Exploring Whitebark Pine Resilience in the Crown of the Continent

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Abstract—Whitebark pine (*Pinus albicaulis*) populations are declining across western North America due to synergies of disturbances, both natural and anthropogenic. Losses at treeline may result in significant changes to the upper subalpine zone, which may result in a regime shift, thus affecting the ecological goods and services whitebark pine systems provide for other species, including humans. Management and restoration should acknowledge the coupled social-ecological dynamics of high-elevation forest systems. Resilience is proposed as an appropriate framework for understanding social-ecological systems because it acknowledges complexity and uncertainty in a changing world. Mismatches of scale (spatial, temporal and functional) are increasingly problematic in management, and can lead to a loss of resilience in connected systems, often years or decades after management strategies have been implemented. Identifying mismatches in whitebark pine systems may inform long-term restoration strategies across jurisdictional boundaries. This paper reviews resilience concepts, with an emphasis on scalar mismatches and the problem of 'fit'. A conceptual framework is proposed to measure the functional fit between institutions in a jurisdictionally diverse, transboundary region and the capacity to manage high-elevation whitebark pine systems.

Introduction

The boundaries of ecosystems are hard to define and rarely, if ever, match the socio-political boundaries that are imposed upon them. Yet the imposition of these boundaries, and how we manage within them, has led to the loss of ecological goods and services from local to global scales (Folke 2006). In addition, conventional natural resource management (NRM) often proceeds under the assumption that we can manage complex systems to yield the most benefits for humans (Walker and Salt 2006). However, this has resulted in ecological surprises that may not be seen or understood until decades later (e.g. loss of biodiversity, changes to biogeochemical cycles, and climate change) (Vitousek and others 1997). In fact, the anthropogenic effects on our natural systems are so pronounced that many researchers have suggested that we have entered a new era called the Anthropocene (Allenby 2004; Kotchen and Young 2007; Steffen and others 2007). Environmental degradation can also adversely affect our social systems through the loss of ecological goods and services that ecosystems provide making both social and ecological systems less resilient, or more vulnerable to disturbance. Therefore, acknowledgement of our world as a complex amalgam of coupled social-ecological systems is essential to maintain the resilience of these systems.

Land managers and scientists are moving away from traditional NRM paradigms and are beginning to adopt ecosystem-based approaches to management (EBM) that includes goals to maintain *ecosystem health and integrity*. However, defining such goals in explicit terms has proven elusive and makes the measurement of success problematic. The inherent complexity and uncertainty of ecosystems further complicates our ability to implement EBM effectively. Therefore, managers typically choose to manage for certain species, or indicators, that are representative of an ecosystem (Simberloff 1997).

However, the single-species approach mirrors traditional NRM paradigms by assuming that if particular species are present in an ecosystem, then a desired level of ecological health and function will be achieved. Managing under this paradigm may have negative impacts on other parts of the system, or at different spatial or temporal scales than were considered for managing indicator species. Although conservation efforts to protect species in decline are important, the single-species approach to conservation may not be sufficient over the long term.

Ecosystem-based management considers a wider context than a single-species approach by acknowledging that structure and function are both essential to maintain ecosystem integrity. It also acknowledges that human values influence what and how we manage our landscapes and resources. We suggest that EBM must also include a resilience approach that explicitly acknowledges the social-ecological connectedness of our resource and environmental systems. In such an approach, consideration of particular a species is made with a much stronger reference to its overall context. The re-framing of issues can be useful for eliciting new directions in management (Brugnach and others 2008). We suggest shifting our perspective from a single-species to a species-in context approach will result in strategies that better maintain or improve system resilience.

Whitebark pine (*Pinus albicaulis*) is one species that exemplifies how our past management regimes can result in ecological surprises at spatial and temporal scales well beyond what could have been predicted. Whitebark pine (WBP) is considered a foundation and keystone species in upper subalpine regions throughout its range, often growing in harsh windswept sites with poor soil quality (Resler and Tomback 2008; Smith and others 2008). WBP provides the conditions necessary for the succession of other species, and also regulates snowmelt, contributing to watershed dynamics (Ludwig

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and Smith 2005; Smith and others 2008; Tomback and others 1995). WBP produces large, high fat content seeds that are consumed by a variety of wildlife species, and has an obligate mutualistic relationship with Clark's nutcracker (*Nucifraga columbiana*), the primary seed dispersal agent for WBP (Logan and others 2010; Tomback 1982; Tomback and Resler 2007). Life history traits, ecological function, multiple stressors and system complexity, all combine to create a 'wicked problem' (Geist and Galatowitsch 1999; Rauscher 1999) for scientists and managers trying to restore WBP populations. Although ecologically important for the maintenance of high-elevation forests, WBP is only part of a larger social-ecological WBP system that includes its interconnectedness with other species, including humans, and processes. Without human intervention, this system may be lost (Keane 2000). Since WBP is not valued commercially (Tomback and others 1995), it creates an interesting case to examine from a resilience perspective because the values and drivers in this system are different than in a directly exploited system.

This paper will explore high-elevation WBP systems from a resilience perspective in a social-ecological context. We begin by outlining some of the major concepts of resilience theory that we think are pertinent to WBP systems and their decline. We conclude by proposing a framework to assess the capacity of the environmental regimes to maintain WBP across multiple scales in a transboundary region.

