Adaptive capacity in social-ecological systems: A framework for addressing bark beetle disturbances in natural resource management

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Abstract

The ability of natural resource agencies to act before, during, and after outbreaks of conifer bark beetles (Coleoptera: Curculionidae) is important to ensure the continued provision of ecosystem services. Adaptive capacity refers to the capability of an agent or system to adapt to change, regardless of whether it is examined as an independent social or ecological entity, or as a coupled social-ecological system. Understanding the components of a disturbance and the associated effects to ecosystem services, social systems, and natural resource management increases the ability to adapt to change and ensure continued resilience. This paper presents a definition and conceptual framework of adaptive capacity relevant to bark beetle disturbances that was developed through an interdisciplinary workshop held in 2016. The intent is to assist natural resource managers and policymakers in identifying important adaptation characteristics to effectively address bark beetle disturbances. The current state of knowledge regarding institutional, social, and environmental factors that influence adaptive capacity are identified. The mountain pine beetle (*Dendroctonus ponderosae*) in the western USA is used as a specific example to discuss several factors that influence adaptive capacity for increasing resilience. We hope that that our proposed framework serves as a model for future collaborations among both social and physical scientists and land managers to better address landscape-level disturbances that are being exacerbated by climate change.

Key words: adaptation, ecosystem services, forest disturbance, insect outbreaks, resilience, socio-ecological systems

Introduction

In forest ecosystems worldwide, climate change is expected to amplify the frequency and severity of disturbance regimes (Seidl et al. 2017), which will further challenge the readiness of natural resource management agencies, managers and stakeholder groups to prepare for, respond to, and adapt to environmental change. Forest disturbances such as outbreaks of conifer bark beetles (Coleoptera: Curculionidae) and other insects, wildfires, and wind events tend to negatively affect the provisioning of ecological goods and services (Boyd et al. 2014; Seidl et al. 2016). When coupled with increasing land-use pressures, future environmental change will likely lead to diminished capabilities of forest ecosystems to provide the critical ecosystem services on which human society depends (Lindner et al. 2010; Seidl et al. 2015). Therefore, changes in forest dynamics that may result from the combined impacts of climate change and intensifying disturbance regimes present a significant challenge to humankind (Chapin et al. 2009). In anticipation of these changes, research that quantifies the human dimensions of forest disturbances, both in terms of causes and consequences, has become increasingly important in identifying the mechanisms that promote positive and sustainable social and ecological outcomes (Smit and Wandel 2006).

Science and policy discussions on ecosystem resilience to disturbance increasingly emphasize the role of adaptive capacity (AC) (Folke 2006; Kiparsky et al. 2012). In a broad sense, AC refers to the capability of a system to adapt to change, regardless of whether it is examined as an independent social or ecological entity, or as a coupled social-ecological system (SES). The concept of AC has not been defined and conceptualized specifically for bark beetle disturbances in a natural resource management context. Better characterization of AC is needed for the natural resource management community, especially in the face of climate change (Nelson et al. 2015). To improve understanding of the connections among bark beetle disturbances, ecosystem services, and management options for maintaining resilience, a framework is necessary to enhance the capability of a SES to respond to disturbance and mitigate negative impacts to ecosystem services. In this way, a greater degree of AC would foster enhanced forest ecosystem resistance and resilience (Engle 2011; Marshall and Smajgl 2013; Smit and Wandel 2006).

This paper presents a definition and conceptual framework of AC in bark beetle prone forest systems, based on a literature review of 101 scientific documents relevant to bark beetle disturbances, developed through an interdisciplinary workshop held in 2016. Three main categories of AC (environment, society, and ecosystem services) were identified and used to construct this framework. The intent is to assist natural resource managers and policymakers in identifying important adaptation characteristics to effectively address bark beetle disturbances within a SES context. Mountain pine beetle (*Dendroctonus ponderosae*, MPB) is used as an example of a focal stressor in this paper. We were motivated by previous work that identified 25 research questions as priorities for academic research and land management for bark beetles at a workshop in Santa Fe, New Mexico, USA in 2015 (*see* Morris et al. 2017; Morris et al. 2018). One question: “What actions can land managers, policymakers and stakeholders take to bolster the adaptive capacity of social–ecological systems to bark beetle outbreaks?” (Morris et al.

2017, p. 752, Q12) was of particular relevance. Our work is timely because recent bark beetle outbreaks have challenged longstanding community values and management paradigms, especially in regions that had not otherwise experienced a severe epidemic during recorded history (Morris et al. 2018; Fettig 2019). In many instances, land management agencies, governance institutions, and the public and private sectors were required to develop and/or augment approaches to address, and in some cases suppress, outbreaks. For example, more frequent detection and survey techniques may be required to better assess the intensity, spatial extent, and synchrony of outbreaks (Bentz et al. 2010). Recent bark beetle outbreaks in western North America and Europe provide a critical opportunity to build a knowledge base specific to the adaptive strategies that were developed and implemented by affected communities through governance institutions, including natural resource managers.

Bark Beetle Outbreaks

Insects influence forest ecosystem structure and function by regulating certain aspects of primary production, nutrient cycling, ecological succession, and the size, distribution and abundance of forest trees (Mattson and Addy 1975; Schowalter 1981). Elevated insect activity reduces tree growth and hastens decline, mortality and subsequent replacement by other tree species and plant associations. In particular, outbreaks of native bark beetles in North America and Europe have produced striking changes to the structure, composition, and function of forest ecosystems in recent decades (Fettig 2019; Marini et al. 2017). Many traits that influence the success of bark beetles are temperature dependent, and recent shifts in temperature (and precipitation) attributed to climate change have resulted in increases in voltinism (numbers of generations per year), overwintering success and host drought stress causing increases in the severity of some bark beetle outbreaks (Bentz et al. 2010; Kolb et al. 2016). Forest densification has exacerbated the effect in many forests (Fettig et al. 2007). For example, a severe drought in the central and southern Sierra Nevada Mountains of California, USA during 2012–2015 incited outbreaks of a native conifer bark beetle, western pine beetle (*Dendroctonus brevicomis*), resulting in substantial (>90%) mortality of dominant and co-dominant trees (Fettig et al. 2019). The level of tree mortality that has occurred is considered to be unprecedented (Stephens et al. 2018) and will influence many ecosystem services over time. In Europe, outbreaks of the European spruce bark beetle (*Ips typographus*) are most impactful (Schelhaas et al. 2003), but generally result in lower rates of tree mortality than has been observed with several North American *Dendroctonus* species.

Looking towards the future, epidemic populations of conifer bark beetles are forecasted to expand beyond their historical range and encroach into new regions (Bentz et al. 2019), as has already been demonstrated in the MPB in western Canada (Cullingham et al. 2011). In Europe, warming temperatures are increasing the area of spruce habitat that supports two rather than one generation per year of European spruce bark beetle (Netherer et al. 2015) and a higher number of sister broods (i.e., a phenomenon by which female European spruce bark beetle complete oviposition in a host, re-emerge and continue oviposition in a second host without the need to mate; Davídková and Doležal 2017). Both are likely to result in increased impacts. In response to expanding outbreaks, newly published work has called for a broad synthesis of research and policy gathered from recently affected landscapes for transfer and dissemination to natural resource managers and stakeholders in potential host regions (Morris et al. 2018).

Adaptive Capacity Definitions and Frameworks

Responding effectively to bark beetle outbreaks requires transparent and accessible methods to assess adaptive capacity. While various frameworks for assessing AC exist (Cutter et al. 2008; Gallopín 2006; Hinkel 2010; Hopkins 2014; Palmer et al. 2014; Phillips 2014), a key theme in the published literature is that AC is often context-specific and varies from country to country, community to community, and among social groups and individuals through time. AC varies not only in terms of its perceived value but also according to its nature because it is reflective of the resources, knowledge and processes within a given region (Smit and Pilifosova 2003; Smit and Wandel 2006; Yohe and Tol 2002). When assessing AC it is important to consider the assets that agents have at their disposal to adapt, and also the resources and processes whereby institutions guide human behavior, knowledge generation and dissemination, introduction of novel practices and technologies, and governance decision making (Hogarth and Wojcik 2016).

