J.For. 117(2):171–177
doi: 10.1093/jofore/fvy041
Published by Oxford University Press on behalf of the Society of American Foresters 2019.

forest threats

Bark Beetle Infestation of Western US Forests: A Context for Assessing and Evaluating Impacts

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Bark beetles are primary disturbance agents in western US forests. Outbreaks affect goods and services associated with forest ecosystems including timber, water, fish and wildlife habitats and populations, recreation opportunities, and many others. They can also affect wildfire behavior and its intensity. Assessments and evaluations of such impacts are important information to land managers, policy makers, and forest stakeholders, as well as to the broader public. Arriving at a complete and accurate assessment and evaluation is a complex process that necessarily considers effects and impacts on a variety of resources affecting diverse stakeholders over time and space. Within that complex process are interactions and feedbacks between ecological factors and socioeconomic factors. We argue that ecosystem goods and services are an operative bridge between those ecological factors and socioeconomic factors. Hence, they provide a context in which to systematically identify effects and affected resources and consider interactions and feedbacks among them which lead to further impacts. Such a context enhances one's ability to reveal, assess, and evaluate the full range and scope of impacts.

Keywords: Bark beetle, ecosystem goods and services, economic impact, economic value, social impact, community impact

Bark beetles (*Coleoptera curculionidae*) are primary disturbance agents in western US forests. Outbreaks affect many of the goods and services associated with forest ecosystems including timber, fish and wildlife habitats, water, and recreation opportunities, among others. Although gaps exist in our understanding of outbreak dynamics and effects, it is clear that mechanisms contributing to widespread bark beetle outbreaks are complex, involving both density-dependent and density-independent factors with spatial and temporal dependencies at multiple scales (Raffa et al. 2008). Large areas of suitable host trees of susceptible vigor, age, and density are required for an outbreak to develop (Fettig et al. 2007). Because bark beetle populations are sensitive to thermal conditions and host tree vigor is influenced by water stress, outbreaks have been correlated with changing temperature and precipitation patterns (Bentz et al. 2010). In recent decades, millions of forested hectares from Mexico to Alaska have been affected, and billions of trees have been killed by native bark beetles in western forests (Bentz et al. 2009). Temperature and precipitation patterns expected to occur in North America over the 21st century are conducive to continued or increased bark beetle outbreaks and activity in several forest types (Logan et al. 2003, Bentz et al. 2010, IPCC 2014, Kolb et al. 2016).

Effects, Impacts, and Overall Impact

"Overall impact" as it relates to bark beetles is a combination of two related concepts. An effect inevitably follows an action or phenomenon as a result or consequence. Impact is the force of impression of one thing on another—the influence of an action or phenomenon on something or someone (Merriam-Webster online; pediaa.com). "Effect" is a direct outcome (i.e., not mediated by a third or other action or phenomenon [Moon et al. 2010]). For

Received May 10, 2018; accepted August 29, 2018.

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Acknowledgments: *The constructive comments by Tim Harrington and Jeff Kline, along with those from the associate editor and two anonymous reviewers, helped correct, clarify, and greatly strengthen this presentation. Many thanks! Of course, remaining errors and obscurities are solely attributable to the authors. The authors thank the Western Environmental Threats Center, USDA Forest Service for financial support. This paper was funded in part by a grant from the Western WIldland Environmental Threats Center, USDA Forest Service, and was developed as part of a project of the Western Bark Beetle Research Group.*

example, bark beetles infest and often kill trees; one effect is that mountain pine beetles leave a blue stain in the trees they kill. "Impact" is an indirect outcome stemming from the direct outcome or effect of bark beetle infestation but mediated by other actions or phenomena. For example, the increased likelihood that beetle-killed trees will fall changes available recreation opportunities due to concerns for human safety (the bark beetle does not change recreation opportunities, the likelihood of falling trees and increased safety concerns do); dead and downed trees (increased surface fuels) might affect the behavior and intensity of local wildfires (Jenkins et al. 2014, Stephens et al. 2018). The distinction may be subtle; the point is one must look beyond direct effects when considering overall impact. Thus, the overall impact of bark beetle infestation includes dead trees (a direct outcome), along with lost recreation opportunities, and potentially altered behavior of wildfires (indirect outcomes), which would then have further indirect impacts such as property damage, erosion, or changes in wildlife habitat over time, thereby adding to the overall impact.