Resilience Overview

Ecological vs. Engineering Resilience

There are two ways in which resilience has been used in the literature. The distinction was first explored in the seminal paper "Resilience and Stability of Ecological Systems" (Holling 1973). The use of the term *stability* in ecosystems describes the amount of time it takes for a system to return to a state of equilibrium after a disturbance. This is central to the concept of *engineering resilience*, which assumes that ecosystems fluctuate around a single equilibrium or domain of attraction (Gunderson 2000). *Ecological resilience*, however, views ecosystems as having multiple state domains, in which different feedbacks and structures exist (Gunderson 2000). If a system threshold is exceeded, the system will move from one domain of attraction to another. This process is referred to as a regime shift (Folke and others 2004; Gunderson 2000). A classic example of a regime shift is the transformation of kelp forests to sea urchin barrens in the Pacific Northwest (Estes and Duggins 1995). Despite the focus on ecological systems, these concepts apply to complex, self-organizing social, ecological and social-ecological systems.

Social-Ecological Systems (SES)

People rely on ecological goods and services for survival, but the policies we create to manage them can cause environmental degradation and inhibit our capacity to react to environmental change. Thus, in order to manage for resilience, it is essential to consider social and ecological connections (Westley and others 2002; Zurlini and others 2006). The attributes of social-ecological systems are *resilience, adaptability* and *transformability*. As described above, resilience is defined as the ability of a system to absorb disturbance and still maintain essentially the same structure and feedbacks, or remain in the same domain of attraction as before a disturbance occurs (Holling and Gunderson 2002; Peterson and others 1998). The capacity to manage resilience reflects adaptability in the system, which is shaped by the systems of governance and the abundance of social, natural and other forms of capital available to maintain a system in a stability domain (Lebel and others 2006). This requires institutions and actors to self organize to learn and adapt to surprises that emerge from nonlinear behaviour (Lebel and others 2006). Transformability is the capacity to introduce new state variables into a system in order to transform it after a regime shift from one domain of attraction to another (Walker and others 2006; Walker and others 2004; Walker and Salt 2006) . This is necessary when a SES can no longer maintain itself, as seen in regions of Africa where villages shifted livelihoods to an ecotourism-based economy after resource depletion of lands rendered the agricultural systems untenable (Walker and others 2004).

Diversity plays an integral role in determining the resilience of social and ecological systems. In ecosystems, species that provide services, such as pollinators or grazers, belong to the same functional groups. The greater the number of functional groups, or *functional diversity*, the better a system will perform (Folke and others 2004; Walker and others 2006). The number of species that provide similar services acts as insurance for disturbance, so if one member of the group is affected, another can provide services to maintain ecosystem function. This *functional redundancy* is important for system resilience, and is enhanced if members within functional groups have a diverse set of responses to disturbances, called *response diversity* (Folke and others 2004; Walker and others 2006). Diversity in social systems is not as clear, but is intuitive that overlapping governance structures may be useful in event of the institutional collapse, and contribute to the resilience of adaptive governance structures (Walker and others 2006). However, NRM paradigms aim to reduce redundancies for efficiency in production (Walker and others 2006), where resilience recognizes that overlapping structures increases the ability of SES's to reorganize after disturbance.

The Adaptive Cycle and Panarchy Concepts

The core concept of how complex adaptive systems behave is illustrated in the adaptive cycle model (Figure 1) which shows how systems change over time. There are three components to the adaptive cycle; potential, connectedness and resilience (Holling 2001). The first two components are most commonly used to understand how a self-organizing system may undergo four phases in an adaptive cycle: growth, conservation, release and reorganization (Holling 2001; Holling and Gunderson 2002). The front-loop of the system is characterized by rapid growth or exploitation (r-phase) to a slower, more connected and rigid conservation phase (K-phase). The latter phase of the front-loop in resource-based SES's might be characterized by resource domination by a few species, high

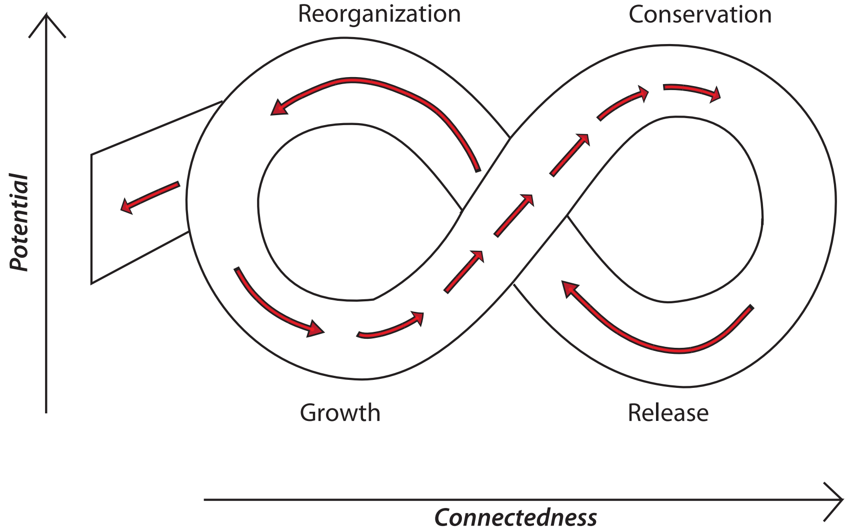

Figure 1. The adaptive cycle—A heuristic four-phase model of complex system behaviour. Arrows show that time in the foreloop (growth -conservation) is typically slow while the back-loop (release-reorganization) is fast. The X and Y-axis show how the connectedness and potential for change fluctuate through the cycle, demonstrating resilience as a dynamic trait of complex systems.