Depending on the timing of implementation, adaptations to environmental change can be proactive or reactive, and can also be spontaneous or planned (Fankhauser et al. 1999; Smit et al. 2000). Brooks (2003) describes adaptation as ‘‘adjustments in a system’s behavior and characteristics that enhance its ability to cope with external stress.’’ Recent studies have proposed adaptation strategies for systems affected by climate change (Seidl and Lexer 2013). Framed in a climate change context, Smit et al.

(2000) refer to adaptations as ‘‘adjustments in ecological-socio-economic systems in response to actual or expected … stimuli, their effects or impacts.’’ Also, in a climate change context, Pielke (1998) defined adaptation as ‘‘adjustments in individual groups and institutional behavior in order to reduce society’s vulnerability to climate.’’ Taken together, adaptations are considered responses to risks associated with the interaction of environmental hazards and human vulnerability. Common variables included in multiple-criteria approaches are benefits, costs, ease of implementation, effectiveness, efficiency, and equity (Adger et al. 2005; Fankhauser et al. 1999; Feenstra et al. 1998; Smith et al. 1998). Such analyses assume there exists, in practice, a process through which adaptation strategies are selected and implemented, and that the relative evaluation analysis fits into this process (Smit and Wandel 2006). Studies on AC tend to focus on the relative vulnerability of geographic units, such as countries, regions or communities, rather than abstract systems, and involve comparing proposed strategies on the basis of multiple criteria (Adger et al. 2004; Brooks et al. 2005; Kelly and Adger 2000; O’Brien et al. 2004a; Rayner and Malone 2001; Van der Veen and Logtmeijer 2005). In these studies, vulnerability (i.e., exposure or risk) is taken as the ‘‘starting point’’ rather than the residual or ‘‘end point’’ (O’Brien et al. 2004b), and it is assumed to be measurable based on *a priori* attributes or determinants (Smit and Wandel 2006).

Application of AC in natural resource management requires integration of tools from a diversity of sub-disciplines that include community development, risk management, planning, food security, livelihood security, and sustainable development, among others (Smit and Pilifosova 2003; Smit and Wandel 2006; Yohe and Tol 2002). In this context, the AC concept directly interacts with the practices and processes of adaptation, although the specific term “adaptation” may not be explicitly used (Gittell and Vidal 1998; Sanderson 2000). Research focuses on documenting how the resource system and an associated community responds to changing conditions, and the consequent associated decision-making processes that result in effective adaptation or provide a means of improving AC (Ford and Smit 2004; Keskitalo 2004; Vásquez-León et al. 2003). An essential characteristic of resource-based AC approaches is that they rely on the experience and knowledge of community members (traditional ecological knowledge) to characterize pertinent conditions, community sensitivities, adaptive strategies, and decision-making processes related to AC (i.e., bottom-up approach) (Smit and Wandel 2006).

Over the past two decades, there has been a growing body of literature on institutional and governance determinants and indicators of AC in different SES (Engle and Lemos 2010; Folke et al. 2005; Gupta et al. 2010; Pelling and High 2005). Common factors considered can be categorized into the following groups; economic resources, technology, information and skills, infrastructure, institutions, equity, social capital, and collective action (Brooks et al. 2005; Engle and Lemos 2010). Across these broad determinants, there has been wide recognition of the importance of integrating institutions and governance mechanisms towards building AC at local and regional levels (Adger et al. 2005). Specifically, these different studies highlight the importance of governance indicators, such as information and knowledge, experience and expertise, networks, transparency, trust, commitment, legitimacy, accountability, connectivity and collaboration, flexibility, and leadership (Hill and Engle 2013).

Without institutional capacity, equity, and social capital, natural resource managers are challenged to increase ecological resilience at meaningful scales (Dietz et al. 2003). Capacity building has been identified as a critical component of an institutional framework that seeks to reduce vulnerability (Huber et al. 2013). As recognition of the role of institutions in developing AC has increased, researchers have developed assessment frameworks to address institutional adaptations (Gupta et al. 2010). Adaptation constraints are those factors that make it harder to plan and implement adaptation actions and include socio-cultural, structural and psychological dimensions that, while often mutable, can combine to undermine AC (Adger et al. 2009; Ensor et al. 2015; Lorenzoni et al. 2007; Moser and Ekstrom 2010).

Adaptive Capacity and Bark Beetle Management

Morris et al. (2017, 2018) highlighted gaps in the published literature on bark beetle disturbances and impacts to SES, identifying 25 priority research questions specific to adaptive strategies and knowledge transfer. While their work did not specifically address definitions of AC, adaptation initiatives were highlighted as a key research area where advances could be pursued.

Current examples from the literature rely on region-specific approaches to inform societal responses to bark beetle outbreaks, especially when environmental information can be tailored to affected communities and landscapes (Smit and Wandel 2006). The adaptation-focused literature reviewed by Morris et al. (2017, 2018) can be categorized into four broad thematic areas that seek to quantify and describe: 1) the dynamics of forest ecosystems; 2) how forest disturbance regimes (e.g., bark beetle outbreaks) disrupt environmental goods and services; 3) the dynamics of stakeholder groups and associated communities; and 4) how forest management activities affect forest ecosystems. Although Morris et al. (2017, 2018) examined adaptation to outbreaks within a SES context, most studies reviewed focused on the ecological outcomes from bark beetle disturbances. There are fewer studies that address the economic and institutional dynamics, and fewer still that address all four dimensions of sustainability holistically and the associated roles of each simultaneously within a SES (Morris et al. 2017, 2018). This paper attempts to help address these limitations.

Among stakeholder groups, the role of cognitive factors, such as perceived risk, perceived AC, awareness, beliefs, attitude and approaches towards uncertainty have generally been underexplored in the literature. For instance, stakeholder awareness of environmental change issues is often limited by the quantity and accessibility of information and knowledge, as well as access to learning and engagement programs that enable the effective and efficient dissemination of adaptation strategies and practices (Mattor et al. 2018). Outside of private lands and related stakeholders, public natural resource agencies differ in that they require legislation, policies, and social acceptance (license) to enable adaptation. It is important that public natural resource management agencies leverage social, political and fiscal capital and include stakeholders in project planning. However, in some cases, given sufficient knowledge and tools, it is unclear whether public natural resource management agencies and managers have sufficient authority, mandate, and autonomy to identify and implement adaptation at even local scales. Challenges to such implementation include political pressures, lack of access to the academic or grey literature, and limited funding and manpower (Mattor et al. 2018; McGrady et al. 2016; Morris et al. 2017). The goal of the conceptual framework presented here is to outline the key, underexplored components of bark beetle disturbance and associated effects to ecological goods and services, social systems, and natural resource management. The intent is to increase the ability to effectively address bark beetle disturbances and ensure continued resilience by identifying important, if poorly studied adaptation characteristics.

Methods

A two-step methodology was used to develop an AC definition and conceptual framework for bark beetle disturbances: 1) review of AC literature, and 2) an interdisciplinary workshop that brought together experts across diverse fields. A literature review of AC and how it's affected by institutional, social and environmental factors, and the associated strategies for enhancing AC in a natural resource management context informed framework development.

In the first phase of the review, 101 documents which included 97 peer-viewed articles and four technical documents (*see* Appendix A) were drawn from the scientific literature based on AC theory, AC frameworks, AC indicators and measures, institutional and socio-ecological criteria. Relevant articles were identified through a keyword search in Science Direct, Google Scholar, and Academic Search Premier search engines available at Colorado State University. Keywords included adaptive capacity, forest management, bark beetle disturbance, mountain pine beetle, vulnerability, and resilience, as well as combinations of these keywords.

All articles were "rated" on an "F" to "A+" scale that we developed for the purposes of this review. Articles were rated according to how closely the content related to AC and bark beetle management. Articles which discussed AC frameworks and/or forest disturbance were rated as "A+" articles (note: the rating was not an indicator of scientific quality of the paper).

