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Resilience Thinking and Structured Decision Making in Social-Ecological Systems

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RESILIENCE THINKING AND STRUCTURED DECISION MAKING IN SOCIAL-ECOLOGICAL SYSTEMS

by

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RESILIENCE THINKING AND STRUCTURED DECISION MAKING IN SOCIAL-ECOLOGICAL SYSTEMS

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Natural resource management may be improved by synthesizing approaches for framing and addressing complex social-ecological issues. This dissertation examines how structured decision making processes, including adaptive management, can incorporate resilience thinking. Structured decision making is a process for establishing a solid understanding of the problem, values, management options, and potential consequences. Adaptive management is a form of structured decision making in which uncertainty is reduced for iterative decisions through designed monitoring and review. Resilience thinking can help conceptualize complex social-ecological systems and draws attention to the risks of managing for narrowly-focused objectives.

This dissertation provides practical advice to managers and can facilitate discussions regarding how to make wise decisions in complex social-ecological systems. Specifically, I explore how an iterative structured decision making process can contribute to the resilience of an oak forest in southeastern Nebraska. Chapter 2 discusses how a structured decision making process can emphasize principles of resilience thinking. I present a suite of management recommendations, drawing on information from practitioners' guides and using oak forest conservation as a case study. Chapter 3 demonstrates how oak forest models can reflect elements of resilience thinking and be used to identify optimal policies. I quantify a state-and-transition model into a Markov decision process by establishing transition probabilities based on resilience assumptions and setting the time horizon (infinite), discount factor, and reward function. Limitations are discussed, including that the optimal policy is sensitive to uncertainty about aspects of the Markov decision process. Chapter 4 provides a practical method for incorporating adaptive management projects into State Wildlife Action Plans, in part based on experience with conservation planning in Nebraska. I present a dichotomous key for identifying when to use adaptive management and a basic introduction to developing adaptive management projects are presented. Chapter 5 describes an initial effort to reduce uncertainty for oak forest conservation in southeastern Nebraska. I use multimodel inference to explore different hypotheses about what environmental and management variables are correlated with oak seedling abundance. The results indicate that the number of large oaks is an important factor. I discuss adaptive management as a potential means for further investigating management effects. Chapter 6 synthesizes the dissertation by considering the management implications for oak forest conservation in southeastern Nebraska, identifying general challenges and limitations, presenting methods for improving the framework, and returning to the broader goal of implementing the social-ecological systems paradigm.

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CHAPTER 1. INTRODUCTION

Under traditional natural resource management, policy makers viewed natural resources as commodities to be controlled by managers for human use (Berkes 2010). Today policy makers are favoring a different perspective focused on joint social-ecological systems, interdisciplinary approaches, and a view that natural resources are a source of ecosystem services and thereby human wellbeing (Millennium Ecosystem Assessment 2003, Berkes 2010). This perspective fits well into the land ethics philosophy espoused by Aldo Leopold (1949), who believed that role of humans in nature should be as a “plain member and citizen of [the land-community]” rather than the “conqueror” (Lee 1993). It is becoming increasingly clear that we value natural resources for more than consumptive uses, and we never have enough knowledge of social-ecological systems for perfect control and predictability.

Natural resource management theory has progressed, as evidenced by the aforementioned paradigm shift, but implementing the modern social-ecological systems perspective remains challenging and requires development of new ways of thinking and making decisions. We must find ways to transcend the discussion of the benefits of a complex social-ecological systems paradigm into actually making informed, defensible decisions under difficult circumstances. We need to know: (a) how various proposed approaches, or combinations of approaches (Polasky et al. 2011), influence the decision making process and (b) under what circumstances decision makers should apply these approaches.

In this dissertation, I use structured decision making as the backbone of natural resource management planning. Structured decision making is a process for making transparent, defensible decisions that explicitly outlines both values and consequences (Hammond et al. 1999, Gregory and Keeney 2002, Gregory et al. 2012). Structured decision making is different than science-based management (no mechanism for dealing with values), consensus-based decision making (consensus as the goal), and economic/multi-criteria decision techniques (expert-driven) (Gregory et al. 2012). The foundational steps involve: 1) defining the problem, 2) determining objectives, 3) outlining alternatives, 4) considering the consequences, and 5) understanding the tradeoffs (Hammond et al. 1999). Adaptive management, a form of structured decision making, uses monitoring and review in order to deliberately improve understanding of the system and management outcomes (Walters 1986, Williams et al. 2002, Martin et al. 2009).

When facing issues in complex social-ecological systems, managers can apply resilience thinking throughout structured decision making. Resilience thinking offers ways of conceptualizing complex social-ecological systems characterized by alternative states and non-linear transitions, and draws attention to the risks of managing for narrowly-focused objectives. Structured decision making emphasizing resilience thinking can help implement the modern social-ecological systems paradigm by creating a linkage to actual natural resource management challenges and decisions.

1. BACKGROUND: RESILIENCE AND STRUCTURED DECISION MAKING

1.1 Resilience

Ecological resilience theory dates back to the early 1970’s when C. S. Holling (1973) first described resilience as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” This emphasis on the amount of change that can be absorbed before a transition occurs diverges from the traditional equilibrium-centered view, which focused on stationarity and rate of return near an assumed equilibrium (Holling 1973, Holling 1996). In the following, I summarize ideas generated by the Holling school of resilience over the past forty years, recognizing that this necessarily excludes numerous developments and critiques, such as the challenges of incorporating social aspects (e.g., Folke 2006, Davidson 2010, Cote and Nightingale 2012) and links to other schools of resilience (e.g., Walker and Salt 2012, Berkes and Ross 2013, Davidson 2013).

Resilience is a property of complex adaptive systems. Complex adaptive systems consist of interconnected components operating around characteristic processes that enable self-organization and adaptation in the face of internal or external perturbation (Holling 2001, Biggs et al. 2012). There are multiple models theorizing the generation of resilience within an ecosystem. Peterson et al. (1998) describe the breadth of these models and propose a model that links ecological resilience, species richness, and scale. The species diversity model (MacArthur 1955) suggests that resilience increases at a constant rate with increasing biodiversity. The idiosyncratic model (Lawton 1994) implies that resilience will be dependent upon the specific species present in the system. The rivets model (Ehrlich and Ehrlich 1981) suggests that overlaps in function exist between species, so not all species are necessary for overall function (though resilience may be reduced by loss of species). The drivers and passengers model (Walker 1992) suggests that resilience is determined by those species that most strongly influence ecosystem dynamics. The cross-scale model proposed by Peterson et al. (1998) hypothesizes that ecological resilience is derived from “overlapping function within scales and reinforcement of function across scales.”

As implied by the cross-scale model of resilience, understanding scale in time and space is critically important. Processes operating across time and space result in natural discontinuities, for example clustered structural attributes such as body mass groups (Allen et al. 2005). Interactions between slow and fast changing variables can result in rapid large changes in ecosystem structure (Carpenter and Turner 2000). Examples of systems with variables operating at different speeds include (1) a forest insect pest system with fast-changing insect populations, intermediate-changing foliage, and slow-changing trees, and (2) a human disease system with fast-changing infectious organisms, intermediate-changing vectors and susceptible individuals, and a slow-changing human population (Holling 1986).

Resilience also applies beyond ecology, recognizing that social systems impact ecological systems and vice versa. Social aspects are considered an integral part of the overall management system rather than an external driver (Folke 2006). Resilience theory is strongly linked to social systems through concepts such as sustainability and adaptability (Carpenter et al. 2001, Berkes et al. 2003, Walker et al. 2004, Davidson 2010). Sustainability implies a goal of maintaining a desirable state (Carpenter et al. 2001), or can be seen as a process capable of dealing with change (Berkes et al. 2003). Adaptability is “the capacity of actors in a system to influence resilience”; in other words, the ability for humans to manage resilience (Walker et al. 2004). As a result, resilience thinkers tend to refer to social-ecological systems, rather than ecosystems or human systems.

Social-ecological systems are complex adaptive systems made up of linked social (e.g., community building, economic viability) and ecological (e.g., nutrient cycling, biodiversity) components and processes (Biggs et al. 2012). These systems are dynamic and generally tend to follow adaptive cycles, moving between growth, conservation, collapse, and reorganization phases (Gunderson and Holling 2002, Walker et al. 2002). Thresholds exist in social-ecological systems that, when crossed, can lead to rapid, dramatic shifts from one stable state to another[1]. These thresholds may be related to critical slow variables whose rate of change is slower than the management scale (Biggs et al. 2012).

One critical challenge to implementing resilience thinking is identifying thresholds. If quantification depends on understanding the effects of key drivers and perturbations, we must have an idea of how much change can be absorbed before a threshold is crossed. Groffman et al. (2006) offer one possible approach for investigating thresholds. Focus on a particular ecosystem service of interest and then identify what structures and functions influence the service. Those structures and functions are in turn influenced by specific factors. Armed with this knowledge, one can then consider whether those factors or their interactions exhibit a threshold response.

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[1] "State" (e.g., RA 2010), "regime" (e.g., Walker and Salt 2012), and "identity" (e.g., Cumming et al. 2005) have all been used in the resilience literature to describe what characterizes where the system is now and where it might transition to if a threshold is crossed. These words can take on multiple meanings depending on discipline and context. For simplicity's sake, we will refer to "states" characterized by components, processes, and feedbacks identified during planning.

Resilience can be described as specified or general. Specified resilience involves avoiding a particular threshold, so the objective is related to “resilience of what to what,” where “to what” is a known disturbance (Carpenter et al. 2001). In contrast, general resilience relates to how the system can handle disturbances, both known and unknown (Walker and Salt 2012). A more generally resilient system is expected to absorb a disturbance better than a less generally resilient system.

Managing for resilience requires openness of options, regional scale considerations, focusing on heterogeneity, and acknowledging uncertainty and potential surprises (Holling 1973). Variability is natural, and suppressing variability can ultimately lead to unexpected and detrimental shifts (Holling and Meffe 1996). Disturbances are critical as they can contribute to a system’s capacity to handle future surprises, such as other disturbances, extreme conditions, or novel stresses. Disturbances can also, however, bring systems closer to crossing a threshold into an alternative stable state. Disturbances may be known or unknown, frequent or infrequent. In some cases, loss of historically frequent disturbances can be seen as a “disturbance” itself, when the system evolved to flourish under disturbance (Walker and Salt 2012, p. 49). Common examples of management practices that reduce resilience include: (a) damming of rivers with naturally high flow variability, (b) suppressing fire in fire-adapted regions, and (c) planting monocultures in place of diverse plant communities (Holling and Meffe 1996). As Peterson et al. (1998) point out, this type of management “channels ecological productivity into a reduced number of ecological functions and eliminates ecological functions at many scales” (p. 16).

Resilience management is a way to acknowledge and operate under intense complexity. We live in a world of uncertainty, where non-linear changes, reflexive human behavior to predictions, and rapidly altering systems make forecasting the future incredibly challenging (Walker et al. 2002). Given severe limitations, we should use management intervention to build capacity for systems to retain critical functions and structures, rather than trying to reduce variability and maximize resource extraction (Walker et al. 2002, Thrush et al. 2009). Walker et al. (2002) propose a resilience management framework founded on the following assumptions: (1) thresholds and hysteretic effects exist; (2) making extremely cautious decisions in the face of uncertainty is a form of rigidity and therefore undermines resilience; (3) agents do not always optimize income and social context matters; (4) market imperfections exist and are the norm; (5) agents care about the process as well as the outcome; and (6) lack of property rights for ecological goods and services means there are not markets.

1.2 Structured Decision Making

Structured decision making is a process for making transparent, defensible decisions that explicitly outlines both values and consequences (Hammond et al. 1999, Gregory and Keeney 2002, Gregory et al. 2012). The foundational steps involve: 1) defining the problem, 2) determining objectives, 3) outlining alternatives, 4) considering the consequences, and 5) understanding the tradeoffs (Hammond et al. 1999). Adaptive management is a special form of structured decision making (Walters 1986, Williams et al. 2002, Martin et al. 2009) and adds monitoring and review to the decision process.

Adaptive management is used to learn about management outcomes over time and adjust management practices to reflect this learning.

In the following literature review, I focus specifically on adaptive management. Given the emphasis resilience thinking places on the prevalence of uncertainty in complex systems, adaptive management is a highly relevant structured decision making framework for managing resilience. In addition, resilience and adaptive management share a common foundation. Resilience was formally introduced in the literature by C. S. Holling in 1973. Five years later, Holling (1978) described adaptive natural resource management and referenced resilience. In 1993, Kai Lee's book *Compass and Gyroscope* pointed to adaptive management as a potential means to maintaining a desirable equilibrium resilient to surprise.

Adaptive management of natural resources got its start in the 1970's, described by C. S. Holling (1978) in the seminal work *Adaptive Environmental Assessment and Management* and furthered by Walters (1986) in his book *Adaptive Management of Renewable Resources*. The approach operates around the central tenant that management should be a continual learning process (Walters 1986). Holling (1978, p. 136) acknowledges, "Adaptive management is not really much more than common sense. But common sense is not always in common use." Fortunately, since its introduction adaptive management of natural resources has grown considerably in popularity to the point where it is commonly used in environmental agency dialogue (Keith et al. 2011).

The U.S. Department of Interior Adaptive Management Technical Guide (Williams et al. 2009, p. v) presents a useful, comprehensive definition of adaptive management, adopted from the National Research Council definition (emphasis added):

> Adaptive management [is a decision process that] promotes **flexible decision making** that can be adjusted in the face of **uncertainties** as outcomes from management actions and other events become better understood. Careful **monitoring** of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an **iterative learning process**. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes **learning while doing**. Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet **environmental**, **social**, and **economic goals**, increases scientific knowledge, and reduces tensions among stakeholders.

This definition highlights a number of key considerations of adaptive management. Clear parallels run between adaptive management and resilience; note the use of the term resilience, mention of natural variability, and combined environmental, social, and economic goals.

The adaptive management process can be conceptualized as a loop. Different authors use different numbers of steps (e.g., see figures in Boyd and Svejcar 2009, Williams et al. 2009, Allen et al. 2011), but the main idea is that adaptive management is an iterative decision-making cycle involving: (1) assessing the system, (2) defining management actions, (3) implementing those strategies, (4) evaluating the results, and (5) making adjustments informed by the process. Adaptive management is not is a trial-and-error or step-wise approach, in which a practice is used until it is deemed unsuccessful. Nor is it a horse race approach, in which multiple approaches are implemented and the "best" selected for continued, static management practice (Allen et al. 2011). Adaptive management, especially active adaptive management, is more than simply allowing for feedback from actions; it is "the idea of using a deliberately experimental design, paying attention to the choice of controls and the statistical power needed to test hypotheses" (Lee 1993, p. 57).

Adaptive management is most appropriate when: (a) a decision must be made, (b) there is an opportunity for learning, (c) there are clear and measurable objectives, (d) information is valuable, (e) there are testable models, and (f) adequate monitoring is possible (Williams et al. 2009). Gregory et al. (2006) suggest four criteria to consider when deciding if an adaptive management approach is appropriate for a given scenario: spatial/temporal scale, dimensions of uncertainty, cost/benefits/risks, and the level of stakeholder/institutional support. Additionally, Lee (1993) mentions that decision makers should acknowledge. Through case study comparisons, Porzecanski et al. (2012) showed that a social-institutional framework must be supported by adaptive management-enabling conditions, including adequate financial resources, experimentation and pathways for learning, effective implementation of policies, and engaged stakeholders.

Adaptive management is likely to fail when there is a lack of stakeholder engagement, experiments are difficult, surprises are not treated as learning opportunities, prescriptions are followed, action is procrastinated, learning is not utilized, risk is unacceptable, leadership is deficient, and planning is never-ending (Allen and Gunderson 2011). Keith et al. (2011) also point to potential institutional barriers (e.g., management is spread across many groups with conflicting interests) and behavioral barriers of self-serving scientists and managers (e.g., scientists overconfident in their modeling abilities and managers ignoring complexity). The authors also suggest that we must find a way to embrace uncertainty such that we move away from focusing efforts on one option perceived to be the "best" and rather examine multiple options.

Reducing uncertainty is an essential feature of adaptive management. In a social-ecological system there are many sources of uncertainty and different categorizations of uncertainties. Sometimes we have known probabilities with known outcomes, sometimes we have an idea of the possibilities but not probabilities or outcomes, and sometimes we know little or nothing at all (Holling 1978). Regan et al. (2002) describe two main uncertainty groups – epistemic and linguistic. Epistemic uncertainty refers to limited knowledge of the system, and linguistic uncertainty refers to language indistinctness. Epistemic uncertainties can be further broken down into measurement error, systematic error, natural variation, inherent randomness, model uncertainty, and subjective judgment. Linguistic uncertainties are vagueness, context dependence, ambiguity, under-specificity, and indeterminacy of theoretical terms. While linguistic uncertainties must be resolved during the course of structured decision making, reducing linguistic uncertainty does not constitute adaptive management. Williams (2011) describes four basic types of uncertainty relevant to natural resource management: environmental variation (including random climate events), partial observability (as a result of inability to perfectly monitor), partial controllability (discrepancy between policy decisions and human behavior), and structural/process uncertainty (incomplete knowledge of the biological and ecological system dynamics). Some authors make the distinction between risk and uncertainty, using the term risk in cases when objective probabilities are known and uncertainty when they are not (Tyre and Michaels 2011). Tyre and Michaels (2011) suggest the use of an umbrella term "indeterminism" to encompass uncertainty and risk, as well as ecological and social sources. The authors emphasize the existence of irreducible uncertainties outside probability application and the need to consider socially generated uncertainty in the management of social-ecological systems.

Similar to resilience, adaptive management has made its way into many disciplines and has begun to be used as a "buzzword," such that labelling a project adaptive management does not indicate much about what is actually being done. Often projects are called adaptive management, even if they do not meet the specific criteria laid out in the literature (Ruhl and Fischman 2010). Advancement of adaptive management requires more examples of proper application of the criteria and continued discussion of the conditions under which adaptive management should be employed and ways to foster successful implementation.

2. PURPOSE

This dissertation draws upon the wealth of knowledge accrued since the initial emergence of resilience and adaptive management in the 1970's in order to discuss how resilience thinking and adaptive management can be rigorously and practically applied to natural resource management issues. Specifically, this dissertation explains how an iterative structured decision making process could contribute to the resilience of an oak forest in southeastern Nebraska that is managed as part of Nebraska's State Wildlife Action Plan, a.k.a. the Nebraska Natural Legacy Project. Chapter 2 investigates how a structured decision making process can emphasize principles of resilience thinking. Chapter 3 demonstrates how oak forest models can reflect elements of resilience thinking and be used to identify optimal policies. Chapter 4 provides a practical method for incorporating adaptive management projects into State Wildlife Action Plans, and Chapter 5 presents an initial effort to reduce uncertainty for oak forest conservation under the Nebraska Natural Legacy Project. In addition to providing advice to managers, the dissertation presents information for discussions between scholars, technical experts, policy makers, and stakeholders regarding how to further the complex social-ecological systems paradigm for natural resource management.

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CHAPTER 2: RESILIENCE THINKING LINKED TO STRUCTURED DECISION MAKING – A FRAMEWORK FOR INCORPORATING RESILIENCE INTO NATURAL RESOURCE MANAGEMENT

1. INTRODUCTION

Natural resource management is trending toward a complex social-ecological systems paradigm in which natural resources are viewed as a source of ecosystem services critical to human wellbeing (Millennium Ecosystem Assessment 2003, Berkes 2010). Traditional steady-state management, also known as the "command-and-control approach" (Holling and Meffe 1996), focused on stability and reliability of resource extraction assuming existence of an optimal equilibrium and reducing natural variability away from this point (Williams and Brown 2014). While steady-state management might succeed in the short term, the ultimate result is likely crisis (e.g., collapsed fisheries, massive wildfires, severe flood damage). Holling and Meffe (1996) described this as the pathology of natural resources: "a system in which natural levels of variation have been reduced through command-and-control activities will be less resilient than an unaltered system when subsequently faced with external perturbations, either of a natural (storms, fires, floods) or human-induced (social or institutional) origin" (p. 30).

Resilience thinking is a driving force behind the paradigm shift in natural resource management (Berkes 2010). Ecological resilience was first described by C. S. Holling (1973) as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (p. 14). Resilient systems have an ability to self-organize, a capacity to learn, and potential for adaptation (Carpenter et al. 2001, Walker et al. 2002, Folke et al. 2004). Resilience can be eroded by steady-state approaches that manage toward a singular goal through the strict control of a specific variable, leading to sudden unexpected transitions (Holling and Meffe 1996, Gunderson 2000). Since its introduction in ecology (Holling 1973), resilience has evolved toward a joint social-ecological systems perspective, in which social aspects are an integral part of the overall management system rather than an external driver (Folke 2006).

Much progress has been made in the realm of resilience theory, and resilience is invoked in policy documents (e.g., USAID 2012, City of New York 2013), but implementation of resilience-based management remains challenging (Davidson 2013). In recent years, a few sources became available for practitioners interested in resilience thinking, including publications of the Resilience Alliance (RA) (2010), Biggs et al. (2015), and Walker and Salt (2012) (see appendix for further description). Resilience thinking independent of natural resource decision making, however, does not lead to better management. Decision makers need methods for transparently and defensibly implementing resilience management. In the absence of such methods, resilience runs the risk of becoming no more than a buzzword, similar to sustainability, and losing its meaning and relevance (Stumpp 2013).

To address the need to make resilience applicable, I propose a systematic framework integrating resilience thinking into a structured decision making process. The primary goal of this chapter is to provide natural resource managers with a clear process for making natural resource management decisions that acknowledges the lessons and warnings of resilience thinking. I also hope to facilitate discussion between resilience scholars, and decision analysts regarding the potential and limitations for resilience to contribute to on-the-ground natural resource management. Some have argued that, thus far, resilience thinkers have not adequately provided practical advice for decision making, while decision analysts have not adequately tackled resilience thinking (Johnson et al. 2013).

I begin by briefly summarizing key components of resilience thinking and structured decision making. I then link advice for practitioners from both areas to present a structured decision making process emphasizing resilience thinking. To illustrate how resilience may contribute to a decision making process, I apply resilience thinking to a case study of oak forest conservation in southeastern Nebraska.

2. RESILIENCE THINKING

In the forty years since Holling's (1973) school of resilience made a formal appearance in the literature, the number of articles and policy documents referencing resilience has grown considerably. I use "resilience thinking" to refer to any scholarship or philosophy driven by or linked to Holling's school of resilience. For brevity's sake, I condense forty years of resilience thinking into a few key concepts and observations to provide context for the resilience thinking practitioner guides (Appendix). I recognize that this necessarily excludes numerous relevant developments in and critiques of resilience thinking, notably as related to social resilience (e.g., Folke 2006, Davidson 2010, Cote and Nightingale 2012) and links to other schools of resilience (e.g., Walker and Salt 2012, Berkes and Ross 2013, Davidson 2013).

Complex adaptive systems consist of interconnected components and characteristic processes that enable self-organization and adaptation in the face of internal or external perturbation (Holling 2001, Biggs et al. 2012). Drivers operating at other scales can influence the set of controlling variables. Management interventions can be a form of perturbation, or they can introduce feedback processes (Walker et al. 2002). Diversity, redundancy, connectivity, and modularity of components are related to system functioning and persistence (Biggs et al. 2012). Emergent properties exist at the system level, limiting the usefulness of reductionist approaches that seek to understand the whole by studying the parts. Complexity results in uncertainty and therefore limits predictability and forecasting (Davidson 2013).

Social-ecological systems are complex adaptive systems made up of linked social (e.g., community building, economic viability) and ecological (e.g., nutrient cycling, biodiversity) components and processes (Biggs et al. 2012). These systems are dynamic and generally tend to follow adaptive cycles, moving among growth, conservation, collapse, and reorganization phases (Gunderson and Holling 2002, Walker et al. 2002). Thresholds exist in social-ecological systems that, when crossed, can lead to rapid, dramatic shifts from one stable state to another[2]. These thresholds may be related to critical slow variables whose rate of change is slower than the management scale (Biggs et al. 2012).

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[2] "State" (e.g., RA 2010), "regime" (e.g., Walker and Salt 2012), and "identity" (e.g., Cumming et al. 2005) have all been used in the resilience literature to describe what characterizes where the system is now and where it might transition to if a threshold is crossed. These words can take on multiple meanings depending on discipline and context. For simplicity's sake, we will refer to "states" characterized by components, processes, and feedbacks identified during planning.

Variability is natural, and suppressing variability can ultimately lead to unexpected and detrimental shifts (Holling and Meffe 1996). Disturbances are critical. They can contribute to a system's capacity to handle future surprises (e.g., other disturbances, extreme conditions, novel stresses) but also bring systems closer to crossing a threshold into an alternative stable state. Disturbances may be known or unknown, frequent or infrequent. In some cases, loss of historically frequent disturbances can itself be seen as a "disturbance" (Walker and Salt 2012, p. 49).

Resilience can be specified or general. Specified resilience involves a particular threshold. The management objective is related to "resilience of what to what," where "to what" is a particular disturbance of interest (Carpenter et al. 2001). In contrast, general resilience relates to how the system can handle disturbances, both anticipated and unanticipated (Walker and Salt 2012). A more generally resilient system is expected to absorb a disturbance better than a less generally resilient system through rapid response or an ability to adapt. While managing specified resilience is important, management that is over-focused on a given threat can make the system less resilient to other disturbances (Walker and Salt 2012). Therefore, managing general resilience is also relevant to decision making.

3. STRUCTURED DECISION MAKING

Structured decision making is "an organized, inclusive, transparent approach to understanding complex problems and generating and evaluating creative alternatives…founded on the idea that good decisions are based on in-depth understanding of both values (what's important) and consequences (what's likely to happen if an alternative is implemented)" (Gregory et al. 2012, p. 6). It is informed by many different areas of expertise, including psychology, decision analysis, policy analysis, negotiation and facilitation, and ecology. Tools are drawn from decision sciences, such as means-ends networks, objective hierarchies, consequence tables, strategy tables, influence diagrams, belief networks, and decision trees (Gregory et al. 2012). In the context of environmental management, structured decision making differs from conventional approaches of science-based management (no mechanism for dealing with values), consensus-based decision making (consensus as the goal), and economic/multi-criteria decision techniques (expert-driven) (Gregory et al. 2012). Ad-hoc, technical solution-focused decision making can cause managers to fail to recognize relationships between problem components and to link to broader organizational goals (Conroy and Peterson 2013). Use of structured decision making, as a formal decision making structure, can prevent these failures.

The core five-step process, abbreviated as PrOACT, involves describing the problem, defining the objectives, choosing alternatives, outlining the consequences, and considering the tradeoffs (Hammond et al. 1999) (Figure 2-1). The problem clarifies the decision context and lays out the scope of the project (Gregory and Long 2009). Objectives describe the components of success and the desired direction of change (Gregory et al. 2012). Objectives can be divided into fundamental and means objectives, where fundamental objectives are what is truly valued and means objectives are important only insofar as they help achieve fundamental objectives (Conroy and Peterson 2013). Alternatives are the management actions under consideration. Consequences represent how well an alternative is predicted to acheive the objectives (Gregory et al.

2012). Unless one alternative achieves every objective better than the other alternatives, tradeoffs will have to be made (Gregory et al. 2012). Although presented as a linear, step-by-step process, continual reassessment and refinement of previous PrOACT steps is encouraged (Hammond et al. 1999, Gregory et al. 2012).

Different authors present additions or amendments to the core PrOACT steps. Under some descriptions of structured decision making, the consequences step is part of a “develop models” step, with tradeoffs treated by weighting the objectives (e.g., Williams et al. 2009, Conroy and Peterson 2013). Modeling is often emphasized as a key tool of structured decision making, where models are loosely defined by Conroy and Peterson (2013) as “any conceptualization of the relationship between decisions, outcomes, and other factors.” Some structured decision making frameworks include monitoring and review, arguing that most natural resource decisions are iterative and involve substantial uncertainty (e.g, Gregory et al. 2012), while others consider this a special form of structured decision making called adaptive management (e.g., Walters 1986, Lyons et al. 2008, Martin et al. 2009, Williams et al. 2009, Conroy and Peterson 2013).

Although the representations vary, the unifying principle of structured decision making is that the quality of a decision can be improved by explicitly identifying: (a) what the decision is about, (b) what we value, (c) what we might do, and (d) how we think the system will respond. In the absence of structured decision making, natural resource managers may address the wrong problem, fail to resolve conflict, confuse facts and values, or overlook important information about the potential impact of a decision. Key sources available to practitioners wishing to implement structured decision making include Hammond et al. (1999), Gregory et al. (2012), and Conroy and Peterson (2013) (Table 2-1, Appendix).

4. INTEGRATING RESILIENCE THINKING INTO STRUCTURED DECISION MAKING

As Walker and Salt (2012) observe, “Rather than *in contrast to* or *instead of*, a resilience framework is *complementary to* other ways of approaching the challenge of improving human well-being” (p199). In the context of structured decision making, Johnson et al. (2013) suggest that resilience thinking should be used to frame the problem, contribute to objective setting where objectives relate to system dynamics, and encourage the development of process models rather than pattern models. While Johnson et al. (2013) largely discuss the technical aspects of incorporating resilience into decision analysis methods, such as optimization approaches, I focus on how managers can work through the structured decision making process in a way that clearly demonstrates resilience thinking. I present advice for how resilience thinking can contribute to each step of structured decision making (Table 2-2) based on a synthesis of sources of practical guidance (Appendix). Additionally, questions found in the Resilience Alliance assessment (RA 2010) are linked to the steps of structured decision making I believe would most benefit from the answers to these questions (Table 2-3).

4.1 Problem

Walker and Salt (2012) call resilience thinking “a problem-framing approach to your system” (p23). The problem statement defines the bounds of the decision context and should identify the decision to be made, who is making it, and when the decision must be made (Gregory et al. 2012). This includes setting the spatial, temporal, and organizational scales (Conroy and Peterson 2013). Regardless of the focal scale selected, resilience thinkers warn that it is all too easy to become over-focused on one scale (Walker and Salt 2012). The challenge, as Johnson et al. (2013) observe, is to account for multiple scales while maintaining analytical tractability and to recognize which linked decisions are under control of the decision maker and which need to be treated as noise or constraints. While slow variables outside the focal scale may be treated as constant in models (Biggs et al. 2012), in the long-term, these slow variables may be trending toward a tipping point during the course of management aimed at faster variables. If critical slow variables are known *a priori*, which they may well not be, they should be noted for discussion of monitoring and review.

The problem should identify “resilience of what, to what” (Carpenter et al. 2001). The current state and alternative states should be described. A “state,” as used in this context, is a characterization of essential system components, processes, and feedbacks identified during planning. In addition, the problem should identify “resilience for whom” because resilience thinking does not dictate who is empowered, how governance is currently structured, or whether policies are progressive or conservative (Nadasdy 2007, Cote and Nightingale 2012, Keesen et al. 2013, Brown 2014). A social-ecological systems perspective may also require detailing which elements of social dynamics should be addressed by management and which can be considered external drivers (Walker and Salt 2012).

Which stakeholders are involved and how they are involved can determine whose interests are considered, how the system and system states are described, and subsequently how management decisions are made. People left out of the discussion may find the ecosystem services they value are not considered, potentially placing their wellbeing in jeopardy. It is important to consider the stakeholder networks and bridges/barriers to collaboration (RA 2010, Table 2-1), in order to proceed through the structured decision making process with a good, representative team of stakeholders. Broadening participation is one of Biggs et al.'s (2015) principles for building resilience; engaging stakeholders can foster trust and lend legitimacy to the decision making process, as well as provide a diversity of perspective. If significant barriers to stakeholder collaboration exist, such as animosity between stakeholders, these barriers may need to be resolved before structured decision making can proceed.

Understanding what triggered the decision can help clarify the decision context by showing why the issue needs to be addressed (Hammond et al. 1999). Did a disturbance or predicted disturbance trigger the process (e.g., natural disaster)? Did a change from scales above (e.g., new regional policy) or below (e.g., technological development) drive the need to make a decision at the focal scale? Was a threshold crossed (i.e., different components and processes now dominant the system)?

Exploring the past with stakeholders can inform the context. What major changes have occurred in the system over time and what caused them? Walker and Salt (2012) find "…for stakeholders this is usually a stimulating exercise as they explore their common understanding of why their system (farm, catchment, region, and so forth) is the way that it is. Its greatest value is that it generates insights into event-driven changes, cause and effect, and what's really important in the system" (p. 51).

4.2 Objectives

Managing for resilience does not always mean increasing resilience of the current state; resilience management can also mean *reducing* resilience to encourage a flip into an alternative state (Cumming et al. 2005). Therefore, before digging deeper into what is valued, it may be useful to first examine whether it is clear if the current state of the system is desirable, or if an alternative is desirable. This will be trivial if the alternative states are known and one state provides critical ecosystem services while the other is incapable of supporting people's livelihoods. A clear example in the resilience literature is a lake system going from an oligotrophic to eutrophic state (Carpenter et al. 2001), where the oligotrophic state is preferable. In other cases, what defines the social-ecological "states" can be a tricky concept, and some states may be desired by some and not by others. Thinking upfront about whether the current or an alternative state is desirable reinforces the idea that increasing resilience may *not* be the objective. In addition, determining preferences for system states can help highlight what people value and how they think the system functions.

Objectives are statements of what matters and the desired direction of change (Gregory et al. 2012). Assigning a direction may require nuance under resilience thinking, particularly given the potential for non-linear relationships. Using social diversity as an example, increasing social diversity can be a good thing if it brings new perspectives, leads to innovation, and reduces ingrained stereotypes. Too much social diversity could cause a community to lose its sense of place, shared understanding, or traditional knowledge. It may be necessary to construct objectives in which the highest value is placed not on extremes (maximum or minimum) but rather on an intermediary quantity. For example, the objective could be to achieve moderately high diversity, rather than maximum diversity.

Walker and Salt (2012) suggest using an ecosystems goods-and-services framework to identify what aspects of the systems people want to be resilient and what they value in and want out of the system. An ecosystem goods-and-services framework allows for outlining both social and ecological concerns, and it also facilitates thinking about processes as well as patterns and outcomes. Determining the relevant ecosystem services may start with asking “What are the direct/indirect uses of natural resources in the system?” and “What are the desirable and undesirable traits of this and alternative states?” (RA 2010, Table 2-3). Although an ecosystem goods-and-services framework can be used in decision making contexts without resilience thinking, structured decision making incorporating resilience thinking is well-suited for incorporating ecosystem goods-and-services.

Objectives, sub-objectives, and performance measures determine how alternatives are evaluated and compared. Therefore resilience thinking must be reflected in the objectives to ensure the lessons of resilience are addressed during discussion of consequences of policy actions. However, objectives are also meant to outline what is valued. One of the benefits of structured decision making is avoiding confusion and conflict as a result of blurring the lines between facts and values. There may be components or processes that contribute to resilience and/or have a non-linear response to management but are not valued in and of themselves. For example, it could be hypothesized that diversity of insect pollinators contributes to ecological resilience of a given social-ecological system, but stakeholders may not value pollinator diversity directly. In this scenario, maintaining pollinator diversity may be a necessary means objective to the fundamental objective of maintaining social-ecological resilience, or pollinator diversity could be one of the performance measures used to clarify what is meant by the resilience objective.

