second, I describe how the collaborative scenario modeling process can be designed to achieve these objectives using our experience applying this approach in the Forest Scenarios Project as an example. Finally, I identify indicators that can be used to measure progress toward these objectives.

This inductive analysis (Lawrence 1997) moves the bar toward a more critical application and evaluation process for integrating ACM theory into practice. Limitations of collaborative scenario modeling as a pre-cursor to adaptive co-management are discussed. I suggest directions for future research at the intersection of collaborative scenario modeling and adaptive natural resource management to shed light on how the results of such interdisciplinary projects are incorporated into future decision-making. This framework is not meant to advocate for the application of CSM to further ACM. Rather, it seeks to connect those engaging in these processes and projects in each field whose goals align with some or all of those encompassed in ACM theory.

COLLABORATIVE SCENARIO MODELING

CSM engages stakeholders in an iterative process of knowledge sharing, information generation, and analysis to improve their decision-making capacity. Approaches to CSM vary in the degree to which experts or stakeholders are involved in the process. Many projects involve participants only in scenario development (Provencher et al. 2007; Wilhere et al. 2007; Van Berkel and Verburg 2012; Carpenter et al. 2015), while some involve stakeholders in model development as well (Low et al. 2010; Meyer et al. 2014). Gustafson and colleagues (2006a) suggest that stakeholder input should inform many stages of the modeling process. The Forest Scenarios Project (FSP) developed an approach that integrates stakeholder input into all stages of the process and applied this approach in the Two Hearted River watershed in the Upper Peninsula of Michigan. Here, I use the FSP as a case to illustrate how a fully integrative CSM project was conducted in practice.

The socio-ecological context and modeling results of the FSP have been described previously (Price et al. 2012; Price et al. 2016); therefore, only a brief introduction to the project is provided here. The Two Hearted River watershed has been the focus of collaborative conservation and forest management efforts by The Nature Conservancy (TNC), the State of Michigan Department of Natural Resources (DNR), local timber investment management organizations (TIMOs), and private landowners since 2006. This 53,653 ha landscape contains a mixture of upland hardwood forests, pine stands, and coniferous forests, as well as wetland systems, including muskeg, bogs, and swamps. In 2008, TNC and other partners in the Northern Great Lakes Forest Project were working to develop management strategies that protected the ecological integrity of the watershed and the Upper Peninsula more broadly (TNC 2005; McGowan 2010; TNC 2010).

To help inform this effort, ecologists with TNC and the University of Wisconsin-Madison came together to create the FSP. The primary aim of the project was to provide insight into which management strategies best achieved watershed conservation goals, as defined by the stakeholder group, under current and potential future climate conditions and improve the decision-making capacity of stakeholders. Rather than a traditional research approach where scientists on the project team conceptualize, plan, and carry out research independently, the FSP team applied a CSM approach that engaged stakeholders to develop a common set of conservation goals for the watershed and to generate, model, and analyze alternative scenarios of forest management and climate change impacts in the area. The results of the FSP are described in Price et al. (2015) and Nixon et al. (2014).

Figure 1 illustrates the major stages of the CSM process used in the FSP—assembling a participant group, collaborative ecosystem assessment (also called situation analysis or situation mapping, Daniels and Walker 2001), conservation target selection, scenario development, iterative ecological modeling, and output. This iterative process can be applied in diverse natural resource management settings to shed light on a multitude of management and conservation challenges.

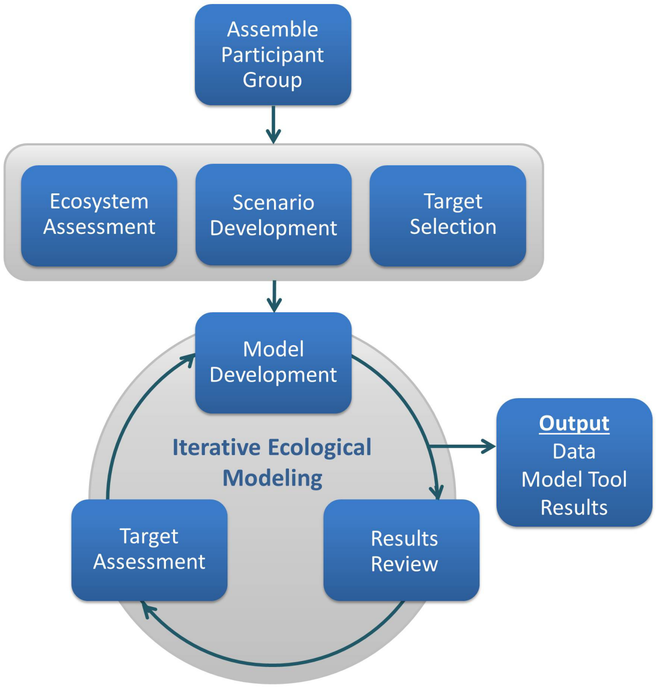

Figure 1. A diagram of the stages of the collaborative scenario modeling process.

Assemble the Participant Group

CSM relies heavily on the ongoing involvement of stakeholders that represent the individuals and organizations responsible for natural resource management and decision-making in the focal area. Similar to Meyer and colleagues (2014), we define *stakeholders* as individuals with both expert knowledge and direct or indirect influence on the conservation or management of the focal area. Martin and others (2012) define expert knowledge as substantive, normative, or adaptive information about a topic, which can be derived from personal experience, training, and research. Additional participants with regional expertise should also be considered, though their direct influence on the focal area may be limited.

Previous research has shown that including stakeholders in natural resource management research, planning, and policy making processes can improve the legitimacy and effectiveness of the outcomes (Gibson et al. 2000; Cash et al. 2002; Baker and Kusel 2003; Ostrom and Nagendra 2006; Seidl 2015). Involving individuals from organizations with management jurisdiction and responsibilities at multiple scales, from local to regional, improves the likelihood of 'fit' between the social and ecological components of the system and the ability to devise cross-scale solutions when environmental challenges arise (Cumming et al. 2006; Olsson et al. 2007). Some projects may choose to conduct a formal stakeholder analysis similar to that performed by Schneider and Rist (2014) to identify the participant group.

Ecosystem Assessment

The first stage of CSM engages participants in a process of knowledge sharing and collaborative learning to assess the social and ecological conditions of the focal area (Cheng et al. 2010). Collaborative assessment acts as a 'sense-making' exercise in which participants gather, interpret, and give meaning to all of the available information on the conditions of the system (Olsson et al. 2004a; Folke et al. 2005). This assessment creates shared knowledge that acts as the foundation for further discussion as new knowledge is integrated. Additionally, this step typically identifies gaps in knowledge or data.

The FSP began with an in-person workshop held near the Two Hearted River watershed aimed at introducing participants to one another and the project as a whole. Discussions focused on the current ecological state of the forests and wetlands in the watershed, the management and conservation goals and challenges of each participant, and their visions of the future of the watershed. The workshop also included a site visit to ecosystems characteristic of those in the watershed. This time on-site was intended to provide participants with an opportunity to discuss ecosystems and their management in the setting most were accustomed to working—out in the field. We observed that these visits catalyzed informal discussions and social exchange. In an analysis of forester networks, foresters in Wisconsin also indicated that on-site meetings and field trainings helped them ‘see eye-to-eye’ and ‘get on the same page’ with others in their network (Knoot and Rickenbach 2014).

Target Selection

Once participants begin to develop a shared understanding of the focal area, the next stage of CSM is selecting management and conservation targets. Here, targets are defined as specific features of the landscape that participants identify as essential to maintaining ecosystem character and function or features that, through their presence or absence, indicate management or conservation success. There is a well-developed literature on the selection of conservation targets (Craighead and Convis Jr. 2013), and the selection of targets for a CSM process has additional, unique considerations. Targets identified during the initial stages of CSM serve as the bar against which scenario outcomes are measured. Therefore, it is imperative that targets are responsive to the ecosystem features and processes addressed by the model and that model outputs can be evaluated for their ability to support the targets.

For example, CSM in the FSP simulated potential land cover change under different management scenarios and climate change impacts. Output maps of potential future land cover under each scenario were analyzed for their ability to support each target. Therefore, all targets for this project had to be mappable to landscape structure or forest composition and be sensitive or responsive to forest management strategies and other drivers of landscape change identified as important in the watershed.

Scenario Development

In the next stage of CSM, the participant group collaboratively constructs plausible alternative scenarios for the future of the focal area. Scenario analysis provides a way to visualize and compare the outcomes of a variety of possible situations and to cope with the uncertainty associated with applying new strategies under changing climate, ecosystem, and socioeconomic conditions (Peterson et al. 2003). Here, plausible scenarios describe alternative futures that are possible, though not equally likely (Mahmoud et al. 2009). CSM can be used to investigate normative or exploratory scenarios. Normative scenarios, also called anticipatory scenarios, define various desirable or undesirable future conditions and seek to understand how each may be achievable or avoidable given specific actions. Exploratory scenarios seek to understand the potential outcomes of a particular set of drivers of change by extrapolating from the past or defining and exploring new drivers (Mahmoud et al. 2009).

In the FSP, participants formulated exploratory landscape scenarios. Landscape scenarios specifically refer the different plausible conditions and factors that underlie landscape change (Nassauer and Corry 2004). The four landscape scenarios developed for the Two Hearted River watershed were: 1) continuation of current management, 2) industrial forestry, 3) increased area under working forest conservation easement, and 4) cooperative ecological forestry. Each scenario represents a unique spatial arrangement of hypothetical ownership boundaries, each with a specific management regime, on the landscape. All scenarios were examined under two natural disturbance regimes—the current natural disturbance regime and with an increased probability of wildfire and windthrow. These scenarios are fully described by Price and colleagues (2015).

Ecological Modeling

Next, CSM uses ecological modeling to simulate the alternative scenarios developed by participants. A variety of ecological modeling approaches are compatible with CSM. The FSP used landscape ecological modeling, which simulates the interactions of pattern and process for landscape elements such as ecological communities, individual species, and ecosystem processes at large spatial scales (Scheller and Mladenoff 2007; Turner et al. 2001). Ecological models have been used previously to compare alternative scenarios of climate, ecological, management, or resource use conditions (Gustafson et al. 2006b; Provencher et al. 2007; Wilhere et al. 2007; Iverson et al. 2008; Scheller and Mladenoff 2008; Zollner et al. 2008). In this capacity, scenario modeling can be applied as a strategic tool for resource and ecosystem management planning by providing insight into the range of possible outcomes of alternative conditions (Scheller and Mladenoff 2007).

We simulated alternative scenarios for the Two Hearted River watershed using the VDDT/TELSA modeling suite, a stochastic, empirical, state and-transition model (STM) designed to project the spatial interactions of succession, natural disturbances, and management at broad spatial scales (up to 250,000 ha) over decades to centuries (Kurz et al. 2000; ESSA Technologies Ltd. 2007; ESSA Technologies Ltd. 2008). We worked with participants to update spatial data and model parameters to capture land cover, ecological dynamics, and management activities in the watershed under each scenario in workshops and one-on-one meetings. Each scenario was simulated for 100 years into the future under both natural disturbance regimes.

Based on participant feedback, we adjusted model parameters to improve its performance. Once models were refined to generate final simulation results, we performed further spatial analysis using ArcGIS, Fragstats, and R statistical software (McGarigal et al. 2002; ESRI 2008; R Core Team 2015) to assess and compare the ability of each scenario to achieve watershed conservation goals and meet selected targets (Price et al. 2016).

Project Output

The collaborative modeling process generates output specific to the project and modeling tools applied. In many cases, new GIS-based information products are generated for use as model input and produced as model output. Additional output may include white papers, peer-reviewed publications, and publically-accessible web-based products. The ecological model itself is also considered an output of the process.

ADAPTIVE CO-MANAGEMENT

ACM has been proposed as an approach to ecosystem-scale management in complex, changing landscapes (Olsson et al. 2004a; Armitage et al. 2007; Armitage et al. 2009). The theoretical base of adaptive co-management is drawn from common property (Ostrom 1990), adaptive management (Holling 1978), and co-management (Berkes 2007; Berkes 2009) literatures. By applying the principles of adaptation to both the social and ecological components of social-ecological systems, ACM aims to ensure that the networks of people and institutions responsible for ecological systems and the systems themselves are resilient to perturbation (Olsson et al. 2004a). In practice, ACM focuses on integrating science with decision-making to foster social learning among stakeholders necessary for resilient, place-based management in the face of uncertainty. This approach has been applied in the areas of wetland conservation (Olsson et al. 2004a; Olsson et al. 2004b; Olsson et al. 2007; Olsson 2007), fisheries management (Ayles et al. 2007), forest resources (Colfer 2005; Cheng et al. 2010; Donoso et al. 2014; McDougall and Banjade 2015), protected areas (Schultz et al. 2011), and other natural resource management contexts (Lundmark et al. 2014).