Impact is based on a quantitative or qualitative comparison of current condition with a reference or baseline condition. Insect-caused disruptions are unlikely to be absent from any forest, and in fact, a certain level of insect activity is essential to the proper functioning of a healthy forest (Mattson and Addy 1975, Dahlsten and Rowney 1983, Castello and Teale 2011). This endemic condition is commonly considered a baseline where insects and other disturbance agents are restricted naturally by interactions with other components of the forest ecosystem.

There are different concepts of impact depending on the context of consideration. "*Ecological impact*" relates to changes in the natural environment, colloquially referred to as "Mother Nature." "Socioeconomic impacts" relate to people and groups of people. There are three basic categories of socioeconomic impacts. "Economic impact" is strictly defined in terms of changes to an economy brought about by a change or perturbation to the system and reflected by employment, income, revenues, and production flowing into or out of the economy. Such impacts involve and result from market transactions. When discussing the "economic value" of changes or perturbations to a system, the concept of impact is one of welfare change, or changes in individual human well-being. Nonmarket values and benefits enter here—the value of a recreation experience, aesthetic value of a landscape, and the value of a reduction in soil erosion, etc. Such values are net of market transactions. "Economic value" is not the same as "economic impact" (McCollum et al. 1992). More importantly, the two are not additive. The third concept of socioeconomic impact is "community/social impact." This affects how people relate to or interact with others and with natural resources, either as individuals or groups of individuals. Sociocultural processes including community perceptions and actions are among the most visible social impacts of economic and environmental changes (Qin and Flint 2017). Again, "community/social impact" is not the same as "economic impact" or "economic value." The three are neither additive nor directly comparable. They are complementary, however, and may overlap. They can all be components of overall impact along with the ecological impact. For the remainder of this article, we use the term impact to refer to effects and impacts in general. When we refer specifically to "ecological impacts," "economic impacts," "economic values," or "community/social impacts," we put them in quotation marks.

Time and timing are important elements when one considers any of these categories of impact. Because forests exist for long periods of time and impacts related to bark beetle outbreaks can come or go or persist over periods of time, timing of impacts is important. In cases where impacts can be assessed a monetary value (e.g., changes in "economic impact" of timber availability or changes to the "economic value" of a recreation experience), time is commonly accounted for using discounting based on the time value of money; one often seeks to summarize future flows of impacts at a common point in time. Future values are weighted higher when a low discount rate is used than when a high discount rate is used. That is, higher discount rates discount the future more than lower discount rates. For example, an impact occurring in year one with a present value of $100 is valued at $74 if it occurs in year 10 with a discount rate of 3 percent. That same impact occurring in year 10 has a present value of $39 if the discount rate is 10 percent.

The element of timing adds to the complexity of impact assessment and evaluation. Some impacts, like pine needles turning red, might occur a year or two after infestation, at which time flammability of the standing tree is increased. Dead trees might not fall for many years, at which time surface fuel loading is increased, but the increased flammability of standing red trees becomes moot. Dead trees might be usable for lumber and timber products for a few years, then their usability declines. Potential for soil erosion will vary depending on whether and when fires occur and the rate at which vegetative cover returns. Care is required in assessments to accurately track these different impact flows. Further, a negative impact in one period may become more or less negative or zero in some future time period. A community might suffer

