Review

Towards Sustainable Forest Management in Central America: Review of Southern Pine Beetle (*Dendroctonus frontalis* Zimmermann) Outbreaks, Their Causes, and Solutions

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Abstract: Outbreaks of the southern pine beetle (SPB) *Dendroctonus frontalis* Zimmermann in Central America have had a devastating impact on pine forests. It remains unclear to what extent these outbreaks are caused by the beetle's ecology, climate, and historical management practices. Using research data and experience accumulated in northern latitudes to guide management of forests in Central America is associated with great uncertainty, given the many unique features of the conifer forests in this region. The main recommendation from this review is that Central American bark beetle outbreaks need to be studied locally, and the local climate, biotic elements, and silvicultural history need to be considered. The key to reducing the impacts of SPB in Central America are local research and implementation of proactive management, in order to facilitate the establishment of forests more resilient to increasing environmental and anthropogenic pressures.

Keywords: landscape resilience; forest ecosystems; forest health; Central American regional strategy

1. Introduction

Bark beetles are a natural component of forests in many regions of the world, but they can also be a major disturbance agent especially in coniferous forests with low tree species diversity, high, density and environmental stresses. In Central and North America, for example, tree mortality caused by bark beetles has been estimated in millions of hectares in recent decades [1,2]. Economic costs include not only timber losses, but also changes in ecosystem services, water retention, climate and carbon loss mitigation, and public health consequences [3]. On one hand, outbreaks and the associated loss of mature trees modify stand and age-class structure, species composition, and spatial distribution and arrangement of surface and canopy fuels, therefore reducing basal area, density, and average diameter at breast height. On the other hand, a great proportion of the outbreaks in coniferous forests across the northern hemisphere are occurring in stands with unnaturally high basal area and in stands impacted by increasing temperatures and/or drought. Therefore, land managers increasingly have to make decisions about whether their management focuses on suppressing bark beetle epidemics or on adapting stands to new climatic regimes. Such landscape-wide, far-reaching decisions may require a departure from a traditional management style, and it is increasingly critical to consider the best available science, public perceptions, and monitoring targets [4].

Most outbreaks of primary bark beetle pests occur in stands with mature trees of large diameter, high-density, and little tree species diversity. During the endemic phase, tree mortality is limited to weakened or felled trees and is relatively constant. In several bark beetle-host systems, however, such as the Central and North American *Dendroctonus* spp. and their conifer hosts, during the epidemic phase more than 80% of the susceptible trees can be killed [5]. In order for outbreaks to occur, multiple processes interact at different spatial and temporal scales. Climate change, a major driver of many outbreaks around the world, is causing new regimes of precipitation including extended drought, unprecedented heat waves, and more frequent and severe weather events, increasing tree stress and reducing defense mechanisms [6]. In addition to climate, outbreaks are facilitated by large contiguous areas of susceptible hosts with little heterogeneity at the landscape level [7,8]. As a consequence, recent bark beetle outbreaks have exceeded the frequencies, impacts, and ranges in the last 125 years [9].

The southern pine beetle (SPB), *Dendroctonus frontalis* Zimmermann, is the most destructive insect pest of pine forests in the southeastern United States, Mexico, and Central America. This native insect lives predominantly in the phloem and the inner bark of pine trees, where females colonize live or freshly dead phloem tissue to construct S-shaped galleries that can effectively girdle a tree, causing its death [10]. Southern pine beetle females carry symbiotic fungi, most commonly *Entomocorticium* species and *Ceratocystiopsis* species, that serve as the predominant source of nutrition for the larvae [11]. Because SPB is considered the most destructive pest of native pine (*Pinus* spp.) forests in Central America, it has been researched in this region since the 1960s [12]. The activity of SPB depends on two robust predictors: the availability of suitable host material (basal area), and predators and parasites, whose abundance may contribute to the outbreak dynamics [13,14]. Climatic parameters control SPB outbreaks on the edges of the insect's distribution [15]. The southern pine beetle is unique among bark beetles in that its outbreaks regularly occur in stands of healthy trees, rather than being dependent on poor stressed trees, as *Ips* and most other *Dendroctonus* spp. [16].

In Central America's coniferous forests, bark beetles, and wildfires are the two most destructive agents [17,18]. Both occur on the same landscape scale, and both are most prominent in dense, overgrown conifer forests. Moreover, because tree proximity facilitates pheromone communication in SPB, dense forests increase the chances of success of mass attacks [19]. However, the specific interactions between bark beetles and fire remain unclear. On one hand, beetle-infested stands may cause extreme fire behavior due to a large amount of fuel availability [20]. On the other hand, bark beetle outbreaks may dampen fire because, after a few months, they leave only standing trees with no needles, which prevents canopy fire [21]. On the short time scale, wildfires may support bark beetle attacks because they reduce inducible defenses of pines and increase the amount of ethanol and volatile terpenes released [22]. On larger time scales, however, a fire-thinned forest is naturally less susceptible to large outbreaks, as seen in the mountain pine beetle *Dendroctonus ponderosae* (Hopkins) [23,24]. Both beetle outbreaks and fire are exacerbated by the same drivers: unnatural density of forest stands often resulting from inadequate thinning or from fire suppression, and changes in climate [6]. Beetle outbreaks are especially severe in regions where the impact of climate change collides with the availability of host material, usually driven by a combination of the two. However, bark beetles and fire do not seem to promote each other, at least in the northern latitudes [25]. Most of the research on the impact of climate change on beetle outbreaks has been conducted in northern latitudes, and the interactions between bark beetles and climate and fire in Central America represent a major research gap.

This paper reviews the recent outbreaks of the SPB in Central America, comparing them with those occurring in North America, describes the current and recent improvements on management in the Central American region, and discusses strategies for increasing the landscape resilience in times of increasing environmental pressures. We critically analyze regional empirical and circumstantial data available from a management and climate perspective.

2. Regional Bark Beetle Outbreak Drivers

Southern pine beetle outbreaks and the consequent damage on pine forests make this species one of the main targets of aggressive suppression programs [26]. Expanding infestations of multiple trees (growing spots) are the primary targets for suppression programs, as they cause the majority of timber losses [26,27]. Under favorable conditions, current and subsequent generations of the beetles rapidly expand the “spot,” until lack of hosts, cold temperatures, or direct control intervene [26]. It is not clear to what extent SPB outbreaks are driven by tree health status or weather. Most authors attribute a minimal role to tree stress in the SPB outbreak dynamics [28], but emerging evidence suggests that weather anomalies do trigger outbreaks where other conditions are in place [29]. Global warming reached approximately 1°C above pre-industrial levels in 2017 [30], and significant warming is projected for the mountain ranges in the Americas with concomitant weather extremes [31].