ACM shares many central concepts with collaborative scenario modeling and other participatory approaches to conservation and natural resource management. Mainly, both approaches engage participants in an iterative process of social learning with the goals of coping with uncertainty and developing resilient natural resource management solutions through collaboration (Armitage et al. 2007). In fact, scenario modeling and participatory action research have previously been proposed as approaches for operationalizing ACM (Wollenberg et al. 2000; Peterson 2007; Ballard and Belsky 2010). Numerous scholars have identified features necessary for the emergence of ACM; see Plummer (2009) and Plummer and colleagues (2012) for helpful syntheses. Drawing from the rich literature and case studies focused on ACM, I have summarized the five features most often identified as essential for establishing the social conditions necessary for collaboration between stakeholders: stakeholder engagement, development of shared vision or goals, social learning through collaborative problem solving, social capital, and adaptive capacity. Features were summarized from the following reviews and synthesis articles: Olsson and colleagues (2004a), Armitage and colleagues (2007), Plummer and Armitage (2007), Plummer and FitzGibbon (2007), Plummer and Armitage (2010), Plummer and colleagues (2012), and Plummer and Baird (2013).

DEFINING SOCIAL OBJECTIVES FOR COLLABORATIVE SCENARIO MODELING

Collaborative scenario modeling projects, at a minimum, seek to engage stakeholders. They may also aim to enhance one or more of these other social conditions, or the ultimate goal may be to set the stage for adaptive co-management or another form of collaboration, specifically. In these cases, social outcomes should be treated as explicit project objectives, and progress toward achieving those objectives should be measured. Clear objectives and indicators allow CSM projects to explicitly address their social goals, be more strategic in process design and implementation, and ultimately be more effective.

The five features essential for establishing collaboration identified by ACM theory serve as a useful starting point for setting the social objectives for CSM processes. These objectives and their indicators are described below and summarized in Table 1. Figure 2 illustrates the potential contribution of each stage of the CSM process (blue boxes) to these objectives (grey boxes) and continued collaboration among stakeholders. As this conceptual model shows, there are important feedbacks between these objectives. For example, social capital enables stakeholder engagement and social learning, which can, in turn, increase social capital and improve adaptive capacity. As a result, failure of CSM projects to be attentive any one of these features can limit success at achieving both scientific and social objectives.

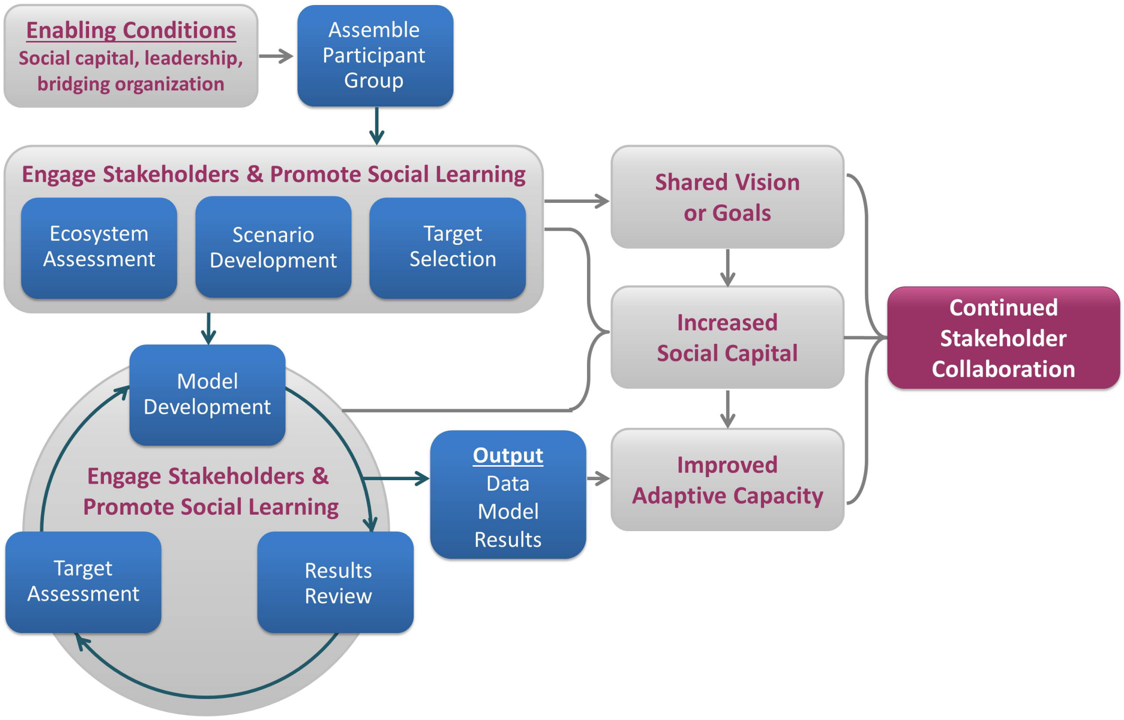

Figure 2. A conceptual model illustrating the potential contribution of each stage of the CSM process (blue boxes) toward achieving the proposed social objectives of projects that aim to facilitate continued collaboration among stakeholders (grey boxes).

Objective 1. Engage stakeholders.

Engagement is the basic process of bringing people together. CSM brings together multiple stakeholders in a shared process of exploring alternative landscape futures. CSM projects should purposefully assemble a diverse participant group that represents all of the individuals and organizations responsible for natural resource management and decision-making in the focal area. Involving all stakeholder groups increases the likelihood that their perceptions, values, and issues are represented by the scenarios and model, increasing the salience and legitimacy of the project to local decision-makers. A lack of legitimacy may result in decision-makers ignoring project outputs (Priess and Hauck 2014). Stakeholders can be involved in just one or all stages of the collaborative scenario modeling process, as illustrated by the FSP. If possible, engage stakeholders at many stages and in an iterative sequence at each stage to create many opportunities for engagement (Figure 2).

The format of stakeholder engagement is an important consideration when planning the collaborative scenario modeling process. Each stage of the process requires different modes of interaction between stakeholders and the exchange of different kinds of knowledge. For example, the FSP used in-person workshops with all stakeholders during ecosystem assessment, scenario development, and target selection, while one-on-one meetings were used during model development. Methodologies of stakeholder engagement and recommendations for their use in collaborative scenario modeling are described by Price and colleagues (2012). As Sayer and colleagues explain (2013), “Effective participation makes demands of stakeholders.” At each stage in which stakeholders are engaged, projects should clearly define the expectations for stakeholder input and track progress at obtaining that input.

Difficulties in practice. Involving *all* stakeholders is difficult for several reasons. First, there may be a large number of stakeholders within a focal landscape, and working with a large stakeholder group is often impractical (Sayer et al. 2013). Further, some stakeholders may not wish to participate; some may not be able to. Participation by stakeholders throughout the process may be limited by availability, funds for traveling, shifting institutional or personal priorities, and staff turnover, as in the FSP (Wollenberg et al. 2000; Price et al. 2016). Some projects have noted difficulties in engaging participation by the environmental justice non-profit sector, specific ethnic groups, and by individuals or groups that have participated in past research efforts (Van Berkel and Verburg 2012; Carpenter et al. 2015). Finally, many studies, including the FSP, acknowledge the difficulty of sustaining stakeholder participation throughout the course of the project (Van Berkel and Verburg 2012; Meyer et al. 2014), with the number of participants fluctuating throughout the process. Active and ongoing efforts by the project team may be required to sustain involvement, and enhanced social capital may help sustain stakeholder participation.

In some cases, incentives can be identified and communicated to garner stakeholder participation. For example, “business” incentives may encourage professionals to participate—the Forest Stewardship Council rewards forester participation in research. Additionally, the CSM process can be utilized to comply with natural resource management policies and conservation mechanisms that require or encourage cross-boundary collaboration, such as the USFS’s 2012 Planning Rule Final Directives for National Forest System Land Management Planning (USFS 2012), Wisconsin’s Managed Forest Law (Knoot and Rickenbach 2014), and working forest conservation easements (Rissman et al. 2007; Rissman et al. 2013).

Objective 2. Facilitate development of a shared vision or goals.

CSM can aid in the development of a shared vision or goals for the focal landscape through collaborative ecological assessment, target selection, and scenario development. In this context, a vision is a shared aspiration for the future state of the focal landscape, and goals are formulated as specific management or conservation targets. Collaborative ecosystem assessment involves sharing information and knowledge of each ownership to characterize the focal area and shift the focus of participants from the individual parcel to the landscape scale (Cheng et al. 2010), which is an essential precursor to formulating a desired future state or states described by a vision or goals. Creating scenarios through a shared visioning process can also help participants develop a systems view of the cross-boundary connections within and between the ecological, social, and economic components of the landscape, establish a guiding mission for the group, and help facilitate problem-solving among participants (Wollenberg et al. 2000; Olsson 2007). Target selection can also facilitate the development of shared goals. By agreeing upon a common set of targets, participants create a common lens through which they can view and evaluate the effectiveness of alternative management scenarios to achieve these goals.

Difficulties in practice. The collaborative scenario modeling process may help generate a shared understanding of the landscape, but garnering consensus among diverse stakeholders around a manageable number of scenarios and targets may be challenging. Agreement around normative scenarios, those that describe the landscape as it *should* be (Nassauer and Corry 2004), can be particularly difficult to achieve when stakeholders' values and aspirations for the landscape are varied. Alternative visions can be more easily accommodated during an exploratory scenario process, which does not require agreement about the desired future state of the system (Carpenter et al. 2015). In the FSP for example, stakeholders identified twelve species and 11 ecosystem services as potential targets for the FSP, reflecting their various valuations of the landscape; and this list had to be narrowed to a practical number by the project team (Price et al. 2016). Further, stakeholders may not apply the shared vision or goals (scenarios or management and conservation targets) generated during the CSM process to natural resource management in practice.

Objective 3. Promote social learning through collaborative problem solving.

Social learning has been defined as "the collective action and reflection that occurs among different individuals and groups as they work to improve the management of human and environment interrelations" (Keen et al. 2005). Social learning is supported by "deliberative processes involving sustained interaction between individuals, and the sharing of knowledge and perspectives in a trusting environment" (Cundill and Rodela 2012). Social learning is synonymous with collaborative learning as defined by Daniels and Walker (2001). The CSM process provides a platform for social learning, and the ecological model serves as a boundary object—a focal point for collective deliberation, information sharing, and data gathering among participants (Star and Griesemer 1989; Cash et al. 2002). Problem solving takes place through the development of alternative scenarios and a model tailored to a local social-ecological system (Berkes 2007). These processes facilitate dialogue and analytic deliberation and create a space in which participants can share differential knowledge and articulate their values, perceptions, and long term visions for the landscape (Wollenberg et al. 2000; Daniels and Walker 2001; Peterson et al. 2003b).

For projects that include participants in model development, participants also become familiar with how the model operates, its strengths, and its limitations. As models of climate change and ecosystem response become increasingly ubiquitous and integrated into the natural resource planning and management conversation, the familiarity of land managers with these tools may lag behind, especially for individual landowners or natural resource management practitioners acting independently of state agencies and other institutions. CSM may improve the modeling literacy of participants and better equip them to understand and integrate the results of other modeling efforts into their planning and management processes. Previous research has shown that involving participants in the modeling process encourages ownership of the modeling tool and the results it produces. As a result, participants are more likely to view results as legitimate and incorporate them into management planning and implementation (Daniels and Walker 2001; Hulse et al. 2004; Gustafson et al. 2006a; Seidl 2015). Not only do participants learn about the ecological system and ecological model, they also learn how to work together, which is another component of social learning (Cundill et al. 2012). Further, CSM can serve as documentation of the collective knowledge of the group and help identify the potential gaps in knowledge that may be explored in the future.