political influence by a few interest groups or even a lack of cultural diversity or innovative ideas (McAllister and others 2006). The growth and conservation phase is generally slow, where as the release and reorganization phase, also known as the back-loop of the adaptive cycle, is fast. The release phase (Ω-phase) is often caused by a trigger or disturbance that releases built up resources in the system which then reorganizes (α-phase), this is the part of the cycle where innovation and opportunity are generated (Holling and others 2002). If the system is reorganized in a manner that is recognizable, in terms of structure and function, it is thought to be in the same domain of attraction. However, if the resilience of a system is eroded, a disturbance may shift the system beyond a threshold into a new regime with new state variables and feedbacks dominating (Holling and Gunderson 2002; Holling and others 2002; Peterson and others 1998). How this plays out can either be a slow, gradual shift, such as with climate change, or fast, as seen with the eutrophication of lakes (Folke and others 2004). Returning to the previous system may be difficult or even impossible because the new system can also be resilient. Although the adaptive cycle model provides a useful heuristic for understanding complex system changes, not all systems will complete a full cycle of the model; a release event may occur when the system is still in a growth phase. The intention is not to use the model to explain what is happening, but to give a sense what might be (Walker and others 2006).

This model is used to describe dynamics at one scale of interest, but stability and function at one scale of influence is not easily generalized to larger scales (Peterson and others 1998). Resilience researchers also developed a conceptual model called *panarchy* (Figure 2) consisting of a nested set of interacting adaptive cycles (Holling and others 2002; Peterson and others 1998). Within this model, cross-scale interactions are identified to explain how bottom-up and top-down dynamics can influence the scale above or below. The panarchy model identifies two cross-scale processes that are essential for system sustainability; *revolt* and *remember* (Holling and others 2002).The *revolt* dynamic demonstrates when a system has become rigid at multiple scales, a small disturbance can trigger a release event that crosses scales, such as a fire moving from a stand to the landscape level. The *remember* dynamic is the source of renewal for a smaller system that is undergoing reorganization and helps regulate patterns across landscapes (Holling and others 2002; Peterson 2002). For example, surrounding mature forests can provide seed sources for stands after a fire event. Memory in social systems can come in the form of trust or cooperation after years of collaboration, or in financial assistance from higher levels of organizations. Panarchy does not assume only three levels of influence, but illustrates that research interests should consider at least one scale above and below when investigating a phenomena. Applying the adaptive cycle and panarchy for resource management appears highly promising. In the context of WBP systems, this approach has the potential to address transboundary problems by nesting the systems and acknowledging that ecosystems operate across scales.

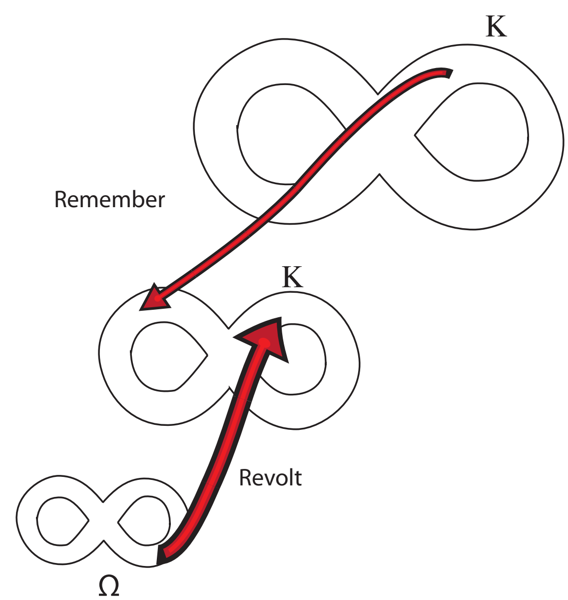

Figure 2. Panarchy—A set of nested adaptive cycles. Complex, self-organizing systems operate at multiple scales and across scales. Pattern and processes in ecosystems arise from the interplay of dynamics across scales.

Scale and Cross-scale Interactions

Scale is extremely important to consider in the natural world. Patterns and processes across a landscape arise from interplay among different spatial and temporal scales (Levin 2000). In the panarchy model, smaller and faster scales tend to induce change to the system above while larger and slower scales tend to constrain or conserve behaviour below (Carpenter and Turner 2000; Drever and others 2006; Peters and others 2007; Peterson and others 1998). Despite the apparent stability in this model, there is also danger that if a system is strongly connected across many scales, small disturbances at one scale can cascade through the system, which may have detrimental consequences (Drever and others 2006; Holling and others 2002; Raffa and others 2008). Cascading effects can flow from larger to smaller scales, and vice versa, as well as through the alteration of disturbance regimes (Folke and others 2004).

There are differences between scales of ecological systems and social systems. Social systems tend to be representative, including the actors and networks that make up the formal and informal mechanisms of governance (Cumming and others 2006). This is largely due to the fact that humans have foresight and act with intention; a quality not found in natural systems. Understanding scale presents new issues and uncertainty into the system when making decisions based in ecological research. Empirical data are difficult to measure across scales and management is often founded upon data collected at a restricted scale of interest (Cumming and others 2006). The subjectivity of the observer and organizational representation often contributes to a mismatch of scale between institutions and ecosystems.