Management and Policy Implications

Temperature and precipitation patterns expected to occur in North America over the 21st century are conducive to continued or increased bark beetle outbreaks and activity. Their impacts will likely continue and compound. Forest disturbances like bark beetle infestations affect the ecosystem and diverse groups of people in a variety of ways. Direct and indirect elements of overall bark beetle impact interact with other elements of the ecological and socioeconomic realms of the complete ecosystem as they iterate through time. More interactions and feedbacks occur, and changes in ecosystem goods and services (EGSs) spark elements of the social and economic realm to perceive and recognize changes in the ecosystem and respond to them, thus stimulating further changes in EGSs that affect both ecological and socioeconomic realms of the ecosystem. Managers need to recognize and even anticipate such interactions as they practice adaptive management and manage for ecosystem resilience and adaptive capacity. Evaluating bark beetle impacts in a systematic framework using EGSs and their inherent feedbacks and interactions over time provides the broad analytical scope needed to fully consider the wide range of potential impacts. Such consideration and understanding of associated impacts and their valuation facilitates managers' knowledge and their ability to mobilize adaptive and mitigating measures.

adverse "community/social impacts" and "economic impacts" initially but experience positive impacts as they adapt over time.

An Ecosystem Goods and Services Context

A useful context in which to think about bark beetles and their effects and impacts is that of ecosystem goods and services (EGSs). Consider the many ecological, economic, and social goods, services, and amenities provided by forests. These include, among others, purification of air and water, regulation of edaphic formation and control of water runoff and soil erosion, fish and wildlife habitat, wood and other forest products, aesthetics and opportunities for outdoor recreation and spiritual renewal, and regulation of climate through complex physical, chemical, and biological processes and interactions. Forests are an important ecosystem, critical to the health, welfare, and survival of human societies.

Forested watersheds capture and clean rain water while modulating rising and falling stream flows and filtering sediment. Locations with forest cover are on the order of 1–2°C cooler in summer and 2–4°C warmer in winter. Three strategically placed trees can reduce household air conditioning costs by 50 percent and winter heating costs by 30 percent (Celik 2006). Trees reduce wind speeds and change local wind patterns; they reduce noise pollution. Healthy forests raise property values and help stabilize local economies by enhancing aesthetics, thereby attracting residents, visitors, and other stakeholders. Celik points out: "Trees help create relaxation and well-being. They relieve psychological stresses; patients in hospital rooms with a view of green and woodland areas have shorter post-operative stays. . . . Trees add beauty and reflection to our everyday lives." Bark beetles can directly or indirectly affect these EGSs by altering conditions of the forest components that are their source.

The introduction to this special section described EGSs and the typology proposed by the Millenium Ecosystem Assessment (2005). Different typologies serve different descriptive and analytical purposes. An important distinction among the various typologies is the precision with which they define individual services for possible measurement (Kline and Mazzotta 2012, pp. 32–36). Typologies are not to put EGSs into pigeon holes but to facilitate systematic analyses.

Beyond typologies and recognizing specific EGSs, one needs to know about the interactions and feedbacks that are embedded in those EGSs. As a concept, EGSs force/enable us to broaden our view and think systematically about potential impacts. It helps us realize the complex influences expressed by biotic disturbances in various types of ecosystems. As indicated earlier, bark beetles can enhance, reduce, or otherwise influence, directly or indirectly, many EGSs to one degree or another. However, unless bark beetles affect something perceived by humans as having value, impact is impossible to define and measure. There needs to be a link between impact or value created and impact or value perceived–between ecosystem condition and processes and human institutions, communities, and well-being.

A Conceptual Framework

Fox et al. (2009; extended by Kreuter et al. 2012 and McCollum et al. 2017) described an integrated social, economic, and ecologic conceptual (ISEEC) framework in which to consider and assess sustainability of an ecosystem. Inherent in assessing sustainability is assessing effects and impacts of disturbances to the system. Central to that framework is the role of EGSs. Ecological systems and processes provide the biological, chemical, and physical interactions underlying ecosystem health and viability. Social and economic institutions, infrastructures, and processes provide the context in which ecosystem use and management occur and perceived ecosystem health improves or deteriorates. All these systems and processes interact and feedback on one another over time and space. The crux of the ISEEC framework is that EGSs act as a bridge between the ecological and socioeconomic realms of the complete ecosystem, thus providing the link between impact created and impact perceived. The framework is illustrated in Figure 1.