Difficulties in practice. Learning is rarely explicitly stated as an objective in CSM and adaptive management projects, and statements of evidence of learning are even more rare (Fabricius and Cundill 2014). In some cases, the presented evidence of learning, such as stakeholder acceptance of modeling outcomes (Van Berkel and Verburg 2012), may be more indicative of social processes other than learning. Therefore, the challenge moving forward is to measure and document learning that occurs during the CSM process, keeping in mind that who is learning and what they learn can vary. Learning can take place by scientists on the project team as well as the stakeholders involved. In addition, these parties can learn about conservation and ecosystem management as well as governance (Fabricius and Cundill 2014). While, this objective focuses on promoting social learning among stakeholders, as it is central to their continued collaboration, documenting the learning of the project team can be equally informative and important for the success of projects and advances in the field.

Objective 4. Increase social capital among stakeholders.

The face-to-face, sustained stakeholder engagement, collaborative sense-making and visioning, and social learning facilitated by CSM have been shown to build trust and social capital among natural resource managers (Dietz et al. 2003; Plummer and Fitzgibbon 2004; Knoot and Rickenbach 2014). Social capital is defined as “the social norms, networks of reciprocity and exchange, and relationships of trust that enable people to act collectively”

(Armitage et al. 2009). Creating social capital among participants is an ongoing process, and the strength of the social bonds of participants tends to grow as the CSM process develops. Plummer and FitzGibbon (2006) identify three stages of social capital formation—unarticulated, formulating, and conjoint. Participants likely enter the CSM process in the ‘unarticulated’ stage, where each has ‘inherent’ social capital with other individuals and organizations working on the landscape, and progresses to the ‘formation’ stage of social capital development through sustained interactions during ecosystem assessment, scenario development, and modeling. These stages improve trust and establish social capital between stakeholders by making their objectives and values transparent to the group. Once established, this social capital enables transition to the “conjoint” stage where participants continue to cooperate and may constructively resolve future conflicts (Daniels and Walker 2001; Adams et al. 2003; Pretty 2003; Ostrom and Nagendra 2006).

Difficulties in practice. Social capital is many-faceted and therefore challenging to measure. Further the social capital of individuals and groups fluctuates over time as the result of changes in both social and ecological circumstances (Pretty 2003). Collaborative scenario modeling projects tend to rely on the ‘inherent’ social capital among participants as an enabling condition (Meyer et al. 2014), and none have measured the impacts of the collaborative scenario modeling on this component of the social-ecological system. Social capital formation may also be helped or hindered by past experiences of participants, which should be considered in project design and implementation (see the Discussion and Recommendations).

Objective 5. Improve adaptive capacity of stakeholders.

Adaptive capacity has been defined and applied in multiple disciplines as a way to describe the ability of entities to cope with change; Plummer and Armitage (2010) provide an overview of these distinct but related meanings. Adaptive capacity of social-ecological systems, specifically, has been defined as the ability of the system or its components—the individuals, organizations, and institutions as well as the ecosystems that compose the system—to be robust to disturbance and capable of responding to actual or anticipated change (Plummer and Armitage 2010). Armitage (2007) describes adaptive capacity as "an attribute of resource management that creates opportunities for learning and the ability to experiment, adapt, and foster resilient…strategies in complex social-ecological circumstances." Adaptive capacity is determined by both the resources, or endowments, of a social-ecological system and the social and institutional relationships that determine access to those resources. CSM projects that most successfully improve the adaptive capacity of participants enhance the material or social endowments of the group and enable equal access to these endowments by all participants. CSM can contribute primarily to adaptive capacity by building social capital, by creating a learning community, and by providing technical resources as illustrated in Figure 2. As described above, sustained interaction among participants builds their social capital and encourages formation of social networks and linkages among the actors responsible for management of the focal area. Greater social capital enables these actors to respond to change and uncertainty through collective action that draws on the knowledge and resources of the network (Plummer and FitzGibbon 2007).

Collaborative scenario projects can improve the social endowments of participants by creating a 'learning community' (Ballard and Belsky 2010) among participants. A learning community, also referred to as a community of practice, is “a group, or groups, of people who share a concern for something that they do (e.g., a management team) and learn how to do it better through regular interaction” (Cundill et al. 2012). Sustained interactions focused on knowledge sharing and generation can facilitate a learning orientation, or learning culture, among participants that can be considered an adaptive behavior (Plummer 2013).

The input data, ecological model, and model results all serve as technical resources, or material endowments, for participants. Not only does the ecological model provide information about the outcomes of the specific scenarios and conditions investigated at its inception, it can also be parameterized to capture additional scenarios, test hypotheses and assumptions, and serve as a low-stakes method of applying and evaluating novel conservation or management strategies. In this way, a modeling tool tailored to a local ecosystem can inform the adaptive management cycle as a virtual learning-by-doing tool—a management action can be simulated, the outcomes analyzed, and approaches adapted without the significant time lag or risks associated with new strategies.

Difficulties in practice. The overall adaptive capacity of a system is governed by the complex interaction of material and social endowments that emerges in the presence of a perturbation or challenge to the system. Simply having the potential, or capacity, to adapt does not mean adaptation will actually come to fruition. Therefore, adaptive capacity in action can only be measured by the presence of a disturbance or challenge to the system. For collaborative scenario modeling projects designed to address a current conservation or management dilemma, post-project analysis can examine the contribution of the process to actual decision-making. However, collaborative scenario modeling projects may not be implemented to address a current conservation or management challenge. In this case or in the case of projects that do not plan to continue analysis beyond the scenario development and modeling process, only the project's contributions to material endowments can be assessed.

RESULTING KEY INDICATORS

Measuring progress toward these social objectives is a critical, yet challenging, component of collaborative scenario modeling project design and implementation (Walter et al. 2007; Seidl 2015). Here, I propose indicators and measurement methods that can be used to gauge progress toward each social objective. Importantly, these indicators vary in the timescale within which they operate. Objectives 1, 2, and 3 should be measured during the CSM process so that adjustments can be made to improve social outcomes. Objectives 4 and 5 should be measured longitudinally (before and after the process) and are most appropriate for informing future CSM efforts rather than adaptation within a single project. These indicators are meant to be a starting point for CSM projects considering social objectives. Not all indicators will be appropriate for all projects, and some projects may choose additional indicators or methods of measuring them based on project specifics.

Indicators of stakeholder engagement

I propose three indicators of successful stakeholder engagement. First, the participant group includes all stakeholders within the focal area. Measuring this objective requires the project team to compare the individuals and organizations involved in the CSM process to the complete list of stakeholders identified by a formal stakeholder analysis (Priess and Hauck 2014; Schneider and Rist 2014). Second, participants provide meaningful input to the scenario development and modeling process. The project team should identify the information needed from stakeholders at each stage of the collaborative scenario modeling process, track progress

Table 1. Proposed social objectives for CSM projects, indicators of success at achieving these objectives, and methods for measuring each indicator. Key references provide information valuable for assessing each indicator.

Objectives and Indicators	**Measurement methods**	**Key References**
1. Engage stakeholders		
i. The participant group includes all stakeholders within the focal landscape. ii. Participants provide meaningful input to the scenario development and modeling process. iii. Participants remain involved throughout the process.	i. Compare composition of the participant group to the full complement of stakeholders identified through stakeholder analysis. ii. Identify the information needed from stakeholders at each stage of the process, track progress toward obtaining the necessary information, and determine if the information is of sufficient quality. iii. Track participation of each stakeholder throughout the processes.	(Martin et al. 2012; Priess and Hauck 2014; Schneider and Rist 2014)
2. Facilitate development of a shared vision or goals		
i. The process generates shared targets and alternative scenarios for the focal landscape. ii. The focus of participants shifts from their individual parcel or jurisdiction to the landscape scale.	i. Document targets and alternative scenarios. ii. Analyze dialogue from one-on-one and group interactions, conduct surveys, or employ cognitive mapping to measure the degree to which stakeholders demonstrate broad-scale thinking.	(Van Berkel and Verburg 2012)
3. Promote social learning through collaborative problem solving		
i. Participants meet the learning goals defined by the project team.	i. Utilize longitudinal questionnaires or surveys to assess whether stakeholders	(Van Berkel and Verburg 2012; Priess and Hauck

ii. Participants use the tools and terminology of the approach to generate new knowledge.	demonstrate knowledge of key topics identified by the project team. ii. Analyze dialogue from one-on-one and group interactions to assess the degree to which stakeholders correctly use terms introduced during the CSM process in their own discourse.	2014)
4. Increase social capital among stakeholders		
i. Participants show evidence of mutual trust. ii. The process expands or strengthens the professional network of participants.	i. Conduct longitudinal interviews or surveys to measure the baseline and final level of trust among participants. Dialogue from one-on-one and group interactions may also provide additional evidence of improved trust among stakeholders. ii. Analyze the size and strength of the professional social network of stakeholders before and after the CSM project. Track future collaborations of participants when possible.	(Pretty 2003; Plummer and FitzGibbon 2007; Walter et al. 2007; Knoot and Rickenbach 2014)
5. Improve the adaptive capacity of stakeholders		
i. The process enhances the material or social endowments of the participant group. ii. Participants incorporate the results of the collaborative scenario modeling into future management and planning efforts.	i. Conduct longitudinal surveys to characterize and compare the baseline and final material endowments of participants. ii. Assess the degree to which results of the CSM process informed natural resource management decision-making in the focal landscape using follow up surveys, interviews, and observations.	(Plummer and Armitage 2010)

toward obtaining the necessary information, and determine if the information is of sufficient quality based on project requirements. Martin and colleagues (2012) describe best practices for eliciting expert knowledge, which includes verifying the quality of expert input and providing stakeholders with feedback. Ideally, knowledge-sharing will be well-distributed among the participant group. Finally, participants remain involved throughout the process. Track participation through time and intervene to increase participation when necessary.

Indicators of shared vision or goals.

Shared targets and alternative scenarios for the focal area generated by CSM projects serve as the indicators of the development of shared vision or goals. Alternative scenarios and targets are critical, intermediate outcomes of the CSM process, and a project cannot progress without achieving this goal. An additional indicator of shared vision or goals is participant focus on landscape-scale dynamics rather than on their individual parcel or jurisdiction. Timely analysis of dialogue from one-on-one and group interactions and surveys of participants can be used to measure the degree to which stakeholders demonstrate broad-scale thinking. Cognitive or mind mapping could be used in a workshop setting to measure the groups conceptualization of the focal landscape, as demonstrated by Van Berkel and Verburg (2012). Such analysis can enable the project team to emphasize these points in subsequent meetings to better achieve this objective.

Indicators of social learning.

Progress toward social learning can be tracked against the learning goals defined by the project team. In general, learning goals for CSM projects focus on the socio-ecological dynamics of the focal landscape, the function and limitations of the ecological model, and the potential responses of the focal landscape to the alternative scenarios. Additional learning goals may focus on participants' knowledge of the values and goals of other participants. Previous studies have used longitudinal questionnaires or surveys to assess whether participating in a collaborative modeling process resulted in stakeholder learning (Van Berkel and Verburg 2012; Priess and Hauck 2014).

Additional evidence of social learning is the use of tools and terminology of the approach by participants to generate new knowledge. As part of the CSM process, participants are asked to compare the outcomes of alternative scenarios, identify the potential impacts of specific drivers of ecosystem change in the focal area, and discuss the tradeoffs between specific conservation targets and management goals in a workshop setting. Analysis of dialogue from the workshop and surveys of participants can be used to measure the degree to which participants demonstrate knowledge of these topics and whether they correctly use terminology introduced during the process.

Indicators of social capital.

The social capital among stakeholders must be measured longitudinally in order to determine the influence of CSM. Approaches for measuring social capital are varied and summarized well by Plummer and FitzGibbon (2007). Two useful indicators of improved social capital are mutual trust and expansion or strengthening of the professional network of participants. Trust between stakeholders can be assessed through observations of their interactions and dialogue as well as surveys and formal interviews. For example, when surveying participants in a transdisciplinary project, Walter and colleagues (2007) asked, ‘‘Did your willingness to cooperate with your fellow citizens on a specific problem increase through the transdisciplinary process?’’ Other questions asked participants about their “readiness to share knowledge with fellow citizens, to intensify co-operation, and to leave important tasks in a joint project to others” (Walter et al. 2007). Collaborative scenario modeling projects must demonstrate maintenance of the baseline level of trust among participants at a minimum and, ideally, increased trust among participants at the end of a project. The improvement of trust through sustained interaction and collaboration is a common proposition CSM projects (Seidl 2015) and supported by anecdotal evidence, but no formal assessment has been applied and would represent an advance in the field. Knoot and Rickenbach (2014) demonstrate methods for characterizing the social capital and networks of stakeholders. Surveys of participants and tracking of future collaborations are also important. With the exception of a brief observation by Priess and Hauck (2014), no collaborative scenario modeling studies have examined collaboration between participants after completion of the collaborative scenario modeling process.

