Rethinking strategies for coexistence with bark beetles in Mexico and beyond

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Temperate forests in Mexico are often inhabited by humans and as such function as social–ecological systems (SES). As elsewhere in the world, these forests are increasingly under threat from bark beetle pests, outbreaks of which will be exacerbated by climate change. Current strategies for confronting bark beetle infestations are typically more technical and reactive, and technology and science have not yet provided economic and practical solutions. Taking into consideration future climate-change scenarios, forest policy agendas must embrace more holistic strategies focused on improving resistance, resilience, and adaptive capacity of forest SES. Forest landowners are crucial stakeholders worldwide, and when provided with reliable information, training, and incentives, can perform the complex and highly demanding responsibilities of forest monitoring, sanitation logging, and restoration. Participatory sanitation logging in Mexico highlights the opportunities and challenges of dealing with bark beetles, from which lessons can be drawn. A holistic strategy that includes management and public policy recommendations for Mexico and elsewhere is proposed as a potential means of coexisting with this challenge to forest health.

Front Ecol Environ 2021; doi:10.1002/fee.2378

Globally, temperate forests cover 6.9 million km^2 and provide multiple resources and environmental services (De Gouvenain and Silander 2017). Conifers represent one of the most common types of trees in temperate regions, with *Pinus* – consisting of approximately 111 species worldwide – dominating many forests (Price *et al*. 1998). Temperate forests support a high diversity of bark beetles, primarily of the genera *Dendroctonus* and *Ips* (Coleoptera: Scolytidae). The conifer–bark beetle relationship in the northern hemisphere can be traced back to at least 190 million years ago, following the diversification of conifers in the Cretaceous (Wood 1982). Bark beetles are key elements of the forest ecosystem dynamic because they modulate the availability of resources for other species due to the changes caused by the elimination of their host trees (Jones *et al*. 1997). In recent years, however, bark beetles have become pests in many areas (WebTable 1), and are responsible for the deaths of millions of conifers in Europe, North and Central America, and Asia (Seidl *et al*. 2014; Hlásny *et al*. 2019). The mass mortality of conifers due to bark beetle outbreaks is the result of interactions among various factors at global, national, and local scales, including climate change, geographic location, presence of species hosts, management history, forest policies, regulations, lack of information on infestation prevention, culture of the forest landowners, and social conflicts, among others (Raffa *et al*. 2008; Biedermann *et al*. 2019). Particular emphasis has been given to climate change (Marini *et al*. 2017), as disruptions attributable to increased temperature result in hydric stress in trees that diminishes their physiological defense systems, facilitating bark beetle outbreaks (WebTable 1; Allen *et al*. 2010; WMO 2013). In addition, forest fires and silvicultural practices reduce canopy complexity to monodominance of bark beetle host species, while inadequate tree density increases competition that can weaken trees and increase their vulnerability (Fettig *et al*. 2007). Moreover, when sanitation logging (also known as salvage logging, a practice in which trees negatively affected by disturbances, including but not limited to bark beetles, are selectively removed; for definitions of additional specialist terms, see Panel 1) is performed incorrectly or not performed in a timely manner, bark beetle outbreaks can persist and scale-up to the landscape level.

At present, there are no economically or practically feasible solutions for dealing with bark beetles, and thus it is important that interdisciplinary and realistic diagnoses be made, ones

In a nutshell:

- Bark beetle infestations are one of many contemporary global environmental challenges likely to expand in the future and simultaneously impact forests and social welfare
- Instead of considering them as a technical problem and focusing solely on their impacts on the ecological subsystem, bark beetle outbreaks should be viewed in the context of a social–ecological system
- As such, actions for addressing infestations should be geared toward increasing resistance, resilience, and adaptive capacity in the social and ecological dimensions
- Community forest management of bark beetle outbreaks in Mexico illustrates the potential of participatory and adaptive strategies in maintaining long-term forest health

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Panel 1. Key working concepts

Adaptive capacity is the ability of a system to adjust to changes like those imposed by bark beetle infestations. Cottrell *et al.* (2019) recognized the importance of "the preconditions of a social–ecological system to adapt to that disturbance in a proactive and/or reactive manner" that depend on the scale and intensity of the bark beetle outbreak; the level of risk perception; and the form and degree of local and multilevel governance.

Forest culture refers to the forest-related customs and beliefs held by a particular group of people that are linked to their collective history, traditions, knowledge, and activities associated with the forest (Soulbury Commission 2012).

Forest health refers to the forest conditions that help preserve structural and functional integrity for maintaining productivity and other ecological processes (DellaSala *et al.* 1995).