Resilience, as originally defined, relates to the amount of disturbance that can be absorbed before crossing a threshold. Therefore, potential thresholds should be discussed. Objectives, sub-objectives, and performance measures may be phrased in terms of location of or distance from a threshold, especially when a threshold is known. Martin et al. (2009) propose determining ecological, utility, and decision thresholds during structured decision making. Ecological thresholds relate to small changes in state variables leading to large changes in system dynamics. Utility thresholds relate to small changes in state variables leading to large changes in value. Decision thresholds relate to small changes in state variables that trigger substantive management changes. Martin et al.’s (2009) framework is intended to help distinguish subjective information (utility thresholds) and technical information (ecological thresholds), but they acknowledge that these thresholds may coincide. The risk of including ecological thresholds in the objectives is once again blurring what people value with what will allow people to achieve what they value. In the pollinator diversity example, in which pollinator diversity was not in itself valued by the stakeholders, it may be useful to describe ecological thresholds as means objectives. Alternatives would be evaluated in part based on their ability to prevent crossing a pollinator diversity threshold, as a means of increasing ecological resilience and achieving fundamental objectives.

Resilience thinking and an ecosystem services perspective could lead to a wealth of potential objectives, sub-objectives, and performance measures. The set of fundamental objectives should be relatively short, as people have trouble handling more than 6–10 objectives (Gregory et al. 2012). Ambiguity can be reduced through sub-objectives and performance measures, but the goal should still be to identify the smallest list that captures all the necessary consequences (Gregory et al. 2012). Resilience thinking acknowledges the need for “requisite simplicity” and notes that most social-ecological systems at a given scale are driven by a small set of key variables (Walker and Salt 2012). Developing an objective hierarchy and/or means-ends network (Gregory et al. 2012, Conroy and Peterson 2013) may be very helpful for organization and presentation of information. These diagrams can: (a) show the difference between what is fundamentally valued and what is valued as a means of acheivement, (b) clarify a higher level objective, and (c) describe how success is measured. They can also display how various objectives interact.

Gregory et al. (2012) discuss the importance of performance measures. Performance measures determine how consequences are actually evaluated for the objectives. Choosing performance measures is both a subjective and technical exercise. These measures can be “natural” (direct measurement), “proxy” (assumed to be linked to objective), or “constructed.” From a resilience thinking perspective, these last two categories are critical. Resilience itself is not a directly quantifiable property (Walker and Salt 2012). Some components of resilience may be readily quantified and serve as proxies of resilience (e.g. the number of functional groups). Others will need to be constructed, especially as related to social ideas (e.g. perceived fairness). Performance measures can patterns, or they can be processes, such as extinction rates; resilience thinking emphasizes the importance of processes (Johnson et al. 2013).

General resilience, the idea of preparing for future surprises by maintaining a system's capacity to handle unanticipated disturbances, presents an interesting conundrum for structured decision making. If focus is limited to specified resilience, general resilience could actually decrease; that is, if management is over-focused on the capacity to address a given threat, the system becomes less able to handle other disturbances (Walker and Salt 2012). In order to ensure that the resilience thinking perspective is not too narrowly-focused on a particular threshold or set of thresholds, general resilience should also be an objective.

However, the general resilience objective must be included in a way that minimizes ambiguity, maintains requisite simplicity, and separates facts from values. In terms of a fundamental objective, "increase general resilience" seems imperative to integrating resilience thinking into structured decision making, but on its own it is an ambiguous objective. Gregory et al. (2012) would call resilience a metaconcept – "several ideas bundled together that need to be unpacked if we are to have any chance of understanding what the speaker is actually meaning" (p.83) – like "naturalness" or "sustainability." I propose building sub-objectives and constructed performance measures from resilience principles identified by Walker and Salt (2012) and Biggs et al. (2015) (Table 2-4). A rapid assessment method, such as Nemec et al.'s (2014) approach, could provide the basis for developing constructed measures. I return to how to evaluate consequences and assess general resilience tradeoffs in later sections.

Separating facts and values is tricky for general resilience. From the start, the principles of resilience were developed through a mix of research, experience, and judgment, and are therefore not impervious to subjective biases. As Brown (2014) notes: “In many ways, resilience is similar to sustainability, in that the very malleability and plasticity of the term itself means that it can act as a boundary object or bridging concept, but may also be co-opted by different interests” (p. 114). Deciding how to measure the properties of resilience will be challenging (e.g., “What aspects of diversity should be considered and how should they be evaluated?”). However a bigger challenge may arise when it comes to making tradeoffs further along in the process, answering questions like “How much natural variability can we sacrifice for the sake of predictability in ecosystem services?” or “How high should diversity be and is more diversity always better?”. Incorporating general resilience will require both technical and subjective judgments.

4.3 Alternatives

Alternatives are management options. Among the seven principles of building resilience developed by Biggs et al. (2015), two of them notably include the word “manage,” namely “manage connectivity” and “manage slow variables and feedbacks.” Managing connectivity may mean restoring connections or altering modularity (Biggs et al. 2015); for example, bringing people together in a community or creating corridors between habitat patches for wildlife. Managing slow variables is less about manipulating slow variables, so much as not forgetting slow variables during monitoring; worrisome trends in slow variables may indicate a need to re-evaluate management (Biggs et al. 2015). Managing feedbacks can mean supporting elements that create a positive feedback for the desirable state or trying to break a feedback loop that is moving a system closer to a threshold.

Resilience thinking also suggests considering how disturbances and thresholds can be managed. Creating a disturbance through management intervention (e.g., prescribed fire, flooding) may be a good alternative, especially if the system is adapted to disturbances. Distance from a threshold can be changed, but sometimes thresholds themselves can be manipulated to increase resilience. Walker and Salt (2012) provide examples of moving an economic threshold between income and debt for a farmer by developing an off-farm source of income, or moving an ecological threshold for grass cover by encouraging perennial grasses over annual grasses because they can handle more variability in rainfall.

Another consideration is whether the adaptive cycle impacts which alternatives are available and the consequences of those alternatives. The adaptive cycle may offer insights because actions may be more or less appropriate depending on what condition the system is in (Walker and Salt 2012). For example, if reorganization is anticipated, it might be worth developing ways of generating system memory[3].

Given general resilience is included as an objective, as recommended in the objectives section, then variability (as a principle of resilience (Table 2-4)) is a sub-objective. Therefore, alternatives leading to variability should be included. For iterative decisions, alternatives do not necessary need to dictate that the same action be taken

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[3] From an institutional perspective, memory could take the form of documented stories produced by senior members. From an ecological perspective, seedbanks could be used to store genetic source material.

every management time step. Alternatives could be state-based, so that the implemented alternative depends on the current state of the system, or could be deliberately randomized based on an agreed-upon algorithm (e.g., allowing a flood on average 1 out of every 5 years). Variability can also come from introducing disturbances.

In terms of meeting general resilience objectives, some of the resilience principles (Table 2-4) are actually accommodated by the structured decision making process itself. In particular, structured decision making can influence the principles of social capital, fairness/equality, humility, and learning. For example, properly conducted structured decision making with appropriate facilitation and a good representation of stakeholders can foster the development of social capital and a sense of fairness and equality in decision making. Structured decision making could encourage or discourage humility depending on the context and the confidence (or overconfidence) of the people at the table, but I believe an emphasis on identifying uncertainty and acknowledging ecosystem services should encourage humility. Learning can occur in the sense of mutual understanding and shared knowledge among stakeholders, as well as directly reducing uncertainty through monitoring and review. Other principles of resilience may require directly targeted alternatives, as I described for variability.

4.4 Consequences

Resilience thinking emphasizes the difficulty of forecasting from limited experience, given a lack of understanding of mechanisms and the presence of “deep uncertainty.” However, decision making must still be built upon models of predicted consequences to remain transparent and to be based on more than intuition (Johnson et al.

2013). System modeling of components and dynamics can help clarify thinking about how alternatives are anticipated to influence the system and thereby achieve ecosystem service objectives. Models should include uncertainty (Johnson et al. 2013), thresholds (Martin et al. 2009, Walker and Salt 2012, Biggs et al. 2015), and links between ecological and social dynamics as appropriate. The goal is to help decision makers understand what is uncertain and the risk involved in making the decision.

One way of thinking about risks and uncertainties, especially those that are irreducible, is to use scenario planning to lay out different possible futures and predict consequences under each scenario (Peterson et al. 2003). Scenarios are essentially stories describing potential system trajectories, based on key uncertainties and drivers of change. Scenario planning allows decision makers to consider how changes beyond their control could alter the context and if those changes would alter the preferred alternatives. Scenario planning could be used to think about what would happen if a transition to an alternative state did occur, including whether the transition would be reversible and at what cost. Scenario planning is useful when system controllability is low (Allen et al. 2011), and therefore may be a particularly good way to think about how other scales are linked to the focal scale. For example, it may be suspected that a new regional level policy will be passed or an invasive species will arrive in the area, changing the context of the focal scale in ways beyond the control of decision makers.

The past history of disturbance can contribute to the development of consequence models, recognizing that complex systems limit predictability. How did the system react in the past? What components or process were best able to recover from disturbance, or were themselves encouraged by the disturbance? If a similar disturbance were to occur in the future, would this system be more or less likely to transition into an alternative state? If the objectives for specified resilience have been well described and used to develop alternatives, the transition should be less likely to occur (unless an alternative state is desirable).

In the case of general resilience, I propose presenting consequences for the constructed measures through the use of spiderweb diagrams (Figure 2-2), similar to those used in Nemec et al. (2014). Spiderweb diagrams offer a quick way to visualize consequences for the principles of general resilience. Requisite simplicity and limited time/effort available for decision making make detailed analysis of every aspect of resilience impossible, but ignoring general resilience altogether could be dangerous.

4.5 Tradeoffs

Various quantitative methods are available for explicitly making tradeoffs (Gregory et al. 2012). Although it is beyond the scope of this paper to explain these methods, it should be noted that optimization, which is sometimes critiqued by resilience thinkers (Walker and Salt 2006), is not inherently antithetical to resilience (Fischer et al. 2009, Possingham and Biggs 2012, Johnson et al. 2013, Williams and Nichols 2014). Optimization applied as part of a structured decision making process emphasizing resilience thinking can serve as a tool for balancing the multitude of objectives and potential consequences in a way that clearly expresses how objectives are weighted and alternatives are compared.

Integrating resilience thinking into structured decision making will invariably involve tricky tradeoffs because people value consistency and predictability whereas resilience thinking encourages variability and flexibility (Walker and Salt 2012). Over-emphasis on the former can have detrimental impacts in the long-term, by increasing the likelihood of transitioning into undesirable stable states (Holling and Meffe 1996). How to balance this tradeoff is not obvious and will require subjective and technical input, but emphasizing resilience at least ensures that the tradeoff is considered, such that variability is not automatically treated as an unfortunate characteristic of a complex system. A reasonable compromise may be establishing pre-defined rules for how variability will be introduced (e.g., based on an explicit probability distribution) such that stakeholders understand how the decision is made and trust that variability is not an excuse for giving the decision maker power to arbitrarily change the policy.

A related tradeoff is linked to risk tolerance of transitioning into an alternative state from an unanticipated disturbance. The consequences of neglecting general resilience are not readily apparent because there are not specified alternative states and associated costs and risks of transition to consider. This inability to understand consequences is a reason why general resilience is often ignored (Walker and Salt 2012). In the context of structured decision making incorporating resilience thinking, stakeholders will need to balance specified and general resilience objectives such that systems in desirable states are well-prepared to withstand specific, anticipated disturbances without becoming vulnerable to unanticipated disturbances.

Although rooted in ecology, resilience thinking should not be synonymous with extreme intolerance for environmental risks. That is, resilience thinking is not about applying the precautionary principle to ecology. It is typically impossible to be simultaneously precautionary on ecological, social, and economic fronts (Gregory et al.

2012). Therefore, no alternative will be risk free, and value-based tradeoffs will have to be made. In addition, even if decision makers strongly value ecological integrity, there would still likely be tradeoffs between ecosystem services, with alternatives improving some ecosystem services while degrading others.

There will be tradeoffs in the number of principles accommodated by an alternative, and how well those principles are achieved. The spiderweb diagrams produced for general resilience cannot tell you what the “best” configuration is, but they can be used to illustrate tradeoffs related to general resilience (Figure 2-2). Possible considerations include the amount of area covered, the evenness of area covered, notable “peaks” and “valleys,” and whether there is balance between ecological and social aspects. The web can be refined by eliminating principles that are outside the scope of the decision at hand (e.g., overlap in governance is likely to be beyond the decision maker’s control) or are equivalent across all alternatives.

4.6 Monitoring and review

Monitoring for resilience can serve multiple purposes. The first is to detect potential warning signs, such as worrisome trends in important slow variables, crossing of predetermined tipping points, dramatic shifts in variability, unanticipated consequences, or context-altering surprises. Monitoring and review can also provide information on the current state of the system (which will determine the action taken for state-based decision making), evaluate progress toward objectives, facilitate learning (Lyons et al. 2008), and tighten feedbacks by more readily linking actions to consequences. If management actions are systematically implemented, monitored, and reviewed such that uncertainty about the system is reduced and used to change how management proceeds in the future, then adaptive management has been achieved.

If key uncertainties were revealed during the structured decision making process that inhibit the ability to determine a best course of action, it is prudent to consider monitoring and review as components of alternatives. If so, consequences and tradeoffs for monitoring would be evaluated as well. For example, there will be tradeoffs in terms of the number of variables monitored, precision of monitoring, and how much effort is needed. What is monitored, how it is monitored, who does the monitoring, and how the data are analyzed are all decisions in themselves that warrant special attention. As with the rest of structured decision making, there are technical and subjective aspects to answering these questions.

Monitoring should be deliberately linked to decision making and make efficient use of limited resources (Nichols and Williams 2006). This may be challenging if critical slow variables are not be known *a priori*, as they may be difficult to identify through efficient monitoring. Tradeoffs will have to be made in order to monitor a variety of potential slow variables without overly detracting from monitoring resources that could be directed toward known reducible uncertainties.

Monitoring for changes in both ecological and social context is important, in part because they may change at different rates. As Berkley (2013) observes, “Attitudes and behavior do not necessarily operate at the same time scales as natural systems. Thus, when using tools to conduct multi-criteria decision analyses or structured decision making to optimize among resources and stakeholder associated values, one should take care the subjective indicator information is current” (p. 69). It is important that the structured decision making process be re-evaluated if the underlying decision context has been altered.

5. CASE STUDY: OAK FOREST CONSERVATION IN SOUTHEASTERN NEBRASKA

To begin exploring how a structured decision making process could apply resilience thinking in the context of a realistic natural resource management issue, I use oak forest conservation in southeastern Nebraska as an example. Although partially informed by true events, the case study presents hypothetical results for a speculative, rapidly assessed structured decision making process. My intention is to show the potential applicability of the recommendations, not to provide a precise description or prescription for any actual management plan.

Specifically, the case study deals with forest management decisions made for Indian Cave State Park, located in the Missouri river bluffs of southeastern Nebraska. Historically the area supported oak-dominated forest communities (*Quercus rubra, Q. velutina, Q. macrocarpa*, and *Q. muehlenbergii*) maintained by a relatively frequent fire regime. Managers are concerned that a lack of fire in the park is facilitating a transition away from an oak forest toward a forest dominated by shade tolerant, less fire-resistant trees, such as ironwood (*Ostrya virginiana*). A diversity of flora and fauna live in the park that are likely to have different tolerances and preferences for fire and its impacts on forest structure, composition, and function.

Indian Cave State Park is within the Indian Cave bluffs biologically unique landscape classified by Nebraska’s State Wildlife Action Plan, also known as the

Nebraska Natural Legacy Project (Schneider et al. 2011). The stated mission of the Nebraska Natural Legacy Project is: "…to implement a blueprint for conserving Nebraska's flora, fauna, and natural habitats through the proactive, voluntary conservation actions of partners, communities and individuals" (Schneider et al. 2011, p. 1). Within Indian Cave bluffs, oak-dominated forest communities are of conservation interest, as are a set of wildlife and plant species. At the state park, oak forest conservation management must also recognize the interests of park visitors and protect the wildlife and plant species targeted by the Nebraska Natural Legacy Project.

5.1 Case study: Problem

Problem statement: How should oak-dominated forest communities be conserved at Indian Cave State Park, while protecting the interests of multiple stakeholders and Nebraska Natural Legacy Project-targeted wildlife and plant species?

Focal scale: The spatial scale is the forested areas of Indian Cave State Park (excluding low-lying, high soil moisture areas immediately adjacent to the Missouri River) (Figure 2-3). The organizational scale is the institution in charge of making forest management decisions for the park. The time scale is yearly.

Scales above: Key larger spatial scales include the entire acreage of Indian Cave State Park (including fields, campgrounds, roads, buildings), the Indian Cave bluffs biologically unique landscape classified by the Nebraska Natural Legacy Project, all oak forests of the Missouri river bluffs of eastern Nebraska, the state of Nebraska, and the Midwestern United States (Figure 2-3). Organizational scales include Richardson and

Nemaha counties, Indian Cave/Rulo Bluffs biologically unique landscapes, and the Nebraska Game and Parks Commission. Larger time scales are decades to centuries.

Scales below: Smaller spatial scales include specific ridges and valleys, management units, tree stands, and microsites (e.g. area immediately surrounding a large tree) (Figure 2-3). Organizational scales include management units and areas surrounding specific trails or landmarks. Smaller time scales are months or days.

Decision: On a year-to-year basis, managers choose what actions to implement and where in the park.

Decision trigger: Triggers include Nebraska Natural Legacy Project developments (above the focal scale), observed regional declines in oak-dominance (above the focal scale), and grant acquisition for oak conservation management.

Decision maker(s): The decision makers are forest managers/ecologists associated with Indian Cave State Park and the Nebraska Game and Parks Commission.

Stakeholders: Beyond the decision makers, other stakeholders include Nebraska Game and Parks Commission employees, park administrators and staff, park neighbors and other local community members, researchers using the park, and visitors (e.g., campers, hikers, picnickers, horseback riders, hunters and gatherers, wildlife viewers, cultural site observers).

Stakeholder involvement: A team assembled by Nebraska Natural Legacy Project organizers to plan conservation of the southeastern Missouri River bluff biologically unique landscapes includes representatives of Nebraska Game and Parks Commission, Nebraska Forest Service, U.S. Fish and Wildlife Service, Northern Prairies Land Trust, The Nature Conservancy, and the University of Nebraska. The team discussed the status of the area and outlined preliminary conservation targets and strategies for Indian Cave bluffs biologically unique landscape[4]. To reach a decision about oak conservation at Indian Cave State Park specifically, a smaller group of stakeholders consisting of the decision makers (forest managers/ecologists associated with Indian Cave State Park), state conservation planning specialists, park administrators, and researchers went through a rapidly assessed structured decision making process.

Other stakeholders (e.g., local community members, visitors) were not directly included in the initial process. Given the minimal anticipated impacts of the decision on neighbors and visitors, it was decided that public hearing meetings or similar forms of stakeholder involvement would be more likely to generate unnecessary conflict and be a poor use of time for all parties involved than be likely to improve the chances of conservation success or prevent future conflict. However, solicitation of stakeholder values through surveys and studies of park usage by visitors informed the process.

<u>States</u>: Ecological states are defined as oak-attracted or shady-attracted (Figure 2-4). All else being equal, in the absence of fire the system is predicted to move from the oak-attracted state to the shady-attracted state. Within the alternative states, the system can be oak-dominated and recently burned, oak-dominated and not recently burned, mixed oak and shade tree, or shady. States could also be described from a social perspective (e.g., a state with a high number of visitors and high visitor satisfaction and an alternative state

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[4] This team exists and did preliminarily establish conservation targets. However, the structured decision making process and results described in the following are hypothetical.

with few and dissatisfied visitors). However, in this case, framing the states in ecological terms is more useful than a social or social-ecological depiction, since few livelihoods are at stake and social states are likely either more or equally resilient to changes in forest dynamics. Social aspects are still included in the objective setting, but the decision is primarily focused on conservation management of the forest.

System history: Ancient petroglyphs etched by Native Americans can be found in the park. The land was used as a trading settlement in the mid-19th Century and grew to a town of 300 people. The settlement was impacted by shifts in the Missouri River channel and disease and was abandoned during the first part of the 20th Century. Remnants of farming fences can be found in the woods, suggesting that the area once supported agriculture (personal observation). The state park was formed by the Nebraska Game and Parks Commission in 1962, using eminent domain rights to claim land for public use (Duerfeldt v. State Game and Parks Commission; 166 N.W.2d 737 (1969), 184 Neb. 242). Since that time, the park has grown to over 3,000 acres and provides ecosystem services to visitors, as well as offering habitat to a diversity of species (Schneider et al. 2011). (Nebraska Game and Parks Commission n. d.)

5.2 Case study: Objectives

The oak-attracted state is preferable to the shady-attracted state. Some desirable traits of the oak-attracted state that would be lost in a shady-attracted state include: (1) a relatively bright and open midstory, (2) many oaks in various life stages (seedling, sapling, tree), (3) presence of wildlife that subsist on acorns.

The fundamental objectives are to increase oak dominance, increase Nebraska Natural Legacy Project-targeted wildlife and plant species, increase satisfaction with recreation, decrease management costs, and increase general resilience (Figure 2-5). Oak dominance is described as having oaks comprise a high proportion of the overstory tree composition. Means of achieving this objective include encouraging the different life stages of oaks, removing shady-tolerant trees, and introducing fire. Increasing the overall set of Nebraska Natural Legacy Project target species could be accomplished by increasing populations of each species. Satisfaction with recreation is influenced by the aesthetics of the forest, the safety of activities, and the opportunities available. Decreasing management costs is self-explanatory. General resilience can be increased by manipulating its components through a constructed measures scoring approach (Table 2-5).

5.3 Case study: Alternatives

Previously applied oak conservation actions include prescribed burning and thinning of shade-tolerant trees in the midstory. These interventions introduce disturbance; prescribed burning mimics the historic disturbance regime for the oak-attracted state, and thinning creates a disturbance that may help the system cross the threshold from a shady-attracted state to an oak-attracted state. Doing nothing is also an option. Actions can be applied to all areas of the park, or management units could be created within the park. Actions can be state-based, although this approach requires sufficient monitoring to assess the system. Based on uncertainties about management impacts, a designed experiment is included, as is a trial-and-error approach. The alternatives are "state-based park management," "state-based unit management," "experiment," and "intensive management trial" (further detailed in Table 2-6).

5.4 Case study: Consequences

As the purpose of the example is to demonstrate what a structured decision making process integrating resilience thinking might look like (rather than to present a precise description or prescription of a real situation), how the consequences were determined is not important. Consequences for oak dominance, Nebraska Natural Legacy Project target species, recreation and cost were predicted, using a crude "++", "+", "~", "-", "- -" scale to represent how each alternative was expected to achieve the objectives; a score "+ +" indicates a relatively high level of predicted success in achieving the objective and a "- -" indicates a low level of success. (Table 2-7). Consequences for general resilience, estimated based on the constructed performance measures (Table 2-5), are graphically represented using spiderweb diagrams (Figure 2-6). Uncertainty is not currently described but would be a necessary component for a thorough structured decision making process.

5.5 Case study: Tradeoffs

The following objectives have equivalent consequences across all alternatives: recreation, acknowledging slow variables, overlap in governance, and fairness. These objectives may need to be monitored but are not helpful in making a decision and are therefore presently ignored. Based on the consequence table (Table 2-7), the best performing alternatives is "state-based unit management." This alternative is predicted to be the most likely to maintain oak dominance and to protect Nebraska Natural Legacy Project target species, and cost is expected to be moderate. The “experiment” and “intensive management trial” alternatives are the poorest rated.

The general resilience spiderweb diagrams (Figure 2-6) suggest that the “state-based unit management” alternative covers a fairly high amount of area, compared to the other alternatives, and has peaks in diversity, modularity, and ecosystem services. This alternative performs as well or better than the “state-based park management” alternative for all the principles. The “experiment” and “intensive management trial” alternatives scored low for ecosystem services and ecological variability compared to the “state-based unit management” alternative, but received higher scores for humility and innovation. The diagrams do not indicate a clear winner but do highlight where tradeoffs occur within the general resilience objective.

Learning is not currently a stated objective, although it is partly addressed by the humility and innovation principles of resilience under the general resilience objective. At this point, an analysis of anticipated benefits of learning should be conducted to further compare alternatives. In addition, objectives have not been explicitly weighted. While the oak dominance objective is presumably the most important objective, learning may also be highly important if the park is used to inform management across oak forests in the state. Risk is another factor that needs to be considered

5.6 Case study: Monitoring and review

All of the management alternatives require some amount of monitoring and review in order to allow for iterative decision making. The state-based alternatives require monitoring to determine the state of the decision prior to each decision. The experiment alternative requires monitoring to generate data for the statistical analysis used for learning. The intensive management trial requires monitoring both to determine the state and to observe changes in the intensive management area. Although not established during the course of the rapid assessment, the decision makers acknowledge that further discussion of monitoring is necessary to determine the resources available for monitoring and to consider what slow variables might need to be followed.

6 CONCLUSION

Polasky et al. (2011) suggest that decision making in a rapidly changing and uncertain world should involve a combination of approaches. Resilience thinking can guide discussions about what’s important and the potential consequences of neglecting to consider the complexity inherent in social-ecological systems. Structured decision making offers a means of thinking critically to prevent making poor choices, which can result from an absence of clear goals or consideration of the consequences. This framework is an initial attempt to show how the pitfalls of traditional management approaches can be better avoided by incorporating the lessons, cautionary tales, and theoretical constructs of resilience into a structured decision making process.

Even though the process is presented as straight-forward and linear, management for resilience is messy and requires flexibility and reflection. The process is not meant to be the perfect prescription for resilience management, which in any case would be inappropriate (Walker and Salt 2012). Using this framework as a starting point, communication between resilience, structured decision making, and adaptive management scholars and policy makers can further refine the framework. The ultimate test of the utility of the framework must necessarily come from practitioners, and future work should involve experimenting with the process for simulated or real world problems. Managing natural resources and balancing multiple interests will always be challenging, but developing methods built upon the foundations of resilience theory and structured decision making is an important step toward implementing the complex social-ecological systems paradigm.

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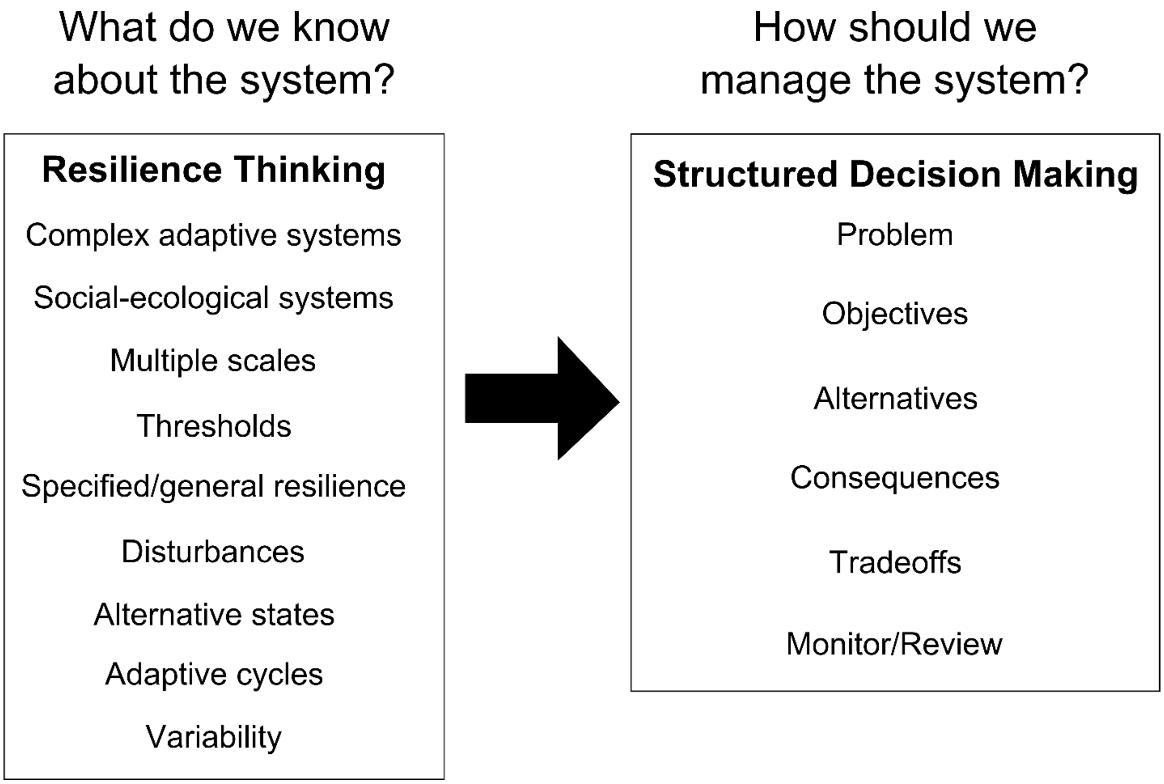


Figure 2-1. Resilience thinking is a way of framing what is known about a given system, while structured decision making offers a process for helping managers plan how to address a given natural resource issue within the system. I propose a framework that links the lessons and warnings of resilience thinking to the steps of structured decision making as a way of developing transparent, defensible natural resource management plans that enable systems to handle and adapt to disturbances.

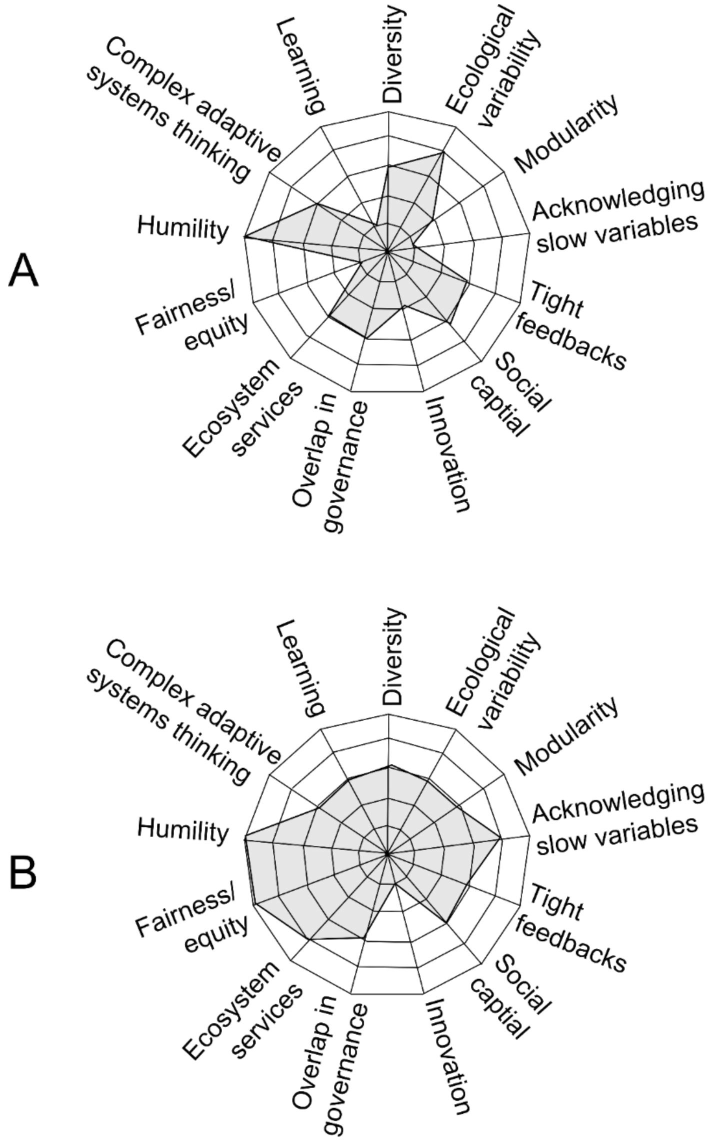


Figure 2-2. Spiderweb diagrams offer a way of graphically representing consequences for constructed performance measures based on properties of resilience. This method allows for visual comparisons of alternatives in the context of general resilience, which can aid in the assessment of tradeoffs. For example, decision makers can look at the area covered and where peaks and valleys occur between alternatives. The diagrams above show the hypothetical general resilience-related consequences for two alternatives (A and B). Alternative B is more evenly spread and appears to cover more area, but there are places where alternative A outperforms alternative B, such as for ecological variability and

innovation. Both alternatives have extreme high and low points, which may be concerning depending on how strongly these performance measures are weighted by the decision maker(s).

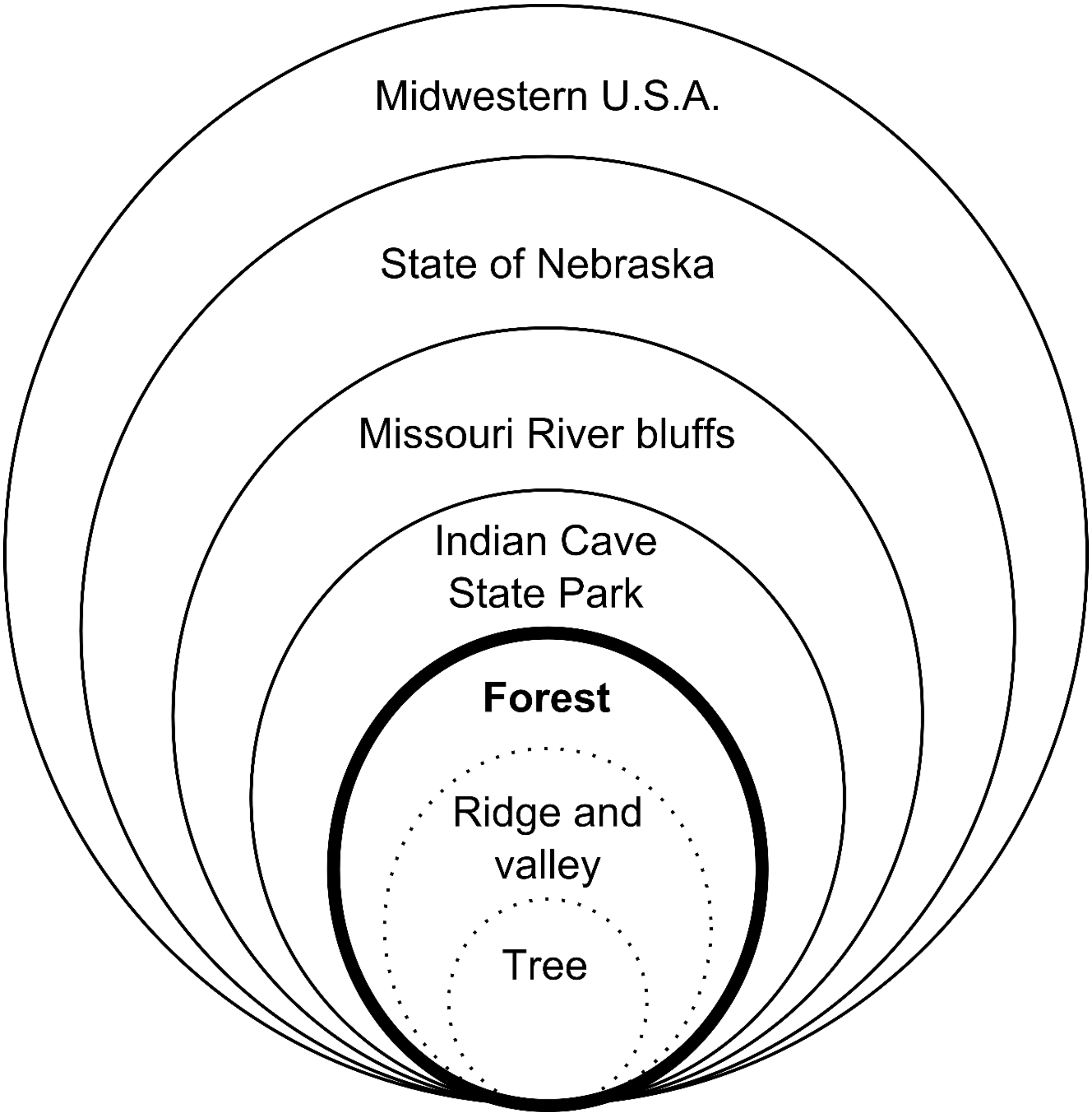


Figure 2-3. Resilience thinking requires acknowledging scales above and below the focal scale. This diagram depicts different scales for the oak forest conservation problem at Indian Cave State Park. The focal scale, forested areas of the park, is in bold. The focal scale is nested within scales above (thinner solid outline) and contains scales below (dashed outline).