Indicators of adaptive capacity.

Similarly, the adaptive capacity of stakeholders must be measured longitudinally, and the timescale for follow-up will depend on the project and the pace of planning and management in the focal landscape. CSM projects that successfully improve the adaptive capacity of stakeholders will enhance the material or social endowments of the participant group compared to a baseline. Surveys of participants and analyses of their organizations before and after the project can be used to assess their material and social endowments. Specific questions for surveys may focus on their access to technical resources, participation in a learning community, and perceptions of their own adaptive capacity. For example, did the CSM project provide new ecological and management information that was not available to stakeholders prior to the modeling effort? Do participants continue to participate in the learning community that was fostered during the CSM process? Do stakeholders feel more prepared to manage natural resources under uncertain future conditions?

Finally, enhanced adaptive capacity is also indicated by incorporation of the results of the collaborative scenario modeling into future management and planning efforts. This is a gold-standard outcome, but projects rarely follow up to examine if and how the social or material outcomes of the project affect or inform subsequent decision-making in the focal landscape. Conduct follow up studies and surveys to determine if the participants adopt strategies identified during collaborative scenario analysis and if they develop mechanisms to monitor or strategies to deal with the uncertainties identified during the CSM process.

DISCUSSION AND RECOMMENDATIONS

This work furthers CSM and ACM theory in two ways. First, it suggests a practical approach for advancing social outcomes implicitly included in CSM projects and identified as pre-cursors for stakeholder collaboration and ACM. CSM projects will be most effective when the social and ecological components of the approach receive equal weight in project planning, execution, and analysis. Second, it provides a starting point for evaluating progress toward achieving these social outcomes and, therefore, the emergence of collaboration or ACM. Without these advances in theory, the social outcomes, i.e. societal effects, of CSM projects cannot be held to the same standards and evaluated with the same rigor as the natural science outcomes, i.e. scientific effects (Walter et al. 2007). Further, the emergence of ACM cannot be tracked and fully characterized without such measures of progress.

This work also reveals the limitations of CSM as a pre-cursor to ACM. Collaborative scenario analysis is fundamentally a decision-support tool that has the potential to produce both scientific and social effects (Walter et al. 2007). While the process and outcomes of CSM can provide a foundation for future stakeholder collaboration, ACM relies on more than just the social relationships between stakeholders. Political and economic factors also play a role in shaping the natural resource and management context within a focal area (Plummer 2009). Emergence of ACM may also require shared authority and decision-making among stakeholders, enabling legislation, funding, and monitoring—all of which contribute to the ability to detect and respond to environmental feedbacks and change (Olsson et al. 2004a; Armitage et al. 2007; Plummer and Armitage 2007; Plummer et al. 2012; Plummer and Baird 2013). These elements are outside of the scope of CSM projects.

Additionally, the lack of post-project analysis is a serious shortcoming in the CSM field that has left many of the propositions regarding its social outcomes and its potential to further ACM untested. A specific cross-boundary natural resource management problem will likely be needed to inspire collective action by stakeholders. Leadership at the individual and organizational levels and the commitment of individuals and institutions will be essential for sustaining the momentum provided by a CSM project and incorporating the information gained into on-the-ground action. This highlights the need for research on *if* and *how* CSM results are incorporated into the decision-making process in various contexts.

Further consideration and improvement of these objectives and indicators are required in light of grounded case studies. CSM practice is necessary to: clarify the relationships between the different objectives as described here and in the literature, improve the indicators provided here and identify new ones, refine methods for measuring these indicators, and present strategies for investigating the long term social impacts of such projects. Such research has the potential to improve the ability to measure social objectives that have thus far rarely been quantitatively evaluated, especially adaptive capacity, and reveal the cases in which some of these or other objectives are most applicable.

The design of CSM projects should also consider the timing, location, and additional objectives of projects. CSM projects are most suitable in situations in which social capital has had time to develop among potential participants, the number of potential participants is tractable from a collaboration standpoint, and the motivating questions are appropriate for ecological modeling. Good working relationships among participants provide a strong foundation for CSM. We recommend that CSM projects work to build on existing social capital, collaborations, and networks in the focal area, which contribute to the enabling conditions for collaborative projects. One can look to other networks focused on a similar issue for examples of successful partnerships or draw from the existing network of well-connected participants. In our experience, individuals with a great deal of social capital within the existing network can function as facilitators and leaders in a CSM project. Also, be cognizant of the lasting impressions, both good and bad, that previous interactions and collaborations have made on individuals and networks, and realize that forming new social capital may require addressing issues that pre-date the current CSM project.

In situations with little existing social capital or with a history of conflict, CSM may be a useful tool for establishing or repairing relationships by providing a boundary object around which focused, low-risk discussion can occur (Cash et al. 2002; Gass et al. 2009; Bizikova et al. 2012). For example, the ecological model can be used to simply capture the ecological dynamics of a focal landscape and create dialogue between participants, leaving contentious issues out of the discussion. However, if participants disagree on or overstep such boundaries, it is likely that the CSM approach may not result in shared goals. On the other hand, it is important for the establishment of ACM that participants express differing knowledge, viewpoints, and values. This collective ‘sense-making’ and subsequent deliberation to formulate shared goals are important for building social capital among the group. Successful navigation of collective differing among participants likely lies within the scope of skilled group facilitation (Daniels and Walker 2001).

CSM is most appropriate in locations with tractable social-ecological complexity. The social complexity of a landscape is characterized by the number of and relationships between stakeholders involved in its ownership, management, and use. In general, social complexity increases as the number of stakeholders increases. For example, only three major landowners were responsible for management of 80% of the Two Hearted River watershed, and the FSP did not include individual, private landowners or stakeholders from the broader community who had no direct land management rights or responsibilities in the watershed. As a result, relatively few stakeholders participated in the project, and social complexity was manageable though not without its challenges. Even with a small participant group, CSM is an involved, multi-year process. Therefore, the CSM process may not be appropriate in areas with highly fragmented ownership and many stakeholders.

CSM is most applicable in contexts in which information about the ecological dynamics of the focal landscape will advance collaboration and management. For example, the aim of the FSP was to provide insight into which management strategies best achieved ecological watershed conservation goals. Importantly, the model output, maps of land over in this case, could be evaluated to quantitatively inform project aims. CSM can be an especially useful tool for bringing together diverse sources of information to characterize landscapes that have not been well-studied.

Finally, carefully choose modeling software. The most appropriate modeling software for CSM projects will be transparent and transferable to land managers and conservation practitioners. STMs, such as that used in the FSP, are well-suited for collaboratively simulating alternative landscape scenarios for several reasons detailed in Price and colleagues (2015). Briefly, STMs represent vegetation communities and ecological dynamics in an intuitive and transparent way that can be easily communicated, explored, and refined through a collaborative process. They can be parameterized using local knowledge to capture the dynamics of focal ecosystems, and parameters can be easily adjusted to explore alternative scenarios.

Irrespective of software choice, ecological modeling is resource and labor intensive. Even with the relatively a user-friendly STM platform such as the one used in the FSP, individuals with technical modeling expertise are needed to translate participant input and feedback into model parameters, to answer questions about model functions, and to process model outputs, such as creating maps and summary statistics, that are understandable by participants with little modeling expertise. Therefore, continued use of a model requires appropriate computing hardware, human resources, and modeling expertise. Application in a collaborative context increases the likelihood that financial and human resources are available among the participating landowners and agencies.

CONCLUSION

CSM has the potential to improve natural resource management decision-making in two key ways—by enhancing stakeholder knowledge about the socio-ecological dynamics of the system and by enhancing the ability of stakeholders to collaboratively make sustainable decisions. Explicitly addressing both the scientific and social aims of CSM projects not only improves the efficacy of individual projects but can have lasting effects on the ways in which natural resource managers address future challenges. CSM presents a practical approach for engaging stakeholders around a central question or problem to share information and learn collaboratively. While the learning aspect of adaptive management has traditionally been through monitoring of past actions, CSM facilitates anticipatory learning by generating knowledge about the potential future states of the social-ecological system and providing a mechanism for exploring key uncertainties and variability. Therefore, CSM has the potential to shift the natural resource management cycle from reacting to anticipating (Wollenberg et al. 2000). Planning a response to anticipated challenges provides opportunities to identify synergies among different actors and strategies that are applicable under a range of future conditions, which both improve natural resource management efficiency and efficacy.

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CONCLUSION

Natural resource management and conservation is increasingly a cross-boundary endeavor. Ecological processes and disturbances are not neatly contained within ownership and management boundaries, and addressing new challenges presented by climate change necessitates innovation and information sharing. At the same time, the management and conservation actions of individual landowners and agencies affect ecosystem characteristics and processes at the landscape scale. As a result, the potential for cooperation and conflict surrounding natural resource management and conservation has never been higher.

Approaches to facilitate collaboration among the diverse stakeholders working to conserve and manage today's landscapes are needed. Managers and decision-makers require the ability to compare the potential outcomes of conservation strategies, management regimes, ecosystem dynamics, and climate conditions (Opdam and Wascher, 2004). To address this need, I developed (Chapter 1) and applied (Chapter 2) a collaborative scenario modeling (CSM) approach to simulate the potential long-term, cumulative consequences of conservation actions at broad scales as part of the Forest Scenarios Project (FSP). I have also developed a framework for integrating social objectives into the design, implementation, and evaluation of CSM projects that aim to facilitate the emergence of ongoing collaboration among stakeholders in natural resource management settings (Chapter 3).

This conclusion provides an overall critique of the CSM approach as it was applied in the FSP, summarizes lessons learned from CSM results in the THR watershed regarding the ability of specific management and conservation strategies to achieve conservation goals, and examines the broader applicability the CSM approach to facilitate collaboration among stakeholders. I end by highlighting directions for future research utilizing CSM.

Critiques of the CSM approach

The FSP grew out of the conservation context in two landscapes in which The Nature Conservancy (TNC) had partnered with state and federal government agencies, individual and industrial private land owners, and timber investment management organizations to protect lands of conservation concern. Such conservation opportunities tend to arise spontaneously when private land owners choose to sell property. TNC and other land trusts that utilize multiple conservation mechanisms could benefit from a tool to help assess the potential efficacy of different spatial arrangements of these strategies in advance of purchasing land or negotiating a conservation easement, which represent an initial investment of both financial and human resources as well as a long-term commitment to monitoring and management.

The FSP aimed to quickly develop and apply landscape models tailored to local ecological systems to simulate alternative conservation scenarios and inform such rapid conservation opportunities. Focusing on two landscapes, the Two Hearted River watershed in Michigan's Upper Peninsula, which is the focus of this dissertation, as well as the Wild Rivers Legacy Forest (WRLF) in northeastern Wisconsin, the project initially proposed to complete scenario development and modeling in both landscapes in just two years. However, such a rapid process was not realized for several reasons that others seeking to apply CSM should consider.

First, even with available LANDFIRE land cover data and Vegetation Dynamics Models that could be modified to represent the focal landscapes (LANDFIRE 2007a; LANDFIRE 2007b), the CSM is labor-intensive and time-consuming owing to the need for the modeler to regularly meet with participants either in person or in a web-based workshop to review model input and output. In non-collaborative modeling efforts, technical model output can be interpreted and reviewed by modeling experts to inform revisions to the model and its parameters with little extra data processing. In contrast, collaborative model development requires processing of each set of model output to create maps and summary statistics that are understandable by participants with little modeling expertise.

The FSM team chose a state-and-transition modeling (STM) platform that intuitively represents ecosystems and processes to facilitate communication with stakeholders. STMs represent vegetation communities, ecological succession, and the impacts of management and natural disturbances as distinct model components (Costanza et al. 2015). Even with this relatively user-friendly platform, project team members with expertise in modeling and spatial analysis were needed to translate participant feedback into model parameters and to answer stakeholders' about specific model functions. While this improved the participants' understanding of the model, progress toward developing a final, working model was slow, relying on the schedules of participants, who were most often participating in the project on their own time.

Second, the STM modeling software used in the FSP was still under development when the research began in 2008. VDDT, the aspatial component of the modeling suite, was in final release format and widely used in other TNC projects (Forbis et al. 2006; Provencher et al. 2007; ESSA Technologies Ltd. 2009). TELSA, the spatial component of the suite, was relatively new and available as a 'beta version.' Over the course of the project, limitations and 'bugs' in the software required extensive trouble shooting, software corrections by the developer, and work-around solutions, delaying project progress. Development of the TELSA software was halted in 2008, and resources were shifted to new STM software.