Nevertheless, research on pine beetle outbreaks has been mainly conducted in the northern latitudes, while pests of the subtropical pine systems remain understudied. Because pine species and the environmental conditions in Central America and southern Mexico are different than those in the North, conclusions from temperate and boreal systems may not always apply here, and it is critical to tailor research to the region. In this section, we describe the differences and similarities between pine beetle outbreaks in Central and North American regions (Figure 1).

Figure 1. Regional differences in bark beetle outbreak drivers and management strategies.

2.1. Central America

Central America consists of Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama, with tropical conifer forests that held a high diversity of *Pinus* species, dominated by *P. caribaea* Morelet [32].

Southern pine beetle outbreaks periodically affect a large number of hectares of pine forests in Central America. In Honduras alone, for example, SPB has killed more than 580,000 ha in the last twenty years during unprecedented outbreaks [18]. Moreover, the role of changing climate on bark beetle outbreaks has been studied marginally, but several studies point to local extreme weather as a strong factor. In Honduras, climatic anomalies in warm months that increase the frequency of wildfires were correlated with SPB outbreaks [33]. This correlation does not necessarily indicate a direct effect of climate on the outbreaks, as an abundance of dense, unmanaged pine stands frequently weakened by wildfire could be the main driver. However, drought models for Honduras predict an increase in the

overall susceptibility for SPB attacks in a climate change scenario [34]. Another climate-related factor that distinguishes Central America from other regions is the effect of low temperatures. In the North, SPB range is limited by winter temperatures [15], which will not be the case anywhere south of Mexico.

On lands used for agriculture in Central America, fires are commonly used to eliminate old crop residues or increase grass cover beneath pine forests to feed livestock. It has been suggested that frequent fires are a predisposing factor that contributes to starting new SPB outbreaks in the Central American region [17]. In addition, the lack of timber markets has reduced dead tree removal, which may have contributed to the subsequent wildfires in the region [17]. However, as we discuss below, data from northern-latitude forests suggest that the relationship between beetle outbreaks and fire is tenuous, and probably not causative. In addition, burning reduces stand age diversity, as it kills most pine seedlings and produces widespread even-aged stands of *Pinus oocarpa* Schiede and *P. caribaea*, making them more susceptible to SPB outbreaks [17].

Much of the pioneering research about Central American pine beetle outbreaks was conducted by Ronald Billings. Dr. Billings and colleagues have extensively documented the damage and management of SPB in the region since 1982 and produced a great body of silvicultural recommendations [12,17,35–39]. Most of the recommendations have clear roots in data generated in the SE USA, and therefore many will still require properly designed and replicated studies in local, Central American conditions. Among Billings' early recommendations was to establish and maintain a record-keeping system for bark beetle outbreaks in Honduras and other Central American countries to document associated timber losses in both time and space [35].

2.2. Eastern North America

In the southeastern U.S., the majority of pine mortality due to bark beetles is caused by a single species, the southern pine beetle. Most SPB damage during the last two decades has occurred in forests that are overstocked, often residues of poorly managed plantations, or regions where pine was allowed to colonize previously deforested soil [28]. Outbreaks of SPB in the South East are influenced by several well-studied factors: abundance and distribution of susceptible pine stands [40], stand basal area, which increases with density and age, seasonality (spring and early summer often witness greatest outbreaks), the abundance of natural enemies [41], and previous levels of infestation, suggesting complex interactions between tree health, the beetles' host-finding capability, and the local biotic buffer.

Weather and climate have not been considered a major factor in explaining SPB regional outbreak dynamics in the southeastern U.S. [28]. Climate models for the region predict mildly higher temperatures and precipitation, which are likely to increase pine productivity and vigor [42,43], possibly resulting in greater resistance against SPB attacks. However, the frequency of weather-related stress is also expected to increase, possibly triggering stress-related outbreaks. Many states in the region have experienced exceptional drought and unusually warm winters in the last decade. Temperature appears to have played a significant role in SPB outbreak dynamics [44], and more recently, McNulty et al. [29] showed that climatic variables, such as interannual variation of temperature and evapotranspiration, are significant predictors for SPB outbreaks across the southeastern U.S. [45].

An increasingly studied question in the southeastern U.S. is the interaction between forest fires and southern bark beetle outbreaks. In the southeastern U.S., prescribed fire is now routinely applied as a silvicultural practice. The actual method depends on the land manager's objective, but most forests are burned in the dormant season to remove midstory vegetation in even-aged, naturally regenerated stands, as well as in pine plantations [46]. Prescribed burning increases natural pine regeneration, releases nutrients into the soil, reduces fuels in fire-prone forests, and reduces competition [47,48]. Most results from the southeastern U.S. show that there is lower bark beetle activity in prescribed burn areas, and that most tree mortality occurs within one year after the fire with no increase in attack to nearby areas [49]. Long-term studies have shown that stands with frequent low-intensity fire and more open conditions are more resilient [50,51]. Following a devastating SPB outbreak in *Pinus echinata* Mill., fire promoted natural pine regeneration with seedlings growing more vigorously than those in the

unburned areas [52]. Only rarely is a positive relationship between fire and beetles reported in the South East. In young plantations of *Pinus taeda* L. in Texas, spots of SPB-caused pine mortality were more common in burned stands compared to unburned areas [53]. However, the authors tentatively attributed it to the large area covered by even-aged stands and the nearby beetle activity.

2.3. Western North America

Pine beetle outbreaks in western North America may appear similar to the previously described regions, but the species involved and their interactions are distinct. Several different outbreaking species of *Dendroctonus* co-occur here, but none of them develop outbreaks with such rapidity as the SPB [9]. Contrary to the southeastern and more humid regions, the major impact of the warming climate as one of the main drivers of northwestern bark beetle outbreaks is beyond dispute. Climate-related models forecast an increase in bark beetle populations and tree stress, providing favorable conditions for outbreaks of several bark beetle species in western North America [54]. Some bark beetles were also able to expand their range as a result of increasing temperatures and began to occupy regions with naïve hosts [55].