Scale Mismatches and the Problem of Fit

Understanding how systems interact across scales is extremely important for understanding emergent behaviour that cannot be understood or predicted by focusing on one scale of interest (Peters and others 2007). However, these dynamics are not always as clear in social systems and mismatches between social and natural systems can become problematic (Levin 2000). Identifying mismatches may be crucial to develop strategies to maintain resilience. When the scale of social institutions that manage ecosystems and the scale of environmental variation of those ecosystems do not align, inefficiencies and disruptions of the social-ecological system, or important components are lost. This is what is termed a scale *mismatch* or *misfit* (Cumming and others 2006; Galaz and others 2008). Typically, there are three types of mismatches that are acknowledged in the literature; spatial, temporal and functional (Cumming and others 2006; Ekstrom and Young 2009; Young 2002)

Spatial mismatches are common. They can occur when the jurisdictional boundaries do not align with the ecological system boundaries. Some collaborative agency approaches have emerged to deal with landscape connectivity issues as a result of this. However, this does not ensure that a mismatch will be resolved. Another form of spatial mismatch can occur when centralized decisions are employed homogenously across landscapes without considering local biophysical differences (Galaz and others 2008).

Temporal mismatches can occur in a number of ways. For example, political cycles of planners and decision-makers may follow shorter cycles, perhaps every four years, but are making decisions on ecosystems that have evolved over hundreds or thousands of years. Inversely, environmental crises or surprise typically occur quickly by ecological standards, yet social responses to environmental change are slow (MacMynowski 2007).

Functional mismatches occur when institutions are unable to respond to the functionality and dynamics of the ecosystems they are managing (Ekstrom and Young 2009). A major source of misfit arises from a lack of knowledge, formal or informal, of ecological systems (Young 2002). Understanding when a threshold is being approached, or the consequences of management actions on other parts of the system, is highly uncertain. Often thresholds are only understood once they have been surpassed.

Ecosystem complexity and dynamics have inherent uncertainty which can make decision-making difficult, particularly when there are trade-offs to consider (Brown 2003). Misfits can arise from changes in variability of social or ecological systems, or dynamics from social-ecological interactions (Cumming and others 2006; Young 2002). However, the source of misfits may not be easy to identify and even more difficult to resolve. Due to the complexity of interactions within and across scales of social and ecological systems, a resolution to scalar mismatches will likely not occur at one scale, but require restructuring at multiple levels (Cumming and others 2006).

Whitebark Pine Resilience

Whitebark pine ecosystems are declining largely because of the mismatches we have created in our management regimes over the last 100 years. Despite the fact that much of WBP range is in wilderness areas and remote access areas (Keane 2000), anthropogenic stressors still negatively affect WBP populations. The levels of mortality through human drivers of change have threatened the very survival of this species in the long-term (Logan and others 2010). If whitebark pine were extirpated from these high-elevation regions, downstream hydrological impacts are likely, and the flashiness of run-off in spring may alter watershed dynamics (Ellison and others 2005; Yarnell and others 2010). Further potential consequences of loss over the long term could alter successional dynamics and further losses of biodiversity (Ellison and others 2005). Time lags, synergies and institutional/social barriers all have contributed to the current status of whitebark pine health. The implications for management are uncertain, particularly with potential climate change impacts for high-elevation forest dynamics.

Endogenous and Exogenous Stressors

Disturbance is a natural agent of renewal in social-ecological systems. Stressors can be endogenous or internal to system dynamics (such as fire regimes in WBP forests or staffing changes in an institution) or they can be exogenous, to the system (such as climate change or lack of funding).

Whitebark pine has a number of endogenous stressors that are natural sources of renewal. Fire regimes have been identified as a key ecological process that drives the structure and function of high-elevation forests. Mixed severity fires are most common in WBP stands, but large stand-replacing fires with a return interval of over 250 years tend to drive how it's distributed across the landscape (Keane 2000). Low severity fires, which WBP bark is adapted to resist, creates conditions favourable for seed dispersal by Clark's nutcrackers (Keane 2000; Resler and Tomback 2008). Avalanches also contribute to landscape patterns in high-elevation forests and are regulated by topography, snowpack and forest structure (Bebi and others 2009).

Mountain pine beetle have also played a role historically, with large outbreaks in the 1930's and 40's, and again in the 1970's (Brunelle and others 2008; Keane 2000; Logan and others 2010). They act as important sources of renewal by increasing the amount of woody debris on the forest floor, increasing streamflow in watersheds, and driving landscape heterogeneity (Raffa and others 2008). These disturbances act synergistically over space and time to drive the structure of WBP systems. For example, drought conditions may lead to larger stand-replacing fires, which reduces the amount of mature stands in an area, reducing the availability and suitability of host species for bark beetle outbreaks (Raffa and others 2008). Because these dynamics are internal to the system, the outcomes may be predictable when considering landscapes over longer time frames.

Exogenous stressors, on the other hand, are unpredictable and can alter dynamics across all scales of interest. Stressors outside the system tend to be anthropogenic. Climate change is a good example, and perhaps one of the greatest concerns for all social-ecological systems because changes are at the global scale. Scientists and managers are faced with the enormous challenge of managing ecosystems that may not behave as they have historically. Many researchers have asked the question whether studying historical ranges of variability will be useful for the future. Predictions of ecosystems shifting to higher elevations or latitudinal gradients could make it difficult for WBP to persist on the landscape (Logan and others 2010).