The second phase narrowed the list to 42 documents (yellow highlights Appendix A) based on an A-rating from the fore-mentioned criteria. From that list 19 papers with A+ ratings (*see* yellow/bold highlights Appendix A) with clearly noted AC concepts, AC indicators, AC frameworks, reference to sustainability dimensions as well as implications for SES were selected for review and discussion during the workshop.

Definitions specific to AC instructive for tailoring a definition to bark beetle disturbances and natural resource management were then identified by the workshop organizers (Cottrell, Mattor and Morris) from the 19 papers. These definitions were used to guide an interdisciplinary workshop held at Colorado State University in Fort Collins, Colorado, USA 24–25 October 2016 with 16 social and physical scientists. Social and physical scientists were selected for invitation based on their contributions to the fields of bark beetle disturbance and/or AC in natural resource management (*see* Appendix B).

Work on bark beetle related topics were identified from Colorado State University, Forest Service and published literature focused on bark beetle research and adaptive capacity in natural resource management (*see* Appendix B). A range of disciplines and sub-disciplines (forest management, fire management, political governance, forest health, ecology, climate change, etc.) were represented, spanning the social and physical sciences and qualitative, quantitative, and mixed-methods analytical approaches. Workshop participants were asked to review 12 primary definitions of AC culled from the literature review (Table 1) and rank three definitions most relevant to their area of specialization.

A five-step nominal group technique (NGT), a structured group brainstorming decision-making process (Greenberg 2002), was used for the ranking process. NGT steps included: Step 1, individually ranked top three definitions; Step 2, each participant openly explained the reasoning for their top three definitions; Step 3, open discussion about the rankings for clarification and adjustments (if necessary); Step 4, tallying the top three definitions on a flip chart; Step 5, open discussion of the top three definitions. The group discussion that followed identified key thematic components among the preferred definitions.

<< INSERT TABLE 1 APPROXIMATELY HERE >>

After selecting definitions, workshop participants crafted a singular definition of AC for bark beetle disturbances that included consideration of the following criteria drawn from the literature review: 1) probability of current and forecasted risk of outbreaks, 2) perceptions of agency, efficacy, and risk, 3) spatial scale and context specific environmental conditions, 4) measurement of risk, and 5) role of uncertainty.

This exercise culminated in a definition of AC for bark beetle disturbances and transitioned to the development of a conceptual framework for further operationalizing AC for management of bark beetle disturbances. We initiated the conceptual framework design through a review of six AC frameworks (Table 2). These frameworks were pertinent to the discussion because they emphasize the relationships of vulnerability, exposure, sensitivity, and AC, and reactions to stressors in the environment, particularly climate change and bark beetle disturbance. The resulting definition and framework are outlined below.

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Results and Discussion

Defining Adaptive Capacity

Workshop participants reviewed 12 definitions of AC from the literature review and converged on the three definitions most pertinent to bark beetle social-ecological systems (non-shaded definitions in Table 1) through NGT. From this process, AC was defined "as the preconditions necessary for a SES to adapt to disturbances in a proactive and/or reactive manner." It is important to note that SES are connected human (actors, individuals, and groups) and natural systems (biological and physical elements, components, and processes). In the bark beetle context, AC is affected by the scale and intensity of the disturbance, as well as the perceptions of risk, availability of capital (social, human, and economic), and cross-jurisdictional management and governance opportunities (local, regional, national, and global processes) within the human system.

Conceptual Framework of Adaptive Capacity

Participants identified important elements from existing frameworks to include in the conceptual framework of AC for bark beetle disturbances presented in Figure 1.

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Three main categories are identified in the AC framework: 1) environment including the stressor (i.e., MPB), exposure (i.e., system connectivity) and sensitivity (i.e., forest health) factors; 2) society including impacts (i.e., metrics), public opinion (i.e., communication, perceptions and attitudes), and management (i.e., proactive & reactive); and 3) ecosystem services including aesthetics, air quality, carbon sink/source, timber resources and water quality/quantity. This framework identifies a multi-dimensional relationship where environmental aspects influence ecosystem services, which in turn influence societal factors that affect forest management actions, which influence the environment and overall SES adaptation to bark beetle disturbances. Below we discuss factors that influence AC for increasing resilience to bark beetles using MPB in western North America as an example. As such, this conceptual model potentially provides managers and policymakers a framework for identifying local or regional limitations to AC in hopes of addressing these in the future. This conceptual framework focuses on increasing SES resilience to bark beetles by minimizing undesirable impacts to ecosystem services associated with changes in forest structure and composition, but is likely applicable to other disturbances (e.g., fire).

Environmental factors

Mountain pine beetle is identified as the focal stressor in this paper. The SES vulnerability is characterized by the levels of exposure to the stressor, its sensitivity, and the existence of policy management approaches to address the stressor.

Stressor

Bark beetles are important agents of change in many conifer forests and their impacts often exceed that of wildfire (Hicke et al. 2016). MPB is one of the most significant native forest insect in North America, and colonizes at least 15 tree species (Negrón and Fettig 2014). The first epidemic was recorded in the Black Hills of South Dakota, USA in

1895 (Blackman 1931). Since then, a century of research in western North America has yielded significant insight into the ecology of this species. Like some other bark beetles, MPB uses a complex system of semiochemicals (i.e., chemicals released by one organism that elicit a response, usually behavior, in another organism) in host location, selection, colonization, and mating behaviors (Progar et al. 2014; Seybold et al. 2018). Once a host tree is selected, colonization requires overcoming constitutive and inducible tree defenses, which include anatomical, physical, and chemical components (Franceschi et al. 2005). Tree death occurs only when a critical minimum number of beetles are attracted to the host tree.

Exposure

Exposure is a function of proximity and severity of adjacent populations (infestations). Forest susceptibility is largely considered a function of stand density, stand age, and geographic location, as represented in several risk and hazard rating systems for MPB (Fettig et al. 2014). Historically, the geographic distribution of MPB ranged from southern British Columbia, Canada, east to South Dakota, USA, and south to Baja, California, Mexico and New Mexico, USA (Negrón and Fettig 2014). This range was restricted by climatic conditions unfavorable to brood development. However, MPB is expanding its range due to climate change and other factors. Populations were detected for the first time in Alberta, Canada in 2003 (Cudmore et al. 2010), in Nebraska, USA in 2009 (Costello and Schaupp 2011), and in the Northwest Territories, Canada in 2012 (Natural Resources Canada 2013). By the end of the 21st century, thermal suitability for MPB population success is projected to be high at the most northern extent of pines in Canada, although portions of the historical range are projected to become unsuitable due to excessive warming that disrupts overwintering and adult emergence timing (Bentz et al. 2019).

Sensitivity

The number of beetles vary with changes in host tree vigor, the *sensitivity* (variation) of which is influenced by weather and climate (e.g., temperature, precipitation, solar radiation, and wind), forest condition (e.g., composition, structure, and distribution), and other predisposing and inciting factors (Figure 1) (Cudmore et al. 2010; Cullingham et al. 2011). Together *exposure* and *sensitivity* yield the preconditions to enable or prevent forest adaptation to the disturbance and in turn, the effects to ecosystem services (Franceschi et al. 2005) (*see* Figure 1). AC encompasses more than just environmental factors (stressor, exposure, sensitivity, and vulnerability), which is why the AC framework is shown to influence ecosystem services along with societal factors to the right in Figure 1.

Society

In our framework, society includes impacts, public opinion, and management factors pertinent to bark beetle mediation efforts. There is a need to increase understanding of social acceptability of bark beetle disturbances through understanding the values people hold. In doing so, perhaps managers and policy makers will be better equipped to plan and implement effective management interventions (Flint et al. 2009; McGrady et al. 2016).