Resilience is the capacity of a forest system to recover following a disturbance (Holling 1973).

Resistance is defined as the aptitude of a system for absorbing the effects of disturbances and the ability to remain essentially unchanged (DeRose and Long 2014).

Sanitation logging is a type of forestry intervention in which trees affected by bark beetles (and other biotic threats) are selectively removed to preserve forest health (Hlásny *et al.* 2019).

Social–ecological systems (SES) are complex and adaptive systems composed of social and ecological subsystems with inherent interactions, feedbacks, and time lags among the components, all of which occur at different temporal and spatial scales (Berkes *et al.* 2000; Janssen and Ostrom 2006a; Ostrom 2009). In forest SES, the social subsystem is typically composed of forest governance institutions, property rights over forest areas, access to timber and non-timber resources, and local knowledge of and cultural aspects relating to the regional environment and forest resource use. The ecological subsystem commonly refers to self-regulating communities of organisms interacting with one another and with their environment. However, in forests subjected to human interventions, it can also correspond to the communities of organisms generated by combined natural and anthropogenic forces. In a timber extraction zone, the ecological subsystem is usually focused on the tree component in the canopy and understory. Interactions, feedbacks, and time lags are typically linked to forest resource harvest and management, which bring the ecological system to conform with expected characteristics according to the purpose for which it is managed (Fischer 2018).

that consider not only forests in their own right but also the human communities that rely on the benefits provided by forest ecosystems. Depending on the country, the rights of ownership of forests and forest products vary greatly, from smallholders, to family forests, to common property (White and Martin 2002; Bray 2013; Butler *et al.* 2016), underscoring the need to recognize that these forests constitute social–ecological systems (SES), along with awareness of the interactions between the social and ecological components or subsystems (forest SES; Panel 1; Figure 1; Berkes *et al.* 2000; Janssen and Ostrom 2006a; Fischer 2018). Although the strength of the relationship between forests and the human communities that depend on them may vary, participatory practices can nevertheless encourage practices for preserving forest health (Flint *et al.* 2009; Durán and Poloni 2014). Attention to forest health must be made a priority of government forest agendas, as bark beetle infestation will become even more of a problem in the future (Millar and Stephenson 2015; Morris *et al.* 2017; Hlásny *et al.* 2019). We emphasize the importance of assuming that bark beetles will continue to have negative impacts on forest systems, and that stakeholders must learn to coexist with this threat and attempt mitigation using an SES approach in acknowledgement of the crucial importance of the social dimension. Mexico, and examples from the state of Oaxaca in particular, illustrate the opportunities and challenges of an SES approach as well as the involvement of local communities in promoting forest health. The framework proposed here emphasizes actions that focus on improving the resistance, resilience, and adaptive capacity of forest SES in areas affected by bark beetles.

The forest social–ecological system

Although most forests function as SES (Panel 1), when bark beetle outbreaks arise in a region, traditionally the attention is on the ecological subsystem, possibly in part due to visibility of the mass mortality of host trees. As such, researchers and government forest agencies commonly focus on technical aspects of bark beetle control. Yet this is only one aspect of the problem, and little attention is given to its social dimension in situations outside of government forestlands and large corporate forests (FAO 2009; Butler *et al.* 2016; Morris *et al.* 2017), despite the fact that millions of hectares of affected forests are held in communal or family tenure regimes. News media tend to focus on the broader social impacts of bark beetle infestations, such as detrimental impacts on real estate, tourism, and the provision of ecosystem services (Flint *et al.* 2009; Morris *et al.* 2018), and less so on its impacts on family forests and community properties. Forest pest control is the responsibility of the landowners, including government, the timber industry, individual families, and communities, but in a few instances, particularly in Central America and Europe, the military has also taken charge (Amador 2015; BBC 2019). Cases of local collaborative and participatory bark beetle control have received less attention, even though landowners are involved in and critical for forest health protection. Participatory sanitation logging has been practiced for decades in community forests in Mexico (Durán and Poloni 2014), usually with the support and backing of the National Forest Commission (Comisión Nacional Forestal, CONAFOR). Engaging people who own community and family forests in control and prevention measures is critical, because such landowners generally implement the most effective small-scale control through the felling, debarking, and burning of bark debris of infested trunks and branches (Figure 2; Dobor *et al.* 2020). These practices are complex, dangerous, expensive, and labor intensive, and have remained largely unchanged for nearly a century (Ringle 1940).