Another exogenous stressor for high-elevation WBP systems is white pine blister rust (WPBR) which has devastating effects over much of WBP range (Smith and others 2008). Introduced via infected white pine nursery trees in 1910, WPBR rapidly spread through much of the lower elevations of the white pine range by 1923 (Tomback and others 1995). Despite a complex life cycle that requires an alternate host (*Ribes*) to spread, this pathogen has been extremely successful in high-elevation WBP ecosystems where resistance to the rust has been estimated to occur in only 1 percent to 5 percent of the population (Tomback and others 1995). Elimination of the rust from the system is not considered an effective or possible strategy. Naturalization, which would shift WPBR from an external to internal stressor of the system through evolutionary adaptation is most desirable, assuming that management interventions of today will keep whitebark pine persisting on the landscape in the future.

Fire suppression is another exogenous stressor and a unique type of anthropogenic disturbance because it derives from the alteration of natural regimes, allowing less fire resistant species, subalpine fir and Engelmann spruce, to outcompete WBP and reduce the availability of microsite locations for natural regeneration processes (Keane 2000).

Threats to WBP are not homogenous; different regions are affected by a different set of stressors. For example, the Greater Yellowstone Ecosystem is primarily affected by an unprecedented level of mountain pine beetle infestations, while the Glacier-Waterton International Peace Park has high infection and mortality rates of WPBR (Berringer and others these proceedings, Logan and others 2010; Smith and others 2008). In most cases, it is the interaction of multiple disturbances that are responsible for WBP decline. Typically, WPBR does not kill a mature tree it infects for many years, but will kill cone-bearing branches, thus reducing the potential for regeneration and increases the ability for successional replacement of spruce and fir (Keane 2000). At some point, if cone production in a stand it too low, Clark's nutcrackers will begin to seek alternate food sources which may isolate stands, and thus reduce genetic diversity (McKinney and others 2009). Infected whitebark pine seedlings, on the other hand, will die within a couple years (Smith and others 2008). Moreover, blister rust weakens the tree, increasing its susceptibility to beetle attack or other agents.

Historically, bark beetles were constrained by cold winters, taking nearly three years to complete their life cycle in high-elevations. Increasing temperature from climate change has reduced that cycle to only one year, explaining why the current outbreak is considered to be outside the range of historical variation (Logan and others 2010).

Fire suppression has also contributed to unprecedented pine beetle outbreaks by creating the conditions that allow them to flourish (Raffa and others 2008). Looking at the adaptive cycle from the resilience literature, a mature forest is representative of the conservation phase (K-phase). By suppressing the natural agents for renewal, we allowed for the system to become too rigid and overconnected, thus increasing the potential for a larger disturbance event that may compromise the ability of the forest to regenerate within the same state domain. Since fire suppression was utilized over large landscapes and over long periods of time, the forest was too homogenous, and the MPB outbreak propagated across multiple scales, decimating the forest resources and the communities and institutions reliant upon them (Raffa and others 2008). Understanding interactions across space and time will be essential for increasing and maintaining resilience in WBP systems over the long term.

Conceptual Framework

Bounding the System—Study Site

The aim of this research is to identify mismatches of scale between institutions and ecosystems in WBP systems. We have chosen to bound our study in a regional transboundary context that reflects a diverse set of institutional scales. We have chosen to focus on the Crown of the Continent transboundary region for a number of reasons. First, it is considered to be a jurisdictionally fragmented region, representing institutions that range from federal levels of governance to individual households. Second, collaborative governance structures have begun to emerge from a desire to manage across scales by integrating EBM principles into management goals. Third, the geographic location of this area is centered between the northern and southern ranges of WBP ecosystems, and has the potential to serve as a core area for WBP regeneration in the face of climate change. Fourth, the region contains the Continental Divide, and is the source of water for many watersheds and agricultural regions downstream. Given the ecological role of WBP in watershed function, it provides an interesting social-ecological context for consideration. Finally, we are choosing to focus on WBP systems in the upper subalpine areas near treeline, where the role of WBP as a keystone species is most pronounced.

Proposed Framework and Methods

The theory and practice of understanding SES dynamics is still in its infancy, thus researchers are exploring new approaches to address the capacity of social systems to deal with uncertainty and change in managing natural systems over time (Folke 2006). A quantitative framework was recently suggested by Ekstrom & Young (2009) to assess the functional fit of institutions and ecosystems. The techniques described in their paper are intended to identify gaps in governance. The framework begins by creating an ecosystem model or matrix representing the system. The "ecosystem model" is generated around the ecosystem being managed or maintained, but includes identifying the key ecological and social components at multiple scales of the system in question. Then institutional data, which can be in the form of laws, management plans, meeting transcriptions or research, are collected and compared against the ecosystem model. Gaps are determined by the presence and absence of links acknowledged in the institutional data as compared with the ecosystem model, and a measurement of fit is produced for one or more regions.

We have adapted this model to determine the functional fit of institutions responsible for the recovery of WBP systems in the Crown of the Continent. To create the ecosystem model, we began by constructing a framework around conservation regimes for WBP recovery at multiple scales (Figure 3). The ecological components reflect the species-in-context approach by looking at specific species as well as more ecosystem-based dynamics. We began by considering genetic factors as well as other species connected to whitebark pine dynamics or its decline. Ecosystem functions are those processes that WBP systems provide as ecological goods and services. Ecosystem processes are those that are a source of renewal in the system, or are endogenous stressors. Only key components, derived mainly from literature on WBP research, are included in this representation of the ecosystem.