Prior to the Euro-American settlement in the West, an open forest structure was maintained by frequent low-intensity fires [56]. Fire suppression, extensive harvesting, and replanting during the 20th century created an abundance of uniform conifer stands highly susceptible to bark beetle attack and large wildfires [20,57,58].

In western North America, bark beetle outbreaks and fire severity are linked, but it depends on the outbreak stage and several fire factors [59,60]. In the short term, prescribed burning diminishes tree resistance to beetles [61,62]. When not conducted properly, prescribed fire weakens or kills non-fire adapted tree species [46]. In the long term, however, benefits of the reduction of beetle-susceptible stands and wildfire fuels outweigh small tree mortality [63,64]. Despite scientific evidence of prescribed fire as an effective means to reduce the risk of wildfires and increase ecosystem resilience, annual prescribed burning in the western U.S. remained stable or decreased in the last 20 years, suggesting that the best available practices are not being adopted into management [65].

3. Influence of Different Management Styles on Outbreaks

Because bark beetle outbreaks are usually associated with poor forest management, a long-term strategy is critical, including increasing technical capacity, support by governments, between and within-country communication and evidence-based, climate-adaptive management. Managing existing outbreaks is usually difficult and may be impossible in Central American socio-economic conditions. We suggest that a critical contemporary need in the region is to prevent future outbreaks by creating resistant and resilient forests on a regional scale. Short-term emergency reactive management reduces the chances of effective long-term protection [66]. A long-term approach, based on prevention strategies rather than direct control, includes, for example, the recognition of the conditions that make stands more susceptible to SPB attacks. In intensively managed production forests, thinning or prescribed burning accomplish that [53]; in forests where fewer inputs are desirable, other strategies are needed, such as lower densities, increasing woody plant diversity, increasing dead wood volume, and variable age composition [26,49,67]. Thinning, for example, is one of the most effective practices for preventing and mitigating impacts from SPB [50]. Once an outbreak develops, mechanical control strategies, such as salvage removal (cut-and-remove), cut-and-leave, and burning, are recommended [26] but their timing is critical [68].

In Central America, management options lack empirical evidence. For example, it is not clear whether “removing damaged and weakened trees” [17,39] is effective in suppressing SPB populations because of the unclear relationships between individual tree health and *Dendroctonus frontalis* infestation. Currently, the most widely recommended strategy for SPB suppression in the region involves identifying actively expanding spots and applying mechanical control tactics (mostly cut-and-leave) to disrupt further spot growth [69] (Figure 2). Practical application of cut-and-leave in Honduras since 1984 and

in Guatemala, Nicaragua, and El Salvador in more recent years during SPB outbreaks suggests the effectiveness of this SPB direct control tactic [17,36–38], but a research study of these practices with proper control treatments and replication in the region has yet to be conducted.

In Honduras, large SPB outbreaks were reported from the 1980s to the 2000s in dense stands of *Pinus oocarpa* and *P. caribaea* [17]. More than 9000 spots were treated with cut-and-leave or cut-and-remove strategies with a 69% success rate [36,37]. During 2014, only 6% of the infestations were managed in the country, which may have led to the almost half a million ha damage in the subsequent years [38]. In each case, however, no empirical evaluation of different methodologies was conducted, and different tree species and, in some cases, different bark beetles were affecting the region.

Figure 2. Cut-and-leave control method applied in Honduras during the 2015 southern pine beetle (SPB) outbreaks. Photo by Ronald Billings.

In Nicaragua, SPB killed half of mature pines in the northern region from 1998 to 2001 [17]. Hundreds of spots were treated with cut-and-leave to stop the outbreak through financial and technical assistance from the USDA and FAO. The SPB outbreak collapsed in 2001, whereas infestations continued in adjacent countries where little or no control applications were applied [12]. However, other factors could have influenced the collapse of the outbreak during that year, as direct control measures are a short-term response to reduce tree losses, and there is little evidence that suppression of individual spots will manage outbreaks on larger scales [49]. All outbreaks recorded in Nicaragua started in protected areas, where no forest management is conducted, and tree densities are extremely high. Despite the permits that have been issued for thinning in protected areas, there was no market for the small diameter extracted wood, and the thinning was economically unsustainable [70].

4. Management Shortcomings Identified in the Central American Region

Some of the main challenges identified in the region are that the concept of sustainability and resilience in forest management are not well established, perhaps given the lack of interdisciplinary research. In the region, infestations of SPB are usually controlled by means of cut-and-leave or sanitation

harvesting with an emphasis on taking wood out of the forest and selling it, whereas prevention methods are not prioritized nor developed [18]. Policy makers and land managers need to focus on proactive thinning programs to reduce beetle-induced tree mortality. Natural resource agencies in the U.S. usually have the tools, information, and policies to modify stand conditions [4]. However, this is not always the case in Central America. For example, the outbreaks in the 2000s in Belize, Nicaragua, Honduras, and Guatemala were suggested to be caused mainly by favorable environmental and host conditions, lack of training at the national level, lack of funding, and lack of equipment and markets to rapidly harvest infested trees [12]. The recent outbreaks in the region further demonstrate the necessity for sustainable forest health programs for integrated pest management of bark beetle outbreaks.

Because governmental structures and forest resources are similar across the region, there are common problems that need to be addressed at the regional level [18]. Large areas of natural forest in Central America are protected but were set up with unsustainable tree density and are still under human pressure. Sustainable forest protection practices such as prescribed burning or thinning are not common practices [12]. Therefore, even protected areas develop into highly dense forests of pines more susceptible to bark beetle outbreaks [71]. Moreover, areas attacked by bark beetles are often converted to agricultural use and grazing of livestock, preventing forest restoration and accelerating forest degradation [72]. Management of forest pests in Central America needs to be based on regional science [71]. However, local research in forest health topics is not always conducted, and academic programs need to be updated, as important concepts of sustainable forest management have been missing [73]. For example, the recent description of *D. mesoamericanus* Armendáriz-Toledano and Sullivan, a species of a pine-infesting bark beetle that commonly co-occurs with *D. frontalis* in the region, makes it clear that more research is needed in order to better understand local forest ecology and develop long-term integrated pest management plans. For most Central American foresters and technicians, access to adequate training has been limited.