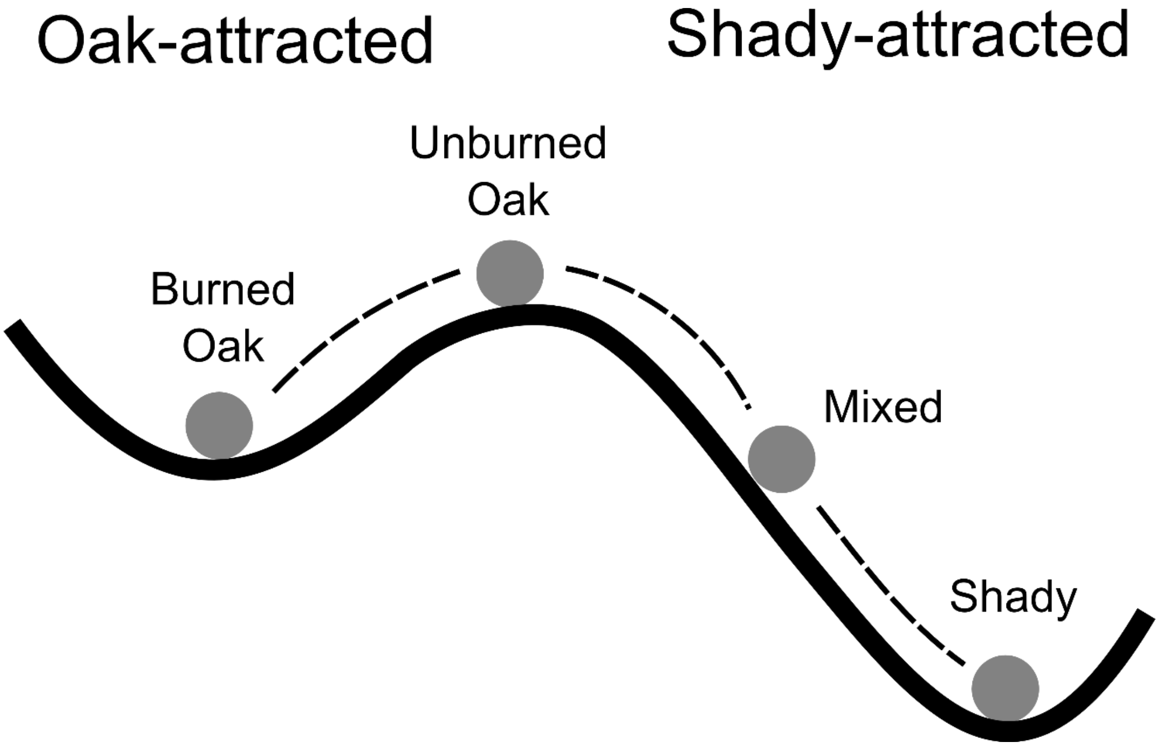


Figure 2-4. Ball-and-cup diagram of two alternative stable states (oak-attracted, shady-attracted) for the forest system at Indian Cave State Park. Within the alternatives states, the system can be (a) oak-dominated and recently burned, (b) oak-dominated and not recently burned, (c) mixed oak and shade tree, or (d) shady. In the absence of fire, all else being equal, the system is predicted to move from the oak-attracted state to the shady-attracted state. The system exhibits hysteresis, such that it takes more effort to cross back over the threshold from the shady-attracted state to the oak-attracted state than it does to go from oak-attracted to shady-attracted; this is indicated by the deeper “cup” for the shady-attracted state than the oak-attracted state.

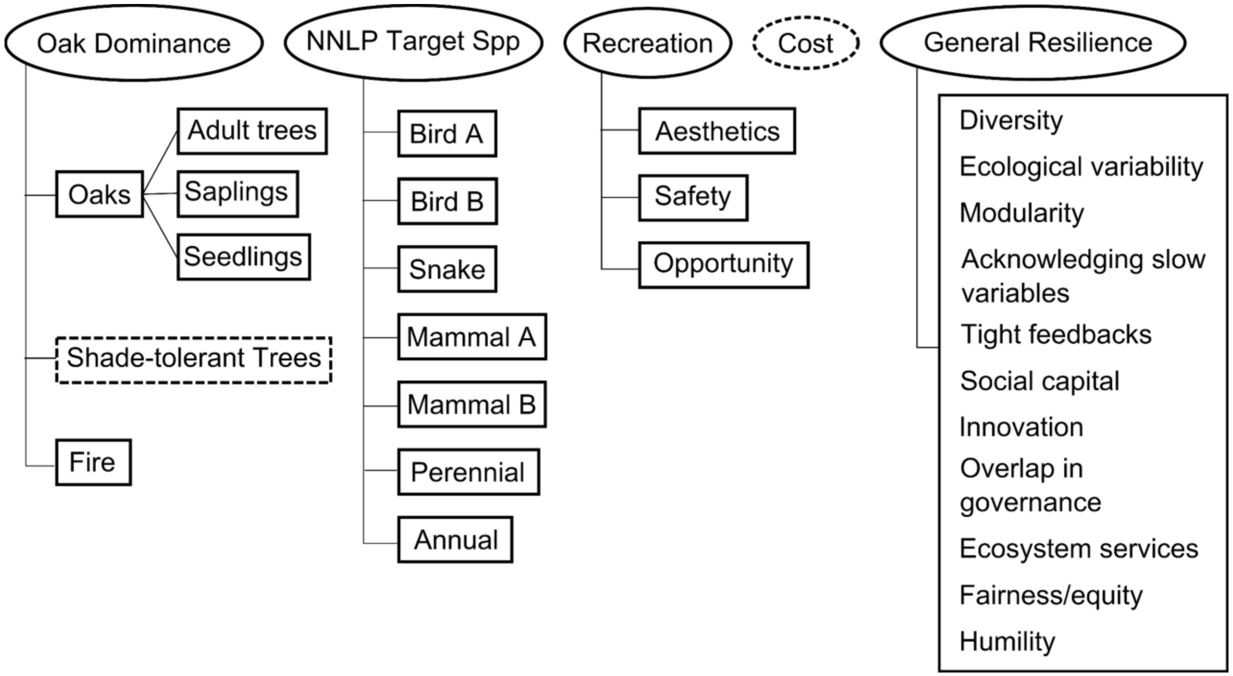
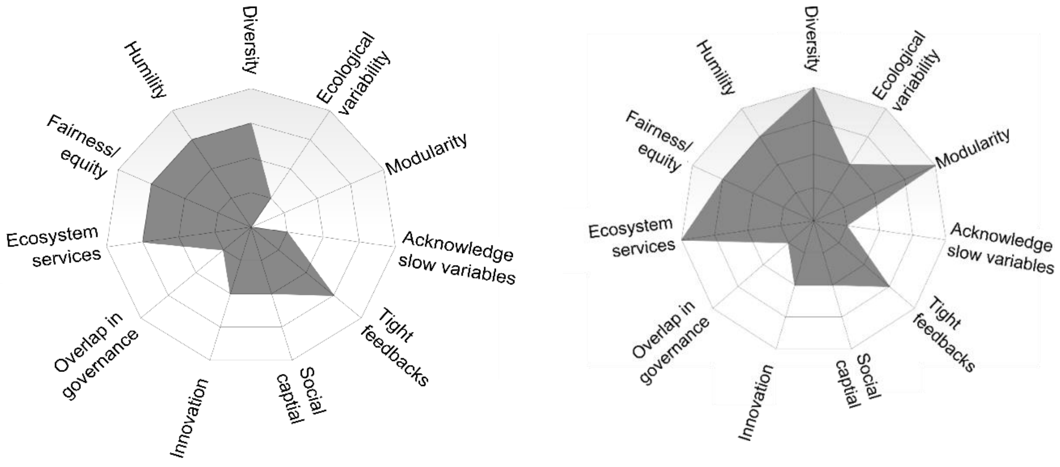
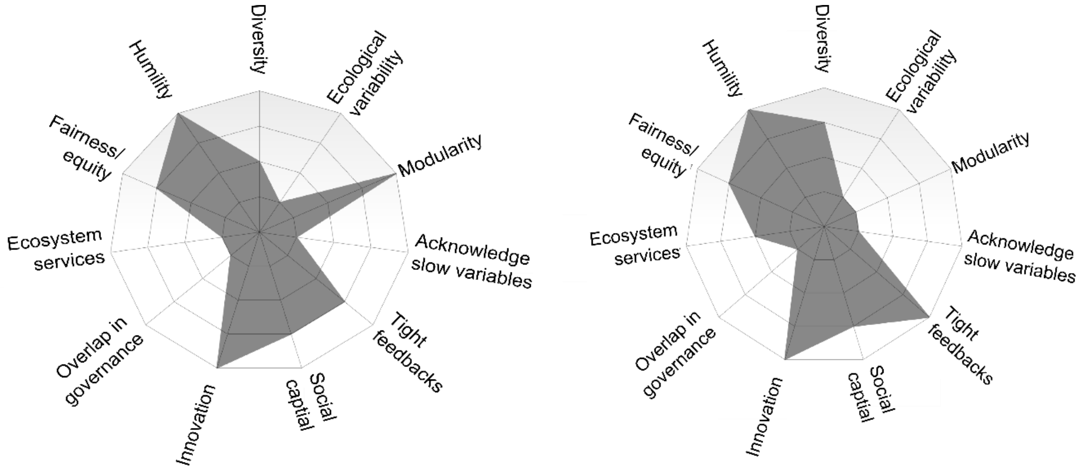


Figure 2-5. Objectives selected for the Indian Cave State Park structured decision making process. Fundamental objectives appear in circles. Means objectives, whose achievement contributes to the fundamental objectives, appear in rectangles. Dashed lines indicate objectives for which decreases of the components are valued. In contrast, solid lines typically indicating a desired increase, with the exception the components of general resilience objectives, which do not easily lend themselves to a classification of desired increase or decrease. NNLP = Nebraska Natural Legacy Project



Alternative: State-based park management

Alternative: State-based unit management



Alternative: Experiment

Alternative: Intensive management trial

Figure 2-6. Spiderweb diagrams of the general resilience constructed performance measure scores for comparison across alternatives of the Indian Cave State Park structured decision making process. The "state-based unit management" alternative covers a comparatively high amount of area, has peaks in diversity, modularity, and ecosystem services, and performs as well or better than the "state-based park management" alternative for all the principles. The "experiment" and "intensive management trial" alternatives scores comparatively low for ecosystem services and ecological variability, but receives higher scores for humility and innovation than the "state-based unit management" alternative.

Table 2-1. The following is a summary of structured decision making guidance based on [1] Hammond et al. (1999), [2] Gregory et al. (2012), and [3] Conroy and Peterson (2013). For a review of the tools of structured decision making, readers are referred to page 53 of Gregory et al. (2012).

Problem	Be creative and challenge constraints[1]
	Turn problems into opportunities[1]
	Establish a workable scope[1] with defined spatial, temporal, and organizational bounds[3]
	Take sufficient time[1], reassess as you go[1], and anticipate change[2]
	Determine who needs to be involved and how[2]
Objectives	Brainstorm what matters[1,2,3]
	Convert into succinct statements[1] of ‘what matters’ and desired direction of change[2]
	Don’t limit based on available data[1]
	Allow individual thought and anonymous sharing as needed[3]
	Separate means from ends by asking “why?”[1,2,3]
	Define sub-objectives to clarify ambiguous terms[2]
	Don’t start weighting objectives yet[2]
	Establish performance measures as metrics for describing consequences[2]
	Use constructed performance measures to accommodate less quantifiable objectives[2]
	Don’t allow others’ objectives to be rejected based on anticipated conflict later in the process[3]
Alternatives	Challenge constraints[1,3]
	Think beyond business as usual and incremental changes[1]
	Create alternatives before starting to evaluate them[1]
	Should be complete, comparable, value-focused, fully specified, internally coherent, and distinct[2]
	Allow creativity[1,3] and individual thought[3]
	Establish a reference case[2]
	Recognize that preferences change in the presence of alternatives[2]
	Consider a process alternative for decision making (e.g., coin flip)[1]
	Don’t wait until alternatives are narrowed down for you[1]

Table 2-1. Continued

Consequences	Need sufficient detail to assess alternatives but not more[12] Mentally put yourself in the future[1] Create a consequences table[12] Address key uncertainties[12] and expose key tradeoffs[2] Separate facts and values[2] Use multiple framings[2] Give different sources of knowledge equitable treatment[2] Elicit expert opinion with proper preparation and skills[3]
Tradeoffs	Eliminate dominated alternatives[1] Should be: informed, context-specific, consistent, stable, and transparent[2] Use multiple framings and elicitation methods[2] Use weighting as a new way of thinking about what matters and to whom[2] Recognize that tradeoffs are inevitable[2] Account for risk tolerance[1] Can combine objectives into a utility function[3], but “expected value” approaches assume risk neutrality[23]
Monitoring/ Review	Identify which uncertainties most influence the chosen alternative[2] Link monitoring to objectives and performance measures[2] Discuss whether monitoring is likely to reduce uncertainty[2] May demonstrate a commitment to transparency and accountability[2]

Table 2-2. I propose a natural resource management planning framework based on steps of structured decision making and incorporating resilience thinking. This table presents a summary of recommendations for going through the process, built from guidance found in structured decision making and resilience thinking literature for practitioners.

Problem	Know what decision to be made is and who the decision maker(s) is (are)
	Identify the focal scale (spatial, temporal, organizational) and key scales above and below
	Define the current state and alternative states (part of the context)
	Outline what triggered the decision. Disturbance/anticipate disturbance? Change in the adaptive cycle? Transition to a different state? Change from system above or systems below?
	Know who's resilience is under consideration (stakeholders and which aspects of the social system)
	Know how stakeholders will be involved
	Think about the stakeholder network and potential bridges/barriers to collaboration before picking a team
	Explore the system's history with the stakeholders
Objectives	Develop a list of fundamental objectives (≤10) using an ecosystem goods and services framework
	Use subobjectives and performance measures to clarify ambiguous terms (e.g. resilience - of what, to what)
	Use constructed performance measures as necessary to address subjective information or to condense technical
	Include general resilience using the principles of resilience to clarify the objective
	Describe the desired and undesirable traits of current and potential alternative states
	Determine if the group agrees which state is most desirable
	Recognize if the position in the adaptive cycle can help guide objectives
	Include drivers of thresholds and critical slow variables
	Go back to the previous step as needed

Table 2-2. Continued

Alternatives	Consider non-static strategies that either embrace state-based variability or intentionally introduce variability
	Include manipulation of disturbances or disturbance response
	Know what alternatives are available given the current position in the adaptive cycle at the focal scale and scales below and above
	Identify alternatives that manipulate position relative to a threshold, or that move a threshold itself
	Consider changing or instituting rules and how they are enforced
	Go back to previous steps as needed
Consequences	Represent uncertainty, which may include partial controllability based on rule enforcement
	Use models to conceptualize system components and dynamics
	Consider influence from other scales or on other scales, including how thresholds at other scales
	Identify assumptions across experts and participants
	Use past disturbance history to help predict future responses
	Include probabilities of flipping into an alternative state, considering known or anticipated thresholds
	Discuss the anticipated reversibility of a flip
	Identify how an alternative influences system drivers, including critical slow variables
	Consider what the transition would be like (not just the end state)
	Think about how an alternative may influence trends in properties of general resilience (e.g., diversity)
	Go back to previous steps as needed

Table 2-2. Continued

Tradeoffs	Eliminate objectives that do not help distinguish between alternatives to simply
	Know the tradeoffs between ecosystem services and between alternative states
	Understand the potential risks, particularly related to sudden transitions
	Recognize the risk tolerance of decision makers
	Consider how changing one threshold or position relative to a threshold may influence other thresholds
	Go back to previous steps as needed
Monitoring/ Review	Look for trends, in terms of quantities and rates (e.g., increasing variability)
	Follow both fast and slow variables (even if they were eliminated as objectives during the tradeoffs step)
	Consider how key uncertainties might be reduced through thoughtful monitoring and analysis
	Look for changes in attitudes/values
	Go back to previous steps as needed

Table 2-3. Here I link the questions from the Resilience Alliance’s Workbook for Practitioners (RA 2010) to the steps of structured decision making (indicated by an X in the respective column), with short descriptions of why I believe the answers can inform the particular step(s) of structured decision making. Pr = Problem, O = Objectives, A = Alternatives, C = Consequences, T = Tradeoffs

Topic	Questions	Pr	O	A	C	T	Explanation
Issues and values	What are the main issues?	X					Same as what is the problem
	What attributes are valued?		X				Same as asking “what do we care about”
Uses of natural resources	What are the direct/indirect uses?		X				Some objectives will likely to relate to how people use the system
	Who are the stakeholders?	X					To determine whose concerns are considered and how they are included in the process
Disturbances	What is the history of disturbance?	X		X	X		Managing disturbances may be the problem; alternatives may involve returning disturbances regimes; consequences can be informed by past disturbances
	What are present and predicted disturbances?	X		X	X		Same as above
	How are disturbances currently managed?			X	X		Disturbance management may be a critical component of the alternatives; Past experience with disturbance management can help evaluate consequences
Systems at different scales	What are the systems at scales above and below the system of interest?	X			X		Knowing the other scales is part of understanding the focal scale; Consequences are likely impacted by the status of scales above and below the focal scale
	What are the patterns and drivers of those systems?	X			X		Same as above

Table 2-3. Continued

Adaptive cycle	What does the adaptive cycle look like?	X	X	X	X		The problem may relate to being in a particular part of the adaptive cycle; The objectives, alternatives, and consequences may depend on the position in the adaptive cycle
	What are the indicators?	X					Part of describing the state of the system
Alternative states	What are possible alternative states?	X			X		Knowing the alternative states is part of the context; Consequences may involve chance of flipping into an alternative state
	What states have been observed historically?		X		X		Same as above
	What is the reversibility of alternative states?				X	X	Consequences in terms of future ability to affect change; Tradeoffs in terms of willingness to accept risk or cost of returning later
	What are the desirable and undesirable traits?		X			X	Switching states may be an objective; There may be tradeoffs involved in being in a state with both desirable and undesirable traits
Transitions and thresholds	What would transitions be like?				X		A transition may be a potential consequence
	What drives the threshold?		X	X	X		A driver may be valued or a means to an end; Alternatives may involve manipulating thresholds or positions relative to thresholds; May need to evaluate how an alternative influences a driver
	What are the consequences of crossing a threshold?				X		If a threshold is crossed, what would be the result in terms of the objectives
	What are the critical slow variables?		X		X		Slow variables could be an important performance measure; Consequences should consider how slow variables are being influenced
	Where are thresholds located (if possible)?				X		It is important to consider the probability that implementing a given alternative could lead to a threshold being crossed

Table 2-3. Continued

Adaptive cycles for other scales	What do the adaptive cycles look like?			X	X		The status of other scales could constrain or facilitate some alternatives; It may be important to consider feedbacks on other scales
	What is the influence on the focal scale (e.g., memory, capital)?			X	X		Same as above
Threshold for other scales	How certain are thresholds at different scales?				X	X	Consequences in terms of proximity to thresholds of other scales; Tradeoffs in risk of causing a threshold to be crossed at other scales
	How do thresholds interact?				X	X	Consequences may differ depending on threshold interactions; Changing one threshold could influence another
Assessing trends	What are the trends for diversity, openness, tightness of feedbacks, system reserves, and modularity?		X		X		Objectives could involve changing trends; Consequences may involve influencing a trend or may be subject to a trend
Decision-making institutions	At what levels are key decisions being made?	X					This relates to the organization bounds of the problem
	How are rules enforced?			X	X		Rules and rule enforcement could be part of alternatives; Consequences may depend on if and how rules are enforced
Stakeholder network	What are the connections between stakeholders?	X					This is part of the context and may determine who should be involved and whether facilitation is necessary
	What is the centrality?	X					Same as above
	How cohesive are subgroups?	X					Same as above
	Who are the central actors?	X					Same as above
	What are the bridges/barriers to stakeholder collaboration?	X					It may be necessary to facilitate stakeholder collaboration to move further

Table 2-4. Walker and Salt (2012) and Biggs et al. (2015) proposed principles for managing resilience. These principles can be used for the design of resilience thinking-based objectives and alternatives.

Principle	Walker and Salt (2012)	Biggs et al. (2015)
Diversity	Promote all forms of diversity (biological, landscape, social, economic)	Maintain diversity and redundancy
Ecological variability	Work with rather than control ecological variability	
Modularity	Make sure system components are not too fully connected or too isolated	Manage connectivity
Acknowledging slow variables	Focus on the handful of controlling variables associated with thresholds	Manage slow variables
Tight feedbacks	Cost/benefit and system change feedbacks must be sufficiently tight	Manage feedbacks
Social capital	Promote trust, develop social networks, and establish effective leadership	
Innovation	Learn and adapt to change	
Overlap in governance	Mixed access rights and redundancy in governance structures	Promote polycentric governance systems
Ecosystem services	Know the important ecosystem services, included unpriced services	
Fairness/equity	Acknowledge equality among people and encourage democracy	Broaden participation
Humility	Acknowledge dependence on ecosystems and that we can’t know everything	
Complex adaptive systems		Foster complex adaptive systems thinking
Learning		Encourage learning

Table 2-5. Preliminary attempt to develop constructed performance measures for general resilience objective using the principles of resilience (Table 2-4) as applied to the Indian Cave State Park oak conservation example. The scores for the performance measure are relative and lie along a spectrum from 0 to 4, where 4 is the best possible score. The table below describes the ends of the spectrum. The "Oak Forest Example" column briefly discusses each principle in context of the case study.

Principle	High end of the spectrum	Low end of the spectrum	Oak Forest Example
Diversity	High diversity, high redundancy	Low diversity, low redundancy	Whether there is wildlife and plant species diversity
Ecological variability	High variation in time and space	Low variation in time and space	Whether the park has different areas or changes over time
Modularity	Moderately separated components	Totally connected or disconnected components	Whether there are isolated areas of the park or the park operates as one entity
Acknowledging slow variables	Slow variables monitored	No monitoring for slow variables	Whether there is monitoring for trends in forest condition
Tight feedbacks	Desirable feedbacks tight, undesirable loose	Desirable feedbacks loose, undesirable tight	Whether feedbacks for oak-attracted state are tight (e.g., oak and fire) and shady-attracted loose (shade-tolerant trees making shade)
Social capital	Greater shared understanding and mutual respect	Little shared understanding and low tolerance	Communication and good relationships between decision makers and stakeholders
Innovation	Management flexible to change and facilitates learning	Management inflexible to change and learning unlikely	Whether decisions can be changed and whether learning is encouraged

Table 2-5. Continued

Overlap in governance	Management across scales and with different decision processes	Management all at one scale with one decision process	Whether management of the oak forest, within and surrounding the park, are addressed by multiple groups
Ecosystem services	High levels and diversity of services	Low levels and diversity of services	How well the park provides the ecosystem services valued by the various stakeholders
Fairness/equity	Decisions perceived as fair	Decisions perceived as unfair	Whether stakeholders are satisfied with how management decisions are made and implemented
Humility	Recognizes limits to predictability	Assumes near perfect predictability	Whether uncertainty is addressed or ignored

Table 2-6. Descriptions of the alternatives under consideration for the Indian Cave State Park oak forest example. The first two alternatives are variations of a state-based management policy in which decisions are determined by the current state of the system. The third alternative is a method for active learning about management impacts. The last alternative is a combination of a state-based approach and a trial-and-error exploration of intensive management.

"State-based park management"	Every year, managers either do nothing, burn, thin, or burn and thin the entire park depending on whether the park is recently burned oak, unburned oak, mixed, or shady. Results will be compared to model predictions to refine understanding.
"State-based unit management"	Every year, managers either do nothing, burn, thin, or burn and thin for three individual management units depending on whether the park is recently burned oak, unburned oak, mixed, or shady. Results will be compared to model predictions to refine understanding.
"Experiment"	The park is divided into experimental units and the four management actions are applied as the experiment treatments.
"Intensive management trial"	Most of the park is always treated as in the "state-based park management" alternative. One area of the park is used to test an intensive form of management involving burning, thinning the overstory as well as the midstory, and planting oak seedlings and saplings. This is closer a trial-and-error approach than adaptive management and is intended to test whether the oak dominance objective can be achieved with intensive conservation effort.

Table 2-7. Rapidly assessed consequences table for the Indian Cave State Park management example, given the specified fundamental objectives and alternatives. Consequences are described along a scale and represented by symbols (“++”, “+”, “~”, “-”, “- -”), where a “+ +” indicates a relatively high level of predicted success in achieving the objective and a “- -” indicates a low level of predicted success. As the purpose of the example is to demonstrate what a structured decision making process integrating resilience thinking might look like (rather than to present a precise description or prescription of a real situation), how the consequences were determined is not important. State-based unit management scores as well or better than all other alternatives, except for the management cost objective.

	Oak Dominance	NNLP Target Spp	Recreation	Cost	General Resilience
“State-based park management”	+	~	~	+	See Figure 2-6
“State-based unit management”	+ +	+	~	~	″
“Experiment”	—	— —	~	+	″
“Intensive management trial”	+	—	~	— —	″

8 APPENDIX: Suggested readings

Resilience Alliance (RA). 2010. Assessing resilience in social-ecological systems: Workbook for practitioners. Version 2.0. Online: http://www.resalliance.org/3871.php

Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners, Revised Version 2.0 is a product of the Resilience Alliance "designed to assist in resolving specific resource issues and in developing and implementing management goals without compromising the resilience and integrity of the system as a whole." A major component of the assessment is answering a set of questions related to the social ecological system of interest in an effort to characterize its resilience. These questions have been summarized in Table 2.

Biggs, R., M. Schlüter, and M. Schoon (eds). 2015. Principles for building resilience: sustaining ecosystem services in social-ecological systems. Cambridge University Press, Cambridge, UK.

This is a short book presenting principles for building resilience, along with examples and key points for implementation. Biggs et al. (2012) contains similar information, presented in a journal article format. The Stockholm Resilience Centre released a pamphlet summarizing the book, "Applying resilience thinking: seven principles for building resilience in social-ecological systems," which is available online: http://www.stockholmresilience.org/21/research/research-news/4-22-2014-applying-resilience-thinking.html

Walker, B. H., and D. Salt. 2006. Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, D.C.

Walker, B., and D. Salt. 2012. Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, D.C.

Resilience Thinking (2006) and *Resilience Practice* (2012) are a sequence of short books by Walker and Salt that describe the main tenets of resilience science and present suggestions about how resilience-based management may be implemented in simple, understandable language. Book reviews and personal experience indicate that these books are a great starting place for exposing practitioners to resilience concepts in an easily accessible format.

Conroy, M. J., and Peterson, J. T. 2013. Decision making in natural resource management: A structured, adaptive approach. John Wiley & Sons, Chichester, West Sussex, UK.

This textbook by M. Conroy and J. Peterson is intended for scientists, managers, and students interested in applying a structured approach to complex natural resource issues. It includes descriptions of the components of structured decision making and detailed discussions on the development of decision models.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., and Ohlson, D. 2012. Structured decision making: a practical guide to environmental management choices. John Wiley & Sons, Chichester, West Sussex, UK.

This textbook by R. Gregory, L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson (2012) provides an in-depth description of the structured decision making process and presents case-study examples. They describe how to defensibly make tough environmental resource management decisions based on both values and facts.

Hammond, J. S., Keeney, R. L., and Raiffa, H. 1999. Smart choices: a practical guide to making better life decisions. Broadway Books, New York, New York, USA.

Smart Choices by Hammond, Keeney, and Raiffa (1999) is a short book written to teach people how to make better life decisions. It has received much attention and been used by individuals for self-help purposes, by professors in classroom settings, and in professional training programs (Hammond et al. 1999). The book discussions both what people do, drawing from psychology, and what people should do. *Smart Choices* offers descriptions of the steps of structured decision making in simple, understandable language.

CHAPTER 3: OPTIMIZATION AND RESILIENCE THINKING FOR MANAGEMENT OF A HYPOTHETICAL MIDWESTERN OAK FOREST

1. INTRODUCTION

Resilience was originally defined in the ecology discipline by C. S. Holling (1973) as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (p. 14). Resilience thinking is one of the major drivers behind a shift in natural resource management toward a complex social-ecological systems paradigm (Millennium Ecosystem Assessment 2003, Berkes 2010). Key concepts of resilience thinking include: (a) the potential for alternative stable states and non-linear responses, (b) the importance of variability and disturbance in maintaining a system state, (c) cross-scale linkages between/within systems, (d) the presence of emergent properties, and (e) limited predictability as a result of inherent uncertainty (Walker and Salt 2006). This is in contrast to traditional steady-state management that sought to reduce variability from an assumed equilibrium for part of the system (Williams and Brown 2014). Strictly controlling a system to consistently achieve a given objective may succeed in the short term but will likely erode resilience and ultimately result in a sudden unexpected transition (Holling and Meffe 1996, Gunderson 2000).

State-and-transition modeling can conceptually represent a complex system with alternative stable states and non-linear transitions, and has been suggested as a practical way of incorporating resilience thinking into management decision making (Westoby et al. 1989, Bestelmeyer et al. 2004, Briske et al. 2008, Suding and Hobbs 2009, Walker and

Salt 2012). In fact, the state-and-transition modeling approach emerged in rangeland ecology partly in response to the multiple stable states concept of Holling’s (1973) ecological resilience theory (Briske et al. 2005, Briske et al. 2008). State-and-transition models were originally designed to frame rangeland management contexts and consisted of discrete states (described by vegetative composition) and transitions between states (Westoby et al. 1989). More recent approaches distinguish states, phases within states, transitions, and thresholds (Stringham et al. 2003).

States are domains of relative stability established through ecological processes. Phases are recognizable patterns within the bounds of natural variability characteristic of the state. Transitions are trajectories of change. Thresholds are boundaries between states for which transitions are irreversible without substantial management input. Additional modifications, proposed by Briske et al. (2008), further emphasize resilience concepts in state-and-transition models by explicitly describing triggers, at-risk communities, feedback mechanisms, restoration pathways, and process-specific indicators. Their revised state-and-transition model encourages broader inclusion of variables and processes influencing state resilience and focuses management attention on influencing proximity to thresholds rather than identifying thresholds (Briske et al. 2008).

The purpose of this chapter is to use a resilience thinking perspective to explore the potential and limitations of optimizing a state-and-transition model, using a hypothetical Midwestern oak forest conservation example. Optimization methods, namely those based on maximum sustainable yield, have been criticized as a primary cause of past natural resource management catastrophes (e.g., collapsed fisheries, massive wildlife fires) (Walker and Salt 2006). However, optimization and other decision analysis techniques are not inherently at odds with resilience (Fischer et al. 2009, Possingham and Biggs 2012, Johnson et al. 2013). When applied as a decision making tool within a larger resilience-driven management perspective, optimization can identify policies that are most likely to best achieve the objectives, based on models of values, consequences, and uncertainty. I use the framework proposed by Briske et al. (2008) to incorporate resilience concepts into a qualitative state-and-transition model, and then further apply resilience thinking to quantifying the model for use as a Markov decision process. Optimal management decisions are identified based on expected value. I briefly explore uncertainties and tradeoffs and consider how optimization could inform decision making within a larger resilience thinking paradigm.

2 BACKGROUND

The context of the example is loosely based on experience with an oak forest system in the Missouri River bluffs of the Midwestern United States. A hypothetical setting allows for the investigation of management decisions without appearing prescriptive and provides freedom to manipulate model parameters to make various points relevant to resilience in the absence of data. In reality, insufficient data can greatly challenge the applicability of decision analysis tools, making it important to use a combination of approaches when choosing a management option (Polasky et al. 2011).

The hypothetical oak forest is located on a state park that is managed for environmental conservation and visitor satisfaction objectives, while also considering management cost. Historically the area supported oak-dominated forest communities (*Quercus rubra, Q. velutina, Q. macrocarpa,* and *Q. muehlenbergii*) maintained by a relatively frequent fire regime. A general trend of declining oak dominance has been observed across eastern North America where fire has been excluded (Abrams 1992, Fei et al. 2011). Managers are concerned that a lack of fire in the park is facilitating a transition away from an oak forest toward a forest dominated by shade tolerant, less fire-resistant trees, such as ironwood (*Ostrya virginiana*). A diversity of flora and fauna live in the park and have different tolerances and preferences for fire and its impacts on forest structure, composition, and function.

3 STATE-AND-TRANSITION MODEL AND MANAGEMENT OPTIONS

Following the recommendations of Briske et al. (2008) for developing a state-and-transition model under a resilience thinking perspective, I explicitly describe triggers, at-risk communities, feedback mechanisms, and restoration pathways (Figure 3-1). Two overarching alternative system states have been identified. One state is characterized by a tendency toward continued oak dominance, and the other is characterized by a tendency toward dominance by shade tolerant tree species (Nowacki and Abrams 2008). Indicators of the oak-attracted state include a high number of oak trees and seedlings and a low density midstory, and indicators of the shady-attracted state include shade-tolerant trees in the midstory and low light availability in the understory.

The reference state (“oak-attracted”) is maintained by feedbacks encouraging oak regeneration and discouraging invasion of shade-tolerant trees. For example, oak leaves would facilitate burning, and burning would lead to conditions favoring oak seedling survival and ultimately oak regeneration. Fire would suppress shade-tolerant trees that tend to be less adapted to fire. In contrast, the alternative state (“shady-attracted”) is maintained by feedbacks that suppress oak regeneration by decreasing light availability to oak seedlings. The threshold between the reference state and the alternative state is determined by the density of shade-tolerant trees, and decreased frequency of fire can trigger crossing of the threshold. Once the threshold has been crossed, the only way to possibly return is to follow the restoration pathway by implementing thinning with or without burning. Thinning and burning is more likely to reverse the transition. The system property of being much easier (in terms of management effort) to cross the threshold into the shady-attracted state than it is to return to the oak-attracted state (which requires significant management input) is an example of hysteresis (Scheffer and Carpenter 2003).

Within the oak-attracted state, the system can exist in a recently burned oak condition or an unburned oak condition. These two conditions are assumed to have distinguishable community structure, composition, and function but are still within the same domain. Within the alternative state, the system can be in a mixed condition with some oaks remaining or in a shady condition without oaks. In the absence of management, the system will eventually transition to the shady condition. The unburned oak condition can be thought of as the at-risk community[5] phase and may cross the threshold if triggered by lack of fire.

4 MARKOV DECISION PROCESSES

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[5] We use the term “community” without specifying what characterized the community beyond presence of oak and/or shade-tolerant tree species. We assume that there are differences in community composition between burned and unburned oak forests. (For example, there may be changes in dominant herbaceous plants.)