Four states or conditions are acted upon by processes, represented by the large downward arrows. On the left side of Figure 1 are ecological and natural resource processes including but not limited to reproduction, growth, death, and decomposition, as well as water cycles, nutrient cycles, carbon cycles, succession, migration, adaptation, and competition. On the right side of the figure are social and economic processes including but not limited to birth, death, morbidity, demand, production, consumption, investment, depreciation, management, social regulation, social interaction, institutional processes, and so on. The processes act on the conditions and capitals existing at time t_n and result in a new set of conditions and capitals at time t_{n+1}.

The integration of ecological factors with social/economic factors is represented

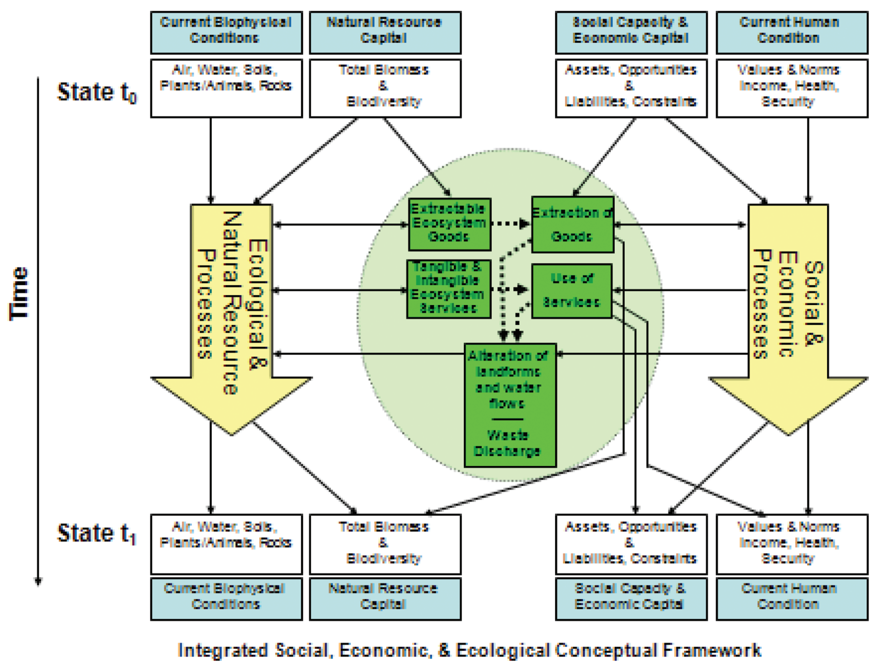

Figure 1. Overview of the Integrated Social, Economic and Ecological Conceptual (ISEEC) Framework (source: Fox et al. 2009, https://www.tandfonline.com, used with permission).

in the framework by the circle between "ecological and natural resource processes" and "social and economic processes." Representing EGSs, this explicitly calls to attention that ecological and natural resource conditions and processes affect and are affected by social and economic capital stocks/capacities and conditions and by social and economic processes. As indicated in Figure 1, the framework asserts that those interactions occur by way of extraction of ecosystem goods, alteration of landforms and water flows, waste discharges, and other EGSs and their uses.

Such interactions between EGSs and social/economic and ecological factors are reinforced by Morris et al. (2018) in their discussion of interactions and feedbacks within a social-ecological system that has experienced a disturbance. They note that "the primary drivers of bark beetle outbreaks are the interacting factors of a warming climate and susceptible stand conditions. Severe outbreaks modify the provision of ecosystem services relative to undisturbed forests. . . . How humans perceive and respond to these phenomena depends on the cognitive traits of individuals . . . patterns of human behavior both directly and indirectly shape public policy and economic programs" (Morris et al. 2018, p. S40).