The social components focus on the management activities recommended for the recovery of WBP systems. Not all restoration tools are listed in this section, but multiple activities are considered under a single management action. For example, "cone caging" will also include cone collection for genetic seed bank storage and seedling production as that is the intention of the management action. We also included human values as a separate category because they can be a driver for conservation or may constrain the capacity of managers to act if not aligned with management goals. Anthropogenic stressors, despite being ecological in effect, are driven by human activity, thus are considered a social component in this framework. Furthermore, these exogenous stressors contribute high levels of uncertainty in the system, often without historical precedents that scientists and managers can draw upon to make better decisions. The WBP ecosystem model is then translated into matrix format by listing all the key ecological and social components identified in the conceptual framework along each axis (Table 1), then links between these components are identified.

The next phase of this research will be to collect the data to populate the framework. Institutional data will be collected through semi-structured interviews rather than through document review for two reasons. First, we have assumed that because the issue of whitebark pine decline is relatively new as a conservation priority, it is unlikely that ecosystem links are being acknowledged in documentation or that such documentation has been fully developed. Second, management prescriptions on paper may not get implemented on the ground (Ekstrom and Young 2009). Therefore, interviews will be used to collect the most accurate, current data for WBP systems, however an analysis of documentation may be considered later if additional data is required. The analysis of the data will also use a weighted representation of the ecosystem model to include priorities of concern for whitebark pine recovery.

Institutional mechanisms, such as learning, trust, and co-operation across jurisdictions, will not be included in the matrix, although it is our intention to address them in the semi-structured interviews. Recommendations to improve resilience will be made to improve transboundary management of WBP ecosystems. This research may further provide a framework for researchers working on other five-needled pine species, where the social-ecological context may have different feedbacks and structures to consider.

Conclusion

Whitebark pine systems are losing resilience, and adaptive approaches that try to cope with surprise may be insufficient without considering the social-ecological context. By gaining a better understanding of the capacity of institutions in managing ecosystem dynamics across scales, and where mismatches between them occur, we may be able to craft a better strategy to manage resilience in high-elevation ecosystems. With increased uncertainty due to climate change threats, adaptation will be essential for humans to cope with environmental change. How information is shared, learned and trusted across social-political boundaries will influence resilience, particularly in transboundary nations embodying multiple levels of governance.

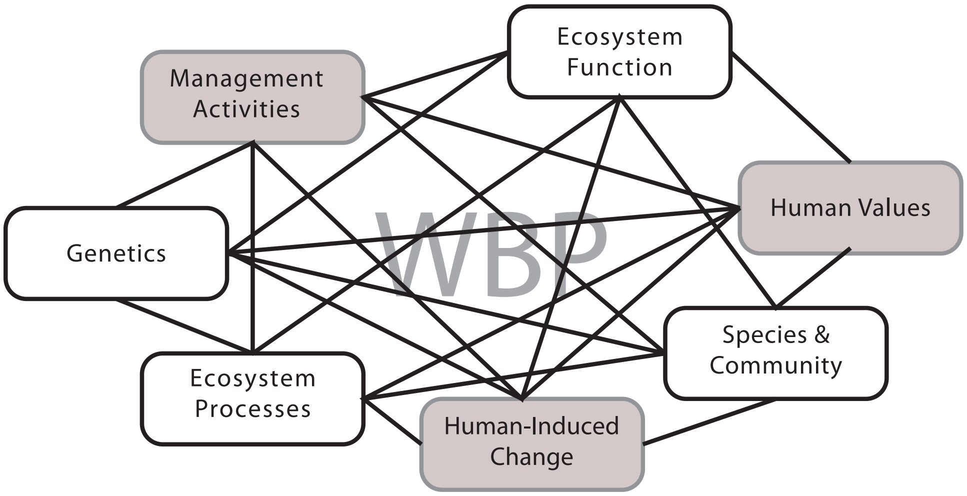

Figure 3. Conceptual framework—Component of whitebark pine restoration as a social-ecological system. Connections at the genetic, species and community levels are considered within high-elevation forests. Also, important functions and processes are included to capture cross-scale interactions that are essential to maintaining and restoring WBP populations. Social components consist of anthropogenic stressors, management activities and human values.

Table 1 - Proposed ecosystem matrix [a] - key ecological and social components at multiple scales as adapted from literature and relationships between variables are identified.

			rust resistance	whitebark pine	Clark's Nutcracker	squirrel/bear	mychorrizal fungi	*Ribes*	snow	slope stability	dispersal	establishment	competition	pine beetle	fire	white pine blister rust	fire suppression	climate change	cone caging	planting	pheremone	site alteration	aesthetic	recreation
ECOLOGICAL	**Genetic**	rust resistance	-	1	0	0	0	0	0	0	1	0	0	0	0	1	?	0	1	1	0	0	0	0
	Species & Community	whitebark pine	-	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Clark's Nutcracker	-	-	-	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	1	1	1
		squirrel/bear	-	-	-	-	0	?	0	0	0	0	0	0	0	0	0	0	?	0	0	0	1	1
		mychorrizal fungi	-	-	-	-	-	0	0	0	0	1	0	0	?	0	0	?	0	1	0	?	0	0
		Ribes	-	-	-	-	-	-	0	0	0	0	0	0	0	1	?	?	0	0	0	1	0	0
	Processes & Ecosystem Function	snow	-	-	-	-	-	-	-	1	0	1	0	0	0	0	0	1	0	1	0	0	1	1
		slope stability	-	-	-	-	-	-	-	-	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		dispersal	-	-	-	-	-	-	-	-	-	1	0	0	1	1	1	?	0	1	0	1	0	0
		establishment	-	-	-	-	-	-	-	-	-	-	?	0	1	1	?	1	0	1	0	1	0	0
		competition	-	-	-	-	-	-	-	-	-	-	-	?	1	?	1	1	0	0	0	1	0	0
		pine beetle	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	0	0	1	1	1	?
		fire	-	-	-	-	-	-	-	-	-	-	-	-	-	?	1	1	0	0	0	1	1	1
SOCIAL	**Human-Induced Change**	white pine blister rust	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	0	0	1	0
		fire suppression	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0	0	0	1	?	0
		climate change	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0	0	0
	Management Activities	cone caging	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	0	?	0
		planting	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	1	0	0
		pheremone	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
		site alteration	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
	Human Values	aesthetic	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
		recreation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