Fortunately, the Central American region is currently improving the management of natural forests [38,71]. Honduras and Guatemala already adopted a national forest health strategy [73]. Investments have been made into education, legislation, low-budget monitoring, fire suppression, and control in forest ecosystems, although sustainable forest management is still not embraced adequately [71,74]. International tree breeding organizations, such as CAMCORE (Central America and Mexico Coniferous Resources Cooperative), have been active in the region, aiming initially to conserve genetic resources of native pine species, and more recently supporting forest restoration after SPB outbreaks and suggesting planting of more tolerant species to increase resilience [75]. However, recommendations on forest restoration and tolerant tree species were not fully taken into account for implementation due to political and financial constraints. Therefore, the lack of regional policy in forest health strains the interaction among institutions, which is reflected in regional organizations such as the International Regional Organization for Agricultural Health (OIRSA). In addition, forest health monitoring databases, which include sustained data on seasonal pest activity, abundance, and area affected, are uncommon, qualitative rather than quantitative, and not easily accessible in the region [71]. Honduras, which has maintained data on SPB outbreaks and their impacts since 1982, is a notable exception [12,35–38].

5. Recommendations and Opportunities for Sustainable Management in Central America

Understanding the spatial and temporal processes that drive beetle outbreaks is essential to attain sustainable forest management in Central America. Management and suppression strategies will only be effective if they are applied at the right outbreak stage [9]. Small-scale scattered treatments do not effectively reduce the susceptibility of forests to bark beetle infestation in the long-term, as they do not address overall forest health and pest spread from treated stands into untreated areas [49,76]. Moreover, forest pest solutions should mainly focus on integrating management approaches regionally, rather than within single countries [77]. Forest landscapes are complex socio-ecological systems that demand collaborative transdisciplinary problem framing [78]. From a landscape perspective, sustainable forest

management needs to be integrated with the management of adjacent areas. Because individual forest stands interact with other landscape elements, human manipulation at the local level have cumulative effects at the landscape scale that can affect an entire region [79]. Sustainable forestry, focused on ecosystems, is based on planning at the landscape level and recognizes that different scales are essential for different species and processes [80].

For long-term forest protection, broadscale land-management policies are the best option as they reduce the extent of forests susceptible to future outbreaks largely resulting from anthropogenic inputs [9]. Conservation lands and outbreak initiation are often linked in Central America due to fire suppression and inadequate management [81]. As part of an integrated pest management, silvicultural treatments should focus on increasing landscape heterogeneity, such as shorter rotations, multiple age classes, and reduced basal area [82]. In addition, a much higher predator/prey relationship is typically observed in mixed stands, as found in spruce-pine stands for *Ips typographus* L. and its predator *Thanosimus formicarius* L., compared to pure spruce stands [83].

Short-term management of SPB has also been successfully accomplished in the southeastern U.S. and in some countries of Central America using pest detection systems, stand evaluation, and timely control of spots [38,68,84]. Because SPB outbreaks cannot be predicted based only on regional infestation dynamics [85], national databases to keep historical data are needed for planning and properly integrate public and private forestry institutions. When spatial and temporal data is available, governance institutions have the capacity to lead suppression strategies [4]. To facilitate commercial utilization of beetle-killed trees in Central America, Billings [38] suggested that governmental charges for salvage logging operations should be reduced when the wood has presence of S-shaped galleries, a distinctive sign of SPB.

The Central American region has a unique opportunity to fully embrace the challenge of climate change and future bark beetle outbreaks, a response that has been slow in the Eastern U.S. Under increasing climate change pressures, forest resilience—improved by prevention activities and sustainable forest management—will reduce future problems resulting from *Dendroctonus* outbreaks. This is important because climatic changes projected for the mountain ranges in the Americas could be favorable for SPB activity, as well as other non-aggressive bark beetle species, that under aridification can become pestiferous or increase the number of generations per year [86]. In Honduras for example, projections under a climate change scenario suggest an increase of area affected by SPB (Figure 3) [33].

Figure 3. Observed, modeled, and projected damage of *Dendroctonus frontalis* in Honduras in a climate change scenario. Figure adapted from Rivera Rojas et al. [33] [available online <http://revistas.inia.es/index.php/fs/article/view/1168>].

The severe outbreaks of SPB in Guatemala, Honduras, El Salvador, and Nicaragua during 2004 led to the creation of a regional strategy on forest health management for Central America and the Dominican Republic [87]. This strategy was later updated by the Central American Environment and Development Committee to include preventive aspects for native and exotic forest threats [18].

The strategy focuses on the update of study plans for forest managers, development of local research programs, and forest health policies at the national level for each country, with the objective to increase resources and qualified personnel in all countries, and to implement prevention programs in the region [18]. The strategy also suggests that each country should have an entity in charge of forest health with trained personnel, as well as its own financial resources, to coordinate and support prevention, detection, monitoring, and control programs. In addition, it suggests that strategic synergies should be implemented at the inter- and intra-institutional level and include NGOs. Cooperation agreements among institutions will allow long-term capacity building to improve each country's technical skills, including identification, management, and monitoring of native and invasive pests. Because of the regional experience with pheromone trapping, early detection and monitoring systems could be successfully implemented in the region [18]. However, importing commercial traps and pheromones is sometimes a challenge and, in addition, identification of insect specimens requires experts which are currently scarce in the region [73].

Focusing on a regional network facilitates technical and policy improvements in the most critical areas. Countries such as Honduras, Nicaragua, Guatemala, and Panama have the experience and expertise that could be shared regionally. For example, the first project on Integrated Pest Management for Central America was funded in Honduras in 1984, including regional pest and forest protection coordinators that address fire and outbreak problems, and a database where detailed records of infestations has been kept [17,38]. Regionally, a network of specialists was formed and has met, but it has not been active recently due to lack of funding and personnel ([38,70]). Capacity building has to be a continuous effort where each country is responsible for targeting the right audience, including forest entomologists and forest managers. Since 2017, a bark beetle course has been held in Mexico organized by the National Forestry Commission of Mexico (CONAFOR) and the International Regional Organization for Agricultural Health (OIRSA) with a focus on identification, biology, monitoring, control measures, and policy. However, such initiatives require a cohesive regional approach, including regional legislation and sustainable forest management concepts. Other forest health workshops to improve national capacity are currently being organized in individual countries, but the effect on regional and local policy remains to be seen.