A Markov decision process is a mathematical model for a time series of discrete transitions in state with an action taken at each time step, under the assumption that past conditions do not impact future transitions (Marescot et al. 2013). Components of a Markov decision process include: (a) possible states and actions, (b) transition probabilities among states, (c) a reward (i.e. objective, utility) function based on the state and action taken, and (d) a specified time horizon and discount factor. An overlap in terminology between state-and-transition models and Markovian decision processes can lead to confusion (Standish et al. 2008). This overlap is not a coincidence, however, as both types of models capture the idea of a system being composed of discrete states that can transition to other states. To reduce ambiguity, in the rest of the chapter, states of the state-and-transition model (Figure 3-1) are referred to as “conditions” (burned oak condition, unburned oak condition, mixed condition, shady condition). “States” are either (a) Markovian states (synonymous with condition for the single unit example and are counts of units in each condition for the multiple unit example), or (b) alternative stable states from the resilience thinking perspective (oak-attracted state = burned oak or unburned oak condition; shady-attracted state = mixed or shady condition). “Transitions” are movements among Markovian states.

In the following sections, I further specify the Markov decision process described above and determine the stationary optimal policy[6] using MDPSolve (Fackler 2011, available at https://sites.google.com/site/mdpsolve/) in Matlab (R2011a). I discuss the time horizon, discount factor, and initially selected transitions probabilities (referred to as

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[6] A stationary optimal policy dictates the action for each state that is optimal at any time step (i.e., time independent).

the “original”[7]). I first optimize a simple version of the system, in which the park is considered a single management unit, for which it is relatively straightforward to translate the state-and-transition model (Figure 3-1) into a Markovian decision process model. However, the single unit example does not allow for diversity in condition within the park for a given time step. As I later discuss, diversity in condition may be desirable from a resilience thinking perspective. To accommodate different conditions at one time, I then use a multiple unit example in which the park is divided into three units.

4.1 Time horizon and discount factor

An infinite time horizon and a discount factor of 0.95 were specified for the Markov decision process. The decision context does not indicate a reason to select a particular time horizon (e.g., expiration date of a grant). An infinite time horizon was selected over an arbitrary finite horizon because the optimal decision in the short term may not be the same as the long term optimal decision (Marescot et al. 2013). Discount factors can run from 0 to 1, where 0 means future rewards have no value and 1 indicates rewards received in the future are worth the same as they would be if received in the present. Given the importance of economic costs and existing social benefits, I felt 0.95 was appropriate for describing the relationship between rewards now and in the future; a reward in 14 time steps is approximately half of the current reward. However this discount factor devalues the future more strongly than is sometimes recommended for long-term planning (e.g., 0.965 for mature European economies (European Union

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[7] In later sections, the implications of uncertainty about transition probabilities are explored by evaluating alternatives to the “original.”

Regional Policy 2008)). In later sections the discount factor is varied to test the sensitivity of the optimal policy to the selected discount factor.

4.2 Transition probabilities

Transition probabilities are dependent on which management action is taken ($p_{ij}(a)$), where actions are a_1 = do nothing, a_2 = burn, a_3 = thin, and a_4 = burn and thin. Initially I assume that transition probabilities are known with certainty. In a later section I manipulate the transition probabilities to explore the implications of uncertainty; therefore, I refer to this set of transition matrices as the "original."

The following basic principles were used in the quantification of transition probabilities (Figure 3-2, Table 3-1):

- In a given time step, a unit may remain in the same state ($p_{ii}(a)$) or transition once ($p_{ij}(a)$).
- In the absence of management intervention (action: a_1 = do nothing), there is a strong tendency to move to the condition immediately to the right along a pathway from burned oak to unburned oak to mixed to shady (high probabilities for $p_{12}(a_1)$, $p_{23}(a_1)$, $p_{34}(a_1)$).
- Transitions to a condition more than one step to the right is impossible (i.e., burned oak cannot transition directly to mixed ($p_{13}(a) = 0 \; \forall \; a$), and unburned oak cannot transition directly to shady ($p_{24}(a) = 0 \; \forall \; a$)).
- Transitioning to prior conditions is only possible through management intervention ($p_{43}(a_1) = p_{42}(a_1) = p_{41}(a_1) = p_{32}(a_1) = p_{31}(a_1) = p_{21}(a_1) = 0$).

Intervention is also needed to remain in the burned oak condition ($p_{11}(a_1)$ = 0).

- The shady condition can only move backwards to the mixed condition (i.e., shady never transitions to unburned oak or burned oak ($p_{42}(a) = p_{41}(a) = 0 \ \forall \ a$)).

Certain actions can ensure particular transitions. When managers do nothing (a_1) or thin (a_3), burned oak is guaranteed to transition to unburned oak ($p_{12}(a_1) = p_{12}(a_3) = 1$) and shady is guaranteed to stay shady ($p_{44}(a_1) = p_{44}(a_3) = 1$). Burning ($a_2$) guarantees that burned oak remains burned oak ($p_{11}(a_2) = 1$), unburned oak transitions back to burned oak ($p_{21}(a_2) = 1$), and shady remains shady ($p_{44}(a_2) = 1$). Burning and thinning (a_4) guarantees that burned oak remains burned oak ($p_{11}(a_4) = 1$) and unburned oak transitions to burned oak ($p_{21}(a_2) = 1$).

All other transitions lie between 0 and 1. In the hypothetical system, fire disturbance is integral to the dynamics maintaining the oak-attracted state. To represent this with transition probabilities, in the absence of burning the unburned oak condition has a strong chance of transitioning into the mixed condition ($p_{23}(a_1) = p_{23}(a_3) = 0.90$) and low chance of keeping the system in the oak-attracted state ($\mathrm{p}_{22}(a_1) = \mathrm{p}_{22}(a_3) = 0.10$). As previously mentioned, burning guarantees transitioning from unburned oak to burned oak ($p_{21}(a_2) = p_{21}(a_4) = 1$).

The mixed condition covers a range of variability in tree species composition, as it represents the time between shade-tolerant trees arriving and when a shady forest is firmly established. In the absence of interventions, the probability of transitioning from mixed to shady ($p_{34}(a_1) = 0.80$) is slightly lower than the transition probability for unburned oak to mixed ($p_{23}(a_1) = 0.90$) because of the wide range of conditions I assume the mixed condition covers. Crossing the threshold back into the oak-attracted state requires more management input than was needed to leave the oak-attracted state, so the system exhibits hysteresis. Thinning (a_3) is more costly than burning (a_1) and is the cheapest available action that brings the transition probability from the mixed condition back to the oak-attracted state above 0. Thinning in the mixed condition will generate a low probability of transitioning to the unburned oak condition ($p_{32}(a_3)=0.20$) and also greatly reduces the probability of transitioning into the shady state ($p_{34}(a_3) = 0.20$ compared to 0.80). Burning and thinning generates an even higher chance of returning from a mixed condition to the oak-attracted state ($p_{31}(a_4)=0.40$) , this time to the burned oak condition since burning is involved, but the same risk of transitioning to the shady condition ($p_{34}(a_4) = 0.20$). Burning and thinning has a very low, but non-zero, chance of triggering a transition from the shady condition back to the mixed condition ($p_{43}(a_4) = 0.05$). Therefore the shady condition is near-trapping condition, meaning that once shady a unit is highly unlikely to “escape” from this condition.

4.3 Single unit: Model description

For the single unit example, in which the park is considered as a single management unit, the possible Markovian states correspond to the state-and-transition model states, referred to as conditions (burned oak, unburned oak, mixed, shady), and the management actions are the same as described previously (do nothing, burn, thin, burn and thin). With four states (s) and four actions (a) available for each state, there are 16 state/action combinations ($s * a$).

The reward values are determined by the condition-based return and the cost of the management action (Table 3-2), where reward = return - cost. As this is a hypothetical example, I am able to place the returns, which are largely non-monetary in nature, in the same “currency” as the costs. Essentially, an index is used to represent relative returns and costs. The oak-attracted state is given the highest return (3). I assume that burned oak and unburned oak conditions are equal in return, such that, in the absence of risks of transitions and management costs, decision makers would be equally satisfied with a recently burned or an unburned oak forest. A mixed forest is assigned a low but non-zero return (1) because this forest still contains some oaks and can presumably support at least some of the flora and fauna of interest. The shady condition has no return (0). Management costs are lowest for doing nothing (0), moderately low for burning (1), moderately high for thinning (3), and highest for burning and thinning (4).

A policy iteration algorithm was used to find the stationary optimal policy for the Markov decision process (Fackler 2011). This policy dictates the management action that should be taken given the current state of the system, regardless of the particular time step. Of course, a stationary policy does not mean that the system will end up in the same state indefinitely. Five simulations of system dynamics over 25 years were conducted with MDPSolve (Fackler 2011) in Matlab (R2011a), using the optimal policy, to explore potential system trajectories for patterns and variability over time.

4.4 Single unit: Results

The optimal decision in the burned oak and shady conditions is to do nothing, in the unburned oak condition is to burn, and in the mixed condition is to burn and thin

(Table 3-3). The greatest expected values occur when the system starts in the burned or unburned oak condition (Table 3-3). Approximately half that value occurs when starting in the mixed condition. Zero value is expected if the system starts in the shady condition.

Simulated time paths (Figure 3-3 - original) reveal a pattern of oscillating between the burned and unburned oak conditions if the system starts in either condition of the oak-attracted state. If the system starts in the mixed condition, the system eventually moves to the oscillation between oak conditions or moves to the shady condition. Once in the shady condition, the system stays in the shady condition.

4.5 Single unit: Interpretation

The oscillation between the burned and unburned oak conditions makes sense given how the model was specified. When in the burned condition, managers do nothing because burning would cost money and the next condition (unburned oak) is just as valuable. Burning is guaranteed to work and is relatively cheap, so managers burn once in the unburned oak condition, causing the oscillation between burned and unburned oak conditions. The oscillation also explains the similarity in expected value between the two oak conditions.

From a resilience thinking perspective, the fact that the system is not burned every time step may be a good thing; a system that is adapted to frequent disturbance may become less generally resilient to less frequent or surprising disturbances (Walker and Salt 2012). In addition, the system may support greater diversity by discouraging dominance of the most fire adapted species. However, it seems plausible that the constant, predictable oscillation might also cause changes in general resilience. Careful monitoring of the system is advisable to alert managers to worrisome, unexpected trends.

The trajectory for the system if it starts in the mixed condition is highly uncertain. The only thing that does appear fairly certain, based on the five simulations, is that the mixed state is unlikely to stay stationary for more than a few time steps. Despite the optimal policy being the most intense form of management (burn and thin), the simulations and expected values indicate the system may still end up in the return-less shady condition. From a resilience thinking perspective, this is worrisome because it means that is no management solution is guaranteed to prevent the system from degrading to a point of no return. However, as the model is specified, as long as the system starts in the oak-attracted state, management prevents ever moving into the mixed condition.

When starting in the shady condition, management has an extremely low chance of succeeding, such that money spent trying to revert to a different condition would be wasted (based on the valuation scheme and discount factor); therefore the best expected outcome is zero value and the shady state is trapping. This result is unsurprising given that the transition probabilities were assigned under the assumption that the shady condition is strongly resistant to management interventions.

The single unit example is relatively simple, in terms of number of states and state/action combinations, and straightforward to interpret. However, if the whole park is considered as a unit that is either burned oak, unburned oak, mixed, or shady, then it is not possible for burned and unburned oak conditions to exist simultaneously or to apply management to only a portion of the park for a given time step. A forest of half burned oak and half unburned oak may be preferable to a forest that is either one or the other, given that species in the park have varying sensitivities to the impacts of fire on the landscape. I assume that a part burned, part unburned forest has higher ecological variability, which is valuable from a resilience thinking perspective (Walker and Salt 2006). It may also be possible that management costs are reduced by dividing the park into units if cost is based on area covered. Therefore, I now explore a more complicated model with multiple units.

4.6 Multiple units: Model description

To accommodate diversity in condition and action, while also maintaining computational and cognitive tractability, the park is now hypothetically divided into three units. For the multiple unit example, the Markovian states are determined by the number of units in each condition category (burned oak, unburned oak, mixed, shady); this type of model is referred to as a category count model (Fackler 2012). With three units (*N*), four condition categories (*q*), and four possible actions (*a*) in each condition, there are 20 states (given unique index number identifiers, I^x) (Table 3-4) and 816 state/action combinations.

The rewards I now discuss are referred to as "original," as rewards will later be manipulated to explore the impact of different objectives and weightings. When all three units are in the same condition, the state return is equal to what its corresponding state in the single unit example. Greater value is placed on the park when it exists in a combination of oak conditions, rather than just burned or unburned oak (Table 3-4 - original). Markovian states where 2 units are in one condition of the oak-attracted state and 1 unit is in the other have the highest return (4) (which is higher than the maximum return in the single unit example (3)). Also, more value is placed on the park if there is 1 unit each of burned oak, unburned oak, and mixed (2.5), than if there are 2 units in one type of oak and 1 unit in mixed (2). It is assumed that the shady condition is highly undesirable, such that if any of the units are in the shady condition the park has 0 return.

Costs are assumed to be area-dependent. The per unit treatment cost in the multiple unit example is one-third the cost in the single unit example, for which the entire park was treated as a single unit (Table 3-2). For example, thinning cost in the single unit example was 3, so the per unit thinning cost is 1 for the multiple unit example. Per unit treatment costs were multiplied by the number of units receiving each treatment and then summed to determine the cost for each possible action combination (indexed by A^x) in the multiple unit example (Table 3-5). Rewards were calculated based on state returns and action costs for the 816 state/action combinations.

4.7 Multiple units: Results

The expected values (Table 3-6, original) differ from the single unit example (Table 3-3) for 3 of the 4 Markovian states that represent conditions found in the simpler model (3 burned oak, 3 unburned oak, 3 mixed, 3 shady), although the optimal decision (Table 3-7) is different for only 1 of the 4. When the park is all shady, the expected value is still 0 and the optimal decision is still do nothing throughout. When the park is all mixed, the expected value is lower than it was in the single unit example (16.33 compared to 25.96), but the optimal decision is the same – burn and thin. When the park is all burned or unburned oak, the expected value is higher than in the single unit example

(69.09 compared to 50.26 and 67.63 compared to 49.74, respectively). The all unburned oak state still has an optimal decision of burning everywhere, but the all burned oak state optimal decision is to burn one of the three units and do nothing on the other two.

States with two or more units in the shady condition have an expected value of 0, as does the state with two mixed and one shady. States with one unit in shady (other than 2 mixed, 1 shady), exhibit low, but non-zero, expected values. States with two mixed units and 1 oak (burned or unburned) unit, have moderate expected values that are approximately two-fifths of the highest expected value. States with two oak units (the same or different conditions) and one mixed unit have expected values approximately three-fifths the highest expected value. The highest expected values occur when all three units are in oak conditions.

The optimal decision for a majority of the states (13 out of 20) involves a combination of actions (Table 3-7). Thinning is never optimal. Forty percent (8 out of 20) of the states involve doing nothing on at least one unit. Units in the unburned oak condition are always burned, except for when two units are shady. Units in the burned oak condition are most frequently left alone, but 1 burned oak unit is burned in 2 out of the 10 states with at least 1 burned oak unit. Mixed units are almost always burned and thinned, with the exception of doing nothing when the park is all in the shady-attracted state (2 mixed, 1 shady or 1 mixed, 2 shady). Nothing is done to the shady units unless there are two units in an oak-attracted condition, in which case the shady unit is burned and thinned.

Examining the five simulations over 25 years (Figure 3-4), patterns include going to and staying in state 1 (all 3 shady), going to and staying in state 14 (1 burned oak, 1 unburned oak, 1 shady), and oscillating between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak). However, in some cases, the system is able to “escape” state 14 (1 burned oak, 1 unburned oak, 1 shady) and move to the oscillation.

4.8 Multiple unit: Interpretation

Differences in expected value and optimal decisions for the multiple unit example equivalents of the single unit example (i.e., all three units are in the same condition) reflect the differences in valuation (e.g., higher value for a combination of oak states than for either alone, any part of the park in the shady condition resulting in 0 return) and in cost (i.e., the ability to use a combination of approaches). This does not mean that either the single or multiple unit method is better than the other, but does indicate that how the decision problem is set up will influence the policy. From a decision making perspective, it is important to think about what type of model makes the most sense given the context. If management is being approached from a resilience thinking perspective, the nuance of allowing condition diversity within a time step probably justifies using the more complicated model.

Although the valuation scheme favors a combination of oak conditions over just one type, the expected value is approximately the same for a system starting with three units divided between the two oak conditions and a system starting with three units all burned or unburned oak (Table 3-6). Considering this result along with the patterns observed in the simulations (Figure 3-4), this suggests that the three units of all burned or unburned oak are expected to quickly transition into the oscillation between the two different possible combinations of oak (2 burned, 1 unburned and 1 burned, 2 unburned);

given the certainty the model places on the transition from burned to unburned oak under the do nothing action and the transition from unburned oak back to burned oak with burning, this pattern makes sense.

As in the single unit example, the oscillation causes burned areas to become unburned and unburned to be become burned, so no site is in the same oak condition for consecutive time steps. From a resilience thinking perspective, it is worth contemplating the impact this oscillation could have on diversity. I previously argued that species in the park have varying sensitivities to the impacts of fire on the landscape, such that a combination of burned and unburned condition may be preferable. However, I did not discuss how fire actually changes the landscape or the time scale at which those changes occur. Possible fire impacts include alterations in forest structure, soil moisture, and nutrient availability. If these changes do not occur at the same time scale as management, then the oscillation may not actually result in two distinct oak conditions and rather result in some in-between condition throughout the park that may actually support *less* biodiversity than a constantly burned or unburned oak condition. Another concern may be that some species and/or populations are unable to travel between sites during a time step (e.g., a perennial, specialist plant species). I discuss an alternative way to model the system later in the chapter.

Despite the low probability of transitioning out of the shady condition, there are Markovian states for which treating a shady condition is actually optimal, namely when two-thirds of the park is the oak-attracted state. From a resilience thinking perspective, the most interesting result may be that it is rational (based on expected values) to try to exit the shady condition, such that there is hope that the park may someday return to an all oak-attracted state; this is supported by the simulations that show some time paths moving from 1 burned oak, 1 unburned oak, 1 shady to the oscillation between oak conditions. However, the multiple unit example is not able to prevent scenarios in which the entire park exists in the shady condition.

5 UNCERTAINTY AND SENSTIVITY ANALYSIS

I initially assumed that the model components were known with certainty. However, one of the key points of resilience is that uncertainty is recognized as inevitable in a complex system. In order to demonstrate the potential impacts of uncertainty related to how the system was characterized, I conducted a partial sensitivity analysis. I use the term “sensitivity analysis” in the sense of Conroy and Peterson (2013, p. 203), defined as “systematic perturbation of model inputs or parameters to see the influence on decision making.” Sensitivity analysis is useful for identifying what aspects of the model most impact the expected value and selected decision alternative, as well as testing if the model is behaving as expected (Conroy and Peterson 2013).

5.1 Incorporating parameter uncertainty

5.1.1 Alternative transition matrices

In order to explore the influence of the transition matrices on the optimal result, I explore two sets of alternative transition matrices. The first set of alternative transition matrices (“oak resilient”) (Table 3-8) assumes that the unburned oak condition, and thereby the oak-attracted state, is more resilient; in the absence of burning, the unburned oak is condition is more likely to stay in the unburned oak condition (0.70 compared to

0.10 in the original), and therefore less likely to transition into the mixed condition (0.30 compared to 0.90 in the original). Both the original and the "oak resilient" quantifications of the state-and-transition model are driven by resilience thinking, but they represent different hypotheses and assumptions about the resilience of the system.

The second alternative ("mixed resistant[8]") (Table 3-9) assumes that the mixed condition is less likely to transition into the shady condition. This hypothesis implies there may be a longer time period in which the transition back across the threshold is reasonably likely, given sufficient management input. Under the do nothing and burn actions, the probability of transitioning from the mixed condition to the shady condition is 0.30 (compared to 0.80 in the original) and the probability of staying in the mixed condition is 0.70 (compared to 0.20 in the original). When thinning is applied, the probability of staying in the mixed condition is again 0.70, but there is only a 0.10 chance of transitioning to the shady condition (compared to 0.20 in the original). When burning and thinning is applied, the mixed condition is as likely to transition back to the burned oak condition as it was under the original matrices (0.40), but is more likely to stay in the mixed condition (0.50 compared to 0.40 in the original).

5.1.2 Sensitivity to transition probabilities: results and interpretation

When the alternative transition matrices are applied to the single unit example, the simulated time paths (Figure 3-3) reveal the same patterns as the original: oscillation between burned and unburned oak, constant shady condition, and mixed going to either

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[8] "Resistant" in place of resilience here because we are interested in the rate at which the mixed state moves into the strongly persistent shady state. This does not constitute crossing a threshold between stable states (oak-attracted and shady-attracted), as described by the resilience-based state-and-transition model.

the oscillation or shady condition over time. The optimal decisions are the same for all three transition matrices (Table 3-10). The expected values are nearly identical, other than the mixed condition having a higher expected value under the “mixed resistant” transition matrices (Table 3-10); this makes sense because of the decreased probability of transitioning into the value-less shady condition.

Differences in assumptions about the resilience of the oak-attracted state between the original and “oak resilient” did not result in different management actions. While this result is not unthinkable, other possible results would also have been believable. For example, it would be reasonable to hypothesize that the “oak resilient” matrix would result in an optimal policy of doing nothing in the unburned oak condition, and the “mixed resistant” matrices would result in an optimal policy of thinning in the mixed condition. The lack of difference in optimal policy suggests that the model is not sensitive to the particular transition probabilities that were manipulated, and resolving uncertainty about the strength of resilience for the oak-attracted state or the resistance of the mixed state is unnecessary from a decision making perspective.

When the alternative transition matrices are applied to the multiple unit example, under the original valuation scheme, the simulations (Figures 3-5 and 3-6) look very similar to the original (Figure 3-4) with no obvious pattern changes. The optimal decisions and expected values do not change with the “oak resilient” model (Tables 3-6 and 3-7). However, the optimal decision is different under the “mixed resistant” transition matrices for 3 of the 20 states (Table 3-11), and expected values are generally higher. When there are 2 mixed units and 1 shady unit (state 3), all units are burned and thinned rather than left alone. When there is 1 unburned oak, 1 mixed, 1 shady (state 6), the optimal decision is to burn the unburned oak and burn and thin both the mixed and shady, rather than doing nothing on the shady unit. When there is 1 burned oak, 1 mixed, 1 shady (state 12), the mixed and shady units are burned and thinned, rather than doing nothing on the shady unit.

The lack of difference for the “oak resilient” transition matrices further supports the conclusion that the decision is not sensitive to the resilience of the oak-attracted state. However, the set of “mixed resilient” matrices produces some interesting results from a resilience thinking perspective. The increased intensity of management for some of the Markovian states suggests that the threshold between the shady-attracted state and the oak-attracted is more reversible than it is under the original matrices. Based on this result, managers could find that further investigation of this uncertainty is warranted.

5.2 Different objectives and weightings

The optimal decision may be impacted by how values were assigned to the various conditions/states and across time. Given that different stakeholders would assign values differently depending on what was important to them (Westoby et al. 1989), the impact of varying valuation is worth investigation. To do so, I alter the returns for the multiple unit example to explore the impact of how the conditions/states are valued, and I manipulate the discount factor to change how strongly the future is devalued.

5.2.1 Alternative state returns

In the original valuation, shady forests were highly undesirable, such that if any unit was shady the whole park was assigned a zero return. High value was placed on oak forests (burned or unburned), with a preference for a diversity of oak types. If all units were in the mixed condition, the park received a low score, with scores increasing as the number of oak conditions increased. I consider two alternative valuation schemes (Table 3-4), and assume management cost is the same as before. The first alternative ("two-thirds not shady") is not as strongly opposed to part of the park being in the shady condition; the only time the park is assigned zero return is when more than one site is shady. Diversity is still valued, such that a combination of the two oak conditions is preferable to just one type of oak. The second alternative ("no shady") is only concerned with keeping the park out of the shady condition. All other condition categories are equally valued. This valuation may make sense for stakeholders who enjoys recreating throughout the park (e.g., hiking, horseback riding) and aesthetically appreciate a forest that is not densely shaded but are not concerned with the composition of the forest community. Therefore, they place 0 return on any part of the park being shady, but otherwise value the rest of the park the same.

5.2.2 Sensitivity to state returns: results and interpretation

The simulation patterns for the "two-thirds not shady" value scheme (Figure 3-7) are largely similar to the original model, except that there appears to be less chance of leaving the 1 burned oak, 1 unburned, and 1 shady state (14). There are changes to some of the optimal decisions (Table 3-12) and expected values (Table 3-13). The optimal decision with 2 mixed, 1 shady (state 3) changes to burning and thinning the mixed units rather doing nothing throughout the park. When there are 2 unburned oak, 1 shady (state 8) the optimal decision involves do nothing to the shady unit, rather than burning and thinning. The optimal decision for 1 burned oak, 1 unburned oak, 1 shady (state 14) and for 2 burned oak, 1 shady oak (state 17) changes management of the shady condition to doing nothing, rather than burning and thinning. The expected values increase for 60% of the states, and remain the same for the remaining states. These results make sense given that having one shady unit no longer eliminates all value for the park, so states with 1 shady unit have non-zero returns and costs are lower since there is less incentive to manage a singular shady unit.

The “two-thirds not shady” valuation scheme results in a smaller chance of the entire park returning to the oak-attracted state. From a resilience perspective, if the rest of the park is able to support sufficient biodiversity, this is unimportant. However, if more area in the oak-attracted state increases biodiversity, the park may be less resilient under the “two-thirds not shady” valuation.

The simulations for the “no shady” scheme are different than the original, and there are changes in the optimal decision (Table 3-14) and expected values (Table 4-13). There is no holding at 1 burned oak, 1 unburned oak, 1 shady (state 14), and there is a new oscillation between 3 unburned oak (state 10) and 3 burned oak (state 20). Perhaps counter-intuitively, the “no shady” valuation leads to more initial states ultimately transitioning permanently into 3 shady units (Figure 3-8). However, this may be reasonable given that once any unit is in the shady condition the entire park has zero return, and the maximum return is lower than in the original valuation (3 rather than 4).

The “no shady” scheme results may be unsatisfactory from a resilience thinking perspective because the system may end up resembling the single unit example (all burned to all unburned), which I argued may be less resilient, and the system frequently ends up permanently in the shady-attracted state. The results again support the previous conclusion that the optimization decision is sensitive to how valuations are determined.

5.2.3 Alternative discount factors

Selection of the discount factor is a value judgment in itself, expressing how much the near future is worth compared to the distant future (Constanza et al. 1989); future worth is closer to present worth as the discount factor approaches 1. Past natural resource management policies that resulted in reduced resilience are partly a consequence of heavily discounting the future (Johnson and Williams 2015). Choice of discount factor can affect the optimal decision (e.g., Constanza et al. 1989, Hauser and Possingham 2008). To explore this impact, a range of discount factors from 0.90 to 0.99, at increments of 0.01, were used for optimization of the single and multiple unit examples under the original transition probabilities and valuation scheme.

5.2.4 Sensitivity to discount factor: results and interpretation

For the single unit example, the optimal policies are identical over the range of discount factors tested, except for a discount factor of 0.99 (Figure 3-9), which results in a decision to burn and thin in the shady state (Table 3-15). When the future is strongly valued, as it is for a discount factor of 0.99, management intervention in the highly resistant, near trapping shady state is optimal. Placing more weight on future conditions would fit a resilience perspective, which is concerned about long-term sustainability of the desirable stable state (oak-attracted) and avoiding or transitioning out of the undesirable stable state (shade-attracted).

More decisions changes are evident for the multiple unit example than for the single unit example (Figure 3-10), demonstrating sensitivity to the selected discount factor. Compared to the original discount factor of 0.95, the optimal decision is different for at least one of the twenty states for every discount factor, with a maximum of seven changes. When the future is more strongly devalued (discount = 0.90), the optimal decision is different for states in which there is one shady unit and two oak units (burned or unburned) and for the state characterized by one unburned oak unit, one mixed unit, and one shady (Table 3-16); the policy involves doing nothing in each of those states, where previously some of units were burned or burned and thinned. Given zero present returns for states with any units in shady and lower value received from future improvements, this change in policy is unsurprising.

However, placing more emphasis on maintaining resilience over time would raise rather than lower the discount factor. At a discount factor of 0.99, which strongly values the future, burning and thinning is more often the optimal decision (Table 3-17). When the system is in a state with two or more shady units, these units are now burned and thinned rather than left alone. Similarly, when there are two mixed and one shady or one oak (burned or unburned oak), one mixed, and one shady, the decision is burn and thin the mixed and shady units rather than do nothing. By increasing the value of future rewards (compared to discount = 0.95), there is sufficient future expected value to justify management cost, even when the system is currently receiving zero return (in the presence of a shady unit). From a resilience perspective, this suggests that the long-term chance of transitioning back across the threshold from the shade-attracted stable state to the oak-attracted stable state justifies intensive management.

6. CONCLUSION

Resilience thinking informed the specification of this system model, particularly thinking about probabilities of transitioning to and from alternative stable states, the importance of disturbances, and the choice of an infinite time horizon. This is not to suggest that the methods are a novel way of conducting stochastic dynamic programming. Rather, the purpose of the chapter is to illustrate how resilience thinking could be used in framing the optimization problem. There are additional ways resilience thinking could influence the decision making process. In the following paragraphs I discuss how social resilience, value of variability, cross-scale linkages, uncertainty, and risk tolerance could impact management decisions for the oak forest. I also explore applicability to the principles of a resilient system proposed by Walker and Salt (2012) (Table 3-18).

One way in which the decision process model is currently lacking from a resilience perspective is in the incorporation of the social system (beyond a basic reward function and management intervention), although the loss of oak-dominance is directly related to prior human behavior in the form of fire exclusion. A more sophisticated social-ecological model could include dynamics in the social system and interactions between the ecological and social components (Cote and Nightingale 2012). For example, if certain stakeholders stopped visiting the park (e.g., those that are highly sensitive to the openness of the forest), this could change how many people visited the park, how the park was used, and/or what aspects of the park are valued. Dynamics could also exist in funding, such that management actions are only possible when grants are available.

In addition, resilience thinking involves valuing variability (Holling and Meffe 1996). Variability is partly accounted for by valuing a mix of oak conditions in the multiple unit example. Value is not placed on variability through time in the model, and the policy (optimal decision) is static. However, as the simulations demonstrate, a static policy is not the same thing as a static state. Depending on the model and starting state, the long term projections sometimes showed the system ending up in the same state time after time, and sometimes showed oscillations between states. It is also occasionally possible to “escape” a steady state and move into a different pattern. The simulation can help decision makers decide if there is sufficient variability over time, and if not consider how variability might be introduced or valued in the model.

Cross-scale linkages are not addressed by the current model. Decision makers should be aware of how the park is nested within a larger system and the important scales within the park. These linkages could influence the success of management action, and management could be contributing to changes at other scales. For example, the larger system could be moving toward a landscape of shade-tolerant dominated forests, which serve as a continuous seed source for the less desirable tree species and eliminate the probability of acorns being naturally dispersed into the park. Or the effectiveness of the management action may be strongly impacted by microsite conditions, such as the availability of leaf litter for fuel or soil drainage.

The sensitivity analysis revealed that the optimal decision and expected values are, unsurprisingly, impacted by the transition matrices, state returns, and discount factor.

I explored uncertainty by specifying new models, but I did not attempt to combine the models for the example. I also did not explore how the lack of uncertainty for particular transitions (e.g., burning an unburned oak condition is guaranteed to lead to a transition back to the burned oak condition) might have played a role. Optimization procedures exist that consider different potential models and select an optimal decision based on the suite of models (Williams et al. 2002). Adaptive management, in which uncertainty is reduced through a structured decision making process involving model predictions, deliberate monitoring, and review of management consequences (Holling 1978, Walters 1986, Lyons et al. 2008, Williams et al. 2009), can reduce uncertainty and refine the system model (Briske et al. 2008, Rumpff et al. 2011).

An important uncertainty that was not evaluated is partial controllability. Partial controllability refers to uncertainty related to the difference between the targeted action and what management action is actually implemented (Williams 2011). Typically partial controllability is a result of a regulation, such as allowable harvest, in which managers are only indirectly in control of the action. In the oak forest example, partial controllability is related to the ability to implement the optimal decision at a given time step because, in reality, burning requires specific climatic conditions in order to be a safe, effective management option. Estimates of how frequently burning would be feasible could be included in the model to incorporate the reality of partial controllability (Johnson et al. 2013).

By using the expected value to determine the optimal decision, which assumes risk neutrality (Gregory et al. 2012), I have not accounted for the risk tolerance of decision makers. With the potential of ending up in a highly undesirable and resilient alternative state, decision makers may not be risk tolerant and may be willing to accept a lower expected value (i.e., spend more money) to increase the chances of avoiding a bad outcome. Further investigation could describe the probability of ending up in an undesirable condition for a given policy. It may be necessary to add a constraint to the optimization problem that does not allow the system to end up in the shady condition.

Perhaps the biggest concern about the current characterization of the system is whether the assumptions about oak condition diversity are actually reasonable. I discussed in the multiple unit example interpretation that there may be concerns about the time-step to time-step oscillation between the two identified oak conditions. Biodiversity could be reduced if the rapid flip between conditions erodes differences between the conditions and/or eliminates slow dispersing species. Therefore, the oscillation could in fact be *negatively* impacting resilience of the oak-attracted state. An alternative model approach could include uniquely identifying units (rather than a category count model, which only considers the number of units in each condition) and placing higher value on a unit remaining in the same oak condition (burned or unburned) for multiple time steps. However, this method requires greater computational power and more complicated interpretation, potentially limiting the usefulness to managers in terms of understanding the consequences and tradeoffs involved in making the decision.

Although modeling and optimization can inform decision making, the decision is not automatically controlled by the output. Nevertheless, quantitative methods can be used as part of a well-structured decision process that clearly defines objectives, explores creative alternatives, and builds on a solid understanding of consequences (Gregory et al. 2012). Models representing the system are tools for exploring assumptions, consequences, and tradeoffs. Models can also be engaged to focus the decision on the key aspects of the problem and system. When used as part of an adaptive management framework, learning can improve model representation over time and surprises can be addressed as they arise. Optimizing state-and-transition models developed with a resilience perspective, as in the oak forest example, can help managers conceptualize and make tough decisions in complex systems.