Participatory sanitation logging is based on local forest knowledge and forest governance institutions, as well as organizational capacity and individual abilities. Local stakeholders may already own or have access to the necessary equipment, and forest owners may be able to count on help from neighboring communities and members of their local and regional forest organizations. These organizations can provide leverage for (1) increasing political power to negotiate funds for sanitation, protective equipment, and infrastructure; (2) ensuring greater involvement of forest agencies; and (3) accelerating authorization for sanitation logging (WebTable 2; Cheng *et al.* 2015; Abrams *et al.* 2017).

However, participatory sanitation logging is unrealistic for extensive bark beetle outbreaks (for instance, over thousands of hectares), for reasons of logistics, cost, and labor. Such cases necessitate large-scale regional planning and government-led action, with involvement from local stakeholder organizations, although the nature of the government–local stakeholder collaboration will vary depending on the circumstances of each forest SES (Figure 1; Raffa *et al.* 2008). Moreover, with respect to both local and regional outbreaks, the forest SES may also provide substantial opportunities not only for sanitation logging, including preventative measures to inhibit the spread of bark beetles, but also for subsequent forest recovery (Hlásny *et al.* 2019).

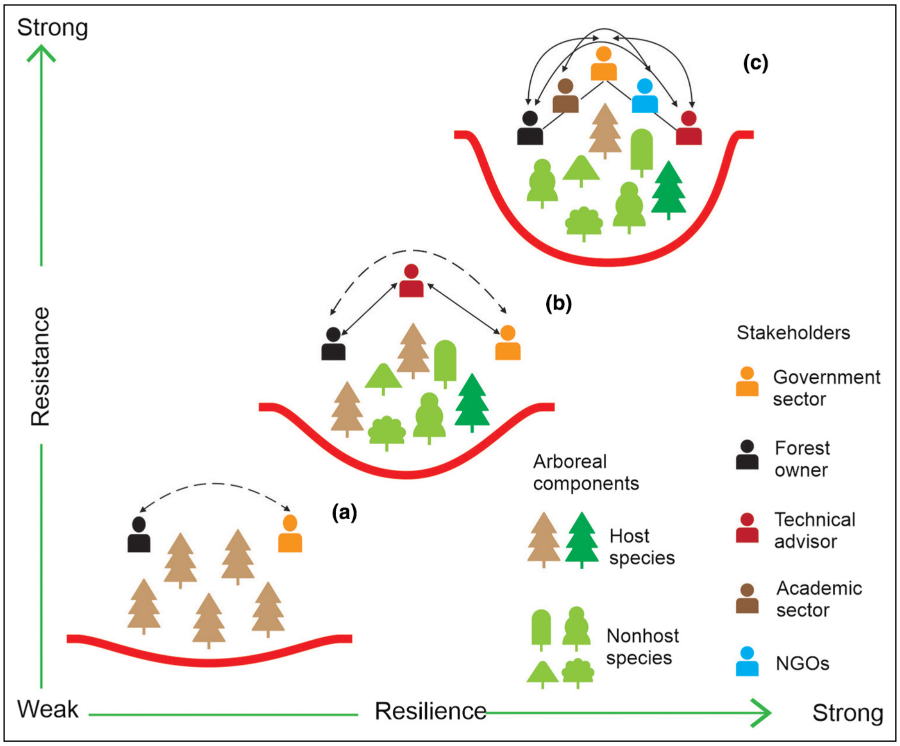

Figure 1. A reworked version of Holling's (1973) "ball-and-cup" model illustrates different levels of resistance (height of the cup) and resilience (width of the cup) in a forest social–ecological system (SES; ball): (a) low (undesirable status), (b) medium (acceptable status), (c) high (desirable status).

Resistance, resilience, and adaptive capacity

Forest SES are dynamic by nature, and while unlikely to have a unique equilibrium state in the long term, a threshold of relative stability may be attained (Janssen and Ostrom 2006b). This stability is conferred by three properties: resistance, resilience, and adaptive capacity (Panel 1; Folke 2006; DeRose and Long 2014; Cottrell *et al.* 2019). Even if bark beetles modify structure and function in the ecological subsystem, a forest SES may have the capacity to adapt in a relatively short period of time, thereby avoiding transition to a different and less desirable stable state (Figure 1; Holling 1973). This stability permits stakeholders in forest regions to plan strategies for improving forest management at decadal scales, with a focus on timber and non-timber extraction products and conservation, but also to ensure a stable foundation for local forest-based livelihoods, cultures, and economies (Flint *et al.* 2009; Fischer 2018; Morris *et al.* 2018). Forest SES that exhibit resistance and resilience to bark beetles should promote development of strategies to retain the SES; however, forest SES susceptible to bark beetle impacts require development of measures to improve the ecological conditions and the social capacity that mitigate the effects of infestation (Figure 3). The analysis of a forest SES should therefore take its current status into account, including assessment of its internal variables and potential drivers of change (Figure 4; Table 1).