Although the FSP was able to complete modeling of both landscapes in the VDDT/TELSA platform, further use of these models may be limited, as this platform will not be improved or upgraded. Unfortunately, the newest STM software from the same developers does not yet have the same capabilities as TELSA. From these experiences, I suggest that CSM projects utilize established modeling platforms when possible so that stakeholders can continue to use the model to simulate additional scenarios as part of future planning efforts. Additional training of participants in the use of modeling software would likely be needed.

The CSM approach aims to develop and simulate scenarios that capture the management and conservation concerns of the stakeholders participating in the process. In addition to informing ongoing and future natural resource management and conservation, stakeholders may also seek to apply this approach for other purposes. For example, the impetus for conservation action on the part of many organizations is a response to perceived threats to the conservation values of the area. In many landscapes, including the THR watershed and the WRLF, the current complement of ownership and management strategies represents the culmination of an extensive investment of both time and money on the part of many organizations to protect these conservation values. As a result, conservation organizations and others may seek to compare the outcomes of conservation or management alternatives to a case in which no conservation action was taken in hopes of evaluating the effectiveness of a particular strategy.

For example, parcelization is a major concern in northern forest landscapes (Gass et al. 2009; Knoot and Rickenbach 2014). Parcelization occurs when a single tract of land is divided into many smaller parcels and distributed among different owners. In forested landscapes dominated by timber production, forestland is often subdivided and sold when the value of the land for other uses, such as home development, exceeds the value of the land for timber production. This trend is problematic for several reasons. First, each new landowner may have differing land use and management goals that impact the landscape in myriad ways, making conservation of landscape function more complex and challenging. Further, parcelization can result in the loss of forestland to other land uses, such as housing. Therefore, when a landowner chooses to divest in a large tract of land, conservation organizations or government agencies may acquire the land with the aim of preventing parcelization and conversion to other land uses.

This was the case in both the THR watershed and the WRLF, where TNC, state Departments of Natural Resources, and other partners worked to prevent parcelization and the loss of forestland to housing development and other uses during a period of growth in the U.S. housing market during the early 2000's. From this context, participants in the FSP were curious if their efforts to protect these landscapes against parcelization and forest loss effectively abated this perceived threat and suggested a 'no conservation action' scenario in which recent trends in housing development were projected forward.

In the case of the THR watershed and the WRLF, we found that the perceived threat—parcelization and the continued loss of forestland as housing development expanded—was not supported by recent trends in housing construction in either area (Nixon, unpublished data; Radloff, unpubished data). Those seeking to evaluate alternative futures must recognize that such 'no conservation action' scenarios have the potential to be biased toward participant's perceived or anticipated threats to the landscape and may not represent likely alternative futures. To truly measure the ability of conservation strategies to abate or mitigate threats to a particular area, a landscape must be compared to another, similar landscape in which there has been no conservation action. In practice, this counterfactual or null case is often difficult to find. In the absence of a counterfactual landscape, the effectiveness of particular conservation strategies can only be evaluated relative to other scenarios, and no claims about the effectiveness of current management at abating or mitigating particular threats can be made.

Further, it is also critical to point out, as suggested in Chapter 2, that not all of the impacts of various management and conservation strategies are best quantified by landscape modeling and metrics. As the example above illustrates, threats to landscape function and conservation values are ever changing; some perceived or anticipated threats may impact landscapes decades later or not at all. Such changes are especially difficult to project into the future in areas that have a history of boom and bust cycles of development and resource extraction, such as the Upper Peninsula of Michigan (Karamanski 1989). In addition, the protections offered by conservation actions, such as preventing parcelization and land use conversion, may not be realized in the form of changes in land cover or lack thereof.

As a result, I suggest that CSM as we demonstrate here is not suitable for rapid evaluation of conservation strategies, informing conservation acquisitions as they arise, or evaluating the effectiveness of current conservation relative to inaction by a conservation organization. The rapid development of conservation opportunities likely outpaces the slow momentum of collaborative landscape modeling.

As explained in Chapters 2 and 3, the CSM approach may be better suited to accompany natural resource management planning processes, especially in landscapes owned and managed by multiple actors. This approach can inform cross-boundary natural resource management by engaging diverse stakeholders to collaboratively develop and model scenarios representing a range of management alternatives. Further, application in a collaborative context increases the likelihood that financial and human resources would be available among stakeholders to enable the development of expertise necessary for the continued use of the modeling tool.

Lessons learned from the scenario modeling results

Modeling results for the THR watershed, detailed in Chapter 2, provide insight into the ability of specific management and conservation tools, as they are applied here, to maintain landscape spatial heterogeneity and conserve mature forests and wetlands. These results show that applying multiple conservation strategies in targeted areas of the landscape, such as single-ownership forest reserves and working forest conservation easements (WFCEs), may better achieve these conservation goals than either strategy applied alone in the same area. Results indicate that current WFCE restrictions can support both natural resource extraction and conservation of late succession forest in the THR watershed.

However, when the same restrictions were applied to an area with a greater proportion of wetland, the area of late succession wetland classes declined substantially. Here, the expansion of the easement area simulated the application of current easement restrictions to an adjacent area on the landscape that was not explicitly considered when the easement was drafted. As such, the restrictions and management plan did not preclude timber harvest in forested wetlands (boreal acid peatland and alkaline conifer hardwood swamp cover types), resulting in a loss of mature wetland. Currently, organizations that negotiate and purchase easements devote substantial time and resources into crafting easement documents with the aim of protecting the conservation values of a landscape in perpetuity. By illustrating a case in which an easement was applied to an area for which it was not designed, these results underscore the necessity of tailoring easements to local conditions, especially in ecosystems with long successional trajectories or that are slow to recover from disturbance.

The unique nature of individual WFCEs presents an interesting challenge to any attempt to understand the effects of WFCEs at broad scales. While forest landscape modeling is widely used to simulate alternative management scenarios, it has rarely been applied to simulate the impacts of WFCEs. Easements are usually tailored to fit the conservation and management context of a particular location. As such, the WFCE restrictions and accompanying management plan are unique in every landscape. Though easements are a matter of public record, the management plans often specified by WFCEs are not, and the translation of easement restrictions and management plans into management action is at the discretion of the land manager. This presents a challenge to research seeking to understand the impacts of this conservation mechanism on the ecology of a landscape, as knowledge of one particular easement cannot be extrapolated to other easements, and makes this research unique and valuable.

Overall, these results support the assertion that multiple strategies can be utilized to better tailor conservation to ecological and management contexts. Planning and application of multiple conservation strategies in a landscape is a challenging task. Such an undertaking requires spatial ecological data, knowledge of the various management and conservation options, and an understanding of the ecological response to those options at multiple scales. CSM is an especially useful tool for planning in this context, as modeling alternative management scenarios can illuminate the benefits and tradeoffs of applying different strategies in specific locations.

Results also point to a potential tradeoff between conserving mature forest and wetland for conservation purposes and susceptibility of the landscape to stand-replacing natural disturbances including wildfire and windthrow. Mature forest and wetlands have higher susceptibility to wildfire and windthrow disturbances than younger age classes. Therefore, an increase in the proportion of these seral stages through cooperative ecological forestry or other management strategies aimed at promoting old growth characteristics also increased the sensitivity of the landscape to changes in these stand-replacing disturbances. The frequency of these disturbances is projected to increase in the Northern Great Lakes region. The probability of fire in the eastern Upper Peninsula is estimated to increase by 40 to 60% by 2100 (Guyette et al. 2014). At the same time, the frequency of high wind events (> 70km/hr) in the region of Canada bordering Lake Superior is estimated to increase by approximately 60% by 2100, with wind gusts > 90km/hr showing an even greater increase (Cheng et al. 2014).

Land managers and conservation practitioners identified potential changes in the frequency of wildfire and windthrow events due to climate change as a major management concern in the THR watershed. These results indicate that the sensitivity of the landscape to these disturbances can be at least somewhat mitigated by management. Management, specifically timber harvesting in older stands, can reduce the area of the landscape most susceptible to wildfire and windthrow events and lessen the overall impact of those events on the landscape. However, this may be at the expense of maintaining older, more structurally diverse stands, which may provide habitat for focal species (Nixon et al. 2014). Where promoting mature forest and wetland is a goal, managers should consider strategies to reduce fuel loading and the probability of ignition and spread. Currently, the majority of wildfires in the study area are caused by human ignition (Michigan DNR, unpublished data). Therefore, reducing ignitions by people working and recreating in this landscape has the potential to offset, at least partially, the increased probability of ignition from natural sources as climate change shifts the natural disturbances regime. Further, natural resource managers and agencies may also choose to strategically locate fire breaks or firefighting resources to allow faster access to areas of mature forest and wetland that have a higher probability of ignition. Susceptibility to windthrow can be mitigated by reducing the amount of forest edge, creating edges with a gradient of vegetation height and residual basal area to reduce windspeed and force affecting mature trees at the forest edge, and strategically arranging edges to avoid areas of high windspeed, such as hills or areas perpendicular to the direction of prevailing wind (Mitchell and Rodney 2001; Ruel et al. 2001; Steil et al. 2009).

As with many potential impacts of climate change, the resulting changes in the wildfire and winthrow regimes is difficult to discern. The precise response of fire return intervals, intensity, and size distribution to climate change and the interactions with fire suppression efforts is unknown. Likewise, researchers assert that understanding of tornado and derecho formation remains inadequate for precisely predicting the location or severity of windstorms in the future, though efforts are underway to relate severe wind events with climate variables (Coniglio and Stensrud 2004; Dale et al. 2001; Peterson 2000). Given the uncertainty in these dynamics, ecological modeling is a useful tool for examining a range of natural disturbance regimes. While such results are certainly not predictive, scenario results can illustrate a range of potential futures and allow managers to develop resilient and adaptable natural resource management strategies. As results of the FSP illustrate, there may be interesting interactions between natural and anthropogenic disturbances that managers should consider in their planning processes.

Future Research

The CSM approach informs cross-boundary natural resource management by engaging multiple stakeholders working in a landscape to collaboratively develop and model scenarios representing a range of management alternatives. To advance the utility of this tool more broadly, both the social and ecological aims of CSM projects should receive equal weight in project planning, execution, and analysis as suggested in Chapter 3. Landscape modeling projects are often organized and carried out by individuals with ecological expertise, as was the case with the FSP. We chose to pursue a collaborative scenario development and modeling approach in an effort to connect those responsible for natural resource management and conservation in the focal landscapes with modeling tools that inform their planning processes. From previous experience and research, we were also aware of the potential social benefits of engaging stakeholders. However, as in most CSM projects, social objectives aimed at creating or enhancing stakeholder collaboration were not explicitly articulated or integrated into our study design.

Future applications of this approach should plan for and measure both scenario results and the social outcomes for stakeholder collaboration. Designing and implementing projects aiming to measure both outcomes will require interdisciplinary approaches and expertise. Project teams will not only need expertise in ecology, natural resource management, and modeling but also sociological methods for measuring the attitudes and perceptions of participants. Further, project teams must be prepared to measure progress toward achieving social objectives longitudinally throughout the course of the project and, if possible, after the project has ended. The emergence of collaborative, adaptive management rests not only in the development and application of adaptive management practices but also in the strength and flexibility of the social bonds between individuals and institutions responsible for that management. We must measure the impact of the CSM process on these relationships to improve the ability of the approach to facilitate collaboration among stakeholders.

On the whole, the field of ecological modeling will likely continue on its trajectory of creating ever more sophisticated and complex modeling systems. Some in the field assert that as the drivers of ecological systems become more uncertain or diverge from the past, such as climate change, ecological models should shift toward an entirely mechanistic paradigm, where all relationships rely on ‘first principles,’ rather than on empirically derived data describing current or past ecological relationships (Gustafson 2013). Even the most sophisticated models are currently a mix of both empirical and mechanistic components.

I suggest that empirical models such as STMs remain an important tool for simulating the influence of natural and anthropogenic disturbances on ecosystem dynamics for several reasons. These models have the potential to increase the pace of modeling owing to the reduced data, time, and manpower necessary to create and parameterize these models relative to mechanistic landscape ecological models (Cushman et al. 2007; Cuddington et al. 2013). However, as in the FSP, the substantial amount of time necessary for collaborating with stakeholders combined with technical difficulties has the potential to render any time savings negligible. Despite this, STMs have several advantages for application in ecological modeling projects aimed at collaboration at local and regional scales. As described in Chapter 2, STMs explicitly consider the spatial interactions of disturbances at a user-defined scale relevant to local natural resource management and planning; represent a variety of ecosystems in an intuitive and transparent way that is more easily understandable by participants from a variety of backgrounds; and can be parameterized using local and expert knowledge.