Impacts

Impacts (direct and indirect) as a societal factor refer to the associated metrics including economic, social and human health and the implications for communities (Bennet et al. 2015) in this framework. Direct impacts involve individual and combined impacts on social and ecological spheres of community that link to coping and adapting responses mediated by latent AC and stakeholder forest values (e.g., aesthetic, recreation, spiritual) (McGrady et al. 2016). There are interactive aspects with indirect impacts on community as well produced by interactions, cascading effects or initial amplifying or dampening responses. In British Columbia for instance, MPB infestation forced the Ministry of Forests to increase timber allowable annual cut (AAC) through salvage logging by 14.5 million m^3 from previous outbreak AAC levels (Bogdanski et al. 2011). However, this short term increase of AAC will last only 5 to 15 years; in the following several decades, we may see up to a 75% AAC drop below pre-outbreak levels in central BC (Bogdanski et al. 2011). There are many other direct and indirect impacts of MPB infestation too numerous to present in this paper.

Public Opinion

Public opinion of forest disturbances is an essential element of the adaptive capacity of bark beetle affected systems. While MPB is a native insect important to the ecology of many forests in western North America, extensive levels of tree mortality resulting from outbreaks may have undesirable impacts. This may affect aesthetics, recreation, fire risk and severity, human safety, timber production, and real estate values, among many other factors, which can be perceived negatively (Maguire et al. 2015; McGrady et al. 2016; Morris et al. 2018). These perceptions subsequently influence how individuals and groups communicate experiences though personal narratives, lobbying efforts, and media outreach that in turn shape bark beetle related institutions (i.e. associated policies and management).

Public opinion is an important factor influencing policy direction and forest management decisions. Flint et al. (2009) emphasized the importance of understanding how communication influences public opinion of bark beetles and associated management interventions. Research in Alberta indicated that MPB experts do not have a favorable view of most media reporting of the topic, rather that media outlets disseminate information to the public in ways that are not broadly consistent with dominant scientific perspectives and management interventions (McFarlane et al. 2016). Meanwhile, research in Colorado indicated that awareness of MPB impacts enhanced trust in agency decision making and a greater willingness to accept management intervention (McGrady et al. 2016).

Gillette et al. (2014) described a range of possible outcomes expected from implementation of treatments for MPB, yet little information is available on the social acceptability of them in the western USA In Colorado and Wyoming, states heavily impacted by MPB, respondents to a mail survey were accepting of forest thinning to reduce the risk of wildfire (Clement and Cheng 2011). Although their survey did not directly focus on MPB, one might expect similar support for thinning to increase resistance and resilience to disturbances other than wildfire (e.g., MPB) in this region. McGrady et al. (2016) studied public attitudes towards management of MPB infestations in Colorado and Wyoming, and reported that most respondents were generally supportive of management interventions. The majority had a “do what you need to save the forest” attitude. Similarly, McFarlane et al. (2006) examined public attitudes relevant to management preferences for MPB in Banff and Kootenay National Parks, Canada. All groups agreed that "allowing the outbreak to follow its course without intervention" was not an acceptable option. Preferred options included "sanitation cutting to remove infested trees from small areas" and the "use of pheromones to attract beetles to one area". While in these few studies public opinion does not appear to be a significant obstacle to management interventions, each study was conducted when a large MPB epidemic was ongoing. Similar motivation for such management interventions may not be supported between outbreaks (i.e., when little tree mortality is occurring, but when thinning treatments should be implemented). Overall, ongoing opposition to the extraction of wood products from publicly-owned forests has limited harvesting in the western USA (Jones and Taylor 2005), which in turn has negatively impacted timber-processing infrastructure in the region. Of the 25 questions listed by Morris et al. (2017), nine focused on the need to increase our understanding of human perceptions relevant to bark beetle disturbances. By understanding the values that people hold, managers and policy makers are better equipped to plan and implement effective management interventions (Clement and Cheng 2011; McGrady et al. 2016). Public input is necessary to establish effective proactive and reactive management efforts to minimize bark beetle disturbances and maintain overall SES resilience.

Management

Management of MPB involves proactive and reactive measures influenced by available tools and knowledge, social and physical capacity and policy parameters. Substantial research has been devoted to the development of tools and methods to predict and mitigate (control) undesirable levels of tree mortality attributed to MPB (Fettig et al. 2014). Direct control involves short-term tactics designed to address current infestations by manipulating beetle populations, and includes the use of insecticides, semiochemicals, sanitation harvests, or combinations of these and other treatments. Indirect control is preventive, and designed to increase resistance and resilience within treated areas by manipulating stand, forest and/or landscape conditions (Fettig et al. 2007). The efficacy of methods for managing MPB infestations vary widely (Gillette et al. 2014). Because of this, the public support and policy parameters associated with proactive and reactive treatments vary by location.

In recent years, existing knowledge on MPB has been synthesized in two volumes (Negrón and Fettig 2014; Safranyik and Wilson 2006). Significant institutional knowledge concerning management interventions exists within state and federal land management agencies (e.g., Forest Health Protection, USDA Forest Service), and continue to evolve. Gillette et al. (2014) suggested that in order to be practical and sustainable, costs associated with management interventions (e.g., thinning to reduce stand density) need to be offset by timber revenues. Harvesting revenues are dependent on a timber-processing infrastructure of suitable capacity situated throughout a region impacted by MPB. Annual timber-processing capacity in the western USA was relatively stable from 1970 to the late 1980s, but fell dramatically after 1989 (Keegan et al. 2011). For example, lumber production in Montana, a state heavily impacted by MPB, is about half that of which occurred in 2000 (Morgan et al. 2013), although there has been an increase in the most recent years. Sixty-one percent of forests in Montana are managed by the USDA Forest Service, yet only 12% of timber harvested within the state come from these lands (Montana Statewide Forest Resource Strategy 2010). Other western states have experienced similar trends. For example, in California the forest products industry's capacity to process sawtimber has declined by >70% in recent decades (McIver et al. 2015). Declines in harvests on USDA Forest Service lands have been attributed by some to appeals, litigation, and federal budget cuts (Scudder et al. 2014). As harvesting has declined on public lands in the western USA, harvesting has increased on private lands in the southeastern USA (Oswalt and Smith 2014).

The availability of human and financial capital are significant constraints to AC as a highly-skilled work force is needed to implement forest management treatments (DellaSala et al. 2003). Research in northeastern Oregon, USA suggests that residents do not support raising taxes to fund management interventions (e.g., forest restoration), but about half support raising user fees on federal lands to generate funds for this work (Boag et al. 2015). Raising user fees may be a locally palatable option, but grossly insufficient to fund the massive amount of work that is needed. Similar, in Europe Lindner et al. (2010) reported that a lack of economic activity in the forest sector and of systems for funding remuneration of forest social and environmental services was constraining AC. Addressing these limitations requires quantification of gains in both market-based and ecosystem services realized as a result of management interventions. Sharing of this information with the general public and policymakers is critical (Wu et al. 2011). In some cases, this has been complicated by national politics (Keskitalo et al. 2016; Petersen and Stuart 2014). In the USA, for instance, legislation and political debate has centered on the removal of procedural requirements for environmental analysis, rather than funding and capacity building (Abrams et al. 2018).