Social subsystem

Internal variables in the social subsystem that can increase resistance and resilience to bark beetles include unambiguous rights with respect to property and resources, effective forest governance (local and multilevel), forest knowledge and culture, social organization, and technical capacity among local stakeholders for the participatory maintenance of forest health (Table 1; Figure 3a).

Dialogue and organization among forest landowners can stimulate a sense of shared responsibility for improving forest management (Ostrom 2009; Agrawal *et al.* 2014), culminating in the adoption of collective monitoring, sanitation logging,

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Figure 2. A community brigade undertaking participatory sanitation logging in a forest infested with bark beetles in Ixtlán de Juarez, Oaxaca, Mexico. Both manual and mechanical labor is required for (a) cutting and debarking trees, and (b) burning bark debris of infested trunks and branches.

and restoration actions (Hlásny *et al*. 2019; Thorn *et al*. 2019). For example, in an SES with a mature forest culture (Panel 1), landowners have an interest in preventing pest infestations from escalating, particularly in areas where timber is being harvested for commercial purposes (Table 2; WebFigure 1). It has also been shown that when forest owners have adequate economic means and infrastructure, particularly with regard to timber, they often will perform sanitation logging using their own resources, lowering dependence on external resources. Likewise, stakeholder collaboration can reduce the time and resources needed for organizing, training, and equipping a community sanitation logging brigade (see WebTable 2 for additional details and recommendations).

Ecological subsystem

Resistance and resilience to bark beetles in the ecological subsystem is complex and related to varying biotic and abiotic factors, as well as to forest management practices. Biotic factors include tree canopy diversity, composition, structure, and regeneration capability (Table 1). Because bark beetles prefer specific tree hosts, maintaining a diverse tree canopy in which hosts have a comparatively low presence can improve inhibition and dilution effects (Figure 3b; Guyot *et al*. 2016; Guo *et al*. 2019); in such cases, even if tree hosts are affected by bark beetles, overall forest functionality will persevere (Figure 4a). Silvicultural practices can also improve resistance to bark beetles by managing for optimal host tree density (Rubin-Aguirre *et al*. 2015; Bray 2020). In addition, recovery of resistance and resilience in this subsystem may be shortened if natural regeneration and reforestation are promoted through a mix of local germplasm (site dependent) that includes nonhost and resistant host species (Figure 4a; WebTable 2). In Mexico, for example, combining host trees that have exhibited the lowest incidence of bark beetle infestation (Salinas-Moreno *et al*. 2010), such as Mexican white pine (*Pinus ayacahuite*), pinyon pine (*Pinus cembroides*), Douglas pine (*Pinus douglasiana*), and Herrera pine (*Pinus herrerae*), with native nonhost trees, such as various species of oak (*Quercus* spp), would be recommended. This practice can reduce amplification (Figure 3b), which occurs when host species dominate forest stands across extensive areas, facilitating bark beetle spread and subsequently large-scale tree mortality (Raffa *et al*. 2008). Moreover, trees damaged by fires in forests dominated by host species will become easy targets for bark beetle infestation (Figure 4b; Thorn *et al*. 2019).

Feedbacks, time lags, and cross-scale interactions

Levels of resistance and resilience to bark beetle infestation are also dependent on feedbacks (the modification of a process by its effects), time lags (intervals between human–nature interactions), and cross-scale interactions (spatially nested and temporally interdependent social and ecological conditions and processes) (Fischer 2018). Feedbacks between the social and ecological subsystems are driven by different silvicultural practices and forest management decisions (Table 1). One example of positive feedbacks and time lags is when forest management promotes a mix of bark beetle host and nonhost trees in canopies, which helps to mitigate future large-scale mortality events (Figure 4). An example of a cross-scale relationship would be financial mechanisms, such as payments made from voluntary carbon markets to local forest owners who are planting forests. Although these payments are an effort to mitigate global climate change, they may also contribute to bark beetle control because reforestation can be implemented with nonhost trees (Bray 2020). Additional positive feedbacks may include multistakeholder collaboration that improves technical advice, training for conducting sanitation logging, and funding mechanisms (Pratt 2013; Millar and Stephenson 2015; Fischer 2018). The availability of these factors depends heavily on