While improving the ability of models to accurately represent the behavior of ecological systems is certainly an important goal for future research, landscape ecologists and modelers must also devote attention to how and if models and their results are applied in natural resource management. Due to the financial and human resource requirements of modeling efforts, ecological models have traditionally been accessible only to government agencies and research institutions. As such, ecological models have most often been applied to answer fundamental questions about ecological dynamics and understand the potential outcomes of interventions in areas owned by state and federal governments. CSM can extend the utility of modeling tools to individual landowners, non-governmental conservation organizations, and other stakeholders by including these stakeholders in the scenario development and modeling process. Improving the familiarity of natural resource managers with ecological models can improve their ability to interpret and apply model results as well as understand the uncertainty inherent in model projections.

Closing

As a member of the FSP team, I have had the fortunate opportunity and challenge of working in an applied context. The THR watershed and WRLF are complex ecosystems managed by numerous individuals and institutions. Working with stakeholders has taught me valuable lessons about applied research and conservation. Stakeholders care deeply about the landscapes in which they live and work in many different and complicated ways. Yet opportunities for these stakeholders to engage with one another, learn of their shared and diverse values, and form the social ties necessary for cross-boundary collaboration are uncommon. The realities of distance, time, and professional mandate often mean that landowners and natural resource managers must devote the majority of their time and energy to planning and action on their own properties. The CSM approach demonstrated by the FSP presents one mechanism for bringing together diverse stakeholders and facilitating their ability to consider the cumulative consequences of their management actions. As the FSP comes to a close, the best case scenario is that participants will continue to create opportunities for cross-boundary engagement and cooperation in the THR watershed and WRLF.

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APPENDICIES

Appendix 1. Descriptions of the eight land cover classes found in the Two Hearted River watershed. These summaries of site conditions and vegetation are based on detailed descriptions of each cover type's corresponding LANDFIRE Biophysical Settings Models for Map Zone 51, which served as starting points in this project (LANDFIRE 2007b). Area totals are based on initial conditions (year 2010).

Cover Class and Area	Description
Boreal Acid Peatland 9,546 ha (18% of the watershed)	**LANDFIRE BpS Model.** 5114770 **Site Conditions.** Peatlands form in small ice-block basins and poorly drained, level terrain, ranging in size from a few thousand square meters to several thousand hectares. The overall topography of peatlands is flat to gently undulating with microtopography characterized by hummocks and hollows, which can lead to extreme and fine-scaled gradients in soil moisture and pH. The accumulation of peat within these systems alters drainage patterns and raises water tables. **Vegetation.** The canopy is composed of a few, stunted and flood tolerant conifer species, including tamarack and black spruce, or low ericaceous shrubs and a poor herbaceous layer. Sphagnum moss increases in extent as this landscape matures, reaching peak density in open bogs.
Alkaline Conifer Hardwood Swamp 8,565 ha (16% of the watershed)	**LANDFIRE BpS Model.** 5114810 **Site Conditions.** This system is characterized by dense to open, low to medium tall forest of needle-leaf evergreen and deciduous trees on shallow organic and deep peatland soils, occurring as discontinuous pockets within upland vegetation communities or in large contiguous patches in the eastern U.P. Soils are poorly drained and saturated throughout the growing season in most years. **Vegetation.** Northern white cedar is the characteristic dominant canopy species, and balsam fir, black

	spruce, and tamarack are common. Occasional canopy species include white spruce, hemlock, white pine, black ash, red maple, yellow birch, paper birch, American elm, quaking aspen, and bigtooth aspen. Characteristic shrubs include tag alder, winterberry, mountain holly, red-osier dogwood, elderberrry, huckleberry, autumn willow, and Canada yew. The surface layer is dominated by mosses and a diverse array of sedges, ferns and orchids.
Jack Pine Barrens 3,834 ha (7% of the watershed)	**LANDFIRE BpS Model.** 5114072 **Site Conditions.** This system is endemic to very dry, nutrient poor landscapes with infertile, acidic, sandy soils that have low water retaining capacity. The topography is generally flat to gently rolling, typically with long expanses capable of carrying wildfires with few natural fire breaks. In rolling topography, pine barrens are found among depressions that collect cold air, forming frost pockets. **Vegetation.** Jack Pine dominates the sparse overstory canopy, where trees occur as scattered individuals or in scattered clumps. In the absence of fire, closed canopy forest of jack pine are also present. Other tree species that may occur include red and white pine and pin oak.
Northern Pine Oak Forest 10,758 ha (20% of the watershed)	**LANDFIRE BpS Model.** 5113620 **Site Conditions.** This forest type occurs principally on sandy glacial outwash, sandy glacial plains, and less frequently on glacial drift over bedrock, dune ridges, and moraines. Soils typically coarse to medium textured sand or loamy sand and moderately to extremely acidic. **Vegetation.** Here, a super-canopy of white and/or red pine is found over a canopy of red maple, paper birch, bigtooth aspen, trembling aspen, white oak, red oak, northern pin oak, and hemlock. Sugar maple, beech, or yellow birch can be found in the understory.
Northern Hardwood Hemlock Forest 8,122 ha (15% of the watershed)	**LANDFIRE BpS Model.** 5113022 **Site Conditions.** This forest type occurs on coarse-textured ground and end moraines, on glacial till over

	bedrock and medium-textured moraines, and on kettle-kame topography. **Vegetation.** These uneven-aged forests are characterized by large volumes of coarse, woody debris under multi-storied canopies of different-aged cohorts, with supercanopies of centuries old trees. The dominant tree species, including sugar maple, hemlock, yellow birch, balsam fir, cedar, spruce, and beech, are among the most moisture and nutrient demanding species in the eastern US, and their distribution is confined to glacial landforms underlain by fertile soils. Composition of the ground flora and understory varies along a moisture-nutrient gradient and typically consists of shade-tolerant tree species and mesophilic herbaceous species (blue cohosh, yellow violet, sweet cicely, various ferns and ginseng). In hemlock dominated stands, groundlayer diversity is low due to the nutrient-poor and acidic mor humus and low understory light intensity. Conifer-dominated mesic northern forests usually have hemlock and yellow birch as primary canopy components.
Northern Hardwood Forest 8,600 ha (16% of the watershed)	**LANDFIRE BpS Model.** 5113021 **Site Conditions.** This forest type occurs on moist to dry-mesic sites occurring principally on moraines, fine-textured glacial lake beds, and flat to rolling uplands grading into steep slopes. Soils are typically well- to moderately-well-drained loams and silt loams, with rich loam soils over glacial till. These ‘rich soils’ have circumneutral pH. **Vegetation.** Shade tolerant trees dominate or co-dominate the canopy, including sugar maple, eastern hemlock, American beech, and yellow birch. Other important canopy trees include American basswood, white pine, red oak, and others, while the sub-canopy can include ironwood, American elm, and balsam fir. The northern hardwood forest of this region have a rich and diverse understory with relatively few shrubs and many spring ephemerals and perennial herbs, ferns, and club mosses.
Pine Hemlock Hardwood Forest 2,615 ha (5% of the watershed)	**LANDFIRE BpS Model.** 5113660

	Site Conditions. This forest type occupies moist, moderately drained silty/clayey lake plains and moderate to poorly-drained till plains and outwash plains, especially in the western Upper Peninsula, predominately around lake and bog margins and in complex mosaics with sugar maple-hemlock forest on the surrounding better-drained soils. Elevations are low to moderate, generally less than 2000ft. Soil pH is circumneutral. **Vegetation.** Tolerant species, including eastern hemlock, white pine, and yellow birch can dominate or co-dominate the canopy with balsam fir and white cedar components. Commonly sub-canopy species include ironwood or hop-hornbeam, american elm, hemlock, and yellow birch. Ground layer diversity is low due to the nutrient-poor and acidic mor humus as well as the low understory light intensity.
Shrub Herbaceous Wetland 1,494 ha (3% of the watershed)	**LANDFIRE BpS Model.** 5114940 **Site Conditions.** These systems occur on glacial lakebeds, in channels of glacial outwash, in depressions on glacial outwash and moraines, and along the margins of lakes, ponds and streams where seasonal flooding or beaver-induced flooding is common. While the characteristic soil is organic, well-decomposed sapric peat and saturated mineral soil may also support these systems. Soil pH may range from strongly acid to circumneutral. **Vegetation.** These wetland systems may include emergent marsh, northern wet meadow, northern fen, northern shrub thicket and swamp forest, each having their own species assemblages.

Appendix 2. Model parameters incorporated into each component of the modeling interface.

Adapted from Price and colleagues (2012).

Parameters	VDDT	TELSA	Source
Stand development Seral stages—defines ecological succession in each modeled cover type	Define age and structural characteristics; Assign deterministic succession pathway		Existing LANDFIRE models (LANDFIRE 2007b), current land cover maps
Natural disturbances Wildfire, windthrow, flooding, and insect infestation	Define intensity and transition pathways; Assign return interval through a combination of probability and proportion	Define size and spatial distribution	Existing LANDFIRE models (LANDFIRE 2007b), state records, scientific literature, local and regional experts
Management			
Timber harvest—thinning, selection cutting, clearcutting, plantation management	Define transition pathways	Define stand age and size limits, return interval, and spatial distribution for each cover type and management unit	Local experts
Restoration forestry	Define transition pathways	Define stand age and size limits, return interval, and spatial distribution for each cover type and management unit	Local and regional experts

Appendix 3. Criteria for reclassifying the 39 LANDFIRE land cover and seral stage classes into 16 forest or wetland classes based on age and canopy closure.

Lane Cover Class	LANDFIRE Cover and Seral Stage
Forest Classes	
Early Succession, Mixed Canopy	Pine Oak Early1 - ALL Pine Oak Early3 - ALL Jack Pine Barrens Early1 - ALL Northern Hardwood Hemlock Early2 - ALL Pine Hemlock Hardwood Early1 - ALL Northern Hardwood Early2 - ALL Northern Hardwood Early1 - ALL Northern Hardwood Hemlock Early1 - ALL
Early Succession, Closed Canopy	Pine Oak Early2 - CLS Pine Hemlock Hardwood Early2 - CLS
Mid-succession, Mixed Canopy	Northern Hardwood Mid1 - ALL
Mid-succession, Open Canopy	Pine Oak Mid2 - OPN Jack Pine Barrens Mid1 - OPN
Mid-succession, Closed Canopy	Northern Hardwood Mid2 - CLS Pine Oak Mid1 - CLS Pine Hemlock Hardwood Mid1 - CLS Northern Hardwood Hemlock Mid1 - CLS
Late Succession, Open Canopy	Jack Pine Barrens Late1 - OPN
Late Succession, Closed Canopy	Pine Oak Late1 - CLS Northern Hardwood Hemlock Late1 - CLS Jack Pine Barrens Late1 - CLS Pine Hemlock Hardwood Late1 - CLS Northern Hardwood Late1 - CLS
Uncharacteristic Forest	Northern Hardwood Un-N - CLS Northern Hardwood Hemlock Un-N - CLS Pine Oak Mid3 - CLS
Wetland Classes	
Early Succession, Open Canopy	Shrub Herbaceous Wetland Early1 - OPN
Early Succession, Mixed Canopy	Boreal Acid Peatland Early1 - ALL Alkaline Conifer Hardwood Swamp Early1 - ALL
Early Succession, Closed Canopy	Alkaline Conifer Hardwood Swamp Early2 - CLS
Mid-succession, Open Canopy	Boreal Acid Peatland Mid1 - OPN
Mid-succession, Closed Canopy	Alkaline Conifer Hardwood Swamp Mid1 - CLS
Late Succession, Open Canopy	Shrub Herbaceous Wetland Late1 - OPN Boreal Acid Peatland Late3 - OPN
Late Succession, Mixed Canopy	Boreal Acid Peatland Late2 - ALL
Late Succession, Closed Canopy	Alkaline Conifer Hardwood Swamp Late1 - CLS

	Boreal Acid Peatland Late1 - CLS Shrub Herbaceous Wetland Late2 - CLS Shrub Herbaceous Wetland Late3 - CLS

Appendix 4. Analysis of variance results for three response variables measuring landscape spatial heterogeneity 100 years in the future as a function of four alternative management scenarios. Tests were performed on the results of ten Monte Carlo runs per scenario. Groups refers to scenarios, and within groups refers to the 10 Monte Carlo runs for each scenario.