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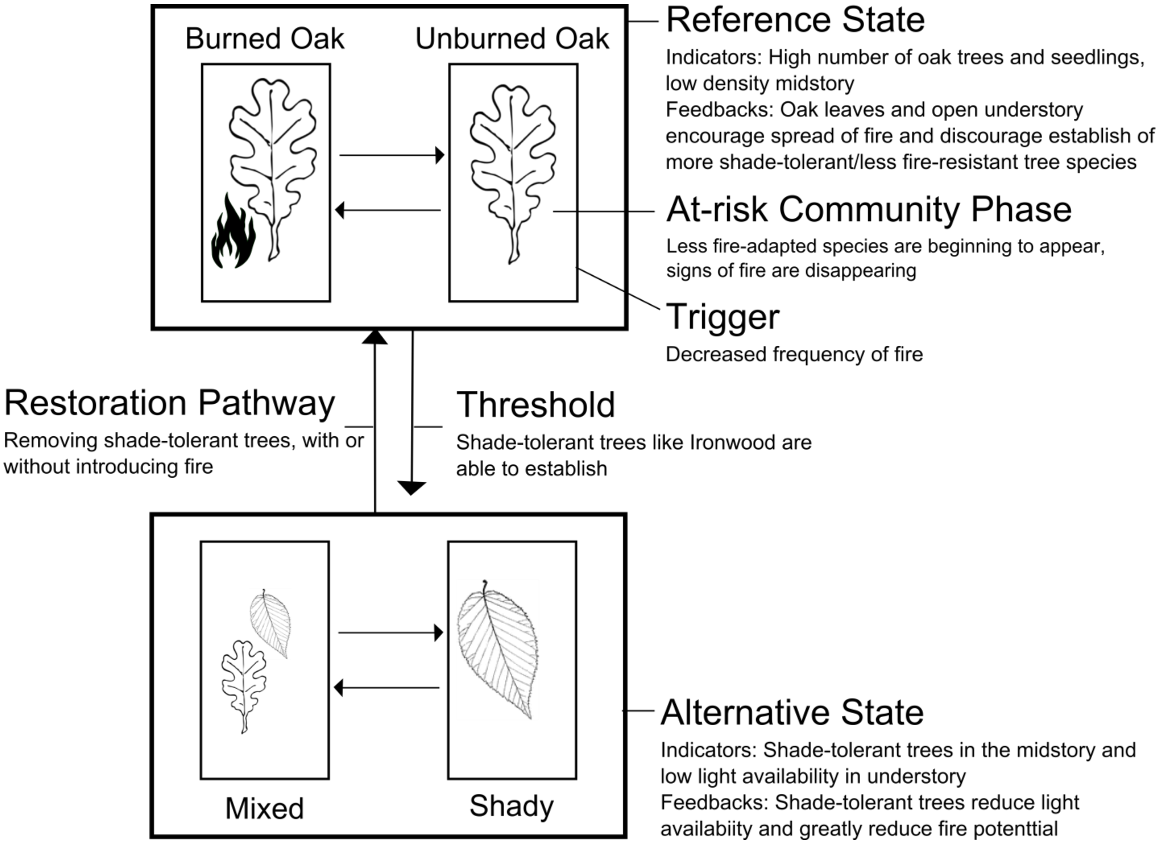


Figure 3-1. Resilience-based state-and-transition model developed following the recommendations of Briske et al. (2008). The reference state (oak-attracted) is characterized by numerous oaks and a relatively open midstory, is maintained by feedback between fire and oaks, and can exist in a burned oak or unburned oak phase. The unburned oak phase is at risk of transitioning into the alternative state (shady-attracted), when decreased frequency of fire enables establishment of shade-tolerant trees. The alternative state is maintained by feedbacks between low light availability and shade-tolerant trees. The state can be in a mixed phase, with a dense midstory and some oaks, or a shady phase, with a dense midstory and few or no oaks. Returning to the oak-attracted state is only possible along the restoration pathway, which requires management input.

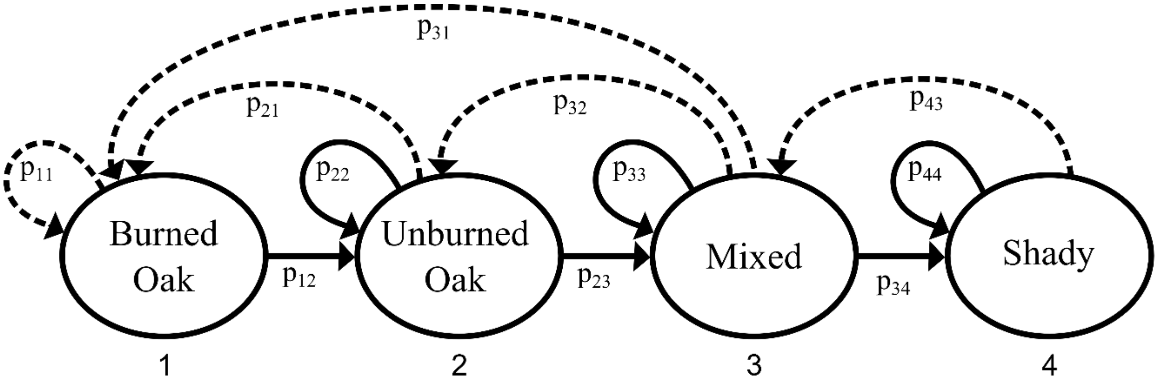


Figure 3-2. Markovian decision process for the oak forest conservation example. A given area of the park (the entire park or an individual unit, for the single and multiple unit models, respectively) can be classified as being in a burned oak, unburned oak, mixed, or shady condition. Arrows represent potential transitions for a single time step ($p_{ij}(a) > 0$ for at least one action), with dotted arrows signifying transitions that are only possible through management intervention (i.e., action other than "do nothing").

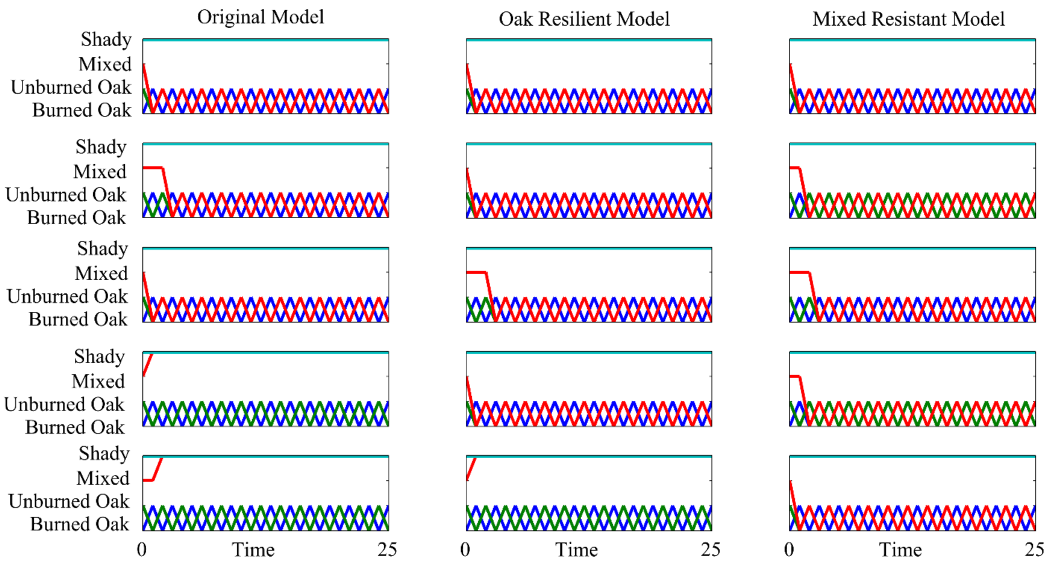


Figure 3-3. For the single unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under three different sets of transition matrices and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. The “oak resilient” model assumes that the unburned oak condition, and thereby the oak-attracted state, is more resilient (i.e., less likely to transition into the shady-attracted state). The “mixed resistant” model assumes that the mixed condition is less likely to transition into the shady condition. Patterns are similar across the original, “oak resilient,” and “mixed resistant” models, and include oscillation between burned and unburned oak and entering the shady state permanently. Different colors represent different starting conditions.

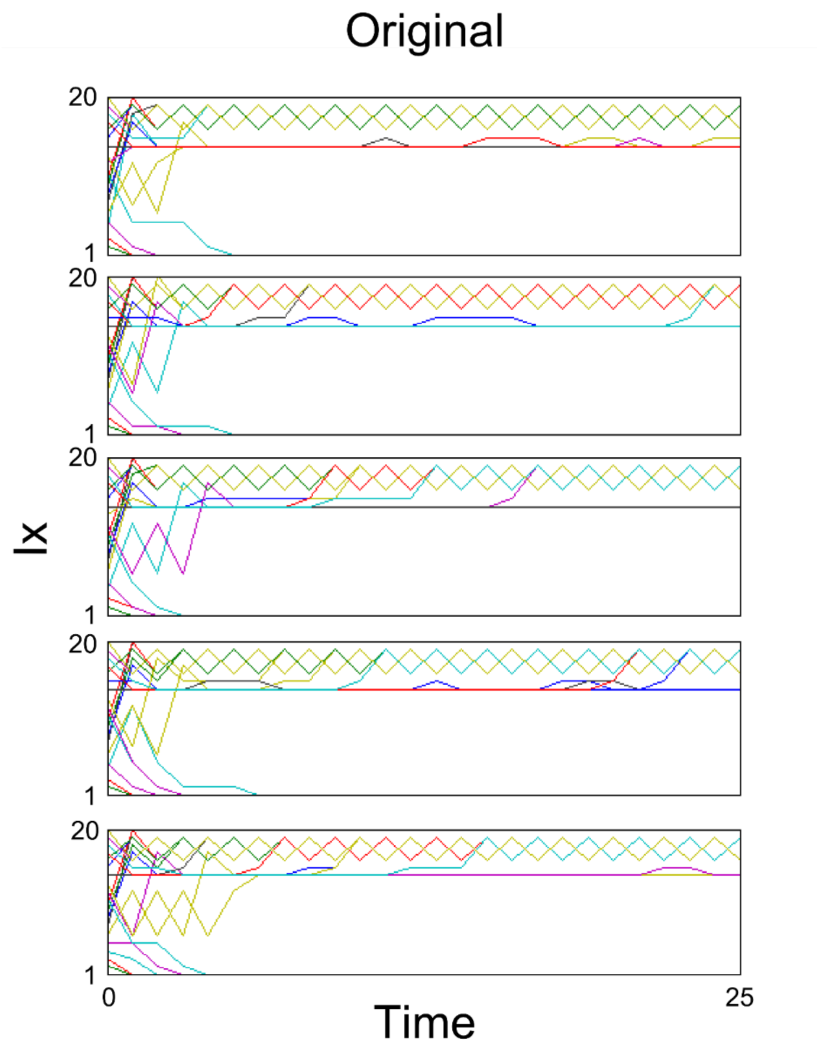


Figure 3-4. For the multiple unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under the original set of transition matrices and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. Patterns include oscillation between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak), permanently entering state 1 (all 3 shady), and permanently entering state 14 (1 burned oak, 1 unburned oak, 1 shady). However, in some cases, the system is able to “escape” state 14 (1 burned oak, 1 unburned oak, 1 shady) and move to the oscillation. Different colors represent different starting conditions.

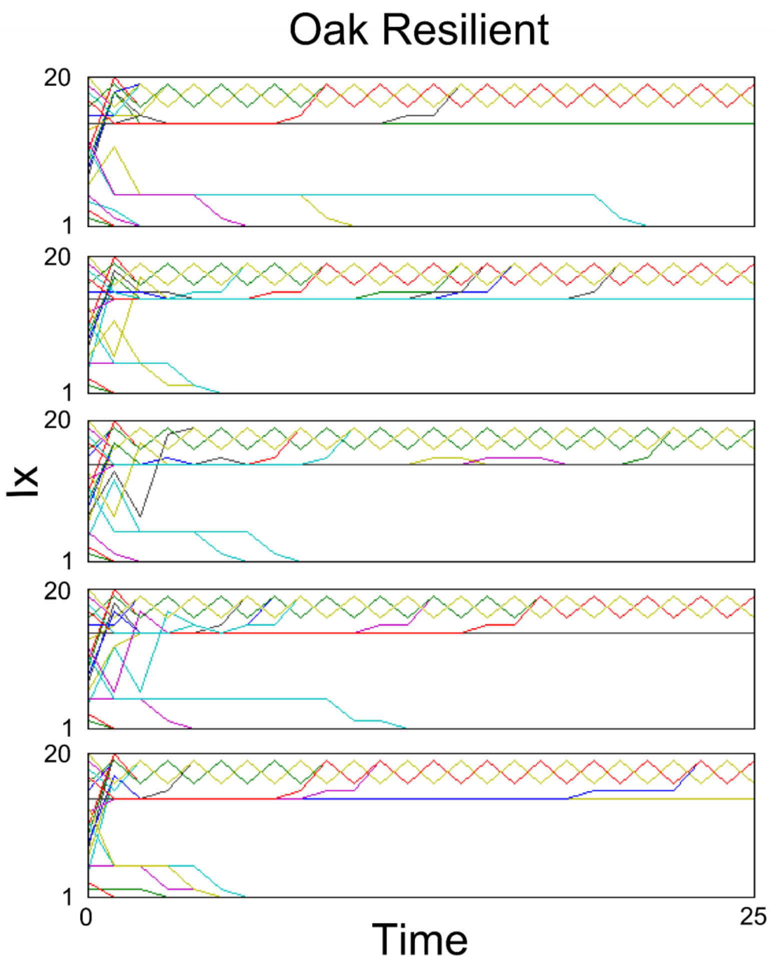


Figure 3-5. For the multiple unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under the “oak resilient” set of transition matrices (for which the unburned oak condition is less likely to transition to the mixed condition) and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. Patterns include oscillation between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak), permanently entering state 1 (all 3 shady), and permanently entering state 14 (1 burned oak, 1 unburned oak, 1 shady). However, in some cases, the system is able to “escape” state 14 (1 burned oak, 1 unburned oak, 1 shady) and move to the oscillation. Different colors represent different starting conditions.

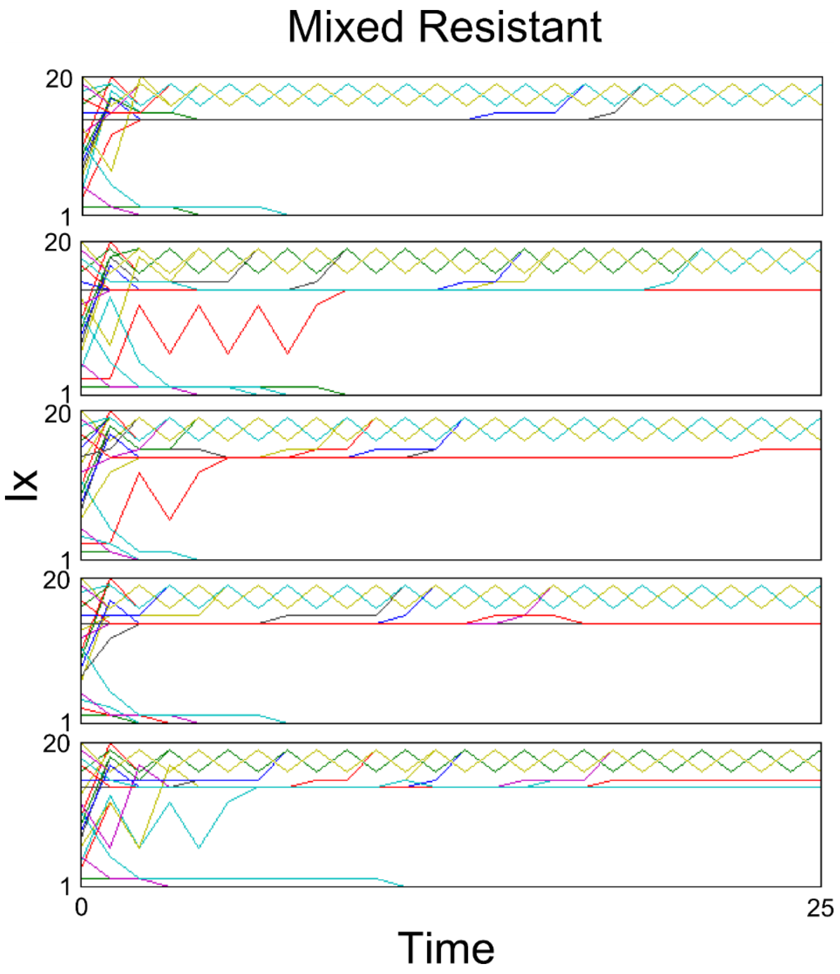


Figure 3-6. For the multiple unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under the “mixed resistant” set of transition matrices (for which the mixed condition is less likely to transition to the shady condition) and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. Patterns include oscillation between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak), permanently entering state 1 (all 3 shady), and permanently entering state 14 (1 burned oak, 1 unburned oak, 1 shady). However, in some cases, the system is able to “escape” state 14 (1 burned oak, 1 unburned oak, 1 shady) and move to the oscillation. Different colors represent different starting conditions.

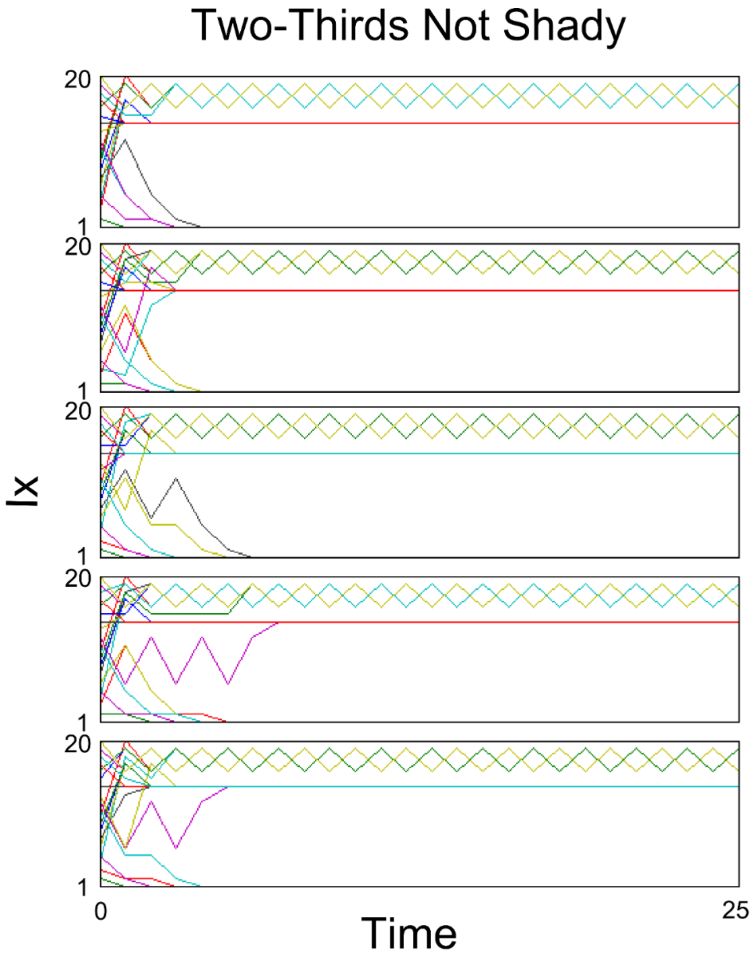


Figure 3-7. For the multiple unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under the “two-third not shady” valuation (for which state returns exist as long at least two units are not in the shady condition) and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. Patterns include oscillation between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak), permanently entering state 1 (all 3 shady), and permanently entering state 14 (1 burned oak, 1 unburned oak, 1 shady). However, in some cases, the system is able to “escape” state 14 (1 burned oak, 1 unburned oak, 1 shady) and move to the oscillation. Different colors represent different starting conditions.

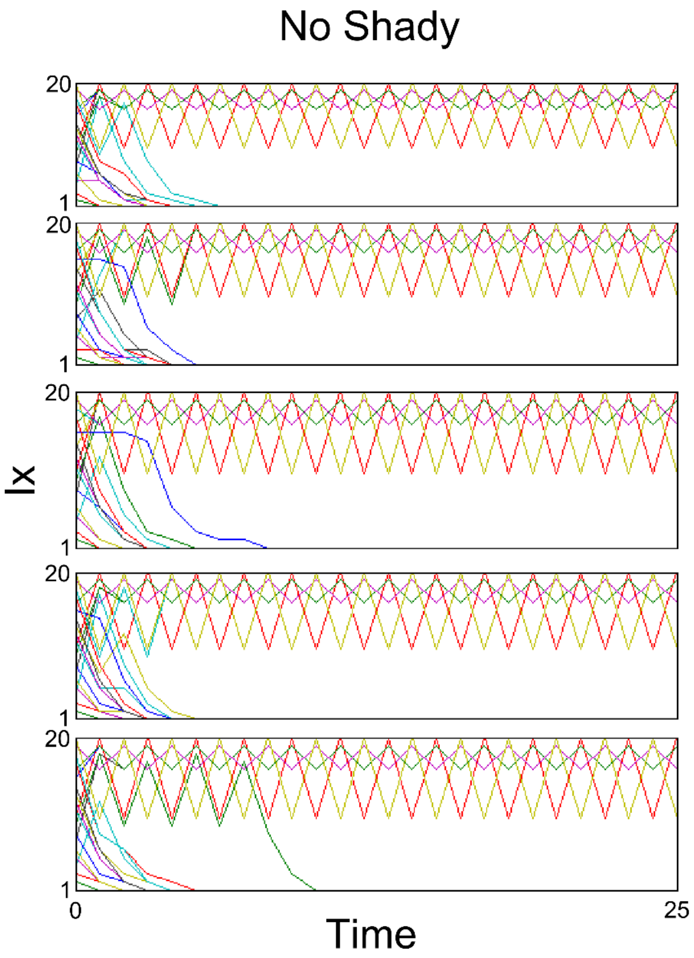
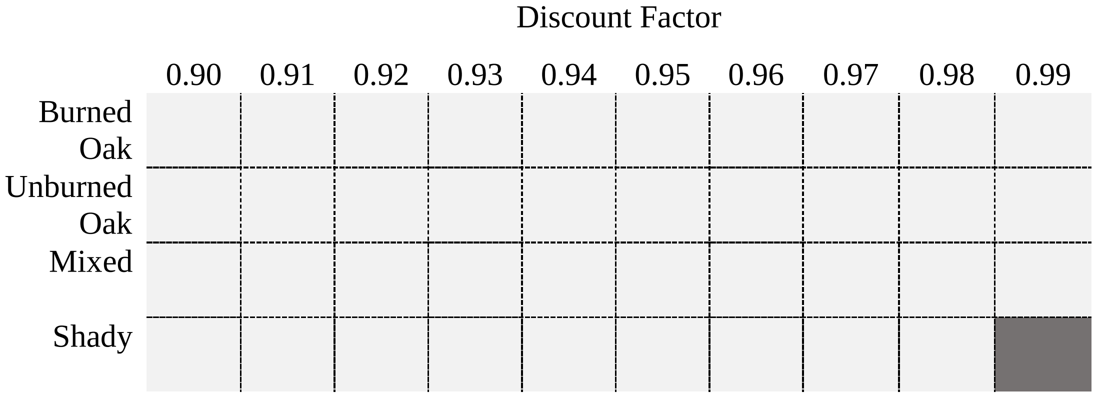


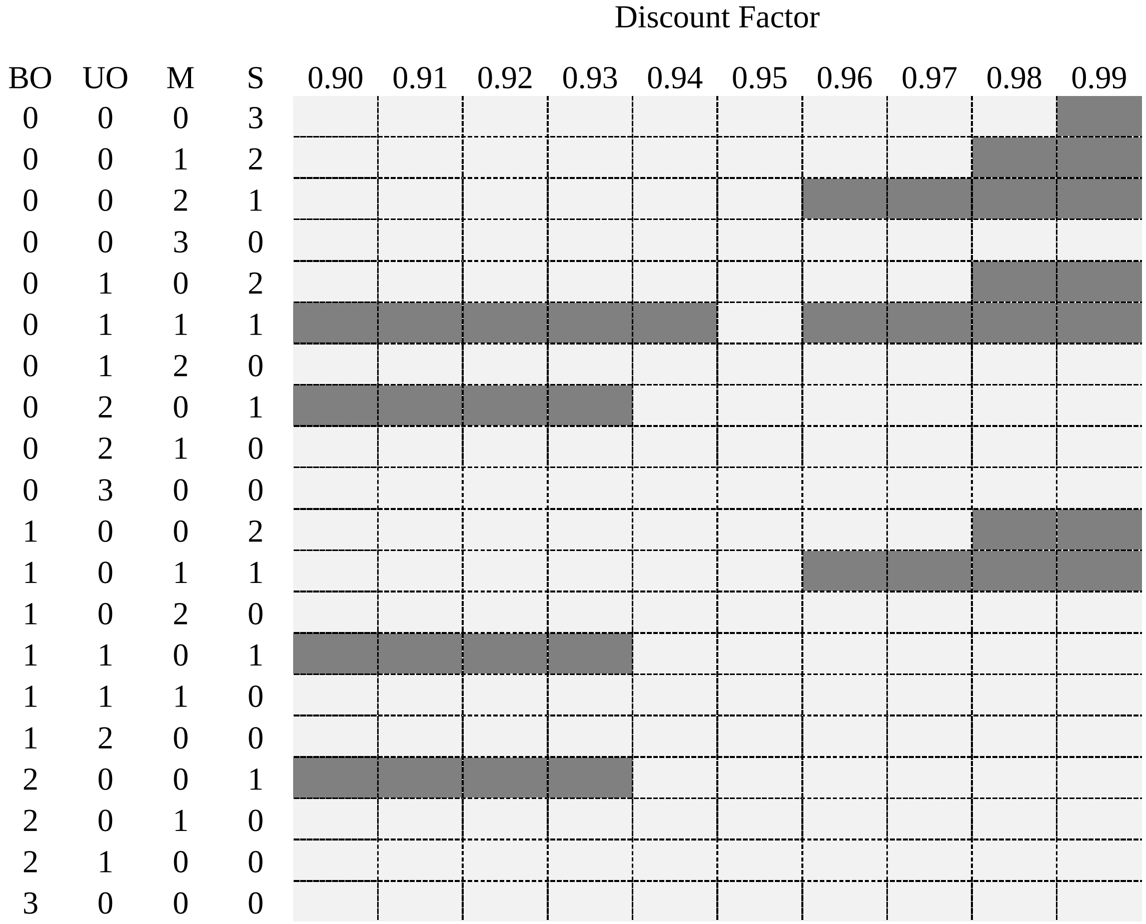
Figure 3-8. For the multiple unit model of the oak forest conservation example, five simulated time path trajectories for a time horizon of 25 years under the “no shady” valuation (for which state returns are equivalent and non-zero when no unit is shady, and zero otherwise) and assuming implementation of the optimal decision (based on an infinite time horizon, discount factor = 0.95) at each time step. Similar to the original valuation results, patterns include an oscillation between states 16 (1 burned oak, 2 unburned oak) and 19 (2 burned oak, 1 unburned oak) and permanently entering state 1 (all 3 shady).Unlike the original valuation, there is no holding at state 14 (1 burned oak, 1 unburned oak, 1 shady), and there is a new oscillation between state 10 (3 unburned oak) and state 20 (3 burned oak). Different colors represent different starting conditions.



Discount Factor

	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99
Burned Oak	░	░	░	░	░	░	░	░	░	░
Unburned Oak	░	░	░	░	░	░	░	░	░	░
Mixed	░	░	░	░	░	░	░	░	░	░
Shady	░	░	░	░	░	░	░	░	░	▓

Figure 3-9. Comparison of optimal policies across discount factors ranging from 0.90 to 0.99 at increments of 0.01 for the single unit model of the oak forest conservation example, using the original transition probabilities and original valuation scheme. Light gray boxes represent decisions that are identical to the results for a 0.95 discount factor. Dark gray boxes indicate that the optimal decision is different for the particular state when a given discount factor is used. In the single unit example, the optimal policy is the same when the discount factor is between 0.90 and 0.98. When the discount factor is equal to 0.99, the optimal decision for the shady state is different than the original result.



				Discount Factor									
BO	UO	M	S	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99
0	0	0	3	□	□	□	□	□	□	□	□	□	■
0	0	1	2	□	□	□	□	□	□	□	□	■	■
0	0	2	1	□	□	□	□	□	□	■	■	■	■
0	0	3	0	□	□	□	□	□	□	□	□	□	□
0	1	0	2	□	□	□	□	□	□	□	□	■	■
0	1	1	1	■	■	■	■	■	□	■	■	■	■
0	1	2	0	□	□	□	□	□	□	□	□	□	□
0	2	0	1	■	■	■	■	□	□	□	□	□	□
0	2	1	0	□	□	□	□	□	□	□	□	□	□
0	3	0	0	□	□	□	□	□	□	□	□	□	□
1	0	0	2	□	□	□	□	□	□	□	□	■	■
1	0	1	1	□	□	□	□	□	□	■	■	■	■
1	0	2	0	□	□	□	□	□	□	□	□	□	□
1	1	0	1	■	■	■	■	□	□	□	□	□	□
1	1	1	0	□	□	□	□	□	□	□	□	□	□
1	2	0	0	□	□	□	□	□	□	□	□	□	□
2	0	0	1	■	■	■	■	□	□	□	□	□	□
2	0	1	0	□	□	□	□	□	□	□	□	□	□
2	1	0	0	□	□	□	□	□	□	□	□	□	□
3	0	0	0	□	□	□	□	□	□	□	□	□	□

Figure 3-10. Comparison of optimal policies across discount factors ranging from 0.90 to 0.99 at increments of 0.01 for the multiple unit model of the oak forest conservation example, using the original transition probabilities and original valuation scheme. Light gray boxes represent decisions that are identical to the results for a 0.95 discount factor. Dark gray boxes indicate that the optimal decision is different for the particular state when a given discount factor is used. In the multiple unit example, the optimal decision is different for at least one of the states for every discount factor (other than 0.95, of course). There is a maximum of seven changes for a given discount factor, which occurs for a discount factor of 0.99.

Table 3-1. Original matrices of transition probabilities between conditions for a single time step under each management action ($p_{ij}(a)$) of the oak forest conservation example.

Management action: Do nothing (a_1)					
		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now (i)	Burned Oak	0	1	0	0
	Unburned Oak	0	0.10	0.90	0
	Mixed	0	0	0.20	0.80
	Shady	0	0	0	1
Management action: Burn (a_2)					
		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now (i)	Burned Oak	1	0	0	0
	Unburned Oak	1	0	0	0
	Mixed	0	0	0.20	0.80
	Shady	0	0	0	1
Management action: Thin (a_3)					
		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now (i)	Burned Oak	0	1	0	0
	Unburned Oak	0	0.10	0.90	0
	Mixed	0	0.20	0.60	0.20
	Shady	0	0	0	1
Management action: Burn and thin (a_4)					
		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now (i)	Burned Oak	1	0	0	0
	Unburned Oak	1	0	0	0
	Mixed	0.40	0	0.40	0.20
	Shady	0	0	0.05	0.95

Table 3-2. Rewards for a given time step, calculated as the return for the Markovian state minus the cost of the management action, under the single unit example. Returns are highest for the burned oak and unburned oak states and lowest for the shady state. Management is cheapest for the do nothing action and most expensive for burning and thinning.

State	Return	Management Action	Cost	Reward
Burned Oak	3	Do nothing	0	3
Burned Oak	3	Burn	1	2
Burned Oak	3	Thin	3	0
Burned Oak	3	Burn and thin	4	-1
Unburned Oak	3	Do nothing	0	3
Unburned Oak	3	Burn	1	2
Unburned Oak	3	Thin	3	0
Unburned Oak	3	Burn and thin	4	-1
Mixed	1	Do nothing	0	1
Mixed	1	Burn	1	0
Mixed	1	Thin	3	-2
Mixed	1	Burn and thin	4	-3
Shady	0	Do nothing	0	0
Shady	0	Burn	1	-1
Shady	0	Thin	3	-3
Shady	0	Burn and thin	4	-4

Table 3-3. For the single unit model of the oak forest conservation example, optimal decision and expected value (infinite time horizon, discount = 0.95) for each state when using the original set of transition probabilities matrices. The greatest expected value occurs when the park exists in the burned oak state, with similar expected values for the unburned oak state. Moderate expected values are anticipated when the park exists in the mixed state. No value is expected when the park exists in the shady state.

State	Optimal decision	Expected value
Burned Oak	Do nothing	50.26
Unburned Oak	Burn	49.74
Mixed	Burn and thin	25.96
Shady	Do nothing	0

Table 3-4. Returns for each of the states (uniquely identified by I^x) when the park is divided into three units (multiple unit example) under three different valuation schemes. The "original" valuation scheme is a modification of the returns for the single unit model, with greater value placed on a mix of oak states. The "two-thirds not shady" valuation scheme allows non-zero returns when only one unit is in the shady state. The "no shady" valuation scheme assigns equivalent and non-zero state returns when no unit is shady, and assigns a zero return otherwise. Values in bold differ from the original values. BO = burned oak, UO = unburned oak, M = mixed, S = shady

	Number of units in each category				Return for each state		
I^x	BO	UO	M	S	Original	Two-thirds not shady	No shady
1	0	0	0	3	0	0	0
2	0	0	1	2	0	0	0
3	0	0	2	1	0	**0.5**	0
4	0	0	3	0	1	1	**3**
5	0	1	0	2	0	0	0
6	0	1	1	1	0	**1**	0
7	0	1	2	0	1.5	1.5	**3**
8	0	2	0	1	0	**2**	0
9	0	2	1	0	2	**2.25**	**3**
10	0	3	0	0	3	3	3
11	1	0	0	2	0	0	0
12	1	0	1	1	0	**1**	0
13	1	0	2	0	1.5	1.5	**3**
14	1	1	0	1	0	**2.25**	0
15	1	1	1	0	2.5	2.5	**3**
16	1	2	0	0	4	4	**3**
17	2	0	0	1	0	**2**	0
18	2	0	1	0	2	**2.25**	**3**
19	2	1	0	0	4	4	**3**
20	3	0	0	0	3	3	3

Table 3-5. Cost of management actions (as combinations of actions from the single unit example, uniquely identified by A^x) based on the number of units treated for the multiple unit model of the oak forest conservation example. Costs are assumed to be area-dependent, such that the per unit cost is one-third the cost of the single unit model (per unit costs: DN = 0, B = 1/3, T = 1, BT = 4/3). For each action combination (A^x), per unit cost was multiple by the number of units applying the given action and then summed to determine the total cost for the management of all three units. DN = Do nothing, B = Burn, T = Thin, BT = Burn and thin

	Number of times action is applied				
A^x	DN	B	T	BT	Cost
1	0	0	0	3	4
2	0	0	1	2	3.66667
3	0	0	2	1	3.33333
4	0	0	3	0	3
5	0	1	0	2	3
6	0	1	1	1	2.66667
7	0	1	2	0	2.33333
8	0	2	0	1	2
9	0	2	1	0	1.66667
10	0	3	0	0	1
11	1	0	0	2	2.66667
12	1	0	1	1	2.33333
13	1	0	2	0	2
14	1	1	0	1	1.66667
15	1	1	1	0	1.33333
16	1	2	0	0	0.66667
17	2	0	0	1	1.33333
18	2	0	1	0	1
19	2	1	0	0	0.33333
20	3	0	0	0	0

Table 3-6. Expected values for optimal decision making for the multiple unit model of the oak forest conservation example given three different sets of transition matrices. The “oak resilient” set assumes that the unburned oak condition is less likely to transition to the mixed condition, and the “mix resistant” set assumes that the mixed condition is less likely to transition to the shady condition. Values in bold differ from the original. The “oak resilient” transition matrices has the same expected values as the original, but the “mixed resistant” matrices results in higher expected values in most cases.