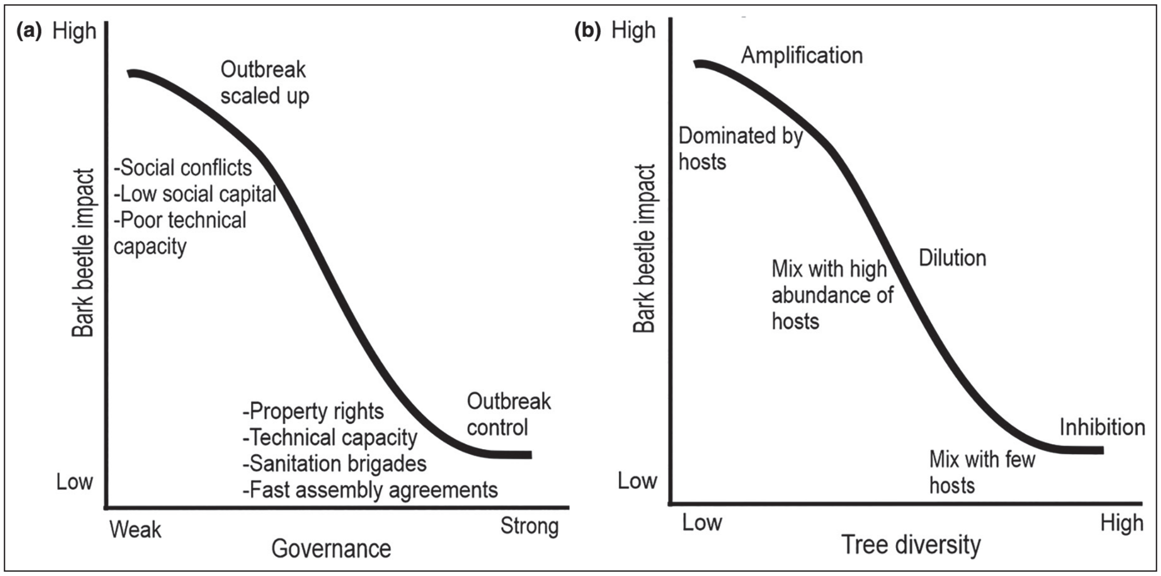

Figure 3. Hypothetical mechanisms that can influence the areal extent of impacts by bark beetles: (a) mechanisms related to governance differences and (b) mechanisms related to tree diversity in forests with different bark beetle hosts.

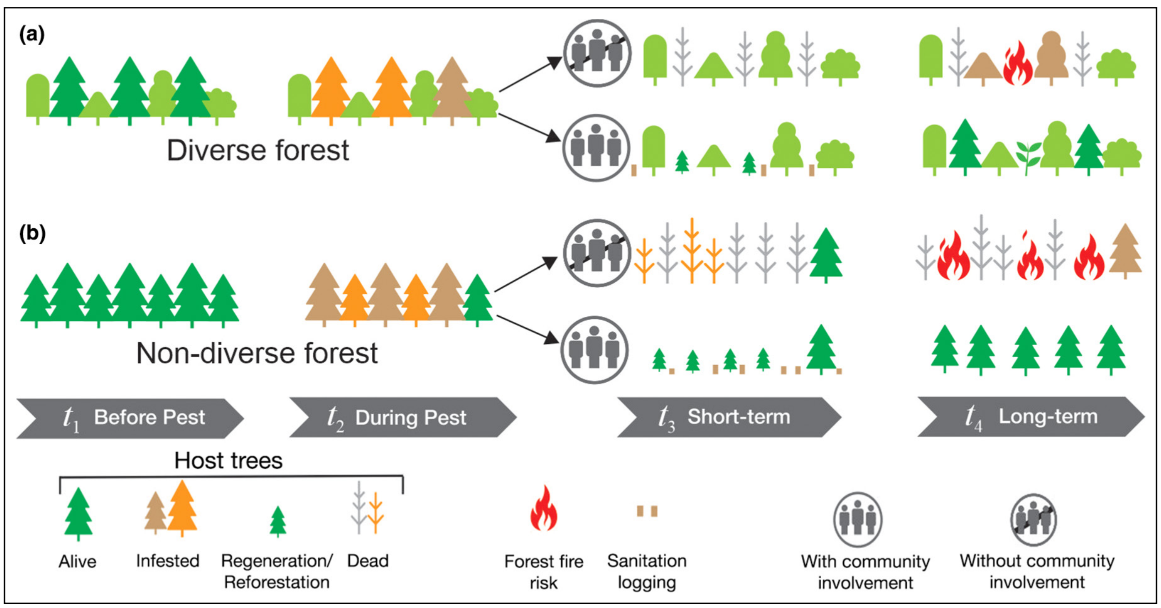

Figure 4. Potential routes in two hypothetical bark-beetle–affected forests (a and b) that differ in tree diversity and community involvement (with and without). Initially (at time t_1), trees are healthy but in the next phase (t_2) bark beetles kill the pines. Afterward, in the short term (t_3) the composition of the forest stand changes while in the long term (t_4) the forest stand may either return to initial conditions or transition to novel conditions.