Disturbances to the system can originate in either the ecological or the social/economic realm. For example, humans extract and use natural resources thereby affecting natural resource stocks and biophysical conditions. In the process of extracting, processing, and using those resources, stocks are consumed and wastes are generated and discharged. Such byproducts affect EGSs that support and sustain life at many levels. Discharging waste material directly into a stream interferes with stream function, affecting water quality, riparian habitat, and recreation opportunities afforded by the stream and its associated habitats. Those altered EGSs and the responses they evoke in terms of ecosystem states, conditions, and processes affect a variety of users. Those users are prompted to further respond by acting in the social and economic realm. They might act to impose standards or regulations on waste discharge; they might require habitat restoration. Such regulations impose additional costs on the waste discharger, possibly resulting in higher prices for consumers and changes in resource allocations as both producers and consumers respond to higher prices. They also stimulate investment in equipment needed to comply with the regulations. Production of that equipment affects other EGSs somewhere else; and effects and feedbacks iterate through time.

Originating from the ecological realm of the ecosystem, a natural disturbance like bark beetle infestation affects the time horizon for quality and availability of biomass for lumber and pulp production. While initially offering potentially usable timber, in time it can increase surface fuel loading, thereby, in concert with weather and topography, potentially influencing the initiation, spread, and intensity of wildfire (Jenkins et al. 2014, Stephens et al. 2018). It affects viewsheds as large areas of trees turn red, then brown, and then fall down. Forest visitors are subjected to increased safety risk from downed and falling trees; trails and campgrounds are closed. An overwhelming amount of biomass may be coupled with weak markets for wood-based products, resulting in timber harvest and silvicultural treatments needing to be done at times when they may not be economically feasible. People and communities respond by seeking alternative uses for the biomass or burn excess biomass if economically feasible uses cannot be found. Recreation users are displaced to other activities or locations. Some business and industry is stimulated while others are forced to contract or close down. Costs are incurred by both property owners and land managers as they attempt to mitigate fire risk and maintain property value. All these changes and actions have ramifications in terms of EGSs. When wildfires do occur, costs are incurred to fight the fires, and impacts are realized as structures are burned and people are displaced. EGSs are affected as water runoff behavior changes and erosion occurs, resulting in other effects on EGSs, providing further feedback to the social-economic realm, and so on.

Evaluating the Impacts of Bark Beetle Attacks

Pest assessments to date have largely been limited to determining the spatial extent of infestation and sometimes the severity (e.g., Man 2013). Change in affected area is used as a proxy for "ecological impact." This proxy is one measure of the direct effect of infestation, but it does not truly address impact. Identifying and distinguishing among resources affected and associating those affected resources with indirect impacts—and then with values—is seldom factored into estimates of loss or gain.

Economic Impact

"Economic impact" can be estimated using data on market transactions and expenditures. Examples of "economic impact" analyses applied to forest management and restoration activities can be found in Nielsen-Pincus and Moseley (2013), Starbuck et al. (2006), and Waters et al. (1994). Bark beetle impacts on local and regional economies can result from multiple sources. Potential increases in logging and salvage operations lead to demand for the services of contractors and mill operators who hire workers and purchase inputs to their production processes. Those purchases and wages paid to workers flow through the economy to create indirect and induced effects. Direct effects result only from expenditures in response to the initial shock to the system, in this case, logging and mill production. Indirect effects result from firms resupplying (after production resulting from the direct effect) inputs used in their production activities. Induced effects result from workers spending their wages on consumer goods and services. (Do not be confused by the terms direct effects, indirect effects, and induced effects in the context of "economic impact." That is just economic jargon, though there are parallels with the mediating influences on impacts discussed earlier). Beetle-killed timber may or may not be suitable for some mill production, which could result in decreased production in some mills leading to reductions in employment and output. Other or new mills might increase employment and output by using beetle-killed trees for other products. One example of this is increased demand from furniture makers and craft lumber mills based on consumer preferences for the characteristic blue stain of beetle-killed lumber (Blevins 2007, Proctor 2010, North Forty News 2012, Garrigan 2013).