The regional strategy proposed for Central America currently acts as a theoretical framework where every country has the responsibility to apply the regional strategy according to each country's resources and vision. The region lacks attention to invasive emerging threats in plantations and protected areas, with little information on interception and establishments [71]. The Southern Cone for example, with a focus on plantations, has held several meetings through COSAVE (the Regional Plant Protection Organization) to harmonize phytosanitary regulations, share information on pests, and even propose an information exchange system [71]. In the absence of a formal regional entity responsible for policy, technical, and scientific aspects of forest threats in Latin America, Central American forestry organizations, and the Southern Cone Forest Invasive Species Network, under the FAO regional forestry commission, should work together and share expertise and information on forest health issues [71].

6. Conclusions

We suggest that the Central American forest management community needs to evolve its focus away from reactive, short-term, pest-focused activities and towards long-term management for healthy, resilient, and sustainable regional forest ecosystems, to prevent the continuation or increase of forest mortality. Any further forest degradation and conversion, together with climate change, may diminish the remaining resilience of the forests and prevent sustainable management [88]. Regional networks should allow each country to build local research and management capacity and develop long-term solutions, including improving methods for developing, transferring, maintaining, and applying knowledge learned during recent outbreaks to prevent or manage future outbreaks [4,8]. Increasing

adequate forestry health practices in times between outbreaks will also lessen the impact of SPB across the Central American countries.

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References

- Clarke, S.R.; Riggins, J.J.; Stephen, F.M. Forest management and southern pine beetle outbreaks: A historical perspective. *For. Sci.* **2016**, *62*, 166–180. [\[CrossRef\]](#)
- Meddens, A.J.H.; Hicke, J.A.; Ferguson, C.A. Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. *Ecol. Appl.* **2012**, *22*, 1876–1891. [\[CrossRef\]](#)
- Grégoire, J.C.; Raffa, K.F.; Lindgren, B.S. Economics and Politics of Bark Beetles. In *Bark Beetles: Biology and Ecology of Native and Invasive Species*; Elsevier Inc.: San Diego, CA, USA, 2015; pp. 585–613, ISBN 9780124171732.
- Morris, J.L.; Cottrell, S.; Fettig, C.J.; DeRose, R.J.; Mattor, K.M.; Carter, V.A.; Clear, J.; Clement, J.; Hansen, W.D.; Hicke, J.A.; et al. Bark beetles as agents of change in social–ecological systems. *Front. Ecol. Environ.* **2018**, *16*, S34–S43. [\[CrossRef\]](#)
- Stone, W.E.; Wolfe, M.L. Response of understory vegetation to variable tree mortality following a mountain pine beetle epidemic in lodgepole pine stands in northern Utah. *Vegetatio* **1996**, *122*, 1–12. [\[CrossRef\]](#)
- Ciellsa, W.M. Wildfires, Climate Change, and Active Forest Management. *For. Source* **2018**, *23*, 20–21.
- Hansen, W.D.; Chapin, F.S.; Naughton, H.T.; Rupp, T.S.; Verbyla, D. Forest-landscape structure mediates effects of a spruce bark beetle (*Dendroctonus rufipennis*) outbreak on subsequent likelihood of burning in Alaskan boreal forest. *For. Ecol. Manag.* **2016**, *369*, 38–46. [\[CrossRef\]](#)
- Hlásny, T.; Krokene, P.; Liebhold, A.; Montagné-Huck, C.; Müller, J.; Qin, H.; Raffa, K.; Schelhaas, M.-J.; Seidl, R.; Svoboda, M.; et al. Living with bark beetles: Impacts, outlook and management options. *From Sci. Policy* **2019**, *52*. [\[CrossRef\]](#)
- Raffa, K.F.; Aukema, B.H.; Bentz, B.J.; Carroll, A.L.; Hicke, J.A.; Turner, M.G.; Romme, W.H. Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *Bioscience* **2008**, *58*, 501–517. [\[CrossRef\]](#)
- Hain, F.P.; Duehl, A.J.; Gardner, M.J.; Payne, T.L. Natural History of the Southern Pine Beetle. In *Southern Pine Beetle II*; Coulson, R.N., Klepzig, K.D., Eds.; Gen. Tech. Rep. SRS-140; U.S. Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2011; pp. 13–24.
- Six, D.L.; Bracewell, R. *Dendroctonus*. In *Bark Beetles: Biology and Ecology of Native and Invasive Species*; Elsevier Inc.: San Diego, CA, USA, 2015; pp. 305–350. ISBN 9780124171732.
- Billings, R.F.; Schmidtke, P. *Central America Southern Pine Beetle/Fire Management Assessment*; USDA Foreign Agricultural Service/International Cooperation and Development: Washington, DC, USA, 2002; p. 19.
- Birt, A. Population dynamics of southern pine beetle in forest landscapes. In *Southern Pine Beetle II*; Gen. Tech. Rep. SRS-140; Coulson, R., Klepzig, K., Eds.; US Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2011; Volume 140, pp. 91–108.
- Reeve, J.D. Predators of the southern pine beetle. In *Southern Pine Beetle II*; Gen. Tech. Rep. SRS-140; Coulson, R., Klepzig, K., Eds.; US Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2011; Volume 140, pp. 153–160.
- Lombardo, J.A.; Weed, A.S.; Aoki, C.F.; Sullivan, B.T.; Ayres, M.P. Temperature affects phenological synchrony in a tree-killing bark beetle. *Oecologia* **2018**, *188*, 117–127. [\[CrossRef\]](#)