1 connected
0 not connected
? uncertain/ may be connected

.[a] matrix to be further developed and clarified through key-informant interviews

References

Allenby, B. 2004. Managing Earth Systems In the Anthropocene. Environmental Forum. 21(6): 42-43.

Bebi, P., D. Kulakowski, and C. Rixen. 2009. Snow Avalanche Disturbances in Forest Ecosystems—State of Research and Implications for Management. Forest Ecology and Management. 257(9): 1883-1892.

Brown, K. 2003. Integrating Conservation and Development: A Case of Institutional Misfit. Frontiers in Ecology and the Environment. 1(9): 479-487.

Brugnach, M., A. Dewulf, C. Pahl-Wostl, and T. Taillieu. 2008. Toward a Relational Concept of Uncertainty: about Knowing Too

Little, Knowing Too Differently, amd Accepting Not to Know. Ecology and Society. 13(2): 1-16.

Brunelle, A., G. E. Rehfeldt, B. Bentz, and A. S. Munson. 2008. Holocene Records of Dendroctonus Bark Beetles in High Elevation Pine Forests of Idaho and Montana, USA. Forest Ecology and Management. 255(3/4): 836-846.

Carpenter, S. R., and M. G. Turner. 2000. Hares and Tortoises: Interactions of Fast and Slow Variables in Ecosystems. Ecosystems. 3(6): 495-497.

Cumming, G. S., D. H. M. Cumming, and C. L. Redman. 2006. Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. Ecology & Society. 11(1): 164-183.

Drever, C. R., G. Peterson, C. Messier, Y. Bergeron, and M. Flannigan. 2006. Can Forest Management Based on Natural Disturbances Maintain Ecological Resilience? Canadian Journal of Forest Research. 36(9): 2285-2299.

Ekstrom, J. A., and O. R. Young. 2009. Evaluating Functional Fit between a Set of Institutions and an Ecosystem. Ecology & Society. 14(2): 1-18.

Ellison, A. M., M. S. Bank, D. C. Barton, E. A. Colburn, K. Elliott, C. R. Ford, D. R. Foster et al. 2005. Loss of Foundation Species: Consequences for the Structure and Dynamics of Forested Ecosystems. Frontiers in Ecology and the Environment. 3(9): 479-489.

Estes, J. A., and D. O. Duggins. 1995. Sea Otters and Kelp Forests in Alaska: Generality and Variation in a Community Ecological Paradigm. Ecological Monographs. 65(1): 75-100.

Folke, C. 2006. Resilience: The Emergence of a Perspective for Social-ecological Systems Analyses. Global Environmental Change Part A: Human & Policy Dimensions. 16(3): 253-267.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. H. Gunderson, and C. S. Holling. 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. Annual Review of Ecology, Evolution & Systematics. 35(1): 557-581.

Galaz, V., T. Hahn, P. Olsson, C. Folke, and U. Svedin. 2008. The Problem of Fit between Ecosystems and Governance Systems: Insights and Emerging Challenges *in* O. R. Young, L. A. King, and H. Schroeder, eds. The Institutional Dimensions of Environmantal Change: Principle Findings and Future Directions. Boston, MA, USA, MIT Press.

Geist, C., and S. M. Galatowitsch. 1999. Reciprocal Model for Meeting Ecological and Human Needs in Restoration Projects. Conservation Biology. 13(5): 970-979.

Gunderson, L. H. 2000. Ecological Resilience—In Theory and Application. Annual Review of Ecology and Systematics. 31: 425-439.

Holling, C. S. 1973. Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics. 4: 1-23.

Holling, C. S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. Ecosystems. 4(5): 390-405.

Holling, C. S., and L. Gunderson. 2002. Resilience and Adaptive Cycles, Pages 25-62 *in* L. Gunderson, and C. S. Holling, eds., Panarchy: Understanding Transformations in Human and Natural Systems. Washington DC, USA, Island Press.

Holling, C. S., L. H. Gunderson, and G. D. Peterson. 2002. Sustainaibilty and Panarchies, Pages 63-102 *in* L. H. Gunderson, and C. S. Holling, eds., Panarchy: Understanding Transformations in Human and Natural Systems. Washington DC, USA, Island Press.

Keane, R. E. 2000. The Importance of Wilderness to Whitebark Pine Research and Management, Pages 9 *in* S. F. McCool, D. N. Cole, W. T. Borrie, and J. O'Laughlin, eds., Wilderness Science in a Time Of Change. Missoula, MT, USDA, Forest Service Proceedings.

Kotchen, M. J., and O. R. Young. 2007. Meeting the Challenges of the Anthropocene: Towards a Science of Coupled Human-biophysical Systems. Global Environmental Change Part A: Human & Policy Dimensions. 17(2): 149-151.