national forest policies and regional or national markets (Fischer 2018; Thorn *et al*. 2019). In contrast, negative feedbacks occur when bark beetles affect forest stands in the absence of social involvement, reducing the possibility of participatory sanitation logging. This may result in greater accumulation of dead wood and consequently elevated risk of forest fire, along with subsequent forest degradation (Figure 4). Given that recovery from a degraded state may require 50–100 years, a thorough understanding of the social–ecological processes involved is therefore critical, taking into account timber harvesting (Hernández-Díaz *et al*. 2008) and additional time for functional integrity to rebound (Do *et al*. 2010).

Case study: Mexico

In Mexico, temperate forests make up about 51% of the country's >64.9 million ha of overall forest cover (Torres-Rojo *et al*. 2016) and are largely composed of *Pinus*, with 61 species (Gernandt and Pérez-de la Rosa 2014). Many *Pinus* species are bark beetle hosts and overlap geographically with at least 12 species of *Dendroctonus*, six of which

Table 1. Conditions in the internal variables for subsystems and interactions that impose contrasts in resistance and resilience levels in forest social–ecological systems affected by bark beetles

Subsystem and interactions	Internal variables	Resistance/resilience level: *Low*	*Medium*	*High*
Social	Property rights	Unclear	Partially clear	Clear
	Rules for forest use	No rules	Flexible rules	Clear, strict rules
	Forest knowledge and culture	Weak	Moderate	Strong
	Participatory pest monitoring	Absent	Occasional	Frequent
	Own budgets and infrastructure to control pests	Limited	Insufficient	Adequate
	Multilevel governance	Weak	Occasional	Always
Ecological	Tree canopy diversity	Low	Medium	High
	Tree density management	Null	Irregular	Constant
	Regeneration capability	Incipient	Medium	Good
	Bark beetle biological controls promoted	Weak	Regular	High
	Complexity in the organism community	Low	Medium	High
Feedbacks, time lags, and cross-scale interactions	Forest management	Single purpose	Emphasis on timber	Multipurpose, integral
	Adaptive management	Never	Sometimes	Always
	Technical advice and training	Without or limited	Occasionally	Constant
	Financial mechanisms for participatory pest control	None	In process	Established and accessible
	Bark beetle information campaigns	None	Only during periods of risk	Constant, updated
	Forest health departments[1]	Pathological[1], insufficient staff and budget	Bureaucratic[1], inadequate staff and budget	Adaptive[1], adequate staff and budget
	Normativity for sanitation logging[2]	Not clear	Not updated	Updated
	Bureaucratic processes for sanitation logging	Complex, slow	Difficult	Simple, fast

Notes: [1]based on the "stereotypical organizational types" presented in Meffe *et al*. (2002); [2]based on forest health dynamics in each country, but with revisions and continual adjustments.

may be associated with outbreaks. Nationally, Durango pine (*Pinus durangensis*), Apache pine (*Pinus engelmannii*), Hartweg's pine (*Pinus hartwegii*), Chihuahua pine (*Pinus leiophylla*), and Mexican yellow pine (*Pinus oocarpa*) experience the highest incidence of bark beetle infestation (Salinas-Moreno *et al*. 2010). The dominant host species may change in different geographic regions; for example, patula pine (*Pinus patula*), the dominant commercial pine species in Oaxaca, is the most susceptible pine species to infestations. For more than a decade, CONAFOR has been developing a national strategy to deal with bark beetle outbreaks, which includes annual aerial surveys, early mapping alerts, subsidies for sanitation logging (~US$70 per hectare), establishment of Forest Health State Councils, and more recently, organization of community sanitation logging brigades. In addition, government agencies and academics have organized forums at local to national levels to present and discuss the bark beetle pest problem. However, a technical focus continues to prevail, and action is most often taken only after a bark beetle outbreak occurs.