	Degrees of freedom	Sum of squares	F-value	Prob > F
Current Natural Disturbance Regime				
Number of Patches				
Between groups	3	44746625	2162	<0.001
Within groups	36	248317		
Mean Patch Size				
Within groups	3	20.57	1825	<0.001
Between groups	36			
Contagion				
Between groups	3	95.37	358.7	<0.001
Within groups	36	3.19		
Increased Probability of Wildfire and Windthrow				
Number of Patches				
Between groups	3	83257640	1902	<0.001
Within groups	36	525234		
Mean Patch Size				
Within groups	3	18.37	1583	<0.001
Between groups	36	0.14		
Contagion				
Between groups	3	90.64	339.3	<0.001
Within groups	36	3.21		

Appendix 5. Results of the Tukey's HSD post hoc tests to compare mean values of three response variables measuring landscape spatial heterogeneity 100 years in the future as a function of four alternative management scenarios. Tests were performed on the results of ten Monte Carlo runs per scenario.

		Mean difference	Lower bound	Upper bound	Adjusted p-value
Current Natural Disturbance Regime					
Number of Patches					
Current management	Industrial forestry	355.9	255.87	455.9322	<0.001
	Expanded easement	-1517.7	-1617.73	-1417.668	<0.001
	Ecological forestry	1445.8	1345.77	1545.832	<0.001
Industrial forestry	Expanded easement	-1161.8	-1261.83	-1061.768	<0.001
	Ecological forestry	1801.7	1701.67	1901.732	<0.001
Expanded easement	Ecological forestry	2963.5	2863.47	3063.532	<0.001
Mean Patch Size					
Current management	Industrial forestry	-0.24259	-0.31642	-0.16876	<0.001
	Expanded easement	1.19616	1.12233	1.26999	<0.001
	Ecological forestry	-0.81526	-0.88909	-0.74143	<0.001
Industrial forestry	Expanded easement	0.95357	0.87974	1.02740	<0.001
	Ecological forestry	-1.05785	-1.13168	-0.98402	<0.001
Expanded easement	Ecological forestry	-2.01142	-2.08525	-1.93759	<0.001
Contagion					
Current management	Industrial forestry	-0.14588	-0.50443	0.21267	0.694
	Expanded easement	3.69941	3.34086	4.05796	<0.001
	Ecological forestry	2.28768	1.92913	2.64623	<0.001
Industrial forestry	Expanded easement	3.55353	3.19498	3.91208	<0.001
	Ecological forestry	2.14180	1.78325	2.50035	<0.001
Expanded easement	Ecological forestry	-1.41173	-1.77028	-1.05318	<0.001
Increased Probability of Wildfire and Windthrow					
Number of Patches					
Current management	Industrial forestry	487.0	341.517	632.483	<0.001
	Expanded easement	-1542.0	-1687.483	-1396.517	<0.001
	Ecological forestry	2396.8	2251.317	2542.283	<0.001
Industrial forestry	Expanded easement	-1055.0	-1200.483	-909.517	<0.001
	Ecological forestry	2883.8	2738.317	3029.283	<0.001
Expanded easement	Ecological forestry	3938.8	3793.317	4084.283	<0.001
Mean Patch Size					
Current management	Industrial forestry	-0.25699	-0.33191	-0.18207	<0.001
	Expanded easement	0.91120	0.83629	0.98612	<0.001
	Ecological forestry	-0.97485	-1.04977	-0.89993	<0.001
Industrial forestry	Expanded easement	0.65421	0.57929	0.72913	<0.001

	Ecological forestry	-1.23184	-1.30676	-1.15692	<0.001
Expanded easement	Ecological forestry	-1.88605	-1.96097	-1.81113	<0.001
Contagion					
Current management	Industrial forestry	-0.60831	-0.96772	-0.24890	<0.001
	Expanded easement	3.84481	3.48540	4.20422	<0.001
	Ecological forestry	0.65022	0.29081	1.00963	<0.001
Industrial forestry	Expanded easement	3.23650	2.87709	3.59591	<0.001
	Ecological forestry	0.04191	-0.31750	0.40132	0.989
Expanded easement	Ecological forestry	-3.19459	-3.55400	-2.83518	<0.001

Appendix 6. Changes in land cover class metrics under each scenario.

Ecological Forestry Scenario

Mid-succession closed canopy forest experienced the greatest decline in total area from initial conditions, greater in the Ecological Forestry scenario than in any other scenario, followed by mid-succession closed canopy wetland (Figure A4.1). Both of these classes were composed of a greater number of patches with a smaller mean patch area that were more dispersed on the landscape (lower PLADJ) than under initial conditions (Figures A4.2 – A4.4). These cover types were mainly replaced by late succession closed canopy forest and late succession mixed canopy wetland, which experienced the greatest increases in total area from initial conditions among all four scenarios (Figure A4.1). Again, both of these classes were composed of a greater number of patches with a smaller mean patch area that were more spatially dispersed (lower PLADJ) than under initial conditions (Figures A4.2 – A4.4).

Current Management and Industrial Forestry Scenarios

Under both the Current Management and Industrial Forestry scenarios, mid-succession closed canopy and late succession open canopy forest experienced the greatest declines in total area and mean patch area from initial conditions among all forest classes (Figures A4.1 and A4.3). Total area and mean patch area of mid-succession closed canopy forest remained larger under the Industrial Forestry scenario than any other scenario. PLADJ also declined for these forest classes (Figure A4.3), reflecting the breakup of larger, more contiguous patches into a great number of patches with a smaller mean patch area that were more dispersed. Early succession and mid-succession open canopy forest experienced the greatest increases in total area from initial conditions of all forest classes (Figure A4.1) and were composed of a greater number of patches with a smaller mean patch area that were more dispersed on the landscape (lower PLADJ) (Figures A4.2 – A4.4).

Under both the Current Management and Industrial Forestry scenarios, all mid and late succession wetland classes decreased in total area from initial conditions (Figure A4.1) with the exception of mid-succession open canopy wetland, and these classes were composed of a greater number of patches with a smaller mean patch area that were more dispersed on the landscape (lower PLADJ) (Figures A4.2 – A4.4). The magnitude of these changes was greater under the Industrial Forestry scenario than the Current Management scenario. Early succession wetland classes and mid-succession open canopy wetland increased in total area from initial conditions (Figure A4.1). In most of these classes, this increase resulted in a greater number of patches with a larger mean patch area that were more aggregated on the landscape (higher PLADJ) (Figures A4.2 – A4.4).

Expanded Easement Scenario

Under the Expanded Easement scenario, mid-succession closed canopy forest experienced the greatest decline in total area from initial conditions of all forest classes (Figure A4.1) and was composed of a greater number of patches with a smaller mean patch area that were more dispersed on the landscape (lower PLADJ) (Figures A4.2 – A4.4). Early and late succession forest classes showed the greatest increases in total area from initial conditions of all forest classes, and the area of late succession closed canopy forest was greater only under the Ecological Forestry scenario (Figure A4.1). These classes were composed of more, smaller patches that were more dispersed on the landscape (lower PLADJ) (Figures A4.2 – A4.4). Late succession wetland cover classes experienced the greatest declines in total area from initial conditions among all scenarios (Figure A4.1). These classes were composed of a smaller number of patches with a smaller mean patch area that were more dispersed on the landscape (lower PLADJ) (Figures A4.2 – A4.4). This older vegetation was replaced by early and mid-succession wetland classes, which increased in total area from initial conditions (Figure A4.1) and were composed of a larger number of patches with a larger mean patch area that were more aggregated on the landscape (higher PLADJ) (Figures A4.2 – A4.4).

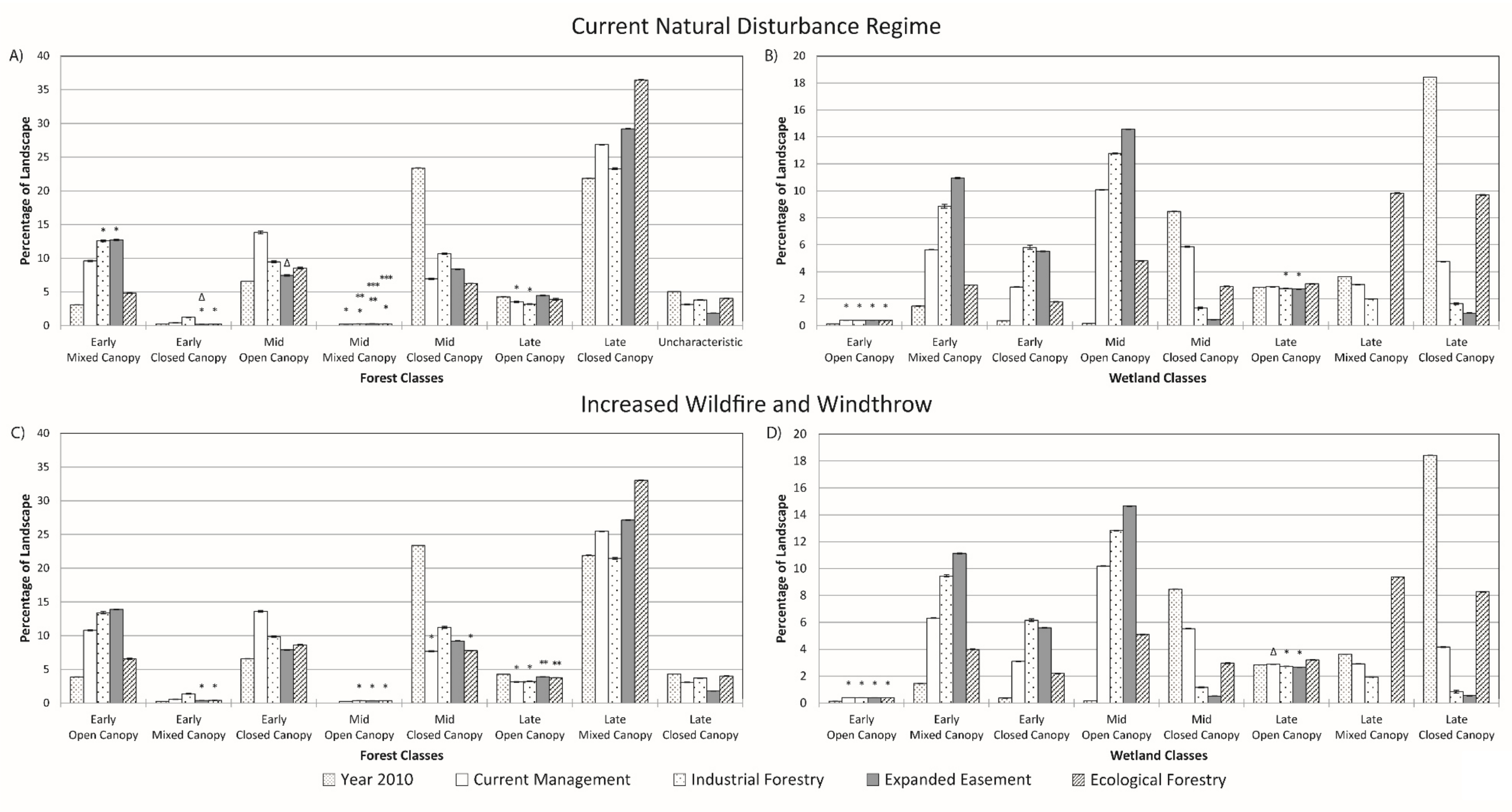

Figure A4.1. Average percentage of the landscape in each cover class at the beginning of the simulation (year 2010) and at 100 years in the future under each of the four alternative scenarios under (A and B) the current natural disturbance regime and (C and D) with increased probability of wildfire and windthrow (n=10 Monte Carlo runs). Error bars represent one standard error. Asterisks indicate

scenarios for which metrics are not significantly different between natural disturbance regimes. Triangles indicate scenarios that are not significantly different from initial conditions (year 2010).