16. Stephen, F.M. Southern pine beetle population dynamics in trees. In *Southern pine beetle II*; Coulson, R., Klepzig, K., Eds.; US Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2011; Volume 140, pp. 51–74.
17. Billings, R.F.; Clarke, S.R.; Mendoza, V.E.; Cabrera, P.C.; Figueroa, B.M.; Campos, J.R.; Baeza, G. Bark beetle outbreaks and fire: A devastating combination for central America's pine forests. *Unasylva* **2004**, *55*, 10–15.
18. CCAD (Comisión Centroamericana de Ambiente y Desarrollo). *Estrategia Regional de Salud y Sanidad Forestal Para Centroamérica y República Dominicana 2016–2026*; Sistema de la Integración Centroamericana: San Salvador, El Salvador, 2017; p. 98.
19. Thistle, H.W.; Peterson, H.; Allwine, G.; Lamb, B.; Edburg, S.; Strom, B. The influence of stand thinning on surrogate pheromone plumes. In Proceedings of the 16th US Department of Agriculture Interagency Research Forum on Gypsy Moth and Other Invasive Species, Annapolis, MA, USA, 18 January 2005; pp. 83–85.
20. Jenkins, M.J.; Page, W.G.; Hebertson, E.G.; Alexander, M.E. Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. *For. Ecol. Manag.* **2012**, *275*, 23–34. [[CrossRef](#)]
21. Jenkins, M.J.; Hebertson, E.; Page, W.; Jorgensen, C.A. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *For. Ecol. Manag.* **2008**, *254*, 16–34. [[CrossRef](#)]
22. Bär, A.; Michaletz, S.T.; Mayr, S. Fire effects on tree physiology. *New Phytol.* **2019**, *223*, 1728–1741. [[CrossRef](#)]
23. Craighead, F.C. Bark-Beetle Epidemics and Rainfall Deficiency. *J. Econ. Entomol.* **1925**, *18*, 577–586. [[CrossRef](#)]
24. Powell, E.N.; Townsend, P.A.; Raffa, K.F. Wildfire provides refuge from local extinction but is an unlikely driver of outbreaks by mountain pine beetle. *Ecol. Monogr.* **2012**, *82*, 69–84. [[CrossRef](#)]
25. Hart, S.J.; Schoennagel, T.; Veblen, T.T.; Chapman, T.B.; Franklin, J. Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 4375–4380. [[CrossRef](#)] [[PubMed](#)]
26. Billings, R.F. Mechanical control of southern pine beetle infestations. In *Southern Pine Beetle II*; Gen. Tech. Rep. SRS-140; US Department of Agriculture Forest Service: Asheville, NC, USA, 2011; pp. 399–413.
27. Leuschner, W.A.; Burkhart, H.E.; Spittle, G.D.; Ragenovich, I.R.; Coulson, R.N. A descriptive study of host and site variables associated with the occurrence of *Dendroctonus frontalis* Zimm. in east Texas. *Southwest. Entomol.* **1976**, *1*, 141–149.
28. Asaro, C.; Nowak, J.T.; Elledge, A. Why have southern pine beetle outbreaks declined in the southeastern U.S. with the expansion of intensive pine silviculture? A brief review of hypotheses. *For. Ecol. Manag.* **2017**, *391*, 338–348. [[CrossRef](#)]
29. McNulty, S.; Cobb, J.; Treasure, E.; Nowak, J.; Sun, G.; Kumar, A. Improved Forest Insect Outbreak Modeling Under Increased Climate Variability. In Proceedings of the IUFRO World Congress, Curitiba, Brazil, 2 October 2019.
30. Allen, M.R.; Dube, O.P.; Solecki, W.; Aragón-Durand, F.; Cramer, W.; Humphreys, S.; Kainuma, M.; Kala, J.; Mahowald, N.; Mulugetta, Y.; et al. Framing and Context. In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*; Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; IPCC: Geneva, Switzerland, 2018.
31. Bradley, R.S.; Keimig, F.T.; Diaz, H.F. Projected temperature changes along the American cordillera and the planned GCOS network. *Geophys. Res. Lett.* **2004**, *31*, 2–5. [[CrossRef](#)]
32. Corrales, L.; Bouroncle, C.; Zamora, J.C. An overview of forest biomes and ecoregions of Central America. In *Climate Change Impacts on Tropical Forests in Central America: An Ecosystem Service Perspective*; Chiabai, A., Ed.; Routledge: London, UK, 2015; pp. 17–38. ISBN 9781317961499.
33. Rivera Rojas, M.; Locatelli, B.; Billings, R. Cambio climático y eventos epidémicos del gorgojo descortezador del pino *dendroctonus frontalis* en Honduras. *For. Syst.* **2010**, *19*, 70–76.
34. Hernandez, A.J.; Saborio, J.; Ramsey, R.D.; Rivera, S. Likelihood of occurrence of bark beetle attacks on conifer forests in Honduras under normal and climate change scenarios. *Geocarto Int.* **2012**, *27*, 581–592. [[CrossRef](#)]
35. Billings, R.F. Evaluation and recommendations for control of the 1982 outbreak of *Dendroctonus* in the pine forests of Honduras. In *Unpublished Report Submitted to USDA Office of International Cooperation and Development*; U.S. Agency for International Development: Washington, DC, USA, 1982; p. 26.