Changes in recreation demand might be an indirect outcome of the beetle infestation that results in "economic impacts," analogous to the "economic impacts" of fire and fuels management activities discussed by Starbuck et al. (2006). The direct effect in this case would be (increased or decreased) expenditures by recreation participants; indirect and induced effects would follow those direct effects. Those same changes in recreation demand could have associated changes in "economic value." There might be more or less recreation participation, or the "economic value" of the experience might change. Other recreation demand–stimulated changes in economic structure or demand, leading to other "economic impacts," might occur as communities take adaptive actions to the bark beetle attack ("community/social impacts"). This illustrates the possible simultaneity and interaction among "economic impact," "economic value," and "community/social impact." The impacts are different, and neither additive nor directly comparable, but one could affect the others.

Economic Value

A substantial literature has developed and evolved around the theory and practice of nonmarket valuation since World War II (Champ et al. 2017). Economic methods can be used to infer values for component parts of overall bark beetle impacts (e.g., both "economic impacts" and "economic value" impacts on nonresident tourism and recreation as alluded to before or "economic value" impacts on local homeowners can be parts of the overall impact of bark beetle infestation. The general method of using monetized values estimated at one time and location and applying them to infer values at others is called "benefit transfer" (Rosenberger and Loomis 2017). For example, if the "ecological impact" of bark beetles affects hunting, wildlife viewing or hiking opportunities, there are studies in the literature that have estimated "economic values" for those activities (e.g., McCollum et al. 1990, Loomis 2005) that can be used to estimate particular "economic value" components of overall bark beetle impact. Few empirical analyses of impacts specifically related to bark beetle outbreaks have been done. In the discussion by Rosenberger et al. (2012) (with citations) of the 22 studies they found of nonmarket "economic values" directly affected by and attributable to forest insect pests, they report most studies (10) were based on recreation value; seven estimated bark beetle impacts on residential property values; four estimated effects on nonuse (or passive use) values; two looked at aesthetics; and six looked at overall or total value. "Economic values" estimated by those studies are primarily short-term in perspective and do not necessarily include monetized estimates of "social impact" or "ecological impact" related to a functioning forest such as biodiversity and maintenance of ecological processes (Rosenberger et al. 2012). One needs to be aware of exactly what is being estimated. But they do illustrate the range of component impacts of bark beetle infestation.

"Economic values" estimated using benefit transfer are not as directly applicable as values estimated in a site-and-circumstance-specific study at the site in question. They can, however, provide a rough estimate of value. Sometimes a rough estimate is all that is needed. Values estimated at sites in the same region or for similar circumstances generally provide better (more transferable) estimates of "economic value." The studies cited by Rosenberger et al. (2012) as being directly attributable to forest insect pests might provide the most transferable estimates of "economic value" components of overall bark beetle impact. One such example is provided by Rosenberger et al. (2013), in which they use benefit transfer to estimate the recreational damages ("economic value") associated with a mountain pine beetle outbreak in Rocky Mountain National Park, Colorado.

The same impacts occurring in different places can have opposing results. For example, Price et al. (2010) and Cohen et al. (2016) found decreased residential property "economic values" resulting from mountain pine beetle outbreaks in Colorado, while Hansen and Naughton (2013) found that large wildfires and the spruce bark beetle outbreak in Alaska combined to increase residential property "economic values." Hansen and Naughton offered a possible explanation for the increase in property values: "Before the occurrence of a large natural disturbance, properties located in the wildland urban interface of the western Kenai Peninsula were surrounded by relatively dense forest. Following the disturbance, the trees are killed and fall, opening up aesthetically pleasing views of Cook Inlet and the Aleutian Mountain Range beyond" (Hansen and Naughton 2013, p. 149).

In quantifying "economic values" of bark beetle infestation, one must control for overlap and double counting, while recognizing people can legitimately hold values that fall into more than one component of overall impact; but once those precautions have been taken, the component impacts are additive. The same precautions would apply to "economic impact" and "community/social impact."

The concept of benefit transfer can be applied to "economic impact" studies as well as to studies of "economic value" (Stynes and White 2006, White and Stynes 2008). Economic expenditures (which are the data underlying "economic impact") related to recreation on national forests, for example, can be found in studies by the American Sport Fishing Association (2007) and Stynes and White (2006).