Ecosystem Services

The adaptive capacity of a coupled social-ecological system can be expressed as the ability of that system to sustainably provide ecosystem services. Indeed, the success or failure of AC-focused management strategies can be evaluated using this metric and hence management strategies should explicitly focus on services as indicators. Ecosystem services are the benefits that humans receive from ecosystems. There are four categories of ecosystem service: 1) provisioning; 2) cultural; 3) regulating; and 4) supporting services (MES 2005). Regulating and supporting services may also be referred to collectively as intermediate services since they contribute to, but not directly influence final ES (Lamothe and Sutherland, 2018). Bark beetle disturbances affect ecosystem services across all four of these categories (Boyd et al. 2013; Hansen and Naughton 2013; Seidl et al 2016) as well as the tradeoffs among them that may arise under different ecological circumstances (Maguire et al. 2015). In the context of systems affected by bark-beetle outbreaks, provisioning services include timber production and water quality. Bark beetle outbreaks have the capacity to negatively affect both of these services (Safranyik and Wilson 2006, Edburg et al 2012). Regulating services include carbon sequestration of forest systems. Bark beetles affect this service differently depending on the scale of the outbreak: endemic populations and small outbreaks (e.g., <15 trees per ha) tend to increase rates of carbon sequestration whereas larger outbreaks produce a net negative effect on such rates (Kurz et al 2008). Cultural services associated with bark-beetle SES include the aesthetic values of forests (Ribe 1989) as well as recreational opportunities (Rosenberger et al 2013). Once again, the effects of bark-beetle outbreaks on these services can vary as a function of the scale of the outbreak. Endemic populations and small outbreaks have subtle positive effects on forest aesthetics due to increased sunlight, reduced tree density and enhanced view sheds (Maguire et al. 2015). Large outbreaks that result in large swaths of dead trees and increased safety risks reduce the utility of those landscapes for recreation (Rosenberger et al 2013). Finally, supporting services include soil quality and biodiversity. Changes in forest structure and density as a result of bark beetle outbreaks can have important effects on the species diversity which can change as the outbreak progresses (Martin et al 2006, Beadert et al 2014). Similarly, small outbreaks have weak positive effects on soil quality that increase as outbreaks get larger (Clow et al 2011). A fundamental challenge to the successful implementation of an AC framework to the management of bark-beetle SES requires more detailed examination of the context dependency of ecosystem service provisioning (e.g., at different points during the outbreak cycle and in different geographic regions), as well a further examination of the tradeoffs that can occur among services (Maguire et al. 2015) .

Conclusions

Since the late 1980s, bark beetle outbreaks have impacted millions of hectares of forest in North America and Europe, with cascading ecological consequences for carbon storage, wildlife habitat, and biogeochemical cycling. Associated changes to landscapes can strongly impact societies; specifically people who value affected forests or otherwise experienced a change in benefits from the ecosystem services following an outbreak. Thus, important feedbacks exist where people affected by bark beetle outbreaks react and respond to changing forest conditions, thereby catalyzing further changes in forest ecosystems. To achieve a holistic understanding of the ultimate consequences of bark beetle outbreaks requires an integrated social-ecological perspective that accounts for both the direct impacts on forest ecosystems as well as the cascading consequences realized by society in response to outbreaks calls for a framework approach. Although there are other (environmental/social) factors that need consideration and assessment of the effects on ecosystem services in order to respond effectively to MPB outbreaks, this paper focuses on integrating components that have tended to remain siloed in the academic and policy community.

In summary, the definition and AC framework applied to bark beetle disturbances leverages the proliferation of bark beetle research and its usefulness for forest management. Our effort to define AC and to develop an AC framework follows a small but growing body of research prioritization in bark beetle ecology (Morris et al. 2017; Negrón et al. 2008). We suggest the use of the workshop to review and rank the AC definitions, followed by crafting the single definition and conceptual framework, are strengths of this study. With 16 participants, an argument can be made that the workshop was not representative of the larger research community. However, we feel it provides a foundation for future research. We aim for this effort to be useful to motivate future research in the assessment of AC to foster collaboration among both social and physical scientists and land manager efforts to manage for bark beetle impacts to SES.

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References

Abrams J, Huber-Stearns H, Palmerin ML et al (2018) Does policy respond to environmental change events? An analysis of mountain pine beetle outbreaks in the western United States. Environ Sci Policy 90:102–109.

Adger WN, Brooks N, Bentham G et al (2004) New indicators of vulnerability and adaptive capacity. Tech Rep 7. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich.

Adger WN, Arnell NW, Tompkins EL (2005) Successful adaptation to climate change across scales. Global Environ Change 15:77–86.

Adger WN, Dessai S, Goulden M et al (2009) Are there social limits to adaptation to climate change? Climatic Change 93:335–354.

Armitage D (2005) Adaptive capacity and community-based natural resource management. Envir Manage 35(6):703-715.

Bennet NJ, Blythe J, Tyler S, Ban NC (2015) Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. Reg Environ Change 16(4):907–926.

Bentz BJ, Régnière J, Fettig CJ et al (2010) Climate change and bark beetles of the western United States and Canada: direct and indirect effects. BioScience 60:602–613.

Bentz BJ, Jönsson AM, Schroeder M, Weed A, Wilcke RAI, Larsson K (2019) *Ips typographus* and *Dendroctonus ponderosae* models project thermal suitability for intra- and inter-continental establishment in a changing climate. Frontiers Global Change 15: doi.org/10.3389/ffgc.2019.00001.

Blackman MW (1931) The Black Hills beetle (*Dendroctonus* ponderosae Hopk.). Tech Pub 36. The New York State College of Forestry, Syracuse.

Boag AE, Hartter J, Hamilton LC et al (2015) Forest views: shifting attitudes toward the environment in northeast Oregon. The Carsey School of Public Policy at the Scholars' Repository 238. 10 p.

Bogdanski B, Sun L, Peter B, Stennes B (2011) Markets for forest products following a large disturbance: Opportunities and challenges from the mountain pine beetle outbreak in Western Canada; Report BC-X-429; Canada Forest Services: Victoria, BC, Canada, 2011. Available online: http://cfs.nrcan.gc.ca/pubwarehouse/ pdfs/32226.pdf.

Boyd IL, Freer-Smith PH, Gilligan CA, Godfray HCJ (2013) The consequence of tree pests and diseases for ecosystem services. Science 342(6160):1235773.

Brooks N (2003) Vulnerability, risk and adaptation: a conceptual framework. Working Paper 38, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich.

Brooks N, Adger WN, Kelly PM (2005) The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environ Change 15:151–163.

Beudert B, Bässler C, Thorn S, Noss R, Schröder B, Dieffenbach-Fries H, Fullois N, Müller J (2015) Bark beetles increase biodiversity while maintaining drinking water quality. Conservation Letters 8(4):272-281.

Chapin FS, Kofinas GP, Folke C, Chapin MC (2009) Principles of ecosystem stewardship: resilience-based natural resource management in a changing world. Springer, New York

Chen, M., Sun, F., Berry, P., Tinch, R., Ju, H., & Lin, E. et al. (2014). Integrated assessment of China's adaptive capacity to climate change with a capital approach. Climatic Change, 128(3-4), 367-380.

Clarvis, M. H., & Engle, N. L. (2015). Adaptive capacity of water governance arrangements: a comparative study of barriers and opportunities in Swiss and US states. Regional Environmental Change, 15(3), 517-527.

Clement JM, Cheng AS (2011) Using analyses of public value orientations, attitudes and preferences to inform national forest planning in Colorado and Wyoming. Appl Geog 31:393–400.

Clow DW, Rhoades C, Briggs J, Caldwell M, & Lewis Jr WM (2011) Responses of soil and water chemistry to mountain pine beetle induced tree mortality in Grand County, Colorado, USA. Applied Geochemistry 26:S174-S178.

Costello SL, Schaupp WC (2011) First Nebraska state collection record of the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae: Scolytinae). Coleopterists Bull 65:21–23.

Cudmore TJ, Björklund N, Carroll AL et al 2010. Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naive host tree populations. J Appl Ecol 47:1036–1043.

Cullingham CL, Cooke JE, Dang S et al (2011) Mountain pine beetle host-range expansion threatens the boreal forest. Mol Ecol 20:2157–2171.

Cutter SL, Barnes L, Berry M et al (2008) A place-based model for understanding community resilience to natural disasters. Global Environ Change 18:598–606.

Davídková M, Doležal P (2017) Sister broods in the spruce bark beetle, *Ips typographus* (L.). For Ecol Manage 405:13–21.

DellaSala DA, Martin A, Spivak R et al (2003) A citizen's call for ecological forest restoration: forest restoration principles and criteria. Ecol Rest 21:14–23.

Dietz T, Ostrom E, Stern PC (2003) The struggle to govern the common. Science 302:1907–1912.

Edburg SL, Hicke JA, Brooks PD, Pendall EG, Ewers BE, Norton U, Meddens AJ (2012) Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. Front Ecol Environ 10(8):416-424.

Engle NL, Lemos MC (2010) Unpacking governance: building adaptive capacity to climate change of river basins in Brazil. Global Environ Change 20:4–13.

Engle NL (2011) Adaptive capacity and its assessment. Global Environ Change 21:647–656.