36. Billings, R.F. *Evaluation of the Southern Pine Beetle Outbreak and Control Program in Honduras: 1982–1988*; Unpublished report provided to U.S. Agency for International Development and the Corporación Hondureña de Desarrollo Forestal; U.S. Agency for International Development and the Corporación Hondureña de Desarrollo Forestal: Washington, DC, USA, 1988; p. 17.
37. Billings, R.F. *Evaluación de la Plaga del Gorgojo Descortezador del Pino (Dendroctonus frontalis) en los Pinares de Honduras con Recomendaciones Para su Control*; Cooperación Hondureña Desarrollo: Lufkin, TX, USA, 2001; p. 19.
38. Billings, R.F. *Evaluación del Programa de Control Directo de la Plaga del Gorgojo del Pino y Establecimiento de un Programa Permanente de Sanidad Forestal y Alerta Temprana*; Unpublished report prepared for Interamerican Development Bank; Proyecto Manejo Sostenible de Bosques: Tegucigalpa, Honduras, 2018; p. 114.
39. Billings, R.F.; Espino, J.V. *El Gorgojo Descortezador del Pino (Dendroctonus frontalis) en Centroamérica: Cómo Reconocer, Prevenir y Controlar Plagas*; Servicio Forestal de Texas: Collage Station, TX, USA, 2005; p. 18.
40. Billings, R.F.; Bryant, C.M.; Wilson, K.H. Development, implementation, and validation of a large area hazard- and risk-rating system for southern pine beetle. In *Proceedings of the Integrated Pest Management Research Symposium*; Branham, D.J., Thatcher, R.C., Eds.; Forest Service General Technical Report SO-United States: Asheville, NC, USA, 1985; pp. 226–232.
41. Turchin, P.; Taylor, A.D.; Reeve, J.D. Dynamical role of predators in population cycles of a forest insect: An experimental test. *Science* **1999**, *285*, 1068–1071. [[CrossRef](#)] [[PubMed](#)]
42. Burkhart, H.E.; Brooks, E.B.; Dinon-Aldridge, H.; Sabatia, C.O.; Gyawali, N.; Wynne, R.H.; Thomas, V.A. Regional simulations of loblolly pine productivity with CO₂ enrichment and changing climate scenarios. *For. Sci.* **2018**, *64*, 349–357. [[CrossRef](#)]
43. Thomas, R.Q.; Jersild, A.L.; Brooks, E.B.; Thomas, V.A.; Wynne, R.H. A mid-century ecological forecast with partitioned uncertainty predicts increases in loblolly pine forest productivity. *Ecol. Appl.* **2018**, *28*, 1503–1519. [[CrossRef](#)]
44. Gan, J. Risk and damage of southern pine beetle outbreaks under global climate change. *For. Ecol. Manag.* **2004**, *191*, 61–71. [[CrossRef](#)]
45. Southern Pine Beetle Outbreak Model (SPBOM). *Forecasting Short- and Long-Term Southern Pine Beetle Risk in the Southeastern US*; Version 1.0; USDA Climate Hubs: Washington, DC, USA, 2019.
46. Guldin, J.M. Silvicultural Considerations in Managing Southern Pine Stands in the Context of Southern Pine Beetle. In *Southern Pine Beetle II*; Gen. Tech. Rep. SRS-140; Coulson, R.N., Klepzig, K.D., Eds.; U.S. Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2011; pp. 317–352.
47. Stark, N.; Steele, R. Nutrient Content of Forest Shrubs Following Burning. *Am. J. Bot.* **1977**, *64*, 1218. [[CrossRef](#)]
48. Vose, J.M.; Clinton, B.D.; Swank, W.T. Fire, drought, and forest management influences on pine/hardwood ecosystems in the southern Appalachians. In *Proceedings of the Fire, meteorology and the landscape. Proceedings, 12th conference on fire and forest meteorology*, Jekyll Island, GA, USA, 26–28 October 1993; pp. 232–238.
49. Fettig, C.J.; Klepzig, K.D.; Billings, R.F.; Munson, A.S.; Nebeker, T.E.; Negrón, J.F.; Nowak, J.T. 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. Manag.* **2007**, *238*, 24–53. [[CrossRef](#)]
50. Nowak, J.T.; Meeker, J.R.; Coyle, D.R.; Steiner, C.A.; Brownie, C. Southern Pine Beetle Infestations in Relation to Forest Stand Conditions, Previous Thinning, and Prescribed Burning: Evaluation of the Southern Pine Beetle Prevention Program. *J. For.* **2015**, *113*, 454–462. [[CrossRef](#)]
51. McNichol, B.H.; Montes, C.R.; Barnes, B.F.; Nowak, J.T.; Villari, C.; Gandhi, K.J.K. Interactions between southern Ips bark beetle outbreaks, prescribed fire, and loblolly pine (*Pinus taeda* L.) mortality. *For. Ecol. Manag.* **2019**, *446*, 164–174. [[CrossRef](#)]
52. Land, A.D.; Rieske, L.K. Interactions among prescribed fire, herbivore pressure and shortleaf pine (*Pinus echinata*) regeneration following southern pine beetle (*Dendroctonus frontalis*) mortality. *For. Ecol. Manag.* **2006**, *235*, 260–269. [[CrossRef](#)]
53. Cameron, R.S.; Billings, R.F. Southern pine beetle: Factors associated with spot occurrence and spread in young plantations. *South. J. Appl. For.* **1988**, *12*, 208–214. [[CrossRef](#)]