					Expected Value		
I^x	BO	UO	M	S	Original	Oak Resilient	Mixed Resistant
1	0	0	0	3	0.00	0.00	0.00
2	0	0	1	2	0.00	0.00	0.00
3	0	0	2	1	0.00	0.00	**0.70**
4	0	0	3	0	16.33	16.33	**29.46**
5	0	1	0	2	0.00	0.00	0.00
6	0	1	1	1	0.66	0.66	**4.40**
7	0	1	2	0	28.08	28.08	**40.10**
8	0	2	0	1	4.88	4.88	**8.81**
9	0	2	1	0	44.50	44.50	**52.52**
10	0	3	0	0	67.63	67.63	67.63
11	1	0	0	2	0.00	0.00	0.00
12	1	0	1	1	0.91	0.91	**4.62**
13	1	0	2	0	28.60	28.60	**40.63**
14	1	1	0	1	5.23	5.23	**9.16**
15	1	1	1	0	45.90	45.90	**53.97**
16	1	2	0	0	69.91	69.91	69.91
17	2	0	0	1	5.23	5.23	**9.16**
18	2	0	1	0	45.40	45.40	**53.47**
19	2	1	0	0	70.09	70.09	70.09
20	3	0	0	0	69.09	69.09	69.09

Table 3-7. Optimal decisions for each state (I^x) of the multiple unit model (infinite time horizon, discount = 0.95) when using the original transition matrices and valuation scheme (same decisions for the “oak resilient” transition matrices). For a given state, the number of units in each condition is the column sum, and the number of times an action is applied is the row sum. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

I^x		BO	UO	M	S	I^x	BO	UO	M	S	I^x	BO	UO	M	S
1	DN	-	-	-	3	8	-	-	-	-	15	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	1		-	-	1	-
2	DN	-	-	1	2	9	-	-	-	-	16	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	2	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
3	DN	-	-	2	1	10	-	-	-	-	17	1	-	-	-
	B	-	-	-	-		-	3	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	-		-	-	-	1
4	DN	-	-	-	-	11	1	-	-	2	18	1	-	-	-
	B	-	-	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	3	-		-	-	-	-		-	-	1	-
5	DN	-	1	-	2	12	1	-	-	1	19	2	-	-	-
	B	-	-	-	-		-	-	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
6	DN	-	-	-	1	13	1	-	-	-	20	2	-	-	-
	B	-	1	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	1	-		-	-	2	-		-	-	-	-
7	DN	-	-	-	-	14	1	-	-	-					
	B	-	1	-	-		-	1	-	-					
	T	-	-	-	-		-	-	-	-					
	BT	-	-	2	-		-	-	-	1					

Table 3-8. “Oak resilient” transition matrices for the oak forest conservation example, where “*_*” indicates the value deviates from the original. Compared to the original, the probability of the unburned oak condition moving into the mixed state is lower, such that the “oak-attracted” state is more resilient.

Management action: Do nothing

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	0	1	0	0
(i)	Unburned Oak	0	*0.70*	*0.30*	0
	Mixed	0	0	0.20	0.80
	Shady	0	0	0	1

Management action: Burn

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	1	0	0	0
(i)	Unburned Oak	1	0	0	0
	Mixed	0	0	0.20	0.80
	Shady	0	0	0	1

Management action: Thin

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	0	1	0	0
(i)	Unburned Oak	0	*0.70*	*0.30*	0
	Mixed	0	0.20	0.60	0.20
	Shady	0	0	0	1

Management action: Burn and thin

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	1	0	0	0
(i)	Unburned Oak	1	0	0	0
	Mixed	0.40	0	0.40	0.20
	Shady	0	0	0.05	0.95

Table 3-9. “Mixed resistant” transition matrices for the oak forest conservation example, where “*_*” indicates the value deviates from the original. Compared to the original, the probability of the mixed condition transitioning into the shady state is lower.

Management action: Do nothing

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	0	1	0	0
(i)	Unburned Oak	0	0.10	0.90	0
	Mixed	0	0	*0.70*	*0.30*
	Shady	0	0	0	1

Management action: Burn

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	1	0	0	0
(i)	Unburned Oak	1	0	0	0
	Mixed	0	0	*0.70*	*0.30*
	Shady	0	0	0	1

Management action: Thin

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	0	1	0	0
(i)	Unburned Oak	0	0.10	0.90	0
	Mixed	0	0.20	*0.70*	*0.10*
	Shady	0	0	0	1

Management action: Burn and thin

		Next time (j)			
		Burned Oak	Unburned Oak	Mixed	Shady
Now	Burned Oak	1	0	0	0
(i)	Unburned Oak	1	0	0	0
	Mixed	0.40	0	*0.50*	*0.10*
	Shady	0	0	0.05	0.95

Table 3-10. Optimal decision and expected values for the single unit example of the oak forest conservation example under the different transition matrices (original || oak resilient || mixed resistant). The "oak resilient" set assumes that the unburned oak condition is less likely to transition to the mixed condition, and the "mix resistant" set assumes that the mixed condition is less likely to transition to the shady condition. All optimal decisions are the same, and the only expected value that is different is for the mixed condition under the mixed resistant matrices (in bold).

	Optimal Decision			
State	Original	Oak Resilient	Mixed Resistant	Expected value
Burned Oak	Do nothing	Do nothing	Do nothing	50.26 || 50.26 || 50.26
Unburned Oak	Burn	Burn	Burn	49.74 || 49.74 || 49.74
Mixed	Burn and thin	Burn and thin	Burn and thin	25.96 || 25.96 || **30.66**
Shady	Do nothing	Do nothing	Do nothing	0 || 0 || 0

Table 3-11. Optimal decisions for each state (I^x) (infinite time horizon, discount = 0.95) for the multiple unit model using the "mixed resistant" transition matrices and original valuation scheme. Underlined states indicate decisions different from the original. For a given state, the number of units in each condition is the column sum, and the number of times an action is applied is the row sum. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

I^x		BO	UO	M	S	I^x	BO	UO	M	S	I^x	BO	UO	M	S
1	DN	-	-	-	3	8	-	-	-	-	15	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	1		-	-	1	-
2	DN	-	-	1	2	9	-	-	-	-	16	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	2	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
3	DN	-	-	-	-	10	-	-	-	-	17	1	-	-	-
	B	-	-	-	-		-	3	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	2	1		-	-	-	-		-	-	-	1
4	DN	-	-	-	-	11	1	-	-	2	18	1	-	-	-
	B	-	-	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	3	-		-	-	-	-		-	-	1	-
5	DN	-	1	-	2	12	1	-	-	-	19	2	-	-	-
	B	-	-	-	-		-	-	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	1		-	-	-	-
6	DN	-	-	-	-	13	1	-	-	-	20	2	-	-	-
	B	-	1	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	1	1		-	-	2	-		-	-	-	-
7	DN	-	-	-	-	14	1	-	-	-					
	B	-	1	-	-		-	1	-	-					
	T	-	-	-	-		-	-	-	-					
	BT	-	-	2	-		-	-	-	1					

Table 3-12. Optimal decisions for each state (I^x) (infinite time horizon, discount = 0.95) for the multiple unit model using the original transition matrices and “two-thirds not shady” valuation scheme. Underlined states indicate decisions different from the original. For a given state, the number of units in each condition is the column sum, and the number of times an action is applied is the row sum. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

I^x		BO	UO	M	S	I^x	BO	UO	M	S	I^x	BO	UO	M	S
1	DN	-	-	-	3	8	-	-	-	1	15	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	-		-	-	1	-
2	DN	-	-	1	2	9	-	-	-	-	16	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	2	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
3	DN	-	-	-	1	10	-	-	-	-	17	1	-	-	1
	B	-	-	-	-		-	3	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	2	-		-	-	-	-		-	-	-	-
4	DN	-	-	-	-	11	1	-	-	2	18	1	-	-	-
	B	-	-	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	3	-		-	-	-	-		-	-	1	-
5	DN	-	1	-	2	12	1	-	-	1	19	2	-	-	-
	B	-	-	-	-		-	-	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
6	DN	-	-	-	1	13	1	-	-	-	20	2	-	-	-
	B	-	1	-	-		-	-	-	-		1	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	1	-		-	-	2	-		-	-	-	-
7	DN	-	-	-	-	14	1	-	-	1					
	B	-	1	-	-		-	1	-	-					
	T	-	-	-	-		-	-	-	-					
	BT	-	-	2	-		-	-	-	-					

Table 3-13. Expected values for the multiple unit model assuming implementation of the optimal decision (infinite time horizon, discount = 0.95) and using the original transition matrices and three different valuations schemes. The “two-thirds not shady” valuation scheme allows non-zero returns when only one unit is shady. The “no shady” valuation scheme assigns equivalent, non-zero state returns when no unit is shady, and assigns a zero return otherwise. Expected values are general higher than the original under the “two-thirds not shady” valuation scheme and lower for the “no shady” valuation scheme.

					Expected Value		
I^x	BO	UO	M	S	Original	Two-thirds not shady	No shady
1	0	0	0	3	0.00	0.00	0.00
2	0	0	1	2	0.00	0.00	0.00
3	0	0	2	1	0.00	**12.46**	0.00
4	0	0	3	0	16.33	**29.64**	**12.73**
5	0	1	0	2	0.00	0.00	0.00
6	0	1	1	1	0.66	**22.49**	**0.00**
7	0	1	2	0	28.08	**41.64**	**20.93**
8	0	2	0	1	4.88	**37.57**	**0.00**
9	0	2	1	0	44.50	**54.96**	**32.70**
10	0	3	0	0	67.63	67.63	**49.74**
11	1	0	0	2	0.00	0.00	0.00
12	1	0	1	1	0.91	**22.81**	**0.00**
13	1	0	2	0	28.60	**42.11**	**21.11**
14	1	1	0	1	5.23	**38.40**	0.00
15	1	1	1	0	45.90	**56.06**	**32.84**
16	1	2	0	0	69.91	69.91	**49.91**
17	2	0	0	1	5.23	**38.15**	**0.22**
18	2	0	1	0	45.40	**55.81**	**33.06**
19	2	1	0	0	70.09	70.09	**50.09**
20	3	0	0	0	69.09	69.09	**50.26**

Table 3-14. Optimal decisions for each state (I^x) (infinite time horizon, discount = 0.95) for the multiple unit model using the original transition matrices and “no shady” valuation scheme. Underlined states indicate decisions different from the original. For a given state, the number of units in each condition is the column sum, and the number of times an action is applied is the row sum. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

I^x		BO	UO	M	S	I^x	BO	UO	M	S	I^x	BO	UO	M	S
1	DN	-	-	-	3	8	-	2	-	1	15	1	-	-	-
	B	-	-	-	-		-	-	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	-		-	-	1	-
2	DN	-	-	1	2	9	-	-	-	-	16	1	-	-	-
	B	-	-	-	-		-	2	-	-		-	2	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	1	-		-	-	-	-
3	DN	-	-	2	1	10	-	-	-	-	17	2	-	-	-
	B	-	-	-	-		-	3	-	-		-	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	-		-	-	-	1
4	DN	-	-	-	-	11	1	-	-	2	18	2	-	-	-
	B	-	-	-	-		-	-	-	-		-	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	3	-		-	-	-	-		-	-	1	-
5	DN	-	1	-	2	12	1	-	1	1	19	2	-	-	-
	B	-	-	-	-		-	-	-	-		-	1	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	-	-		-	-	-	-
6	DN	-	1	1	1	13	1	-	-	-	20	3	-	-	-
	B	-	-	-	-		-	-	-	-		-	-	-	-
	T	-	-	-	-		-	-	-	-		-	-	-	-
	BT	-	-	-	-		-	-	2	-		-	-	-	-
7	DN	-	-	-	-	14	1	1	-	1					
	B	-	1	-	-		-	-	-	-					
	T	-	-	-	-		-	-	-	-					
	BT	-	-	2	-		-	-	-	-					

Table 3-15. For the single unit model of the oak forest conservation example, comparison of the optimal decision for a discount factor of 0.95 (original) and 0.99 (future reward closer to present reward), under the original transition probabilities and valuation scheme. The only difference in optimal decision occurs when in shady state, for which the decision changes from “do nothing” to “burn and thin.”

	Optimal Decision	
State	Discount = 0.95	Discount = 0.99
Burned Oak	Do nothing	Do nothing
Unburned Oak	Burn	Burn
Mixed	Burn and thin	Burn and thin
Shady	Do nothing	Burn and thin

Table 3-16. For the multiple unit model of the oak forest conservation example, comparison of the optimal decision for a discount factor of 0.95 (original) and 0.90 (future reward further discounted), under the original transition probabilities and valuation scheme. States (I^x) that are not listed have the same decision as the original multiple unit example. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

		Discount = 0.95				Discount = 0.90			
I^x		BO	UO	M	S	BO	UO	M	S
6	DN	-	-	-	1	-	1	1	1
	B	-	1	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	1	-	-	-	-	-
8	DN	-	-	-	-	-	2	-	1
	B	-	2	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	1	-	-	-	-
14	DN	1	-	-	-	1	1	-	1
	B	-	1	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	1	-	-	-	-
17	DN	1	-	-	-	2	-	-	1
	B	1	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	1	-	-	-	-

Table 3-17. For the multiple unit model of the oak forest conservation example, comparison of the optimal decision for a discount factor of 0.95 (original) and 0.99 (future reward closer to present reward), under the original transition probabilities and valuation scheme. States (I^x) that are not listed have the same decision as the original multiple unit example. BO = Burned Oak, UO = Unburned Oak, M = Mixed, S = Shady, DN = Do Nothing, B = Burn, T = Thin, BT= Burn and Thin

		Discount = 0.95				Discount = 0.99			
I^x		BO	UO	M	S	BO	UO	M	S
1	DN	-	-	-	3	-	-	-	-
	B	-	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	-	-	-	-	3
2	DN	-	-	1	2	-	-	-	-
	B	-	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	-	-	-	1	2
3	DN	-	-	2	1	-	-	-	-
	B	-	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	-	-	-	2	1
5	DN	-	1	-	2	-	-	-	-
	B	-	-	-	-	-	1	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	-	-	-	-	2
6	DN	-	-	-	1	-	-	-	-
	B	-	1	-	-	-	1	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	1	-	-	-	1	1
11	DN	1	-	-	2	1	-	-	-
	B	-	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	-	-	-	-	-	2
12	DN	1	-	-	1	1	-	-	-
	B	-	-	-	-	-	-	-	-
	T	-	-	-	-	-	-	-	-
	BT	-	-	1	-	-	-	1	1

Table 3-18. Principles for resilient systems from Walker and Salt (2012) as related to the hypothetical oak forest management example.

Property	Relevance to Example
Diversity (biological, landscape, social, and economic)	Biological diversity is assumed to be associated with landscape diversity, which is included in the multiple unit example. Social diversity is not directly included in the model but could play a role in the decision making process. Economic diversity is less relevant for the park system, since the park is supported by visitors and state government.
Ecological variability	The management actions of burning and thinning introduce disturbance, which encourages variability. Ecological variability is also assumed to be linked to landscape diversity. Simulations allow decision makers to explore whether there is variability over time.
Modularity	The category count model is not spatially explicit, so it cannot be used to evaluate how units are connected. This could be important given that most oak seedlings sprout near their parent tree, and it may be harder for a mixed or shady unit to transition back to an oak state if there is not a nearby source of acorns.
Acknowledging slow variables	The transition probabilities may appear constant in the short term but may be following a slow trend over time if changes in underlying ecological process could be occurring.
Tight feedbacks	Reintroducing fires encourages the oak-fire feedback, and thinning discourages the shade-tolerant-light limitation feedback.
Social capital	If stakeholders, with different values and mental models of the system, are included in the decision making process, social capital may be increased.
Innovation	Adaptive management can improve the system model. It may be possible to set aside portions of the park to set-up experiments and expedite the rate of learning.
Overlap in governance	Decision making in the park is nested within a larger state park agency. Private properties surround the park, such that the region includes a mix of public and private rights.
Ecosystem services	Ecosystem services were implicitly used to define the values associated with ecological states. The oak-attracted forest is assumed to provide greater ecosystem services than the alternative shade-attracted state.
Fairness/equity	Similar to social capital
Humility	Acknowledging uncertainty shows a sense of humility about managers abilities to control and predict the system.

CHAPTER 4: INCORPORATING ADAPTIVE MANAGEMENT INTO STATE WILDLIFE ACTION PLANS

1. INTRODUCTION

State Wildlife Action Plans present status assessments and conservation strategies for wildlife, including non-game species, and their habitats in an effort to avoid the listing of species under the Endangered Species Act (Department of Interior and Related Agencies Appropriations Act 2002, AFWA 2014); this is colloquially known as “keeping common species common.” Congress stipulated that State Wildlife Grant funding be contingent upon development of State Wildlife Action Plans (i.e., “comprehensive wildlife conservation plans”) that contain eight mandatory elements (Table 4-1) (Wildlife Conservation and Restoration and State Wildlife Programs 2001, Department of Interior and Related Agencies Appropriations Act 2002, AFWA 2014). While not explicitly requiring structured decision making or adaptive management, the eight State Wildlife Action Plan elements easily fit these approaches (Fontaine 2011).

Structured decision making is a process for making transparent, defensible decisions that define the particular problem and identify clear objectives, alternatives, consequences, and tradeoffs (Hammond et al. 1999, Gregory et al. 2012). Most management projects can benefit from the focus and organization structured decision making provides relative to ad hoc, technical solution-oriented decision making (Conroy and Peterson 2013). Adaptive management is a special form of structured decision making (e.g., Walters 1986, Lyons et al. 2008, Martin et al. 2009, Williams et al. 2009, Conroy and Peterson 2013) in which uncertainty about management effects is deliberately reduced through monitoring and analysis to improve effectiveness of future efforts (Holling 1978, Walters 1986, Lyons et al. 2008, Williams et al. 2009). The required State Wildlife Action Plan elements of identifying problems and actions and planning monitoring/adjustment match the components of structured decision making and adaptive management, yet no State Wildlife Action Plan currently includes an explicit structured decision making or adaptive management framework for immediate project design and implementation for specific taxa, habitats, or threats (Fontaine 2011). There are many possible reasons explicit frameworks may be missing. For example, managers may believe they are already doing adaptive management, there may be an underlying assumption that adaptive management is impractical, or there may be limited experience in planning and implementing structured decision making and adaptive management.

Adaptive management may be critical for conserving wildlife and their habitats, as managers increasingly recognize the prevalence of uncertainty and the potential for unforeseen consequences (e.g., Murphy and Noon 1991, Williams 2001, Regan et al. 2005, Runge et al. 2011). Although learning while managing seems like common sense (Holling 1978), adaptive management is not appropriate or possible in all situations, and there is a rich literature on barriers to successful adaptive management (e.g., Gunderson et al. 1995, Walters 1997, Gregory et al. 2006, Allen and Gunderson 2011). Misapplication of adaptive management can jeopardize natural resources (Doremus 2001), and if failure is falsely attributed to the adaptive management process itself, this may dissuade future uses of adaptive management (Loftin 2014), even in suitable circumstances.

In order to successfully use adaptive management to achieve State Wildlife Action Plan conservation goals, planners must be able to apply structured decision making, identify appropriate situations for adaptive management, and design specific projects that facilitate learning and adjusting. This chapter presents: (a) a brief overview of structured decision making, including adaptive management, (b) a dichotomous key for efficient, critical thinking about when adaptive management may be appropriate, and (c) a preliminary guide for designing an adaptive management project. I then use Nebraska's State Wildlife Action Plan, also known as the Nebraska Natural Legacy Project (Schneider et al. 2011), as a case study to illustrate how current planning strategies can be adapted to structured decision making and to discuss the potential for adaptive management projects based on recent planning efforts. Although other guides exist for structured decision making (e.g., Gregory et al. 2012, Conroy and Peterson 2013) and adaptive management (e.g., Gregory et al. 2006, Williams et al. 2009), my approach is specifically tailored to providing guidance for developing adaptive management projects in the context of State Wildlife Action Plans and includes relevant examples.

2. BRIEF OVERVIEW OF STRUCTURED DECISION MAKING AND ADAPTIVE MANAGEMENT

Structured decision making is a process for making transparent, defensible decisions (Hammond et al. 1999, Gregory and Keeney 2002, Gregory et al. 2012), which differs from ad hoc, technical solution-oriented decision making that often guides natural resource management (Conroy and Peterson 2013). The steps involve: 1) defining the problem, 2) determining objectives, 3) outlining alternatives, 4) considering the consequences, and 5) understanding the tradeoffs (Figure 4-1). The problem definition clarifies the decision context and lays out the scope of the project. Objectives express the components of success and the desired direction of change (Gregory et al. 2012). Objectives can be divided into fundamental and means objectives, where fundamental objectives are what is truly valued and means objectives are important only insofar as they help achieve fundamental objectives (Conroy and Peterson 2013). Alternatives are the management options under consideration. Consequences describe how an alternative is predicted to contribute to the objectives (Gregory et al. 2012). Unless one alternative achieves every objective better than the other alternatives, tradeoffs will have to be made (Gregory et al. 2012). Under some descriptions of structured decision making, the consequences step is part of a "develop models" step, with tradeoffs treated by assigning weights to objectives (e.g., Williams et al. 2009, Conroy and Peterson 2013). Modeling is a key tool of structured decision making, where models are loosely defined by Conroy and Peterson (2013) as "any conceptualization of the relationship between decisions, outcomes, and other factors."

Adaptive management can be viewed as a special form of structured decision making in which iterative decisions are made based on knowledge gained from results of previous decisions. The process builds on the original five steps by: 6) monitoring outcomes, 7) analyzing the data, and 8) adjusting management based on learning (Lyons et al. 2008, Williams et al. 2009, Allen et al. 2011). Adaptive management allows management to proceed despite uncertain consequences and treats management as a continual learning process (Walters 1986). The most basic requirements of adaptive management are a) deliberate learning through management, and b) changing management to reflect what is learned (Walters and Holling 1990, Williams and Brown 2012). Learning, in this case, means the reduction of uncertainty. Although many types of uncertainties exist, adaptive management is concerned with uncertainties related to how systems or species respond to management and the particular mechanisms driving observed responses (Williams et al. 2009).

3. WHEN TO USE ADAPTIVE MANAGEMENT FOR A STATE WILDLIFE ACTION PLAN

Adaptive management is not always possible or appropriate. There are many barriers to successful adaptive management (Gunderson et al. 1995, Walters 1997, Gregory et al. 2006, Williams et al. 2009, Allen and Gunderson 2011), among them irresolvable conflict, uncontrollability, and inability to sufficiently monitor (Williams et al. 2009). Given the plethora of wildlife management uncertainties and limitations of adaptive management, wildlife managers designing State Wildlife Action Plan projects may benefit from a quick way to determine when adaptive management should be considered. I developed a brief dichotomous key as an organized, question-based approach to narrowing down a generated list of uncertainties to those best suited for adaptive management projects within a State Wildlife Action Plan (Figure 4-2).

The key’s questions are grouped into three categories based on whether they address: 1) the appropriateness of an uncertainty for adaptive management, 2) the ability to change, or 3) the ability to learn. These questions are similar to the key issues described by Williams and Brown (2012, p. v): “whether there is substantial uncertainty about the impacts on management, whether it is realistic to expect we can reduce uncertainty, and whether reducing uncertainty can actually improve management." To use the dichotomous key, uncertainties must first be known. Based on experience with the Nebraska Natural Legacy Project, one way to uncover uncertainties is to observe wildlife planning meetings and note questions that emerge, areas of disagreement, and times when people seem uncomfortable with a choice or statement. Uncertainties can also be directly solicited by asking people what will happen if certain management actions are taken and then looking for differences in the answers. It may be useful to frame the uncertainties as questions. These questions can then be run through the key, given the management context, to identify adaptive management project possibilities.

It is also useful to think about when and why adaptive management *should not* be considered, i.e., when an answer in the key is "no." Identifying the limiting factors may illustrate how the management context could be altered to allow for adaptive management or can provide justification for not using adaptive management. In some cases the question cannot be resolved by adaptive management, such as value-based, irreducible, or irrelevant uncertainties. Value-based uncertainties must be resolved prior to management so that clear, agreed-upon objectives can be established[9]. Irreducible uncertainties relate to the limited precision with which the future can be forecasted and are an inevitable consequence of complex systems. Uncertainties unassociated with management impacts or associated with impacts beyond the scope of the identified objectives are irrelevant to decision making. In other cases, the management context precludes adaptive management. If the decision will not be repeated (non-iterative), then

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[9] However, an exception to this rule may be made if there are links between stakeholders' objectives and their beliefs about process structure (Williams 2012). If this is the case, Williams (2012) offers a method for incorporating objective uncertainty into an adaptive management framework, such that the results of monitoring can be used to reduce uncertainty about both objectives and models of system dynamics.

adaptive management is impossible. A lack of alternatives, flexibility, or resources can prevent adaptive management. Table 4-2 describes State Wildlife Action Plan-relevant examples of adaptive management-inappropriate conditions. Even when adaptive management is not possible, basic structured decision making can still be used to help avoid the pitfalls of ad hoc management, such as not addressing the real problem or fundamental objectives, by facilitating organized, transparent decisions (Conroy and Peterson 2013).

4. HOW TO DRAFT ADAPTIVE MANAGEMENT PROJECTS FOR A STATE WILDLIFE ACTION PLAN

Once adaptive management is deemed suitable for consideration (i.e., answered “yes” to all the questions in the dichotomous key), the next step is determining how to achieve adaptive management. The following sections provide descriptions of some of the basic elements of a well-designed adaptive management project[10], and State Wildlife Action Plan-relevant examples illustrate each point (Table 4-3).

4.1 Involve the right people

Getting the “people part” right can be as, if not more, important than the research component. It is important that management acknowledges multiple objectives and that there be stakeholder support for adaptive management (Gregory et al. 2006). The collaborative adaptive management literature supplies a wealth of recommendations for conflict management and emphasizes having clear, agreed-upon decision making

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[10] For further refinement of adaptive management projects, we refer readers to highly detailed sources for practitioners, such as the DOI Applications Guide (Williams and Brown 2012).

processes and objectives (e.g., Johnson 1999, Susskind et al. 2012, Pratt Miles 2013). Science will only influence the decision if it addresses questions people actually care about and it is conducted and communicated in an understandable way. As suggested in the “when” section, value-based uncertainties are not resolved by “learning-by-doing.” Adaptive management cannot proceed until value-based uncertainties are resolved, which requires involving the right people and may necessitate a trained facilitator.

4.2 Prioritize uncertainties

There are likely to be multiple opportunities for reducing uncertainty through adaptive management, even after the key in Figure 4-2 has been used to narrow down the possibilities. With limited resources for learning, it may be necessary to prioritize uncertainties based on the risks of being wrong and the cost and benefits of learning. If the consequences of operating under false assumptions are extreme, the uncertainty should be a high priority. If the improvements to management outcomes are limited, the resource demands of adaptive management may not justify reducing the uncertainty. Quantitative decision analysis tools, such as sensitivity analysis and value of information techniques (Williams et al. 2002, Runge et al. 2011, Lahoz-Monfort et al. 2014, Williams and Johnson 2015a, Williams and Johnson 2015b), can help by highlighting which model components and processes most strongly drive the management outcome and by evaluating tradeoffs between costs of reducing uncertainty and the benefits of improved understanding. There must be a mechanism for documenting and communicating these costs and benefits to stakeholders (Gregory et al. 2006).

4.3 Choose how to learn

Adaptive management can be “active” or “passive.” The active adaptive management approach makes learning an objective and involves implementing multiple alternatives as a designed experiment (Williams et al. 2009, Allen and Gunderson 2011). As such, active adaptive management requires sufficient sample sizes and control of variability (Lee 1993). Passive adaptive management involves implementing the management alternative predicted, based on the top model or model averaging, to best achieve the conservation objective(s). Results are compared to model predictions, making learning a byproduct of management (Williams 2011). Greig et al. (2013) note that a combination of approaches is likely necessary.

Both active and passive adaptive management methods have pros and cons. Experimentation can speed the rate of learning by directly comparing different management strategies. However, experimentation implies that some treatment areas will be subjected to less effective management. In addition, properly designing, implementing, and analyzing an active adaptive management project can be challenging and labor/resource intensive. Learning will be fastest if extremes are tested, but there may be high risk of irreparably damaging the natural resource of interest. Gregory et al. (2006, p. 33) ask “Is the project timeline to obtain verified results compatible with management decision-making requirements?,” and “Does the proposed adaptive management design involve any trade-offs that might be considered taboo by some stakeholders?”.

4.4 Represent hypotheses with models

Uncertainty can be represented by multiple hypotheses about how the system works, how an action will achieve the objectives, or the response of a species or other system attribute. These hypotheses can be translated into predictive models (Conroy and Peterson 2013). Models allow for transparent communication about how different people perceive the world and can be used to clarify thinking (Gregory et al. 2012, Walker and Salt 2012, Conroy and Peterson 2013). Models do not always need to be highly quantitative or complex to be useful, and in fact models are often created that might not be recognized as models, such as simple flow diagrams.

Uncertainty is reduced based on how well predictions match the results observed by monitoring (Williams et al. 2009, Conroy and Peterson 2013), which then alters the support for competing models. This can be done formally using Bayesian updating techniques (Williams 2001, McCarthy and Possingham 2007), or through other methods.

4.5 Discuss and set standards for convincing evidence

Decision makers need to decide the level of statistical and/or biological significance required to justify altering management practices. Predetermined triggers can indicate when monitoring results will lead to management changes. Use of triggers may increase the enforceability of adaptive management plans (Nie and Schultz 2012). An example trigger point might be a specified percentage decline for a desirable species in a given time period such that if the trigger is exceeded with a specified level of certainty mitigation actions would be implemented. Nie and Schultz (2012) note that choosing the trigger point and necessary level of statistical certainty is a political choice in itself, with implications for who carries the burden of proof.

Once again, value of information analysis can help by assessing the amount of information that would have to be collected to improve decision making (Williams et al. 2002, Lahoz-Monfort et al. 2014, Williams and Johnson 2015a, Williams and Johnson 2015b). Gregory et al. (2006, p. 33) ask “Will the information collected through adaptive management have sufficient predictive ability to make a difference to managers?” and “Have potential issues related to background trends and cumulative effects of management actions been addressed in the adaptive management design?”.

4.6 Make it happen

Ultimately, adaptive management requires implementation of the planned strategy. Avoiding continuous debate may be challenging in situations in which the status quo is highly desirable for some influential decision makers, or if the question being asked is overly complex. Adaptive management can be enabled by a strong leader who has an incentive to see the adaptive management cycle completed and has the support of all involved parties (Cave et al. 2013). In addition, time should be devoted to strategizing where resources can be found to support implementation, especially monitoring and analysis. Are there university faculty interested in the question, or citizens willing and capable of collecting data? Is it possible to spread the burden (and the benefits of learning) among managers dealing with similar issues across the state?

4.7 Keep it going

Learning can be slow and funding short-lived. In order to continue receiving funding and stakeholder support, it will likely be necessary to demonstrate the project is leading to better and less contentious management outcomes (if it is). It may be necessary to establish a future funding strategy upfront and to explicitly plan actions given alternative funding scenarios (Nie and Schultz 2012). It is also important to be upfront about when/if the learning will end (particularly for active adaptive management).

Data management and clear protocols will be needed to survive personnel turnover and other forms of institutional change. Mechanisms for on-going interactions between stakeholders and agency decision makers, such as field visits and meetings to discuss progress, can also help sustain the project through institutional change (Cave et al. 2013).

4.8 Decide when to assess and revise, or get out

Adaptive management learning can come in two or three loops, referred to as double loop learning (Figure 4-1) (Williams et al. 2009) and triple loop learning (King and Jiggins 2002, Keen and Mahanty 2006, Armitage et al. 2008) respectively. The first loop takes the information gained to change how management actions are implemented. The second loop goes back to the beginning steps of the decision process to accommodate changes to the management context. The third loop involves learning about the governance process by which the previous loops of learning occurred. Triple loop learning is not addressed here, as the governance system is assumed to be stable.

A protocol is needed for double loop learning, including procedures for how monitoring and evaluation will lead to revised recommendations for implementation and a mandatory reassessment of the project (e.g., after three years, planning meetings will reconvene). Note that Congress explicitly requires that State Wildlife Action Plans include reassessment at regular intervals, no longer than ten years. Spontaneous reassessment may also be necessary in response to surprises, which are to be expected in complex systems. Managers and planners should be prepared to adjust or end individual adaptive management projects along the way. Gregory et al. (2006) recommend that stopping rules be created that minimize perceived risks of failure to species and to institutions.

5. CASE STUDY: THE NEBRASKA NATURAL LEGACY PROJECT

The Nebraska Natural Legacy Project is Nebraska’s State Wildlife Action Plan, with the stated mission: “…to implement a blueprint for conserving Nebraska’s flora, fauna, and natural habitats through the proactive, voluntary conservation actions of partners, communities and individuals” (Schneider et al. 2011, p. 1). As part of the Nebraska Natural Legacy Project, biologically unique landscapes were identified, representing diverse ecological areas for focused conservation efforts. A systematic approach for generating biologically unique landscape-level conservation plans, informed by the context of state-wide and greater regional trends, was developed and is in the beginning stages of deployment. I use the Nebraska Natural Legacy Project to illustrate how current planning strategies can be adapted to structured decision making and to discuss the potential for adaptive management projects based on recent planning efforts within biologically unique landscapes in southeastern Nebraska.

5.1 Nebraska Natural Legacy Project and structured decision making

The Nebraska Natural Legacy Project systematic approach to biologically unique landscape planning involves: 1) prioritizing species and natural communities of concern,

2) setting targets for species and natural communities identified in the first step, 3) describing known threats and stresses, and 4) outlining conservation strategies (Figure 4-1). Although not currently portrayed as structured decision making, this process can be relatively easily mapped onto structured decision making. This structured decision making process can then form the backbone of adaptive management projects.

The overarching structured decision making problem within a biologically unique landscape can be thought of as: “How do we best manage for the conservation of priority species and natural communities within a biologically unique landscape?”. The first step of the Nebraska Natural Legacy Project systematic approach, prioritizing the species and natural communities (hereafter shortened to species), is a sub-decision nested in the larger structured decision making process. Nebraska Natural Legacy Project planners utilize a target selection matrix tool to guide selection of species (Table 4-4). The columns of the matrix can be translated to “objectives”; planners want to focus conservation on as many species as possible that are imperiled, endemic, biologically unique landscape-dependent, and/or habitat-specialized. However, they recognize that bounded rationality and limited resources constrain the number of species that can be realistically addressed. In this context, the alternatives are different possible sets of targets. The consequences can be thought of as the quantification of the selection matrix (how potential species are ranked) and consideration of the consequences of leaving out or including certain targets. Each species will have “consequences” in terms of how imperiled, endemic, biologically unique landscape-dependent, and habitat-specialized it is determined to be (Table 4-4). Each alternative set of species will have “consequences” in terms of how well each category of species (imperiled, endemic, etc.) is represented and the amount of resources needed to address every species in the set. The biggest tradeoff is keeping the list to a reasonable number of species, while also not putting important species at risk by leaving them off the list. Once the set of species is decided on, the overarching structured decision making problem (“How do we best manage for the conservation of priority species and natural communities within a biologically unique landscape?”) is defined.

The second step in the Nebraska Natural Legacy Project systematic approach involves setting targets for each species in the list. Targets are quantified objectives (e.g., “Conserve 3 populations of at least 250 individuals of a given species”, “Conserve 3,000 acres of a given natural community within the biologically unique landscape”). In the language of structured decision making, these are the fundamental objectives, the achievement of which determines project success. In addition to the target-based objectives, managers should include other objectives, such as minimizing cost or maximizing landowner approval, which will influence the management decision.

In the third step of the Nebraska Natural Legacy Project systematic approach, threats and stressors to the species targets are identified. Reduction of threats and stressors are means objectives (e.g. “Reduce herbaceous and woody invasive species to less than five percent of the groundcover”, “Reduce shrub density near den sites to meet specific habitat requirements of a priority species”). Achievement of means objectives should help reach fundamental objectives. In other words, managers do not value the reduction of threats and stressors but hope to thereby protect species that are valued. It is also possible to frame threats and stressors as individual problems (rather than means objectives), nesting another structured decision making process within the larger systematic approach. The objective would then be to minimize the threat, and the alternatives would be conservation actions to reduce the threat. The risk of applying this approach is that the fundamental project objectives of conserving the priority species and communities may be ignored if the focus is shifted to reducing threats and stressors. However, this approach could be the basis for individual adaptive management projects, as there are likely uncertainties about how to reduce threats or how those threats impact priority species. Ultimately though, State Wildlife Action Plan success must be based on species outcomes.