Ensor J, Park S, Hoddy E, Ratner B (2015) A rights-based perspective on adaptive capacity. Global Environ Change 31:38–49.

Fankhauser S, Smith JB, Tol RSJ (1999) Weathering climate change: some simple rules to guide adaptation decisions. Ecol Econ 30:67–78.

Feenstra JF, Burton I, Smith JB, Tol RSL (1998) Handbook on methods for climate change impact assessment and adaptation strategies. UNEP/Vrije Universiteit, Amsterdam.

Fettig CJ, Klepzig KD, Billings RF et al (2007) The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. For Ecol Manage 238:24–53.

Fettig CJ, Gibson KE, Munson AS, Negrón JF (2014) Cultural practices for prevention and mitigation of mountain pine beetle infestations. For Sci 60:450–463.

Fettig CJ (2019) Socioecological impacts of the western pine beetle outbreak in southern California: lessons for the future. J For 117:138-143.

Fettig CJ, Mortenson LA, Bulaon BM, Foulk PB (2019). Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. For Ecol Manage 432:164–178.

Flint CG, McFarlane B, Müller M (2009) Human dimensions of forest disturbance by insects: an international synthesis. Environ Manage 43:1174–1186.

Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. Ann Rev Environ Res 30:441-473.

Folke C (2006) Resilience: the emergence of a perspective for social-ecological systems analyses. Global Environ Change 16:253–267.

Ford J, Smit B (2004) A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. Arctic 57:389–400.

Franceschi VR, Krokene P, Christiansen E, Krekling T (2005) Anatomical and chemical defenses of conifer bark against bark beetles and other pests. New Phytol 167:353–376.

Gallopín GC (2006). Linkages between vulnerability, resilience, and adaptive capacity. Global Environ Change 16:293–303.

Gillette NE, Wood DL, Hines SJ et al (2014) The once and future forest: consequences of mountain pine beetle treatment decisions. For Sci 60:527–538.

Gittell RJ, Vidal A (1998) Community organizing: building social capital as a development strategy. Sage, Thousand Oaks, CA.

Greenberg J (2002) Managing behavior in organizations, 3rd ed.: Pearson Education, Inc., Upper Saddle River, NJ.

Gupta J, Termeer C, Klostermann J et al (2010) The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. Environ Sci Policy 13:459–471.

Hansen WD, Naughton HT (2013) The effects of a spruce bark beetle outbreak and wildfires on property values in the wildland-urban interface of south-central, Alaska, USA. Ecol Econ 96:141–54.

Hicke JA, Meddens AJH, Kolden CA (2016) Recent tree mortality in the western United States from bark beetles and forest fires. For Sci 62:141–153.

Hill M, Engle NL (2013) Adaptive capacity: tensions across scales. Env Pol Gov 23:177–192.

Hinkel J (2010) “Indicators of vulnerability and adaptive capacity”: towards a clarification of the science–policy interface. Global Environ Change 21:198–208.

Hill M, Engle NL (2012) Adaptive Capacity: Tensions across Scales. Environ Pol Govern 23(3):177-192.

Hogarth JR, Wójcik D (2016) An evolutionary approach to adaptive capacity assessment: a case study of Soufriere, Saint Lucia. Sustainability 2016, 8:228.

Hopkins D (2014) Applying a comprehensive contextual climate change vulnerability framework to New Zealand’s tourism industry. Ambio 44:110-120.

Huber R, Rigling A, Bebi P et al (2013) Sustainable land use in mountain regions under global change: synthesis across scales and disciplines. Ecol Scol 18:36.

Jones ES, Taylor CP (2005) Litigating agency change: the impact of the courts and administrative appeals process on the Forest Service. Policy Studies J 23:310–336.

Keegan CE, Sorenson CB, Morgan TA et al (2011) Impact of the Great Recession and housing collapse on the forest products industry in the western United States. Forest Prod J 61:625–634.

Kelly PM, Adger WN (2000) Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climate Change 4:325–352.

Keskitalo ECH (2004) A framework for multi-level stakeholder studies in response to global change. Local Environ 9:425–435.

Keskitalo ECH, Pettersson M, Ambjörnsson EL, Davis EJ (2016). Agenda-setting and framing of policy solutions for forest pests in Canada and Sweden: avoiding beetle outbreaks? For Policy Econ 65:59–68.

Kiparsky M, Milman A, Vicuña S (2012) Climate and water: knowledge of impacts to action on adaptation. Ann Rev Environ Resources 37:163–194.

Kolb TE, Fettig CJ, Ayres MP et al (2016) Observed and anticipated impacts of drought on forests insects and diseases in the United States. For Ecol Manage 380:321–334.

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Safranyik L (2008) Mountain pine beetle and forest carbon feedback to climate change. Nature 452(7190):987.

Lamothe KA, Sutherland IJ (2018) Intermediate ecosystem services: the origin and meanings behind an unsettled concept. International Journal of Biodiversity Science, Ecosystem Services & Management 14(1):179-187.

Lindner M, Maroschek M, Netherer S (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manage 259:698–709.

Lorenzoni I, Nicholson-Cole S, Whitmarsh L (2007) Barriers perceived to engaging with climate change among the UK public and their policy implications. Global Environ Change 17:445–459.

Maguire DY, James PM, Buddle CM, Bennett EM (2015) Landscape connectivity and insect herbivory: a framework for understanding tradeoffs among ecosystem services. Global Ecol Conser 4:73-84.

Marini L, Økland B, Jönsson A et al (2017) Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. Ecography 40:1426–1435.

Marshall NA, Smajgl A (2013) Understanding variability in adaptive capacity on rangelands. Rangeland Ecol Manage 66:88–94.

Martin K, Norris A, Drever M (2006) Effects of bark beetle outbreaks on avian biodiversity in the British Columbia interior: Implications for critical habitat management. Journal of Ecosystems and Management, 7(3).

Mattor KM, Cottrell SP, Stednick JD, Dickenson ERV, Czaja MR (2018) The effects of mountain pine beetle on drinking water: Effective communication strategies and knowledge transfer in the Rocky Mountain Region. In Urquhart J, Potter C, Marzano M (eds), Human Dimensions of Forest Health, Palgrave-Macmillan, London.

Mattson WJ Jr, Addy ND (1975) Phytophagous insects as regulators of forest primary production. Science 90:515−522.

McFarlane BL, Stumpf-Allen RCG, Watson DO (2006) Public perceptions of natural disturbance in Canada's national parks: the case of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins). Biol Conserv 130:340–348.

McFarlane BL, Parkins JR, Romanowski S (2016) Expert perceptions of media reporting on a large-scale environmental risk issue: insights from mountain pine beetle management in Alberta, Canada. Can J For Res 46:1–9.

McGrady P, Cottrell S, Raadik Cottrell J et al (2016). Local perceptions of mountain pine beetle infestation, forest management, and connection to national forests in Colorado and Wyoming. Human Ecol 44:185–196.

McIver CP, Meek JP, Scudder MG, Sorenson CB, Morgan TA, Christensen GA (2015) California's forest products industry and timber harvest, 2012. Gen. Tech. Rep. PNW-GTR-908. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 49 p.

Montana Statewide Forest Resource Strategy (2010) Available at http://dnrc.mt.gov/divisions/forestry/docs/assistance/saresponsestrategy2010.pdf. 34 p.

Morgan TA, Keegan CE, Hayes SW, Sorenson CB (2013) Montana's forest products industry: improved conditions but low expectations. For Prod Outlook 2013:29–30.

Morris JL, Cottrell S, Fettig CJ et al (2017) Managing bark beetle impacts on ecosystems and society: priority questions to motivate future research. J Appl Ecol 54:750–760.

Morris JL, Cottrell S, Fettig CJ et al (2018) Bark beetles as agents of change in social-ecological systems. Front Ecol Environ 16(S1):S34–S43.

Moser SC, Ekstrom JA (2010) A framework to diagnose barriers to climate change adaptation. PNAS 107:22026–22031.

Natural Resources Canada (2013) Mountain pine beetle (factsheet). http://www.nrcan.gc.ca/forests/fire-insects-disturbances/top-insects/13397.