54. Buotte, P.C.; Hicke, J.A.; Preisler, H.K.; Abatzoglou, J.T.; Raffa, K.F.; Logan, J.A. Climate influences on whitebark pine mortality from mountain pine beetle in the Greater Yellowstone Ecosystem. *Ecol. Appl.* **2016**, *26*, 2505–2522. [[CrossRef](#)] [[PubMed](#)]
55. Cudmore, T.J.; Björklund, N.; Carroll, A.L.; Staffan Lindgren, B. Climate change and range expansion of an aggressive bark beetle: Evidence of higher beetle reproduction in naïve host tree populations. *J. Appl. Ecol.* **2010**, *47*, 1036–1043. [[CrossRef](#)]
56. Cooper, C.F. Changes in Vegetation, Structure, and Growth of Southwestern Pine Forests since White Settlement. *Ecol. Monogr.* **1960**, *30*, 129–164. [[CrossRef](#)]
57. Keane, R.E.; Ryan, K.C.; Veblen, T.T.; Allen, C.D.; Logan, J.A.; Hawkes, B. The cascading effects of fire exclusion in Rocky Mountain ecosystems. In *Rocky Mountain Futures: An Ecological Perspective*; Barron, J., Ed.; Island Press: Fort Collins, CO, USA, 2002; pp. 133–152.
58. Mutch, R.W.; Arno, S.F.; Brown, J.K.; Carlson, C.E.; Ottmar, R.D.; Peterson, J.L. *Forest Health in the Blue Mountains: A Management Strategy for Fire-Adapted Ecosystems*; USDA Forest Service General Technical Report; USDA Forest Service: Portland, OR, USA, 1993; Volume PNW-GTR-31, p. 13.
59. Harvey, B.J.; Donato, D.C.; Romme, W.H.; Turner, M.G. Fire severity and tree regeneration following bark beetle outbreaks: The role of outbreak stage and burning conditions. *Ecol. Appl.* **2014**, *24*, 1608–1625. [[CrossRef](#)] [[PubMed](#)]
60. Ray, C.; Cluck, D.R.; Wilkerson, R.L.; Siegel, R.B.; White, A.M.; Tarbill, G.L.; Sawyer, S.C.; Howell, C.A. Patterns of woodboring beetle activity following fires and bark beetle outbreaks in montane forests of California, USA. *Fire Ecol.* **2019**, *15*, 1–20. [[CrossRef](#)]
61. Wallin, K.F.; Kolb, T.E.; Skov, K.R.; Wagner, M.R. Effects of Crown Scorch on Ponderosa Pine Resistance to Bark Beetles in Northern Arizona. *Environ. Entomol.* **2003**, *32*, 652–661. [[CrossRef](#)]
62. Breece, C.R.; Kolb, T.E.; Dickson, B.G.; McMillin, J.D.; Clancy, K.M. Prescribed fire effects on bark beetle activity and tree mortality in southwestern ponderosa pine forests. *For. Ecol. Manag.* **2008**, *255*, 119–128. [[CrossRef](#)]
63. Fettig, C.J.; McKelvey, S.R. Bark beetle responses to stand structure and prescribed fire at blacks mountain experimental forest, California, USA: 5-year data. *Fire Ecol.* **2010**, *6*, 26–42. [[CrossRef](#)]
64. Tabacaru, C.A.; Park, J.; Erbilgin, N. Prescribed fire does not promote outbreaks of a primary bark beetle at low-density populations. *J. Appl. Ecol.* **2016**, *53*, 222–232. [[CrossRef](#)]
65. Kolden, C.A. We're Not Doing Enough Prescribed Fire in the Western United States to Mitigate Wildfire Risk. *Fire* **2019**, *2*, 30. [[CrossRef](#)]
66. Showalter, D.N.; Raffa, K.F.; Snieszko, R.A.; Herms, D.A.; Liebhold, A.M.; Smith, J.A.; Bonello, P. Strategic development of tree resistance against forest pathogen and insect invasions in defense-free space. *Front. Ecol. Evol.* **2018**, *6*, 1–9. [[CrossRef](#)]
67. Coster, J.E.; Searcy, J.L. Site, stand, and host characteristics of southern pine beetle infestations. In *Southern Pine Beetle*; USDA Forest Service: Asheville, NC, USA, 1981.
68. Clarke, S.R.; Billings, R.F. Analysis of the southern pine beetle suppression program on the National Forests in Texas in the 1990s. *South. J. Appl. For.* **2003**, *27*, 122–129. [[CrossRef](#)]
69. Macías Sámano, J.E.; Billings, R.F.; Espino Mendoza, V. *Guía para implementar el método de cortar y dejar y la franja de contención como medios de control del gorgojo descortezador del pino, Dendroctonus frontalis, en Centroamérica y México*; Instituto Nacional de Conservación y Desarrollo Forestal, Areas Protegidas y Vida Silvestre (Tegucigalpa, Honduras) and USDA Forest Service, International Programs, Washington, DC; USFS-IP, ICF: Tegucigalpa, Honduras, 2017; p. 48.
70. Sediles, A.; (Universidad Agraria de Nicaragua, Managua, Nicaragua). Personal communication, 2019.
71. Macías-Sámano, J.E. Sanidad Vegetal (Forestal y Agrícola) y Sanidad Animal (Pecuaria, Pesquera, y Acuicola) y Movilización de Recursos, Cooperación Sur-Sur, Región Latinoamérica y Caribe. *UN-FAO* **2017**, *65*. Unpublished Report.
72. Macías-Sámano, J.E. Observaciones y recomendaciones sobre las actuales infestaciones de descortezadores de pino en Honduras. *USDA-FS-IP* **2015**, *21*. Unpublished Report.
73. Macías, J.; (Forest Health Consultant, Vancouver, BC, Canada). Personal communication, 2019.
74. FAO Global review of forest pest and diseases: A thematic study prepared in the framework of the global forest resources assessment 2005. *FAO For.* **2009**, *156*, 222.
75. Jetton, R.; (CAMCORE, Raleigh, NC, USA). Personal communication, 2019.

76. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96. [[CrossRef](#)]
77. Wingfield, M.J.; Brockerhoff, E.G.; Wingfield, B.D.; Slippers, B. Planted forest health: The need for a global strategy. *Science* **2015**, *349*, 832–836. [[CrossRef](#)]
78. Langston, J.D.; Riggs, R.A.; Kastanya, A.; Sayer, J.; Margules, C.; Boedhihartono, A.K. Science Embedded in Local Forest Landscape Management Improves Benefit Flows to Society. *Front. For. Glob. Chang.* **2019**, *2*, 3. [[CrossRef](#)]
79. Gadow, K.; Pukkala, T.; Tomé, M. *Sustainable Forest Management*; Springer Science & Business Media: Berlin, Germany, 2012; Volume 1, ISBN 0195536045.
80. Franklin, J.F. The fundamentals of ecosystem management with applications in the Pacific Northwest. In *Defining Sustainable Forestry*; Aplet, G., Ed.; Island Press: Washington, DC, USA, 1993; pp. 127–144.
81. Aukema, B.H.; Carroll, A.L.; Zhu, J.; Raffa, K.F.; Sickley, T.A.; Taylor, S.W. Landscape level analysis of mountain pine beetle in British Columbia, Canada: Spatiotemporal development and spatial synchrony within the present outbreak. *Ecography* **2006**, *29*, 427–441. [[CrossRef](#)]
82. Fettig, C.J.; Hilszczański, J. Management Strategies for Bark Beetles in Conifer Forests. In *Bark Beetles: Biology and Ecology of Native and Invasive Species*; Elsevier Inc.: San Diego, CA, USA, 2015; pp. 555–584, ISBN 9780124171732.
83. Warzée, N.; Gilbert, M.; Grégoire, J.-C. Predator/prey ratios: A measure of bark-beetle population status influenced by stand composition in different French stands after the 1999 storms. *Ann. For. Sci.* **2006**, *63*, 301–308. [[CrossRef](#)]
84. Billings, R.F. *Evaluation of a Pine Bark Beetle Outbreak in Honduras and Recommendations for Direct Control*; Unpublished report for US Forest Service/International Programs and US Agency for International Development; US Agency for International Development: Collage Station, TX, USA, 2005; p. 15.
85. Duehl, A.; Bishir, J.; Hain, F.P. Predicting County-Level Southern Pine Beetle Outbreaks from Neighborhood Patterns. *Environ. Entomol.* **2011**, *40*, 273–280. [[CrossRef](#)]
86. Pernek, M.; Lacković, N.; Lukić, I.; Zorić, N.; Matošević, D. Outbreak of *Orthotomicus erosus* (Coleoptera, Curculionidae) on Aleppo Pine in the Mediterranean Region in Croatia. *Southeast Eur. For.* **2019**, *10*, 1–9. [[CrossRef](#)]
87. FAO. *Estrategia Regional Para Sanidad y Manejo Forestal en América Central*; United Nations Food Agricultural Organization Project TCP/RLA/2803; FAO: Rome, Italy, 2004; p. 55.
88. Lewis, S.L.; Edwards, D.P.; Galbraith, D. Increasing human dominance of tropical forests. *Science* **2015**, *349*, 827–832. [[CrossRef](#)] [[PubMed](#)]

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