Mexican law has established that landowners are responsible for the care of their forests, with support from CONAFOR. Approximately 60% of forests in Mexico are owned by local communities (Bray 2020), with an additional 17% consisting of family or small private forest enterprises (Morett-Sánchez and Cosío-Ruiz 2017). About 29,000 forest communities in Mexico manage at least 5 ha of forest and oversee forest health; of these, ~2,000 operate as community forest enterprises (CFEs), in which logging is practiced under management plans approved by the Mexican government (Bray 2020). These communities are best positioned to implement participatory sanitation logging programs (Figure 2), which have been shown to be effective in preventing rapid escalation of bark beetle outbreaks; moreover, the forest sector delivers economic benefits to the communities as well. For example, in 2016, 1,511 official authorizations were granted for timber extraction (mainly pine), along with several hundred for harvesting non-timber products (Torres-Rojo *et al*. 2016). Due to the well-established demand for pine in regional and national markets, government reforestation programs and CFEs have expanded the areal extent of *Pinus* woodlands, although these are primarily composed of species with high commercial value. Oaxaca is one state that boasts of successful CFE operations (Bray 2010); however, Oaxacan forests are also particularly vulnerable to bark beetle infestation (Salinas-Moreno *et al*. 2010). In contrast to successful CFEs, there are numerous community forests and

Table 2. Three cases of community forests in Oaxaca, southern Mexico, showing contrasts in their social subsystems that modify the resistance and resilience of their forests to bark beetles

Cases[1]	Social subsystem	Forest management	Forest impacts[2]
Ixtlán de Juárez (high)	• strong forest governance • no social conflicts • multilevel forest governance • high forest culture • high organizational capacity for sanitation logging	• adaptive and multipurpose (including conservation) • forest monitoring by community brigades • timely sanitation logging	• 1,313 m^3 • only small bark beetle outbreaks • infestations never escalate
Pueblos Mancomunados (medium)	• strong forest governance • internal social conflicts • multilevel forest governance • high forest culture • moderate organizational capacity for sanitation logging	• adaptive and multipurpose (including conservation) • forest monitoring is delayed due to conflicts • timely sanitation logging only in areas where conflicts are absent	• 3,333 m^3 • bark beetle infestation initially escalated but was brought under control several years later
Santo Domingo Ozolotepec (low)	• weak forest governance • intercommunity social conflicts • no multilevel forest governance • low forest culture • low local organizational capacity for sanitation logging	• mainly restricted to timber extraction • no internal forest monitoring • no sanitation logging	• 18,408 m^3 • bark beetle infestation escalated and is currently widespread throughout the region

Notes: [1]"high", "medium", and "low" indicate level of resilience and resistance to bark beetles; see images in WebFigure 1. [2]Data for timber volume impacted by bark beetles for 2017 taken from SEMARNAT (2018).

small private forests that have low resistance and resilience to bark beetles due to poor management, weak governance, and low technical capacity for sanitation logging (Table 1). To illustrate the varying levels of resistance, resilience, and adaptive capacity to bark beetles, in the following sections we discuss three forest SES – Ixtlán de Juárez, Pueblos Mancomunados, and Santo Domingo Ozolotepec – characterized by different forest management, governance, and social conflicts (Table 2; WebFigure 1).

Ixtlán de Juárez

This community in the Sierra Norte region is internally well organized and has diversified forest uses. Although it has experienced small outbreaks of bark beetles over the past decade, these have been brought under control quickly and efficiently through participatory sanitation logging (Figure 2), which has prevented escalation. The community has a relatively high technical capacity for forest management and a willingness to improve social learning. As such, desirable interactions and feedbacks are in operation, and in recent years the community has undertaken routine monitoring and early response measures to bark beetle outbreaks.

Pueblos Mancomunados

Pueblos Mancomunados, also located in the Sierra Norte region, has well-managed forests and diversified forest uses, but internal conflicts have interfered with initiation of sanitation logging. Various factors, along with these conflicts, have delayed obtaining authorization and implementation of participatory sanitation logging, resulting in considerable damage to its forests. The community has high technical capacity for forest management and, after participation in a social learning experience, landowners now have a better grasp of the bark beetle problem. In response, they have improved their capacity to react to bark beetle outbreaks by increasing forest monitoring and treating infestations while still in early stages, despite lingering social conflicts that hinder obtaining authorization to engage in sanitation logging. Although the water supply–bark beetle relationship is complex (Beudert *et al.* 2015), research has shown that forest cover damage due to bark beetles can impact water quality for several years after the outbreak, giving the community additional motivation for preserving the health of their forest.