Negrón JF, Bentz BJ, Fettig CJ et al (2008) USDA Forest Service bark beetle research in the western United States: looking towards the future. J For 106:325–331.

Negrón JF, Fettig CJ (2014) Mountain pine beetle, a major disturbance agent in US western coniferous forests: a synthesis of the state of knowledge. For Sci 60:409–413.

Nelson HW, Williamson TB, Macaulay C, Mahony C (2015) Assessing the potential for forest management practitioner participation in climate change adaptation. For Ecol Manage 360:388–399.

Netherer S, Matthews B, Katzensteiner K et al (2015) Do water-limiting conditions predispose Norway spruce to bark beetle attack? New Phytol 205:1128–1141.

O'Brien K, Leichenko R, Kelkar U et al (2004a) Mapping vulnerability to multiple stressors: climate change and globalization in India. Global Environ Change 14:303–313.

O'Brien K, Erikson S, Schjolden A, Nygaard L (2004b) What's in a word? Conflicting interpretations of vulnerability in climate change research. CICERO Working Paper 2004:04, Oslo, Norway.

Oswalt SN, Smith BW (2014) U.S. forest resource facts and historical trends. Available at https://www.fia.fs.fed.us/library/brochures/docs/2012/ForestFacts_1952-2012_English.pdf. 62 p.

Pahl-Wostl C (2009) A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environ Change 19:354–365.

Palmer S, Martin D, Delauer V, Rogan J (2014) Vulnerability and adaptive capacity in response to the Asian longhorned beetle infestation in Worcester, Massachusetts. Human Ecol 42:965–977.

Parry ML, Canziani OF, Palutikof JP et al (2007) Technical Summary. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Pelling M, High C (2005) Understanding adaptation: what can social capital offer assessments of adaptive capacity? Global Environ Change 15:308–319.

Petersen B, Stuart D (2014) Explanations of a changing landscape: a critical examination of the British Columbia bark beetle epidemic. Environ Plan A 46:598–613.

Pielke R (1998) Rethinking the role of adaptation in climate policy. Global Environ Change 8:159–170.

Phillips H (2014) The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. Envir Sci Policy 47:118-125.

Progar RA, Gillette N, Fettig CJ, Hrinkevich K (2014) Applied chemical ecology of the mountain pine beetle. For Sci 60:414–433.

Rayner S, Malone EL (2001) Climate change, poverty, and intergenerational equity: the national level. Intl J Global Issues 1:175–202.

Ribe RG (1989) The aesthetics of forestry: what has empirical preference research taught us?. Envir Manage, 13(1):55-74.

Rosenberger RS, Bell LA, Champ PA, White EM (2013) Estimating the economic value of recreation losses in Rocky Mountain National Park due to a mountain pine beetle outbreak. In Western Economics Forum (Vol. 12, No. 1837-2016-151843, pp. 31-39).

Safranyik L, Wilson WR (2006) The mountain pine beetle - a synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 304 p.

Sanderson D (2000) Cities, disasters and livelihoods. Risk Manage Intl J 2:49–58.

Schelhaas M-J, Nabuurs G-J, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Bio 9:1620–1633.

Scholtz RW, Blumer YB, Brand FS (2010) Risk, vulnerability, robustness, and resilience from a decision-theoretic perspective. Journal of Risk Research, 15(3): 313-330.

Schowalter TD (1981) Insect herbivore relationship to the state of the host plant: biotic regulation of ecosystem nutrient cycling through ecological succession. Oikos 37:126−130.

Scudder M, Venn T, Morgan TA (2014) Can Montana participate in the lumber export market to China? Forest Prod J 64:11–18.

Seidl R, Lexer MJ (2013) Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. J Environ Manage 114:461–469.

Seidl R, Aggestam F, Rammer W et al (2015) The sensitivity of current and future forest managers to climate-induced changes in ecological processes. Ambio 45:430–441.

Seidl R, Spies TA, Peterson DL, Stephens SL, Hicke JA (2016) Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. J Appl Ecol 53(1):120–129.

Seidl R, Thom D, Kautz M et al (2017) Forest disturbances under climate change. Nature Climate Change 7:395–402.

Seybold SJ, Bentz BJ, Fettig CJ et al (2018) Management of western North American bark beetles with semiochemicals. Ann Rev Entomol 63:407–432.

Smith B, Ragland SE, Pitts GJ (1998) A process for evaluating anticipatory adaptation measures for climate change. Water Air Soil Poll 92:229–238.

Smit B, Burton I, Klein R, Wandel J (2000) An anatomy of adaptation to climate change and variability. Climatic Change 45:223–251.

Smit B, Pilifosova O (2003) From adaptation to adaptive capacity and vulnerability reduction. In Smith JB, Kein RJT, Huq S (eds), Climate Change, Adaptive Capacity and Development. Imperial College Press, London.

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Global Environ Change 16:282–292.

Stephens SL, Collins BM, Fettig CJ et al (2018) Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience 68:77–88.

Van der Veen A, Logtmeijer C (2005) Economic hotspots: visualizing vulnerability to flooding. Natural Hazards 36:65−80.

Vásquez-León M, West CT, Finan TJ (2003) A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US–Mexico border. Global Environ Change 13:159−173.

Wu T, Kim Y-S, Hurteau MD (2011) Investing in natural capital: using economic incentives to overcome barriers to forest restoration. Res Ecol 19:441–445.

Wyborn, C., Yung, L., Murphy, D., Williams, D.R. (2015) Situating adaptation: how governance challenges and perceptions of uncertainty influence adaptation in the Rocky Mountains Regional., Envir Change 15:669-682.

Yohe G, Tol RS (2002) Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. Global Environ Change 12:25−40.

Table headings (saved as a panel photo)

Table 1. Definitions of Adaptive Capacity presented at the Workshop

Table 2. Selected Adaptive Capacity Frameworks Presented at the Workshop

Figure Legends

Figure 1. Adaptive capacity conceptual framework (Figure 1 adapted from Cutter et al. 2008; Gallopin 2006; Hinkel 2010; Hopkins 2014; Palmer et al. 2014; Phillips 2014)