Lebel, L., J. M. Anderies, B. Campbell, C. Folke, S. Hatfield-Dodds, T. P. Hughes, and J. Wilson. 2006. Governance and the Capacity to Manager Resilience in Regional Social and Ecological Systems. Ecology and Society. 11(1): 230-250.

Levin, S. A. 2000. Multiple Scales and the Maintenance of Biodiversity. Ecosystems. 3(6): 498-506.

Logan, J. A., W. W. MacFarlane, and L. Willcox. 2010. Whitebark Pine Vulnerability to Climate-driven Mountain Pine Beetle Disturbance in the Greater Yellowstone Ecosystem. Ecological Applications. 20(4): 895-902.

Ludwig, J. A., and M. D. S. Smith. 2005. Interpreting and Correcting Cross-scale Mismatches in Resilience Analysis: A Procedure and Examples from Australia's Rangelands. Ecology & Society. 10(2): 353-359.

MacMynowski, D. 2007. Across Space and Time: Social Responses to Large-Scale Biophysical Systems. Environmental Management. 39(6): 831-842.

McAllister, R. R. J., N. Abel, C. J. Stokes, and I. J. Gordon. 2006. Australian Pastoralists in Time and Space: The Evolution of a Complex Adaptive System. Ecology & Society. 11(2): 687-702.

McKinney, S. T., C. E. Fiedler, and D. F. Tomback. 2009. Invasive Pathogen Threatens Bird-pine Mutualism: Implications for Sustaining a High-elevation Ecosystem. Ecological Applications. 19(3): 597-607.

Peters, D. P. C., B. T. Bestelmeyer, and M. G. Turner. 2007. Cross-Scale Interactions and Changing Pattern-Process Relationships: Consequences for System Dynamics. Ecosystems. 10(5): 790-796.

Peterson, G., C. R. Allen, and C. S. Holling. 1998. Ecological Resilience, Biodiversity, and Scale. Ecosystems. 1(1): 6-18.

Peterson, G. D. 2002. Contagious Disturbance, Ecological Memory, and the Emergence of Landscape Pattern. Ecosystems. 5(4): 329-338.

Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. BioScience. 58: 501-517.

Rauscher, H. M. 1999. Ecosystem Management Decision Support for Federal Forests in the United States: A Review. Forest Ecology & Management. 114(2/3): 173-197.

Resler, L. M., and D. F. Tomback. 2008. Blister Rust Prevalence in Krummholz Whitebark Pine: Implications for Treeline Dynamics, Northern Rocky Mountains, Montana, U.S.A. Arctic, Antarctic & Alpine Research. 40(1): 161-170.

Simberloff, D. 1997. Flagships, Umbrellas, and Keystones: Is Single-species Management Passe in the Landscape Era. Biological Conservation. 83(3): 247-257.

Smith, C. M., B. Wilson, S. Rasheed, R. C. Walker, T. Carolin, and B. Shepherd. 2008. Whitebark Pine and White pine Blister Rust in the Rocky Mountains of Canada and Northern Montana. Canadian Journal of Forest Research. 38(5): 982-995.

Steffen, W., P. J. Crutzen, and J. R. McNeill. 2007. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature? AMBIO—A Journal of the Human Environment. 36(8): 614-621.

Tomback, D. F. 1982. Dispersal of Whitebark Pine Seeds by Clark's Nutcracker: A Mutualism Hypothesis. Journal of Animal Ecology. 51(2): 451-467.

Tomback, D. F., J. K. Clary, J. Koehler, R. J. Hoff, and S. F. Arno. 1995. The Effects of Blister Rust on Post-Fire Regeneration of Whitebark Pine: The Sundance Burn of Northern Idaho (U.S.A.). Conservation Biology. 9(3): 654-664.

Tomback, D. F., and L. M. Resler. 2007. Invasive Pathogens at Alpine Treeline: Consequences for Treeline Dynamics. Physical Geography. 2(5)8: 397-418.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human Domination of Earth's Ecosystems. Science. 277(5325): 494-499.

Walker, B., L. Gunderson, A. Kinzig, C. Folke, S. Carpenter, and L. Schultz. 2006. A Handful of Heuristics and Some Propositions for Understanding resilience in Social-Ecological Systems. Ecology & Society. 11(2): 80-94.

Walker, B., C. S. Holling, S. R. Carpenter, and A. P. Kinzig. 2004. Resilience, Adaptability and Transformability in Social-ecological Systems. Ecology and Society 9:9pp [online] http://www.ecologyandsociety.org/vol9/iss2/art5/.

Walker, B., and D. Salt. 2006, Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Washington, DC, Island Press.

Westley, F., S. Carpenter, W. A. Brock, C. S. Holling, and L. Gunderson. 2002. Why Systems of People and Nature Are Not Just Social and Ecological Systems, Pages 103-120 *in* L. H. Gunderson, and C. S. Holling, eds., Panarchy: Understanding Transformations in Human and Natural Systems. Washington DC, USA, Island Press.

Yarnell, S. M., J. H. Viers, and J. F. Mount. 2010. Ecology and Management of the Spring Snowmelt Recession. BioScience. 60(2): 114-127.

Young, O. R. 2002, The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale. Cambridge, Cambridge University Press, UK.

Zurlini, G., K. Riitters, N. Zaccarelli, I. Petrosillo, K. B. Jones, and R. L. 2006. Disturbance Patterns in a Socio-ecological System at Multiple Scales. Ecological Complexity. 3(2): 119-128.