Santo Domingo Ozolotepec

Santo Domingo Ozolotepec is a community in the Sierra Sur region with some degree of technical capacity for forest management. Due to boundary conflicts with a neighboring forest community, however, along with poor knowledge of and interest in bark beetles, this community has not yet implemented a sanitation logging program. The boundary dispute first began in 2015, and escalated quickly from there (SEMARNAT 2018); at present, the conflict between the communities remains unresolved, and due to a lack of attention, much of the community forest – as well as forests of surrounding communities and small private forests – has been damaged by bark beetles. Moreover, in 2018, the community decided to break off negotiations promoted by government agencies and abandoned efforts to come to an agreement with neighboring communities over sanitation logging (WebTable 2). The Ozolotepec example demonstrates that local technical capacity for commercial logging is insufficient when social conflict causes a community to make impractical collective decisions (Bray 2020). Consequently, bark beetle infestations continue to impact forests in the region and dead wood continues to accumulate, greatly increasing the risk of catastrophic forest fires (Xie *et al.* 2020).

Ixtlán and Pueblos Mancomunados exemplify the practice of hundreds of Mexican forest SES, where community assemblies discuss how to implement the best collective action for sanitation logging in such a way that timber production in their CFEs is protected from bark beetle pests, as are ecological functionality and human well-being. The example of Ozolotepec, however, illustrates the critical need to: (1) strengthen local forest culture, (2) improve risk perception, and (3) encourage multilevel forest governance. The three key factors mentioned above may influence success for communities and other forest smallholders in Mexico and beyond, and should be incorporated in forest health protocols.

Holistic strategies for coexisting with bark beetles

Because climate disruptions will continue to increase globally in the future, there is an urgent need for forest communities to learn how to cope with bark beetle outbreaks (Biedermann *et al.* 2019; Hlásny *et al.* 2019; Thorn *et al.* 2019). Current responses concentrate largely on technical forest management issues, but it is crucial that more holistic strategies in which forests are regarded as SES be adopted (Table 3). In Mexico, along with many other locations worldwide where smallholders, family or community forests, or other kinds of rights over land and forest resources are common (White and Martin 2002), forest SES are an everyday reality. In these areas, the human dimension is therefore a key condition for mitigating and adapting to bark beetle outbreaks (Figure 4). We propose that future mitigation approaches must (1) promote multilevel governance, (2) implement management at the landscape level, (3) detail transitions from reactive bark beetle policies to more preventive actions, (4) adopt adaptive management, (5) conceive of bark beetle pests as an environmental emergency, (6) enhance social learning, (7) improve education and communication, (8) reduce social conflicts, (9) strengthen means for sanitation logging, (10) encourage reforestation and restoration for bark beetle resistance and resilience, and finally (11) finance and incentivize maintenance of forest health. Proposals for the practical implementation of these proposals, for Mexico and elsewhere, are presented in WebTable 2.

Table 3. Current strategy to combat bark beetle infestations in community forests of Mexico, and a holistic alternative proposal

Current strategy	Holistic strategy
Focus primarily on the tree–forest component (ie the ecological subsystem)	Focus on forests as SES
Problem managed as a technical issue	Problem managed as an integral issue, with the social dimension playing a key role
Traditional forest management	Adaptive and participatory forest management
Interventions when bark beetles are observed, to control or combat outbreaks	Interventions before, during, and after bark beetle outbreaks appear
Sanitation logging subject to bureaucratic delays and outdated regulations	Control of bark beetles conceived as emergency and based on updated regulations
Insufficient economic resources for sanitation logging	Mechanisms for financing and incentives

Conclusions

Bark beetle infestations represent the most important biotic threat to the health of Mexican temperate forests, as well as other forestlands around the world. Although silvicultural practices may improve forest resistance and resilience, strengthening local and multilevel governance is fundamental, and the human dimension must be taken into consideration for interventions before, during, and after bark beetle outbreaks. The devastating impact of bark beetles on forests in the western US and Canada has shown the potential for outbreaks to scale-up rapidly. Forest policies must therefore be revised to incorporate novel strategies for maintaining forest health that are more holistic, participative, and adaptive.

Acknowledgements

GP was granted a scholarship from CONACYT and BEIFI-IPN. Funding for manuscript writing was provided by The Rufford Foundation (grant 24129-1) and the IPN-SIP program (2019-5856). We thank the Oaxaca State Forest Sanitation Council for providing access to official bark beetle information and internal discussions on bark beetle control, and DB Bray for help editing the manuscript.

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