Table 1. Definitions of Adaptive Capacity presented at the Workshop

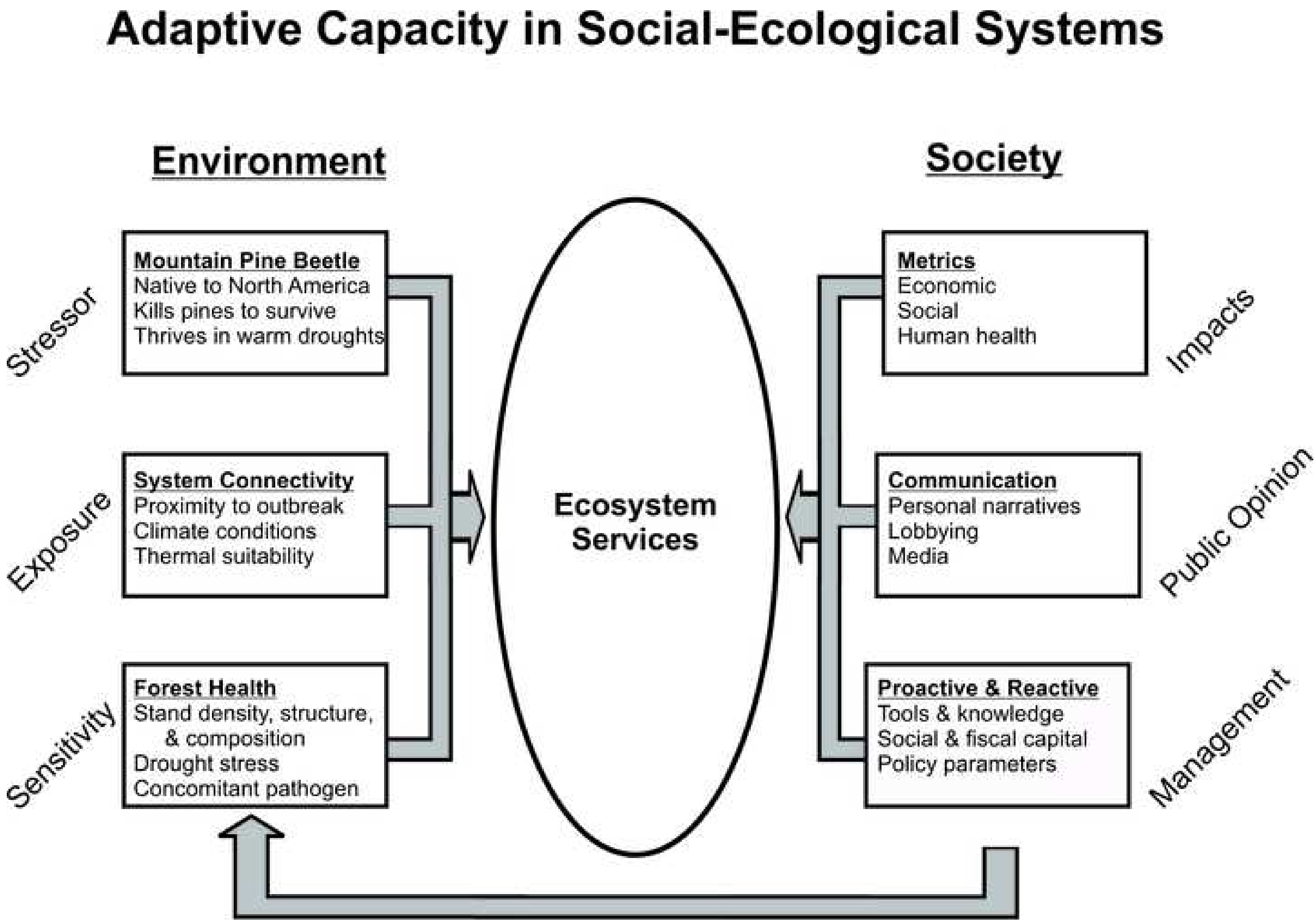
1.	*Adaptive capacity is defined as the ability of a resource governance system to first alter processes and if required convert structural elements as response to experienced or expected changes in the societal or natural environment* (Pahl-Wostl 2009, p. 355).
2.	*A critical aspect of resource management that reflects learning and an ability to experiment and foster innovative solutions in complex social and ecological circumstances* (Armitage 2005, p. 703).
3.	*The ability of actors to (collectively and individually) respond to, create and shape variability, change and surprise in the state of a linked social-ecological system (SES) (Chapin et al. 2009). It can be characterized as the preconditions needed to enable adaptation, both proactive and reactive, including social and physical elements, and the ability to mobilize these elements to anticipate or respond to perceived or current stresses* (Hill and Engle 2013, p. 178).
4.	*The ability of social actors to make deliberate changes that influence the resilience of their complex social-ecological systems. The focus is on the potential for actors to respond to, shape, and create changes in that system. It can also be viewed as the preconditions necessary for adaptive actions, comprising both social and physical elements, and the ability to mobilize them* (Ensor et al. 2015, p. 39).
5.	*The collective ability of a group (or community) to combine various forms of capital which depends on the collective action within the suite of environmental, social, economic, and political entitlements* (Chen et al. 2014, p. 369).
6.	*The extent to which a natural or social system is susceptible to sustaining damage from climate change to the ability to implement prospective or reactive adaptive actions to cope with certain adverse events and their consequences.* (Scholtz et al. 2010, p. 264).
7.	*The ability to act proactively to diminish future vulnerability* (Brooks 2003, p. 8).
8.	*Adaptation process can be characterized as a multi-level process involving diverse actors assessing, experimenting, adjusting, and learning in the context of dynamic resource management systems within particular institutional frames and governance modes* (Nelson et al. 2015, p. 390).
9.	*Adaptive capacity focuses attention on the capacity of different actors, social groups, and institutions to pursue adaptation. [It] is mediated by the availability and distribution of resources and technology, the structure of institutions and governance, levels of social and human capital, knowledge generation and management, and perceptions of agency, efficacy, and risk. Both adaptation and adaptive capacity are scale and context specific, shaped by interacting local, regional, national, and global processes. Because local actors are embedded within these processes, local adaptation actions are constrained or enabled by policies, institutions, and social norms operating at multiple, interacting scales* (Wyborn et al. 2015, p. 670).
10.	*Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities* (Parry et al. 2007, p. 869).
11.	*Adaptive capacity is the ability of actors, individuals and groups to prepare for, respond to, create and shape variability and change in a system. It can be characterized by preconditions necessary to enable adaptation, including social and physical elements, and the ability to mobilize these elements* (Clarvis and Engle 2015, p. 518).
12.	*Essentially, adaptive capacity is the potential to convert existing resources into useful strategies. At the individual scale, it is not simply having access to resources or diverse options that define capacity, even though these factors might be important influences. Adaptive capacity has been described elsewhere at the individual scale as comprising four essential dimensions: 1) the capacity to manage risk and uncertainty, 2) the capacity to plan, learn and reorganize, 3) emotional and financial flexibility to incorporate the costs of change, and 4) the level of interest in adapting to change* (Marshall and Smajgl 2013, p. 89).

* The unshaded definitions (#3, #9, #11) were the top three ranked by the workshop participants.

Table 2. Selected Adaptive Capacity Frameworks Presented at the Workshop

Reference	**Overview of the Frameworks***
Cutter et al. 2008	Utilizes preceding and subsequent conditions to an event to identify the long- and short-term outcomes and abilities of a social-ecological system to adapt to disasters and remain resilient. The model takes into account the existing social, ecological, and infrastructure conditions to assess pre-disaster vulnerability and resilience. It then assesses the event characteristics and the coping responses to identify the outcomes of the disaster for future mitigation and preparedness.
Gallopin 2006	Outlines the systemic relations of vulnerability, resilience, and adaptive capacity across natural and social systems. The vulnerability component of the framework encompasses social and natural system sensitivity, capacity to respond, and levels of exposure.
Hinkel 2010	Identifies the relationship between the concept of vulnerability and the characteristics that define it, including adaptive capacity and sensitivity. The framework recognizes defining factors of vulnerability, adaptive capacity, and sensitivity as stimuli, climate change, extreme weather event, climate variability, ability to adjust, statistical reference distribution, rare event, ability to cope, weather, adverse effects, exposure, and significant climate variations.
Hopkins 2014	Categorizes the external and internal qualities that influence natural and social vulnerability to the effects of climate change. External factors include social, physical, economic, and political characteristics. The internal factors, closely associated with adaptive capacity, include social perceptions, political and economic forecasts, biophysical conditions, and existing adaptation actions.
Palmer et al. 2014	Defines social, ecological, and political characteristics associated with vulnerability and adaptation. While the framework is specific to the response to invasive Asian long-horned beetle infestation in Worcester, Massachusetts, U.S. it provides a specific case of bark beetle influence to adaptive capacity. The framework links adaptive capacity to exposure, sensitivity, and impacts associated with social and political networks and scales.
Phillips 2014	Delineates six traits of adaptive capacity relevant to the preservation of cultural heritage sites. These traits include authority, access to information, learning capacity, leadership, reasoning, and resources, arranged in a circular pattern to display the interconnectedness of these factors in responding to adverse challenges.

* The unshaded references and associated frameworks were identified as most relevant to the workshop discussion and guided development of our framework provided in this paper.


Adaptive Capacity in Social-Ecological Systems
Environment
Society
Stressor
Mountain Pine Beetle
Native to North America
Kills pines to survive
Thrives in warm droughts
Exposure
System Connectivity
Proximity to outbreak
Climate conditions
Thermal suitability
Sensitivity
Forest Health
Stand density, structure, & composition
Drought stress
Concomitant pathogen
Ecosystem Services
Metrics
Economic
Social
Human health
Impacts
Communication
Personal narratives
Lobbying
Media
Public Opinion
Proactive & Reactive
Tools & knowledge
Social & fiscal capital
Policy parameters
Management

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Supplementary Material
Appendix A Full list of citations.xlsx