Finally and critically, the Nebraska Natural Legacy Project seeks to identify conservation strategies. These strategies, or combination of strategies, are the alternatives of structured decision making (e.g., “increase hand-pulling/spraying control for invasive species”, “increase landowner awareness”). In many cases, strategies need to be further refined into alternative ways of implementing a strategy (e.g. a strategy of prescribed burning could mean burning of one hundred acres every five years, burning ten acres every year, or any number of other possible management regimes). To complete the structured decision making process, managers must then consider the consequences and tradeoffs of implementing different alternatives.

5.2 When to use adaptive management within the Nebraska Natural Legacy Project

Recent Nebraska Natural Legacy Project efforts have targeted biologically unique landscapes in southeastern Nebraska that contain areas of oak-dominated forest in the Missouri River bluffs. During planning meetings for the implementation of the systematic approach described above, a number of questions emerged. To demonstrate use of the dichotomous key (Figure 4-2), I use four questions as examples.

(1) Is it necessary to set targets for individual species, or can we just conserve natural communities?

This is a complicated question that could be interpreted different ways. It falls out at the first question of the key if it is a value question – "Do we value the status of individual species, or are we satisfied with functional habitat that presumably supports wildlife?". In this case, observation of the system will not help stakeholders answer the question. However, if the question is: "Are habitat management actions aimed at conserving natural communities also meeting species targets?", this uncertainty could make it through the key, given an ability to change and learn.

(2) Can the different natural communities identified as targets (e.g., Red Oak-Basswood-Ironwood Forest, Oak-Hickory-Ironwood Forest) be differentiated on the landscape, such that conservation success can be evaluated for each community individually?

Observation of the system can help, but management is not needed to address the uncertainty. This is likely an inappropriate uncertainty to address through adaptive management because it is a non-management question. However, external research conducted to answer this question could be integrated with adaptive management and used to adjust the objectives (Williams 2015). Another consideration is whether beliefs about the appropriate objective (combined vs. separate objectives for the two forest communities) are linked to beliefs about how the system will respond to management (similar vs. dissimilar management impacts in the two communities). If choice of objectives and beliefs about hypotheses are linked, it may be possible to incorporate objective uncertainty into the adaptive management framework (Williams 2015).

(3) Where are oak seedlings currently found?

As with the previous question, this uncertainty does not make it through the key because management is not necessary to reduce the uncertainty. However, this question is tightly linked to the following question, and therefore can be answered in the course of addressing management impacts on oak regeneration.

(4) Does prescribed burning and/or thinning increase oak regeneration?

This is the only example question that clearly makes it past the first two questions of the key; that is, it is an uncertainty that can be reduced through adaptive management. In addition, the question implies management options (e.g., different fire regimes, different amounts or targets for thinning, combined strategies versus just burning or thinning). Given adequate flexibility in decision making, learning would be likely to change management because the question directly relates to the target natural communities and the decision to burn/thin can be made on a repeated basis over time and space. If resources are available for implementation, monitoring, and evaluation, then adaptive management should be considered.

5.3 How to draft adaptive management projects within the Nebraska Natural Legacy Project

Assuming the planners agree that the last question ("Does prescribed burning and/or thinning increase oak regeneration?") makes it through the key, adaptive management can be considered as a possibile decision making framework. Using this uncertainty and the biologically unique landscapes of Missouri River bluffs in southeastern Nebraska as an example, I now present a potential progression through the development of an adaptive management project. I describe one adaptive management design for the scenario but acknowledge that many other designs could be appropriate, depending on the conservation context. Although partially informed by actual events, I present the case hypothetically, as an example of one possible way adaptive management could be conducted.

Involve the right people: A team is assembled by State Wildlife Action Plan organizers to plan conservation of the southeastern Missouri River bluff biologically unique landscapes. The team includes representatives of Nebraska Game and Parks Commission, Nebraska Forest Service, U.S. Fish and Wildlife Service, Northern Prairies Land Trust, The Nature Conservancy, and the University of Nebraska. Involving stakeholders outside the state wildlife agency is a step toward "involving the right people," but the group may later need to be expanded to include private landowners who may be impacted or interested in the project.

Prioritize uncertainties: Even though the uncertainty is packaged as one question ("Does prescribed burning and/or thinning increase oak regeneration?"), it is really a set of uncertainties related to how burning and thinning management occurs and the impacts on different aspects of oak regeneration, such as the abundance, height, and mortality rate of oak seedlings. Upon further consideration, the following sub-question is prioritized:

"Is thinning only effective in increasing oak seedling abundance in the presence of prescribed burning?". Thinning is costly and labor-intensive, so if thinning is only effective in the presence of fire, thinning in the absence of fire is a waste of resources. Oak seedling abundance is the focus because seedlings can be rapidly counted and differences in abundance is hypothesized to be one of the first detectable indicator of increased oak regeneration potential.

Represent hypotheses with models: Models are used to link different hypotheses about the impacts (consequences) of thinning with and without burning (alternatives of structured decision making) on seedling abundance. Seedling abundance is related to success of efforts to conserve the targeted oak natural communities (objectives of structured decision making). One model suggests that thinning without burning will have no impact on seedling abundance, while an alternative model suggests that thinning without burning will increase seedling abundance. Burning is assumed to increase oak seedling abundance.

Choose how to learn: An active adaptive management approach, in which experimental units receive different treatments, is determined to be feasible and is preliminarily designed. The treatments are "thinning with burning" and "thinning without burning." Seedling numbers are to be established prior to management, and then measured again following management.

Discuss and set standards for convincing evidence: Decision makers discuss how big of a change would need to be observed in number of seedlings to justify choosing one alternative over another. Planners determine that the change in oak seedling abundance in the thinned without burning areas must be within 10% (for a 95% confidence level) of the change in areas with both thinning and burning in order to justify thinning alone.

Make it happen: A large state park provides study sites for the management experiment, and grant money is acquired to support the project. A park manager steps forward to oversee the implementation of treatments, and a graduate student is funded to conduct the monitoring and analysis. Adaptive management moves beyond planning into the implementation stage.

Keep it going: It is decided that if the experiment meets the evidence criteria described earlier, then management will be adjusted accordingly and this particular adaptive management project will be complete. The graduate student will publish the results, and the State Wildlife Action Plan team will produce a report to document the success of the project. Detailed protocols for experimental design, monitoring, and analysis are developed and stored for future use in the event that sufficient evidence is not obtained with the first experiment.

Decide when to assess and revise, or get out: The evidence criteria determine when management will be altered based on learning, as part of the first loop of double loop learning. The planning team decides to re-evaluate the entire conservation plan in five years as the second loop of learning. In addition, a contact list of participants is maintained by State Wildlife Action Plan organizers to facilitate rapid re-evaluation if a surprise significantly alters the management context, such as a widespread wildfire.

6. CONCLUSION

Structured decision making is beneficial to virtually every resource management decision (Gregory et al. 2012, Conroy and Peterson 2013), but adaptive management is only possible in a limited set of circumstances that involve iterative decision making, uncertainty about management consequences, and an ability to learn and adjust. When applied appropriately, adaptive management has the potential to aid wildlife conservation, by addressing uncertainties and instituting necessary flexibility to make better decisions in the future. Congress facilitated the use of adaptive management for state wildlife conservation by mandating that State Wildlife Action Plans incorporate many of the components of adaptive management, including monitoring and adjustment. Most State Wildlife Action Plans discuss adaptive management as an appropriate approach (Defenders of Wildlife 2006, Fontaine 2011), but they lack explicit structured decision making or adaptive management frameworks (Fontaine 2011), which hinders realization of this potential.

Alternative approaches to structured decision making and adaptive management include ad hoc, wait-and-see, and state-specific management; ad hoc management is essentially trial-and-error, wait-and-see uses observation of natural variability to assess management options, and state-specific management adapts actions based on the current state of the system (Williams and Brown 2014). These approaches may be feasible and/or acceptable depending on the management context. Planners and managers must consider the extent of uncertainty and the potential for learning when selecting an approach. A poorly selected approach can prevent achievement of wildlife and habitat goals and undermine the reputation of the approach itself, especially in the case of adaptive management (Gregory et al. 2006). Failure may manifest as a decline in target species or communities, damaged agency reputation, and lost resources.

Structured decision making can guide the entire State Wildlife Action Plan process, with adaptive management as an important subtype of structured decision making for specific projects when appropriate. I have described a method to help State Wildlife Action Plan planners and managers (1) adapt current planning approaches to the structured decision making process, (2) identify potential uncertainties to address through adaptive management, and (3) begin designing adaptive management projects. As planners go through the steps of structured decision making for conservation at the state, region, or ecosystem level, they can simultaneously look for uncertainties. Planners can then identify uncertainties appropriate for adaptive management using the dichotomous key. From there, specific adaptive management projects can be developed to fit within the larger State Wildlife Action Plan structured decision making process. By following this framework for determining when and how to use adaptive management, State Wildlife Action Plans can harness the benefits of adaptive management to improve conservation of wildlife and their habitats.

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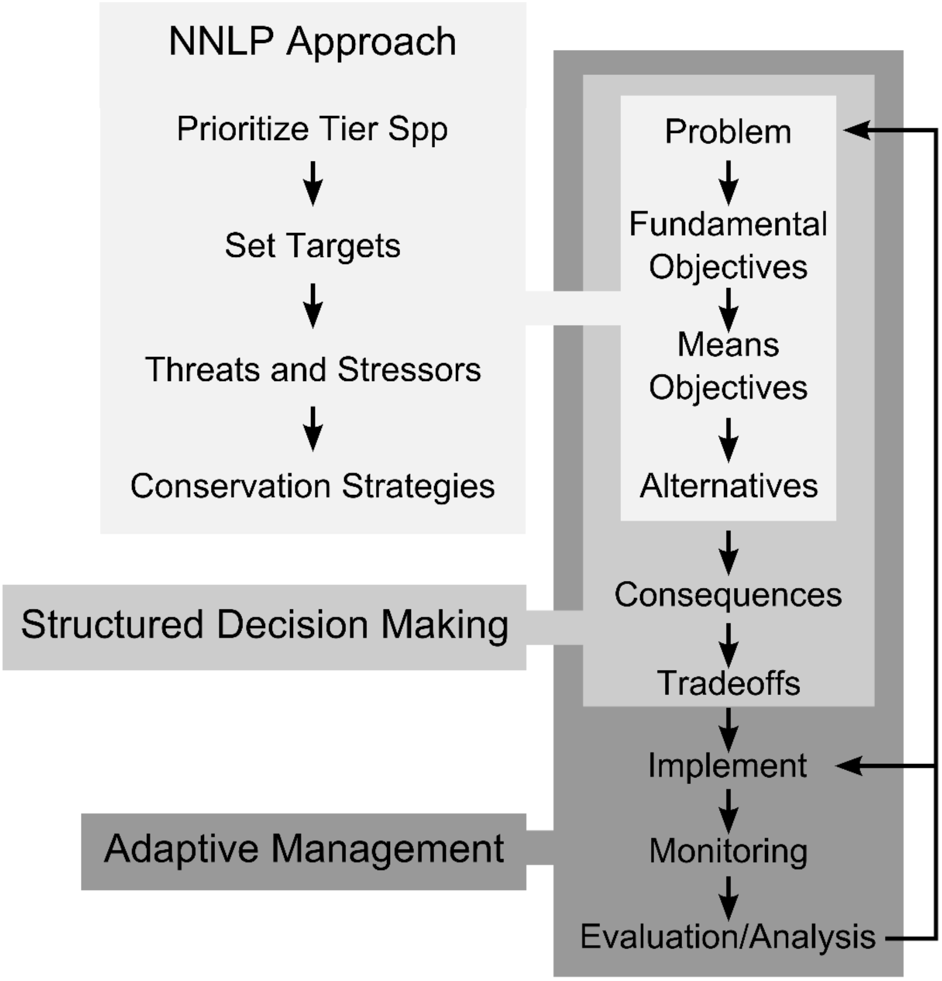

Figure 4-1. Systematic planning approach of the Nebraska Natural Legacy Project (NNLP) in the context of structured decision making and adaptive management (a specific type of structured decision making). The problem is determined by which species are prioritized under the NNLP. Species targets make up fundamental objectives. Means objectives are related to the reduction of threats and stressors to the species. Alternatives can be built from the conservation strategies. The arrows leading off of the evaluation step of adaptive management represent adjustment based on two loops of learning; single loop learning changes implementation and the double loop learning alters the fundamental elements of the decision framework.

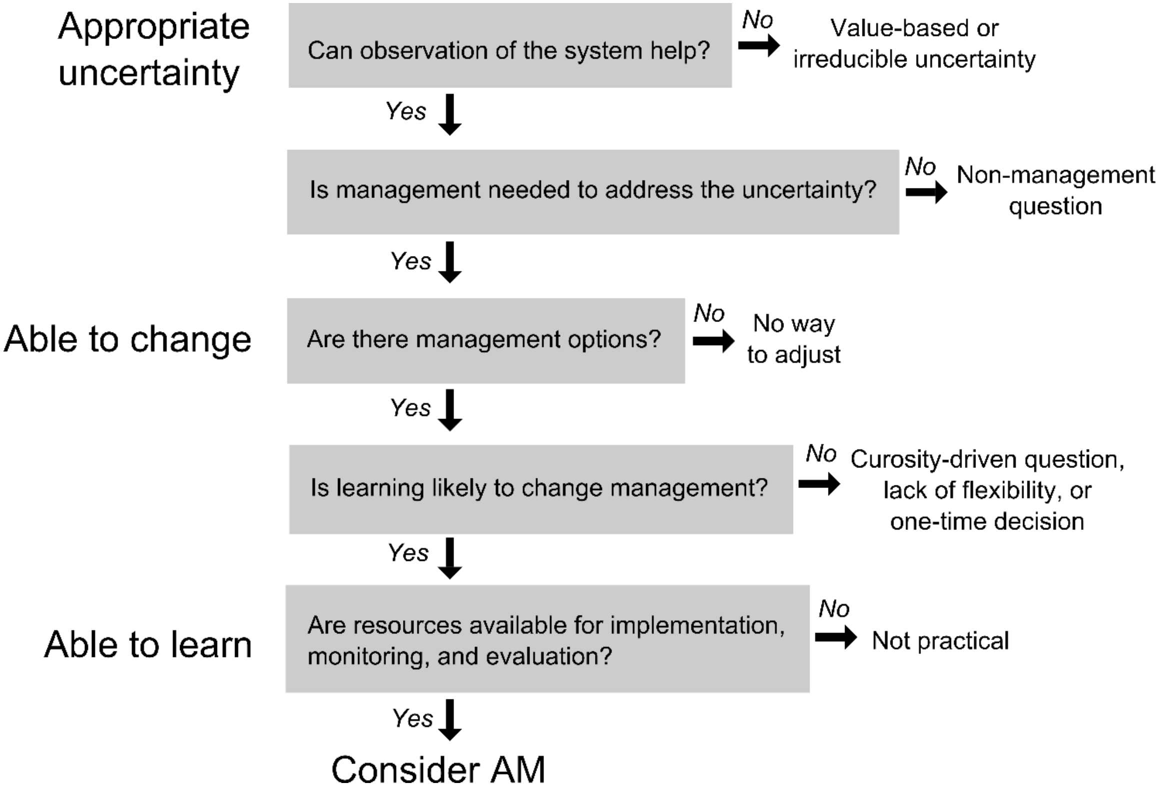

Figure 4-2. Dichotomous key for determining when to consider using adaptive management, given specified uncertainties and knowledge of the management context. The first part of the key evaluates whether the uncertainty is appropriate for adaptive management, such that the uncertainty could be reduced through designed monitoring and review of management consequences. The second part of the key addresses whether the knowledge gained would be useful. The third part of the key relates to whether it is practically possible to reduce the uncertainty. Adaptive management is impossible or unlikely to succeed if the answer to any of these questions is “no.” Potential reasons for the answer being “no” are listed along the right-hand side of the key.

Table 4-1. Eight elements required by Congress to be included in State Wildlife Action Plans. The elements can be readily incorporated into structured decision making and adaptive management frameworks.

Identify or describe the following:	
1. Wildlife species	Distribution and abundance of wildlife species indicative of state’s biological health and diversity
2. Habitats/communities	Extent and condition of essential habitats and communities
3. Problems	Problems affecting species or their habitats
4. Actions	Conservation actions for those species and their habitats
5. Monitoring/adjustment	Plans for monitoring and adjusting conservation actions
6. Review	Procedure for reviewing the plan
7. Coordination	Plans for coordination with federal, state, local agencies, and Indian tribes that manage significant land and water areas in the state
8. Public participation	Ways of including broad public participation

Table 4-2. Types of uncertainty and scenarios that are not appropriate for adaptive management, with examples relevant to State Wildlife Action Plans.

When not to do AM	Examples
Value-based or irreducible uncertainty	Some questions cannot be reduced through adaptive management, such as: “Which species should be the high priority?” (value-based), “Should management be more focused on species or habitat management” (value-based)?”, “Will there be a drought next year?” (irreducible)”, “What will be the impacts of climate change?” (irreducible).
Non-management question	Managers may have questions about natural history characteristics or distribution of a species that cannot be informed by management, even if the answers could inform management. For example, “Where are the den sites for an elusive snake species?”, or “Do target forest communities have distinguishable boundaries, such that objectives can be evaluated for individual communities?”.
No way to adjust	Mandates from a higher authority (e.g., the state governor) or political expectations (e.g., demands of powerful lobbying bodies) may dictate the management action.
Curiosity-driven question, lack of flexibility, or one-time decision	An ecologist may be interested in how management actions to decrease deer browse might affect the tick population, but the problem does not take ticks into account (curiosity-driven). Organizational inertia may make it difficult to change the status quo (lack of flexibility). The decision whether to build a wetland at a particular site, does not involve iterative decision making (one-time decision).
Not practical	Funding may be too restricted, or there may not be personnel with sufficient time and expertise to monitor and analyze results

Table 4-3. Aspects of adaptive management (AM) project design with examples relevant to State Wildlife Action Plans.

How to design AM	Examples
Involve the right people	If a well-respected rancher agrees to work with a state biologist to experiment with techniques for reducing woody encroachment, other community members may become interested. Conversely, if the same rancher feels alienated or that his opinions are undervalued, he may dissuade others from becoming involved.
Prioritize uncertainties	In an agriculture-supported community, a target species depends on wetlands. Two uncertainties emerge during planning: (1) agrochemicals impacts and (2) best methods for wetland construction. Wrong assumptions about the amount of tolerable agrochemicals could lead to terrible consequences for the species, stakeholders, or both. Constructing subpar wetlands is less risky than misregulating chemicals and experiment costs outweigh projected benefits. Therefore, the agrochemical uncertainty should be prioritized.
Represent hypotheses with models	In a fire-adapted oak forest, there may be different hypotheses about the impacts of fire frequency and intensity on oak regeneration and the importance of environmental factors, such as light availability. Multiple models with different variables and relationships can be developed and used to predict oak regeneration following fire management.
Choose how to learn	An NGO wants to test bison grazing as a prairie management tool. There is uncertainty about how many bison can be supported ecologically and economically. Active adaptive management would divide the prairie into units and test different treatments. Some areas may be damaged or money could be lost, but learning would be relatively quick. A passive approach would generate different model-based predictions, implement the hypothesized optimal treatment, and compare results to the models. Learning is slower but safer.

Table 4-3. Continued

Discuss and set standards for convincing evidence	A bird species is rare, and therefore difficult to observe. The bird may be negatively impacted by burning, but burning positively impacts the forest community overall. Active adaptive management is used to investigate effects of burning on the bird. Few birds are observed and results are only marginally statistically significant. Is this evidence enough to justify altering burning practices?
Make it happen	Cooperative Fish and Wildlife Research Units are collaborations between the U.S. Geological Survey, a land-grant university, and state wildlife agency. Graduate students in the coop units may assist in designing, implementing, and evaluating research projects. In addition, graduate students can serve as leaders, as they need to “make it happen” in order to complete a degree.
Keep it going	Substantial planning time can be devoted to upfront problem definition. Monitoring could be written into the job description for some permanent, full-time employees. A data management consultant could be hired to develop an intuitive, computer-based data input and analysis system. Public outreach material can be created to allow stakeholders to follow the progress of adaptive management projects.

Table 4-4. An abbreviated version of the target selection matrix tool used by the Nebraska Natural Legacy Plan to guide choice of focal species within a biologically unique landscape (BUL). Two species are included as examples. Scores are based upon information previously gathered for the Nebraska Natural Legacy Project and stakeholder input. The scoring results suggest that it may be more important to include Timber Rattlesnake than Wood Thrush in the set of targeted species, as this species is described as more imperiled and habitat specific, while being equally endemic and BUL-dependent.

Common Name	Imperilment	Endemism	BUL	Habitat Specific	Total
Timber Rattlesnake	1	2	3	3	9
Wood Thrush	0	2	3	1	6

CHAPTER 5: REDUCING UNCERTAINTY ABOUT OAK SEEDLING ABUNDANCE TO IMPROVE CONSERVATION OF OAK-DOMINATED FORESTS

1. INTRODUCTION

Oak-dominated forests are valued for many reasons, including supporting wildlife, supplying timber, and providing cultural benefits (Fei et al. 2011). Ecologist and forest managers have observed a general trend of reduced oak abundance in eastern North America since the 1980’s (Abrams 1992, Fei et al. 2011). Loss of fire on the landscape is believed to be a major driver of the oak decline. In the absence of fire, more shade-tolerant but less fire-tolerant tree species a competitive advantage over oaks by reducing light availability to oak seedlings (Nowacki and Abrams 2008). Therefore, prescribed burning and thinning of shade-tolerant trees may be necessary to conserve oak-dominated ecosystems.

Studies have examined the general impacts of burning and thinning (Iverson et al. 2008, Abrams and Steiner 2013, Knapp et al. 2015), but the consequences for a given oak forest will likely depend on the historical context, present condition, and how burning and thinning are applied. Adaptive management is a useful framework for learning about specific forest systems by testing different hypotheses about consequences through monitoring and review (Holling 1978, Walters 1986, Lyons et al. 2008, Williams et al. 2009). Adaptive management is appropriate when there is: (a) uncertainty about how systems or species might respond to management or uncertainty about the particular mechanisms driving observed responses (Williams et al. 2009), (b) an ability to learn, and

(c) opportunity to change management based on what is learned (Williams and Brown 2012).

One area of uncertainty related to oak conservation management is the impact burning and thinning will have on oak seedling abundance. Assuming that seedling abundance is indicative of oak regeneration potential, reducing uncertainty about oak seedling abundance through adaptive management can improve oak conservation. Hypotheses (i.e., models) could differ based on management specifics (e.g., frequency and intensity of prescribed burning, amount of thinning), predicted shape of the response (e.g., positive vs. negative, linear vs. nonlinear), strength (i.e., coefficients) of anticipated effect, or the potential for interactions between management actions (e.g., whether the impact of burning is different in the presence of thinning; whether thinning is effective without burning). In order to detect the management effects, variability resulting from environmental drivers will likely need to be accounted for in the models.

To conserve and restore oak-dominated forest communities as part of Nebraska's State Wildlife Action Plan, also known as the Nebraska Natural Legacy Project (Schneider et al. 2011), managers have reintroduced fire at Indian Cave State Park in southeastern Nebraska, in conjunction with thinning of small trees. Management practices can be informed by similar oak conservation efforts elsewhere in the Midwest (e.g., Iverson et al. (2008) found that repeated burning and partial thinning in a southern Ohio forest increased the density of large oak seedlings, and Knapp et al. (2015) found that after 60 years, areas with repeated burning on a four-year fire interval contained more oak seedlings than unburned areas). However, uncertainties remain about how the oak forest communities of southeastern Nebraska will respond, including how management will impact oak seedling abundance.

Previously adaptive management was not possible at Indian Cave State Park because a lack of data prevented formal evaluation of management. As an initial step toward reducing uncertainty through adaptive management, a series of meetings with park managers and state conservation planners was used to develop hypotheses about the environmental and management factors influencing oak seedling abundance and to design data collection methods for an initial inventory of oak seedlings at Indian Cave State Park. In this chapter, I use the inventory data to test hypotheses built from combinations of various environmental drivers and management actions through a multimodel inference/information theoretic approach. I also explore opportunities for further implementing adaptive management, built upon the knowledge acquired from this preliminary effort.

2. STUDY SITE AND DATA COLLECTION

Indian Cave State Park is an approximately 3,300-acre parcel of state protected land in the Missouri River bluffs of southeastern Nebraska (Schneider et al. 2011). The park contains mixed hardwood forest communities dominated by red and white oaks, hickories, and basswood. Based on familiarity with oak conservation practices elsewhere, park managers hypothesize that burning creates suitable conditions for oak seedling germination and thinning improves oak seedling survival by increasing light availability. Prescribed burning was first applied in the park in 2009, and since then prescribed burning and thinning have been applied in sections of the park. Management was not conducted as a formal experimental procedure but rather implemented opportunistically.

Data were collected during the months of June and July 2014. The oak seedling inventory was conducted in tandem with a broader Indian Cave State Park forest community inventory project (unpublished data). A total of 360 points were located throughout the forested areas of the park, using stratified random sampling to collect data from 30 points in each of 12 elevation/aspect combinations; presence of oak communities can be driven by elevation and aspect (Collins and Carson 2004). At each of the points, canopy closure, understory plant groundcover, litter:bare groundcover, oak seedling abundance, and tree composition was assessed.

Canopy closure was estimated at each point using a spherical densiometer, with readings averaged between two observers when possible. Within a 4-m radius plot centered on the point, the percentage of ground covered by plants less than 6-ft tall was visually estimated, as was the percentage of litter to bare ground (summed to 100%). In the same plot, oak seedlings were counted and distinguished as red or white oak seedlings to the best of the observers' abilities. Within a 10-m radius plot, all trees (greater than 6-ft tall) were recorded to species, assigned a size class based on diameter at breast height (dbh) (small: ≤ 10-cm dbh, medium: 10-cm < dbh < 30-cm, large: ≥ 30-cm dbh), and designated canopy or subcanopy (where a canopy tree is defined as receiving direct overhead sunlight). A geographic information systems layer of the park, provided by a manager, was used to determine if points were within 20-m of an opening (edge).

3. RESPONSE VARIABLE AND COVARIATES

The response variable of interest for this study is oak seedling abundance. Red and white oak seedlings are combined to avoid numerous zero values and due to uncertainty about the accuracy of differentiation between red and white oak groups. The covariates, selected based on meetings with park managers and state conservation planners, include a mix of ecological and management variables to explore the factors correlated with oak seedling abundance and to test for evidence of management effects. The covariates are: number of large oaks within 10-m, number of small trees (any species) within 10-m, number of times burned (based on management burn units), number of times burned before mid-2012 (prior to germination following a mast year), and edge (y/n). Canopy closure was excluded from the present study based on the limited range observed in the park (75% of points with canopy closure over 90% and only outliers below 80% closure) and unsupportive results from a pilot study conducted the previous summer (unpublished data).

Large oaks, in comparison to medium and small oaks, have greater basal area for acorn production and tend to produce more acorns per basal area (Greenberg 2000). Many of those acorns settle near their source tree (Sork 1984, Dow and Ashley 1996). In addition, if the environmental conditions at the site (e.g., elevation and aspect, soil moisture) are favorable to large oaks, they may be suitable for seedlings as well, although this is not necessarily the case and may be species specific (Collins and Carson 2004). Therefore, greater numbers of large oaks are hypothesized to increase the number of seedlings. Analysis of a pilot study (30 points collected in 2013) further supports inclusion of large oaks as a covariate.

Thinning has been implemented in areas of the park in an effort to reduce the number of small, shade-tolerant trees. Fewer small trees are hypothesized to increase the number of seedlings by allowing greater light availability. Due to lack of sites that were thinned and not burned, and given the variability in the number of small trees remaining at thinned sites, the number of small trees is used as a surrogate for thinning.

The impact of burning is hypothesized to be influenced by how often a site was burned and whether burning occurred prior to or post the late spring 2012 germination of seedlings produced in the mast of fall 2011. Managers assume that most of the seedlings observed during the study are from the spring 2012 cohort. Fire before the late spring 2012 germination (hereafter pre-germination) is hypothesized to have increased oak seedling abundance by providing suitable germination conditions. The impact of fire post germination is less well understood. Pre-germination, sites were burned zero, one, two, or four times. Given a strong relationship between the number of times burned pre- and post- germination (Table 5-1), the number of times burned post-germination is not as a covariate; instead, models include “number of times burned total” or “number of times burned pre-germination.” For the analysis, number of times burned is modeled as a factor, rather than a count variable, to accommodate potential threshold effects.

There are many ways in which edge could influence seedling counts. Sites near the edge could receive more sunlight and increase the number of seedlings, or edge sites could experience greater human disturbance and decrease the number of seedlings. A model with edge was included to test whether there was evidence of an edge effect. Edge was treated as a binary variable, where “1” indicates a point is within 20-m of an opening, and “0” indicates a point is more than 20-m from an opening (determined using an available GIS data layer).

4. STATISTICAL METHODS

Prior to selecting the models to compare, covariates were tested for collinearity to avoid inclusion of correlated covariates in the same model, as this can generate confusing results (Zuur et al. 2010). The set of models represents hypotheses about what environmental drivers and management actions impact oak seedling abundance (Table 5-2). Most models contain additive covariates, but an interaction between small trees and burning was included to address a specific hypothesis that the relationship between burning and oak seedling abundance may be impacted by the number of small trees present. Each model was fit to the sample data using a negative binomial family distribution, implemented in R (version 3.1.0, 2014) with glm.nb in package MASS (Venables and Ripley 2002). The negative binomial family was chosen to address overdispersion discovered during data exploration under a Poisson distribution. Following the multimodel inference/information theoretic approach to comparing models (Burnham and Anderson 2002), the AICc (Akaike information criterion, corrected to address the small sample size), delta AICc, model weights (a.k.a model probabilities), and cumulative model weights were calculated in R (version 3.1.0, 2014) using package glmulti (Calcagno and de Mazancourt 2010). Model averaged covariate effect estimates, average over the full model set (assuming zero effect for models not containing the covariate) and 95% confidence interval bounds were found using package MuMIn (Bartoń 2015).

5. RESULTS

The number of oak seedlings within the 4-m radius plots ranged from 0 to 76, with a mean of 5.33 and median of 3. Based on the boxplot (Figure 5-1), there are numerous outliers. The number of large oaks within the 10-m plots ranged from 0 to 14 trees, with a mean of 2.97 and median of 2. Based on the boxplot (Figure 5-2), there are two potential outliers. The number of small trees ranged from 0 to 101, with a mean of 19.47 and median of 15. The boxplot (Figure 5-3) suggests a number of potential outliers. Of the 360 points, 47 were designated edge (313 not edge). All outliers were retained but may have influenced the results.

The two quantitative covariates, number of large oaks and number of small trees, were not strongly correlated (r = 0.17) (Figure 5-4). Relationships with and between categorical variables (Figure 5-5) were examined with Poisson generalized linear modeling for count data and binomial modeling for the edge data. Statistically significant effects were detected in most cases (Table 5-3) but because of the relevancy to management and the relatively small size of effects, these covariates were allowed to appear in the same models, acknowledging that this may influence model results.

The top model is “oak seedling abundance ~ number of large oaks” with a weight of 0.33 (Table 5-2, Figure 5-6)[11]. The next closest model is “oak seedling ~ large oaks + times burned pre-germination” with a delta AICc of 1.03 and weight of 0.20. Of the 17 models, eight have a weight greater than 0.005, all of which contain the number of large

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[11] Model averaging was deemed unnecessary for the purposes of displaying the relationship between large oaks and oak seedling abundance because the coefficient for large oaks did not vary widely between models containing large oaks (ranging from 0.165 to 0.177).

oaks. Model averaged covariate effect estimates result in the number of large oaks being the only covariate (ignoring the intercept) with a 95% confidence interval not containing 0 (Table 5-4).

6. DISCUSSION

The results support the hypothesis that the number of large oaks influences the number of oak seedlings. The top model contains this covariate alone, all the models with weight greater than 0.005 include large oaks, and the 95% confidence interval excludes 0 for the model averaged effect estimate. The finding that the number of large oaks is correlated with oak seedling abundance is supported by the results of Collins and Carson (2004).

Unlike other studies (e.g., Iverson et al. 2008, Abrams and Steiner 2013, Knapp et al. 2015), management effects were not detected. Although the covariates for times burned pre-germination and the number of small trees appear in the second and third best models, respectively, the models also contain the number of large oaks and are less supported than the model with large oaks alone. This suggests that these covariates likely do *not* substantially help explain the variability.

Lack of evidence does not necessarily mean that management is failing. Other possible explanations include: (a) management needs more time to make an observable impact, (b) there were too few data points to detect differences, (c) the relationships between covariates or outliers influenced the results, or (d) another covariate could be driving the effectiveness of management, such that the impacts of management cannot be detected without accounting for the covariate. Other environmental factors that were not considered in this analysis include soil conditions, groundcover of different types of understory vegetation (e.g., nettles, hog peanut, sunflower), and detailed topographical characteristics (e.g., degree of slope, drainages). Adaptive management could further resolve uncertainties about environmental drivers and management impacts.

7. ADAPTIVE MANAGEMENT POTENTIAL

The Nebraska Natural Legacy Project encourages the use of adaptive management to reduce uncertainty about how systems in Nebraska work, for the purposes of improving conservation of wildlife and their habitats (Schneider et al. 2011). The models representing different hypotheses about which factors are related to oak seedling abundance, demonstrate uncertainty prior to the study. The results, particularly the relatively low weight (0.33) of the top model (oak seedling abundance ~ number of large oaks), show that substantial uncertainty remains about the drivers of oak seedling abundance.

As management decisions were not made with learning in mind, the present study is closer to external research than adaptive management. However, the study could inform an adaptive management approach (William 2015), especially the establishment of management hypotheses and baseline data that can be used for future comparisons. It may be worth developing an active adaptive management approach, in which learning is an objective driving management decisions. Indian Cave State Park is an ideal, and perhaps the only feasible, setting for experimenting with methods for oak conservation in southeastern Nebraska. The park covers a relatively large area (approximately 3,300 acres), contains a sizeable portion of the oak-dominated forestland in the state (within

Nebraska these natural communities only occur along the Missouri river bluffs on the eastern state border), is supported by state agency (in contrast to private) resources, and has managers experienced with prescribed burning and thinning.

The adaptive management project could use plots established within the park to test different management strategies, such as doing nothing, burning, thinning, and burning with thinning. Although some of these strategies are unlikely to improve oak conservation, such as doing nothing, testing the extremes of management alternatives can increase the probability of detecting an effect, and thus speed the rate of learning. Another way to improve the chances of detecting an effect is to limit variability between plots. For example, the study shows that the number of large oaks has an impact on the number of seedlings. Accounting for this variability could mean identifying sites with similar numbers of large oaks or controlling the number of seedlings by planting seedlings.

8. CONCLUSION

The results of this study highlight the importance of accounting for the number of large oaks in models of oak seedling abundance. While it does not provide evidence that management efforts to date have influenced seedling abundance, this does not mean that management is failing to improve oak forest condition. Given the uncertainty remaining after the preliminary analysis, adaptive management may be appropriate. Although adaptive management requires substantial planning and resources for implementation, the ultimate success of management may depend on learning how to improve the effectiveness of conservation efforts. Indian Cave State Park is perhaps the best place to try an adaptive management approach to oak conservation in southeastern Nebraska under the Nebraska Natural Legacy Project. Our study provides a starting point for implementing adaptive management by having already included managers and conservation planners in the process, developed a monitoring protocol, modeled multiple management hypotheses, and provided baseline data for comparisons over time.