Community and Social Impacts

"Impacts on communities and social institutions" may or may not be quantifiable using the economic methods discussed above. Illustrative of such impacts, Flint et al. found that:

> "despite dramatic differences in community characteristics . . . local residents consistently remarked that the insect disturbance [in Colorado] is a natural process exacerbated by management practices and climatic factors. Perceived negative impacts from the beetle outbreak included aesthetic and scenic loss, the high economic cost of mitigation . . . and effects on the recreation and tourism orientation of the region. Concern about fire hazard was high. On the other hand, economic opportunities for those employed in jobs related to harvesting and processing trees related to beetle activity and threat were seen as positive benefits . . ." (Flint et al. 2009, p. 1,180).

Further, the mountain pine beetle outbreak in Colorado "catalyzed considerable interaction across the region, bringing together different stakeholders and land managers to focus on management strategies and lobby for allocation of resources" to deal with the problems. "In some communities, the beetle issue brought stakeholders and land managers together in new relationships, and these interactions provided a catalytic environment for collective action beyond forest management issues" (Flint et al. 2009, p. 1180). Extended community action was stimulated in some communities to address affordable housing, alternative energy infrastructure, and economic development, among other issues. "In other communities, however, there was bitter resentment about what was perceived as decades of neglect to active forest management blamed on federal land management preference for environmental regulations. This led to profound distrust between local residents and forest managers" (Flint et al. 2009, p. 1180). Other findings pointed to barriers and constraints imposed on land managers by legal actions taken by various interest groups leading to community dysfunction (such as suggested by Flint 2006). Multiple studies by Flint and various colleagues (e.g., Flint 2006, Flint and Haynes 2006, Flint and Luloff 2007, Qin 2015, Qin et al. 2015, Qin and Flint 2017) addressed "community/social impacts" of the spruce beetle outbreak in Alaska; those findings will be more specifically noted in the Alaska case study in this special section. In terms of evaluating "community/social impacts," the message is that such impacts vary across communities and are hard—sometimes impossible—to measure quantitatively. Qualitatively, they can have both positive and negative outcomes, and profound impacts on community capacity, resilience, and sustainability.

Other indicators of "community/social impacts," some of which can be expressed quantitatively, include economic diversity and dependence of the local economy on forest industry employment and income. A mitigating factor to such impacts could be the availability of alternative forest resources. Poverty, family well-being, health, education levels, trust in local leaders and institutions, and physical, social, political, and economic dimensions of community vulnerability could also be elements of "community/social impact" (Christensen et al. 2000, Parkins and MacKendrick 2007).

Discussion, Management Implications, and Conclusion

Temperature and precipitation patterns expected to occur in North America over the 21st century are conducive to continued, or increased, bark beetle outbreaks and activity. Hence, their impacts will likely continue and compound. Forest disturbances like bark beetle infestations affect the ecosystem and diverse groups of people in a variety of ways. Direct and indirect elements of overall bark beetle impact interact with other elements of the ecological and socioeconomic realms of the complete ecosystem as they iterate through time. More feedbacks and interactions occur, and changes in EGSs spark elements of the social and economic realm to perceive and recognize changes in the ecosystem and respond to them, thus stimulating further changes in EGSs that affect both the ecological and socioeconomic realms. Managers need to recognize and even anticipate such interactions as they practice adaptive management and manage for ecosystem resilience and adaptive capacity. Evaluating bark beetle impacts in a systematic framework using EGSs and their inherent feedbacks and interactions over time provides the broad analytical scope needed to fully consider the wide range of potential impacts. Such consideration and understanding of associated impacts and their valuation facilitates managers' knowledge and their ability to mobilize adaptive or mitigating measures.

Readers are encouraged, as they peruse the other articles in this special section, to think about direct and indirect outcomes and how the impacts described might interact with other EGSs and elements of the ecological and socioeconomic realms of the ecosystem as they iterate through time. Only then can one begin to grasp the overall impact of bark beetle outbreaks.

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