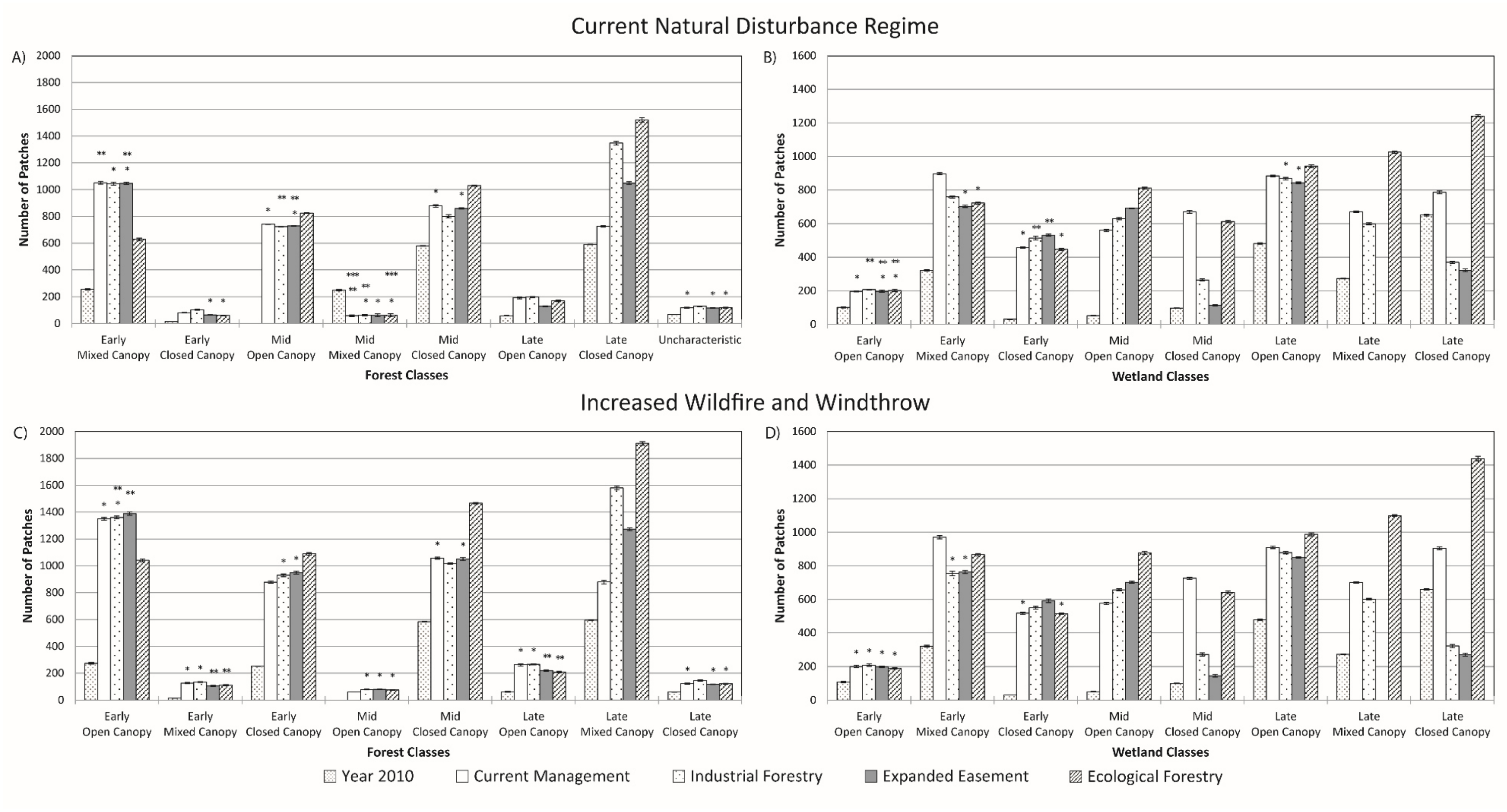

Figure A4.2. Average number of patches in each cover class at the beginning of the simulation (year 2010) and at 100 years in the future under each of the four alternative scenarios under (A and B) the current natural disturbance regime and (C and D) with increased probability of wildfire and windthrow (n=10 Monte Carlo runs). Error bars represent one standard error. Asterisks indicate

scenarios for which metrics are not significantly different between natural disturbance regimes. Triangles indicate scenarios that are not significantly different from initial conditions (year 2010).

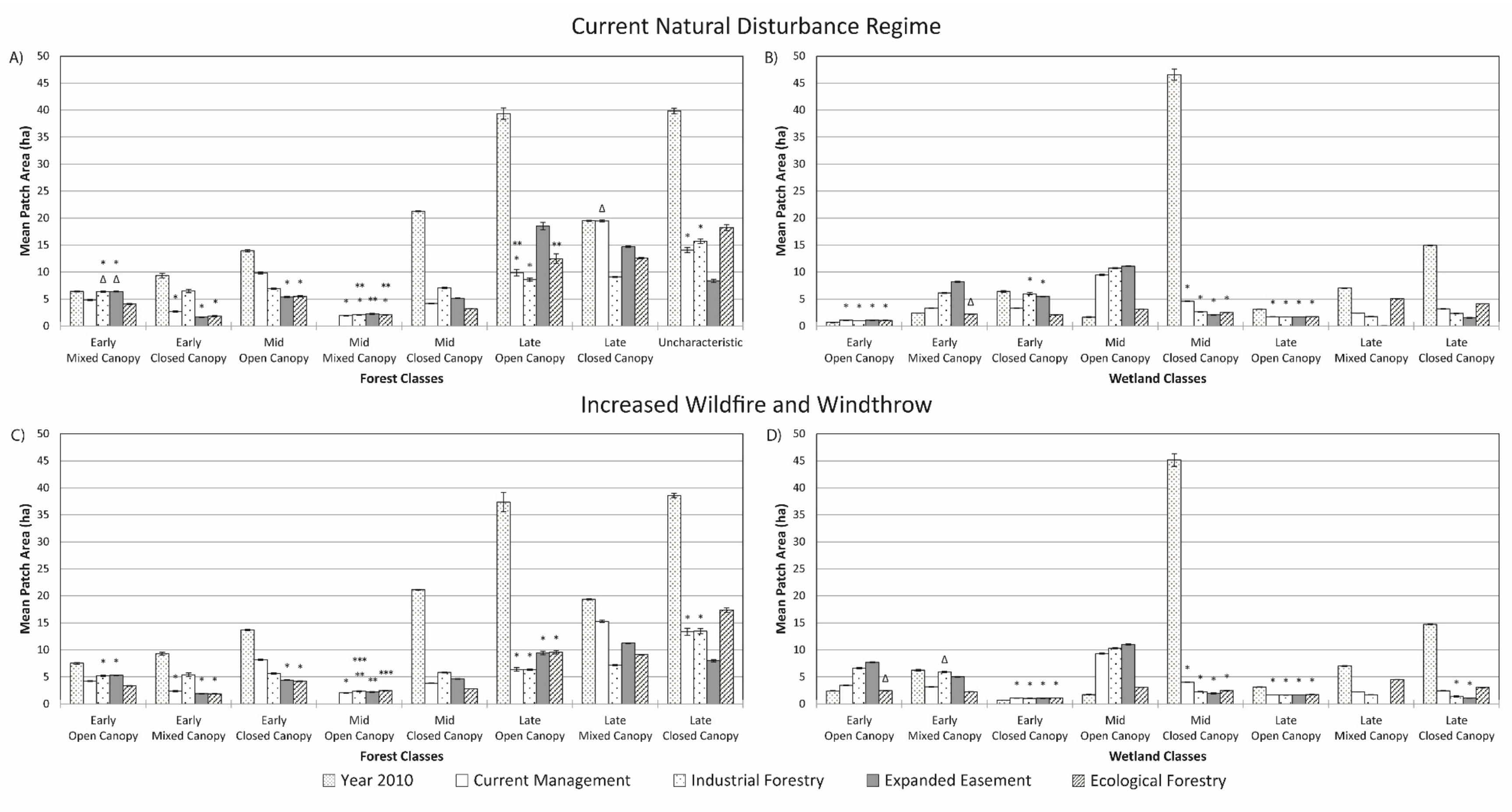

Figure A4.3. Average mean patch area (ha) in each cover class at the beginning of the simulation (year 2010) and at 100 years in the future under each of the four alternative scenarios under (A and B) the current natural disturbance regime and (C and D) with increased probability of wildfire and windthrow (n=10 Monte Carlo runs). Error bars represent one standard error. Asterisks indicate

scenarios for which metrics are not significantly different between natural disturbance regimes. Triangles indicate scenarios that are not significantly different from initial conditions (year 2010).

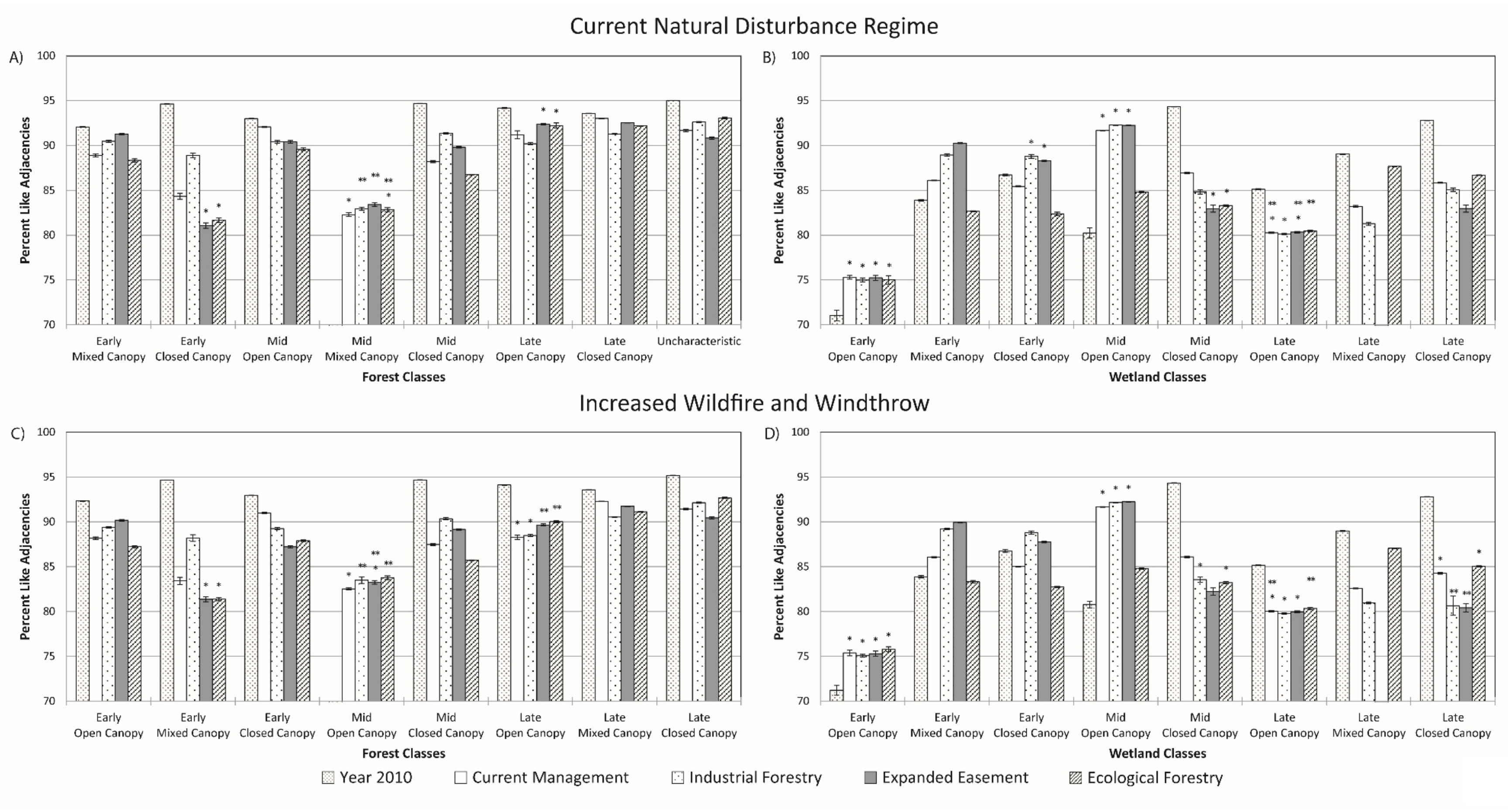

Figure A4.4. Average percent like adjacencies (PLADJ) of each cover class at the beginning of the simulation (year 2010) and at 100 years in the future under each of the four alternative scenarios under (A and B) the current natural disturbance regime and (C and D) with increased probability of wildfire and windthrow (n=10 Monte Carlo runs). Error bars represent one standard error. Asterisks indicate scenarios for which metrics are not significantly different between natural disturbance regimes. Triangles indicate scenarios that are not significantly different from initial conditions (year 2010).