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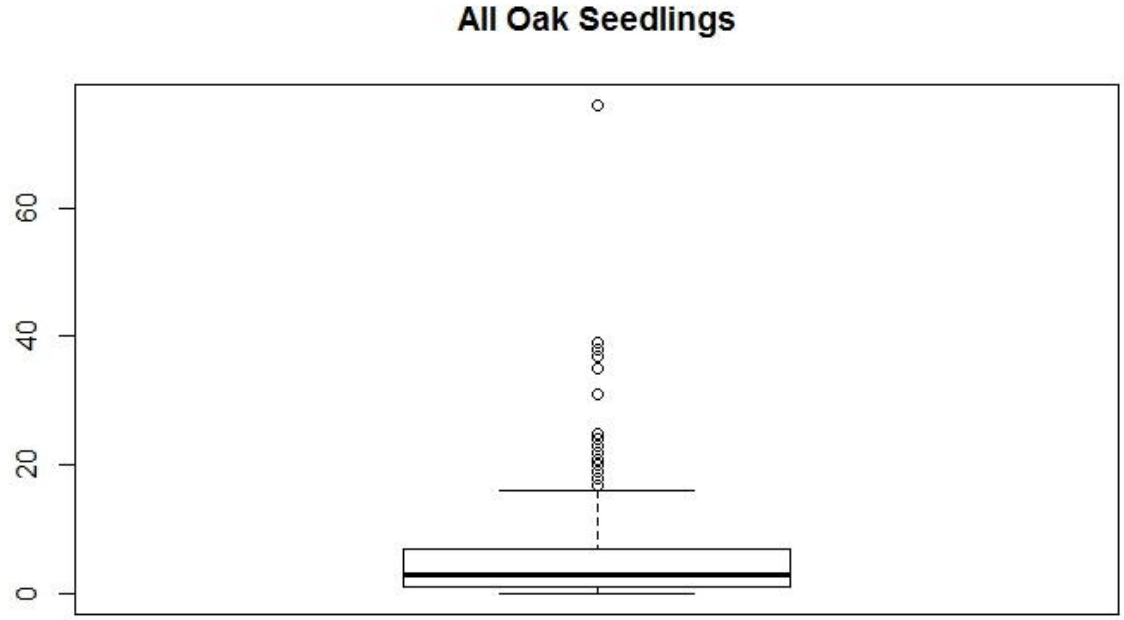


Figure 5-1. Boxplot of oak seedling abundance within 4-m radius plot for 360 locations sampled at Indian Cave State Park in southeastern Nebraska.

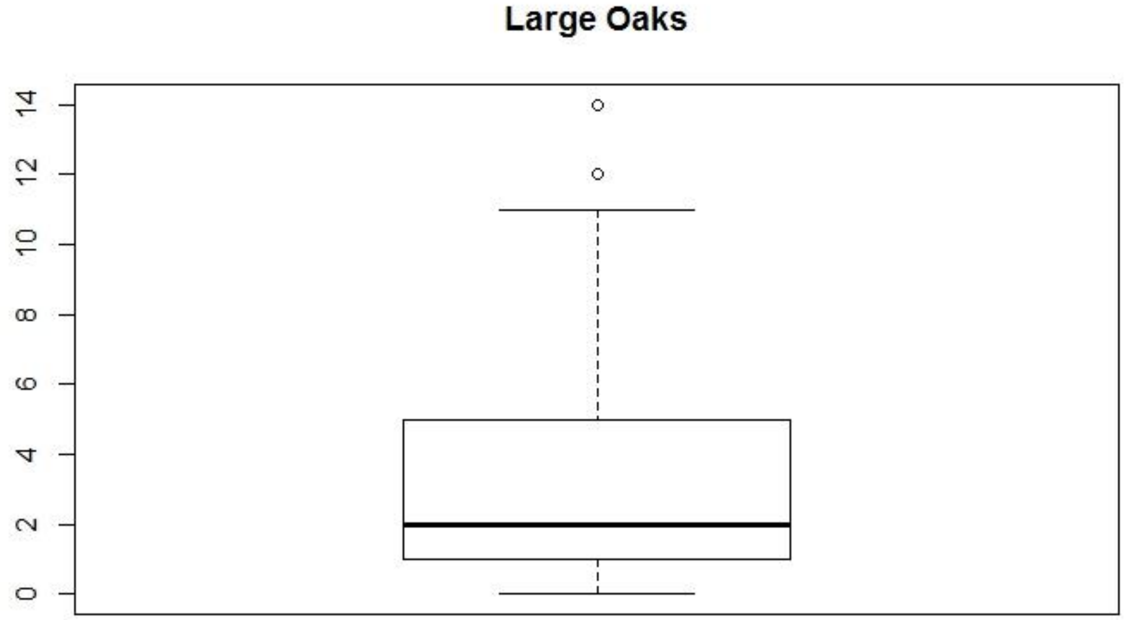


Figure 5-2. Boxplot of the number of large oaks within 10-m radius plot for 360 locations sampled at Indian Cave State Park in southeastern Nebraska.

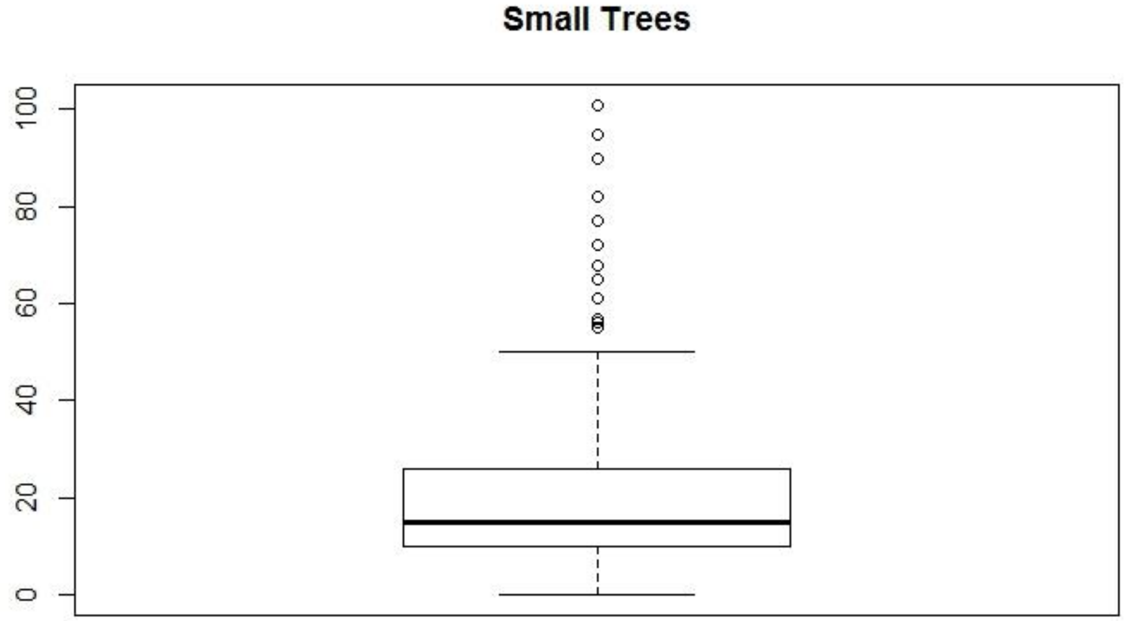


Figure 5-3. Boxplot of the number of small trees within 10-m radius plot for 360 locations sampled at Indian Cave State Park in southeastern Nebraska.

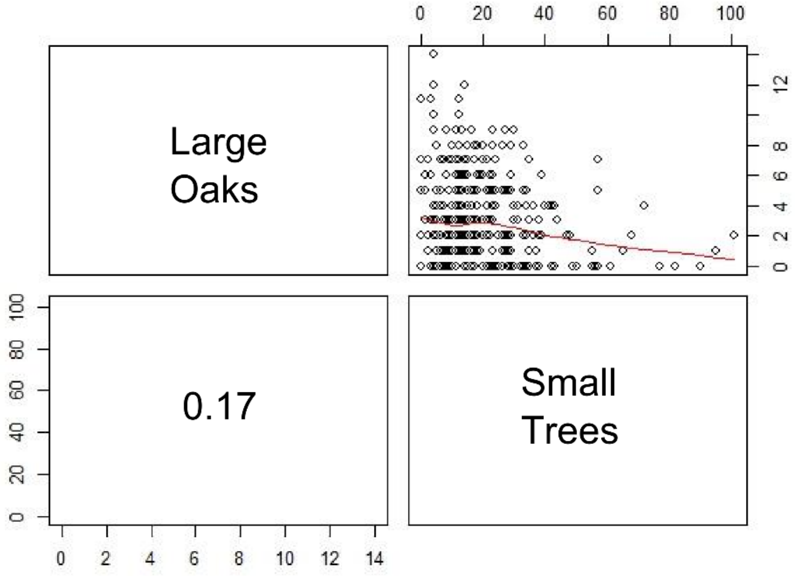
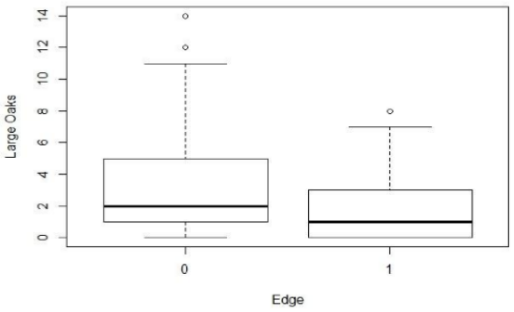
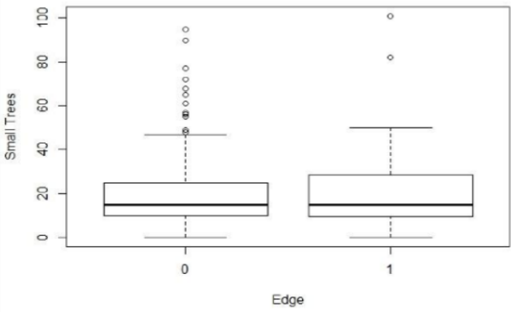
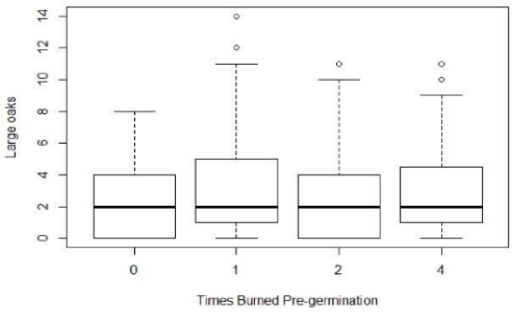
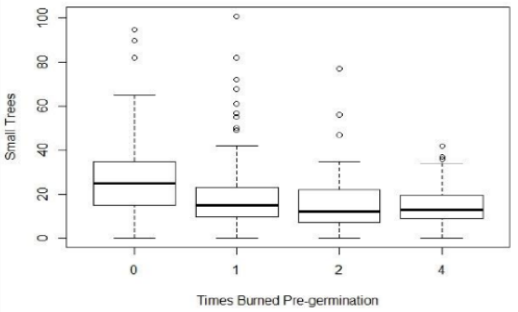


Figure 5-4. Scatterplot showing the degree of correlation between the number of large oaks and the number of small trees within the 10-m radius plots for 360 locations sampled at Indian Cave State Park in southeastern Nebraska.


Large Oaks
0
2
4
6
8
10
12
14
0
1
Edge


Small Trees
0
20
40
60
80
100
0
1
Edge


Large oaks
0
2
4
6
8
10
12
14
0
1
2
4
Times Burned Pre-germination


Small Trees
0
20
40
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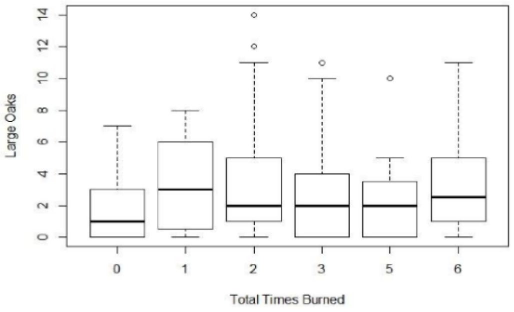
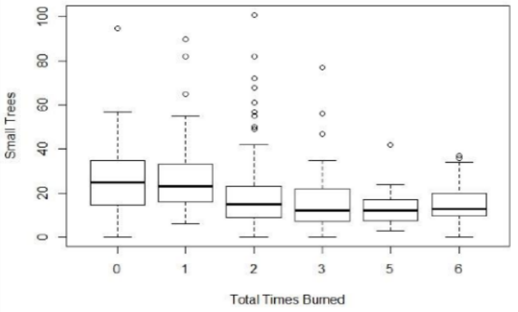
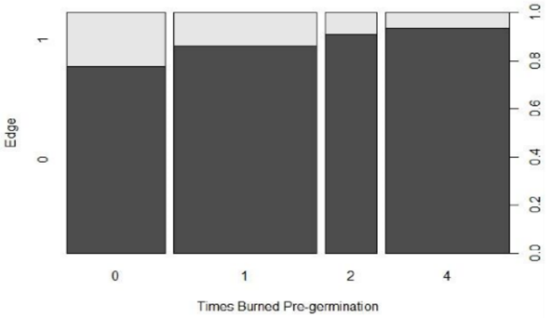
80
100
0
1
2
4
Times Burned Pre-germination


Large Oaks
0
2
4
6
8
10
12
14
0
1
2
3
5
6
Total Times Burned


Small Trees
0
20
40
60
80
100
0
1
2
3
5
6
Total Times Burned


Edge
1
0
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
4
Times Burned Pre-germination

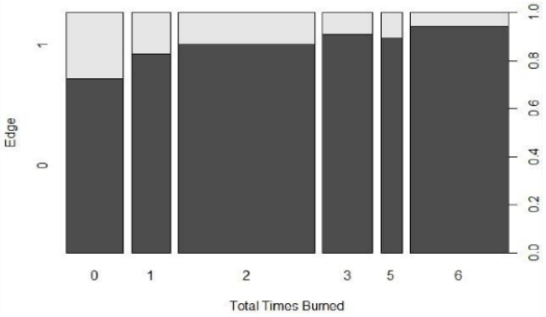

Edge
1
0
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
5
6
Total Times Burned

Figure 5-5. Plots of the relationships between the categorical covariates (times burned pre-germination, total times burned, and edge) and numerical covariates (number of large oaks, number of small trees). The results suggest that there are potentially important differences in central tendency and variability when examining covariates in the context of other covariates, which may impact effect estimates when included together in the oak seedling abundance models.

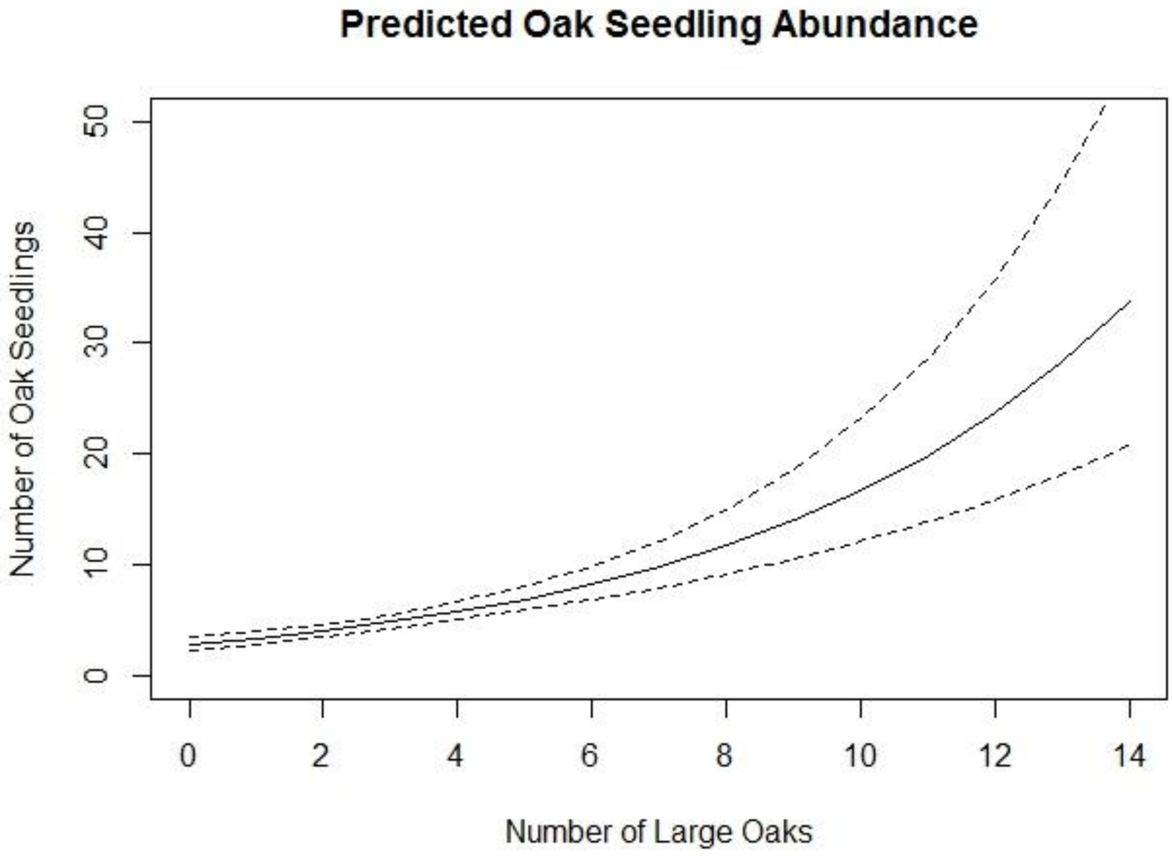


Figure 5-6. Plot of predicted oak seedling abundance based on the number of large oaks, using the top model (oak seedling abundance ~ number of large oaks). Dashed lines indicate the 95% confidence interval. The lines are not straight because the data is back-transformed from the negative binomial generalized linear model.

Table 5-1. Burning within management units at Indian Cave State Park, southeastern Nebraska, can be classified as pre- and post-germination of oak seedlings following a major mast year. Managers are specifically interested if the number of times burned pre-germination and/or the number of times burned total (pre- and post-) are related to the number of oak seedlings. The strong relationship between the numbers of times a unit has been burned pre- and post-germination makes it possible to identify how many times a site has been burned pre- and post- based on the number of times burned total (with an exception for burned once). Interpretation of the number of times burned total by combinations of times burned pre- and post-germination is presented in the table below, along with the frequency of sites in each times burned total category. For example, if a site has been burned a total of 5 times, then the site was burned four times pre-germination and one time post-germination.

Times burned total	Combination of times burned pre- and post-germination	Frequency of sites
0	Never burned	51
1	Burned once post- (except 1 site pre-)	35
2	Burned once pre- and once post-	122
3	Burned twice pre- and once post-	45
5	Burned four times pre- and once post-	19
6	Burned four times pre- and twice post-	88

Table 5-2. Model set of hypotheses about management and environmental variables related to oak seedling abundance at Indian Cave State Park, southeastern Nebraska. Following multimodel inference procedure, the AICc, delta AICc, and weights for each model are provided. Models are order from lowest to highest AICc, such that models towards the top of the list are better at explaining oak seedling abundance than models further down the list.

Model Names	AICc	Delta AICc	Weights
Large Oaks	1935.88	0	0.33
Large Oaks + Times Burned Pre-Germination	1936.91	1.03	0.2
Large Oaks + Small Trees	1937.41	1.53	0.15
Large Oaks + Small Trees + Times Burned Pre-Germination	1938.09	2.21	0.11
Large Oaks + Small Trees * Times Burned	1938.23	2.35	0.1
Large Oaks + Small Trees * Times Burned Pre-Germination	1939.12	3.24	0.07
Large Oaks + Times Burned	1940.78	4.9	0.03
Large Oaks + Small Trees + Times Burned	1941.97	6.09	0.02
Small Trees * Times Burned	1978.59	42.71	<0.005
Times Burned Pre-Germination	1980.89	45.01	<0.005
Null	1982.69	46.81	<0.005
Small Trees + Times Burned Pre-Germination	1982.87	46.99	<0.005
Small Trees * Times Burned Pre-Germination	1983.43	47.55	<0.005
Times Burned	1984.15	48.27	<0.005
Edge	1984.66	48.78	<0.005
Small Trees	1984.71	48.83	<0.005
Small Trees + Times Burned	1986.14	50.26	<0.005

Table 5-3. Potential relationships between numerical covariates (number of small trees, number of large oaks) and categorical covariates (times burned pre-germination, times burned total, edge) and relationships among categorical covariates were examined. Poisson generalized linear modeling was used for count data and binomial modeling for edge data. Statistically significant effects at a 0.05 level (*) were detected in many cases.

Small Trees ~ Times Burned Pre-Germination

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	3.314	0.021	160.15	<0.001
1 Burn Pre-Germination*	-0.364	0.029	-12.46	<0.001
2 Burns Pre-Germination*	-0.484	0.042	-11.61	<0.001
4 Burns Pre-Germination*	-0.633	0.033	-19.36	<0.001

Small Trees ~ Times Burned

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	3.267	0.027	119.506	<0.001
1 Burn*	0.097	0.042	2.334	0.020
2 Burns*	-0.315	0.034	-9.197	<0.001
3 Burns*	-0.438	0.045	-9.647	<0.001
5 Burns*	-0.643	0.068	-9.521	<0.001
6 Burns*	-0.574	0.039	-14.748	<0.001

Large Oaks ~ Times Burned Pre-Germination

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	0.895	0.069	12.906	<0.001
1 Burn Pre-Germination*	0.326	0.085	3.841	0.0001
2 Burns Pre-Germination	0.135	0.113	1.193	0.2327
4 Burns Pre-Germination*	0.197	0.089	2.216	0.0267

Large Oaks ~ Times Burned

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	0.612	0.103	5.929	<0.001
1 Burn*	0.595	0.139	4.298	<0.001
2 Burns*	0.610	0.114	5.342	<0.001
3 Burns*	0.418	0.136	3.068	0.002
5 Burns	0.228	0.183	1.25	0.2114
6 Burns*	0.528	0.120	4.419	<0.001

Table 5-3. Continued

Edge ~ Times Burned Pre-Germination

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	-1.245	0.260	-4.783	<0.001
1 Burn Pre-Germination	-0.585	0.369	-1.586	0.113
2 Burns Pre-Germination	-1.082	0.585	-1.85	0.064
4 Burns Pre-Germination*	-1.414	0.470	-3.01	0.003

Edge ~ Times Burned

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	-0.972	0.314	-3.097	0.002
1 Burn	-0.604	0.547	-1.103	0.270
2 Burns*	-0.919	0.413	-2.226	0.026
3 Burns*	-1.355	0.611	-2.22	0.026
5 Burns	-1.168	0.811	-1.441	0.150
6 Burns*	-1.838	0.557	-3.298	0.001

Large Oaks ~ Edge

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	1.145	0.032	35.931	<0.001
Edge*	-0.541	0.112	-4.814	<0.001

Small Trees ~ Edge

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)*	2.947	0.013	227.514	<0.001
Edge*	0.158	0.034	4.708	<0.001

Table 5-4. Model averaged covariate effect estimates averaged over the full set of models (Table 5-2) with upper and lower bounds of the 95% confidence interval. Beyond the intercept, the number of large oaks is the only covariate for which the 95% confidence interval does not include 0.

Covariate	Estimate	2.5%	97.5%
(Intercept)	0.8502	0.2260	1.4744
Large Oaks	0.1736	0.1316	0.2156
Times Burned Pre-Germination = 1 * Small Trees	0.1318	-0.2858	0.5495
Times Burned Pre-Germination = 2	0.1405	-0.3589	0.6399
Times Burned Pre-Germination = 4	0.0648	-0.3339	0.4635
Small Trees	0.0042	-0.0124	0.0208
Times Burned = 1	0.1133	-0.5823	0.8089
Times Burned = 2	0.1117	-0.4981	0.7215
Times Burned = 3	0.1311	-0.5962	0.8584
Times Burned = 5	0.1980	-1.0017	1.3976
Times Burned = 6	0.1036	-0.5206	0.7278
Small Trees * Times Burned = 1	-0.0032	-0.0238	0.0174
Small Trees * Times Burned = 2	-0.0017	-0.0140	0.0106
Small Trees * Times Burned = 3	-0.0030	-0.0226	0.0167
Small Trees * Times Burned = 5	-0.0132	-0.0941	0.0678
Small Trees * Times Burned = 6	-0.0034	-0.0258	0.0191
Times Burned Pre-Germination = 1 * Small Trees	-0.0004	-0.0057	0.0050
Times Burned Pre-Germination = 2 * Small Trees	-0.0011	-0.0118	0.0096
Times Burned Pre-Germination = 4 * Small Trees	-0.0019	-0.0182	0.0143
Edge = 1	0.0000	0.0000	0.0000

CHAPTER 6: CONCLUSION

Uncertainties and conflicting values are prevalent in complex social-ecological systems and can make it challenging to determine appropriate natural resource management policies. To help managers proceed in the face of these challenges, a number of perspectives and tools have been advanced over the past forty years. Approaches include resilience thinking, structured decision making, adaptive management, and optimization. Combining the benefits of these various, and inherently related, management perspectives and tools may further improve our ability to implement the social-ecological systems paradigm.

Resilience thinking emphasizes the potential for non-linear transitions into alternative stable states and proposes principles for increasing a social-ecological system’s capacity to handle disturbances. A structured decision making process can help managers reach transparent, defensible decisions by articulating problems, incorporating stakeholder values, describing consequences, and representing uncertainty. Adaptive management, itself a type of structured decision making, can improve efforts for iterative decisions by learning through deliberate monitoring, review, and adjustment. Optimization is a tool for identifying optimal policies for a given characterization of the system, including system dynamics and objectives.

In this dissertation, I have attempted to link resilience thinking and structured decision making as a framework for natural resource management, using oak forest conservation in southeastern Nebraska as a case study. Integrating resilience thinking into the structured decision making process should generate transparent natural resources management decisions that defensibly account for the lessons of resilience thinking. Chapter 2 discusses how structured decision making can emphasize principles of resilience thinking. Chapter 3 demonstrates how optimization can identify policies using a Markov decision process reflecting elements of resilience thinking. Chapter 4 provides a practical method for incorporating adaptive management projects into State Wildlife Action Plans. Chapter 5 presents an initial effort to reduce uncertainty for oak forest conservation in southeastern Nebraska. In the following sections, I discuss (1) management implications for oak forest conservation in southeastern Nebraska, (2) general challenges and limitations that cannot be resolved by incorporating resilience thinking into structured decision making, (3) methods for improving the framework, and (4) some concluding remarks.

1. MANAGING INDIAN CAVE STATE PARK

Oak forest conservation is used as a case study throughout the dissertation, with most chapters specifically discussing management of Indian Cave State Park in southeastern Nebraska under the Nebraska Natural Legacy Project. I present an example of how resilience thinking could be incorporated into a structured decision making process for oak forest management at Indian Cave State Park. I use a Markov decision process model to depict hypotheses about: (a) the risk of transitioning out the oak-attracted state, (b) consequences of management actions, and (c) stakeholder values. I provide a method for identifying questions to address through adaptive management and outline a potential adaptive management project for Indian Cave State Park. Lastly, I offer a set of hypotheses related to oak seedling abundance at Indian Cave State Park, identify the number of large oaks as a driver, and suggest ways to further reduce uncertainty. I now discuss how managers and conservation planners could translate my recommendations and examples into a realizable management plan for Indian Cave State Park.

In Chapter 2, I describe hypothetical results of a structured decision making process that incorporates resilience thinking. In actual application, the problem step should be expanded by discussing the system history with stakeholders and explicitly describing what is and is not within control of the group. The objectives should be selected by the group, being sure to consider general resilience and larger Nebraska Natural Legacy Project goals. In addition, learning should be considered as an objective, given the Nebraska Natural Legacy Project's desire to use adaptive management. The example set of alternatives is based on previous practices (e.g., prescribed burning and thinning). Structured decision making encourages creative thinking, so managers should contemplate whether there are other possibilities. The consequences need to be described in detail based on the best available information, with uncertainty explicitly represented. Tradeoffs should be made with a deeper understanding of risk tolerance and the value of learning.

Decisions about monitoring and review should be made based on the key uncertainties, the implications of uncertainty, the anticipated value of learning, and a realistic assessment of the availability of resources. Chapter 4 presents ways of determining when and how to use adaptive management for State Wildlife Action Plans, generally, and includes a draft adaptive management plan for Indian Cave State Park. The example does not explicitly incorporate resilience thinking, but planners could use the information in Chapter 2 to do so. Designing a practical project with a reasonable chance of success would require: (1) involving the right people (the Nebraska Natural Legacy Project conservation planners have already established a working group from a subset of stakeholders), (2) prioritizing uncertainties (which informally occurred by identifying oak seedling abundance as an important management concern (Chapter 5)), (3) representing hypotheses with models (discussed shortly), (4) choosing how to learn, (5) setting standards for convincing evidence, (6) making the project happen (an initial study of oak seedling abundance has occurred, but further study is needed to determine management effects), (7) keeping the project going, and (8) deciding when to assess the project.

The Markov decision processes in Chapter 3: (a) represent a quantified resilience-based state-and-transition model, (b) describe transition probabilities as influenced by management actions, (c) depict resilience thinking assumptions about the consequences of specific actions, and (d) incorporate resilience objectives into the reward function. Optimization was used to help make tradeoffs by determining the state-based policy expected to achieve the greatest value given probabilities of state transitions, the desirability of states, and management cost. Planners can use this Markov decision process optimization approach to determine the specifics for the state-based alternatives of Chapter 2. Uncertainty about aspects of the Markov decision process can be incorporated by developing multiple models.

The Markov decision process models of Chapter 3 are highly simplified (e.g., the reward function does not clearly address all the objectives in Chapter 2) and estimates are not based on data. For the models to be useful for decision making, the defining characteristics of each state need to be precisely described, such that it would be possible to designate units as existing in one of the states. The forest inventory data (Chapter 5) available on tree species composition and size could be used to begin identifying forest states present on the landscape. In addition, the models must be credible and describe consequences in terms of the selected objectives and alternatives. Credibility can be achieved by applying the best available information and having open communication between experts and decision makers. Communication enables inclusion of the relevant objectives, alternatives, and consequences, and allows decision makers to make the necessary value judgments. Chapter 3 highlights the importance of these judgments by demonstrating sensitivity to model parameters. Given present data limitations for Indian Cave State Park, models would need to be heavily assumption-based initially, with multiple models used to represent the range of hypotheses expressed by experts and decision makers. Monitoring data collected in future surveys could be used to revise transition probabilities.

In contrast to the Markov decision process models, the models of Chapter 5 relate to one particular aspect of the oak dominance objective, namely the abundance of oak seedlings. Instead of describing forest state changes across time, these models explore what variables (including management actions) are correlated with the number of oak seedlings for one snapshot in time (seedlings of summer 2014). However, the models can be used to make assumptions about how the system will change over time (e.g., if burning was correlated with high numbers of oak seedlings, burning the park should increase the number of oak seedlings over time and thus increase resilience of the oak-attracted state). The study of Indian Cave State Park revealed that the number of large oaks is related to oak seedling abundance. Management effects were not detected and future data collection is needed to elucidate whether management is having an impact.

One important concern is whether there is an ability to conduct monitoring and subsequently review the data. An initial inventory was conducted (Chapter 5), but additional monitoring is needed for adaptive management at Indian Cave State Park. Given sufficient monitoring and review capabilities, the state park is a prime candidate for an adaptive management project as part of the Nebraska Natural Legacy Project. Indian Cave State Park contains a large portion of Nebraska's oak forest communities, is home to wildlife and plant species targeted by state conservation planners, has experienced oak forest managers, and has management flexibility. By comparing observations to predictions made by multiple models (like those of Chapter 3 or Chapter 5), adaptive management could reduce uncertainty about management effects on oak seedling abundance, or other management-relevant uncertainties. Building from the structured decision making examples of Chapters 2 and 4, and employing the modeling approaches of Chapters 3 and 5, Indian Cave State Park managers and conservation planners can develop an adaptive management plan for maintaining resilience in their oak forest social-ecological system.

2. GENERAL CHALLENGES AND LIMITATIONS

The framework presented here explores how resilience and structured decision making (including adaptive management) can be practically applied. However, implementation will likely still be challenging. Understanding the limitations of the approach is necessary to establish reasonable expectations about what can be achieved.

The framework cannot prevent that: (a) decision making occurs as part of a governance structure, (b) tough value judgments need to be made, (c) monitoring and review are difficult, and (d) demonstrating successful increases in resilience (particularly general resilience) may be impossible.

Structured decision making does not determine the underlying governance structure, such as who the decision makers are and whether decision makers are accountable to stakeholders. The governance structured may be predetermined (e.g., set by federal or state mandates) or may need to be developed (e.g., establishing a group charter), but in either case this must be done prior to the decision making process. Dissatisfaction with how the decision will ultimately be made is a source of conflict that cannot be addressed through the framework.

While structured decision making offers constructive ways of separating conflicts over values (what people care about) from disagreement about facts (potential actions, hypothesized consequences), the process does not eliminate the need to make tough choices about how tradeoffs are made, including how uncertainty and risk are addressed. For example, managers may have to decide if intensive, costly management is justified if there is uncertainty about how management is influencing resilience. Choosing what and how to monitor and review can be especially challenging; on the surface learning while doing sounds simple and worthwhile, but the realities of resource limitations and uncertain returns (in terms of how much will actually be learned and whether the knowledge will influence management practices) can make monitoring and review difficult to efficiently design and implement.

If and how resilience can be measured is a source of debate and has implications for assessing achievement of a general resilience objective. I avoided the issue by assuming that the principles of resilience proposed in the literature were sufficient for assessing general resilience, when used to create sub-objectives as described by constructed performance measures. This approach is useful for comparing among alternatives, but does not provide a means for directly observing changes in resilience over time. Even if an initial decision is reached based on assumptions about the principles of resilience, debate over the tradeoffs between steady, predictable resource delivery and natural variability is likely to arise when the project is later assessed for achievement of objectives.

3. IMPROVING THE FRAMEWORK

Future work is needed to refine and test the framework for synthesizing resilience thinking and structured decision making in social-ecological systems. One method for improving the framework would involve asking experts in a particular approach (e.g., resilience thinking or decision analysis) to examine the process. The experts would review whether (a) their approach is accurately represented and (b) the unfamiliar approaches are understandable. Another method would be to ask natural resources managers to consider if and how their decision making would be different if they used the framework. The framework could be tested by conducting workshops. Multiple groups could go through a given case study using the framework to see where difficulties arise and how the results differ between groups. Workshops could also be used to compare decisions and stakeholder satisfaction between frameworks (e.g., structured decision making without resilience thinking; resilience thinking without structured decision making; ad-hoc decision making) to explore the benefits of applying a particular approach over another. Ultimately, a framework meant for application must be tested through implementation. The usefulness of the framework is based on how well it generates decisions that lead to better natural resources management outcomes than would have been achieved under traditional decision making approaches.

4. CONCLUDING REMARKS

In the introduction, I argued that we must find ways to transcend the discussion of the benefits of a complex social-ecological systems paradigm into actually making informed, defensible decisions under difficult circumstances. I believe developing a management framework that builds upon structured decision making and explicitly incorporates resilience thinking is a necessary step toward increasing our ability to implement the paradigm. To this end, I provide recommendations for the practice of natural resource management and present ideas that can hopefully foster conversations between scholars, technical experts, policy makers, and stakeholders regarding how to address complex management issues. Further progress at the interface of social-ecological systems theory and natural resource management practice will help us enhance the resilience of desirable system states, so that we continue to receive ecosystem goods and services into the distant future.