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ORIGINAL RESEARCH ARTICLE

Bark stripping insects (coleoptera: *curculionidae*) and climate change: Current issues and prospects in temperate forests

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ABSTRACT

Important modifications are occurring in temperate forests due to climate change; in polar latitudes their distribution area is increasing, while in tropical latitudes it is decreasing due to temperature increase and droughts. One of the biotic regulators of temperate forests are the debarking insects that cause the mortality of certain trees. These insects have increased in number, favored by climate change, and the consequences on forests have not been long in coming. In recent times in the northern hemisphere, the massive mortality of conifers due to the negative synergy between climate change and debarking insects has been evident. In Mexico, we have also experienced infestations by bark stripping insects never seen before; therefore, we are trying to understand the interactions between climate change, forest health and bark stripping insects, to detect the areas with greater susceptibility to attack by these insects and propose management measures to reduce the effects.

Keywords: Coniferous Forests; Climate Change; Drought; Scolytinae

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1. Introduction

Temperate forests are dominated by conifers of the Pinus genus with the greatest diversity of species of this genus worldwide, making the country the center of origin and diversification of this group[1]. The *Pinus* genus originated in the Lower Cretaceous (~145 million years ago) and currently has 111 species, of which 46 species with 3 subspecies and 22 varieties are present in Mexico, 55% of which are endemic[2]. Pine forests in Mexico are distributed mainly in the sierras at altitudes between 1,500 and 4,000 meters above sea level. Depending on altitude, exposure and latitude, they congregate in different communities, forming conifer forests, pine-oak forests or oak-pine forests, depending on the dominance of each genus[3].

In addition to its phylogenetic and biogeographic importance, the genus *Pinus* has great social relevance, since its usefulness has become a significant part of Mexico's development and today many rural communities depend on forests for their livelihood.

Pine forest management in Mexico is mainly related to timber harvesting. According to data from the National Forestry Commission (CONAFOR) in 2014, 4.3 million m^3 of pine were harvested and represented an income of 6,039 million pesos[4]; in addition, pine forests

provide other types of non-timber resources such as resin, food animals, medicinal and ornamental plants and very importantly fuel for a significant number of households. It has been estimated that 27 million people depend on firewood for cooking in both urban and rural areas[5]. Pine forests in Mexico are also fundamental for the provision of environmental services such as water capture, carbon capture and storage, temperature regulation, as well as being a safeguard for biodiversity and scenic beauty[6]. However, despite the fact that Mexican temperate forests are subject to significant use and a growing portion of them are under some management program, there is a great disparity in terms of their success. While there are communities with exemplary organization and management, such as Nuevo San Juan Parangaricutiro in Michoacán and Ixtlán de Juárez in Oaxaca, in numerous forest communities there is illegal logging and uncontrolled fires, even with management plans in place, which threatens the sustainable development of temperate forest regions in the country[7].

Currently, pine forests in Mexico cover approximately 10 million hectares; however, according to Challenger & Soberón[1], only 50% are in a good state of conservation and the rest are in some type of deterioration. Due to overexploitation and land use change, some species are damaged and require specific legal protection for their conservation. In fact, at least 20 pine taxa are in some category of risk and two of them, *Pinus maximartinezii* and *P. muricata*, are in danger of extinction[2].

2. Disturbance in temperate forests

Temperate forests have variable disturbance regimes. In some regions fire is the main agent that allows the regeneration of non-dominant species and eliminates weak trees and even some pine species depend on high temperatures generated by fire to open the cones where their seeds are lodged[8]. Because the vast majority of pine forests are managed by humans, the frequency and intensity of natural fires have been modified. In some places, fires are suppressed to prevent the loss of trees, while in others, fires have been excessively promoted to change land use for agricultural or livestock purposes[9,10].

3. Debarkers

The bark stripping beetles are herbivorous beetles belonging to the Curculionidae family of very small size, their body ranges between 0.1 and 0.6 cm and have the habit of being endophytes, they dig galleries under the bark of trees to feed. There are two large groups: those belonging to the subfamily *Scolytinae* that feed directly on the phloem of trees and the beetles known as *Ambrosiales*, within the subfamily *Paltipodinae*, which in addition to perforating the bark, cultivate ambrosial fungi and do not feed directly on the host tree, but on the fungi they cultivate inside it[11]. Thus, it is important to differentiate that although both groups of Curculionidae live inside trees, only some feed directly on the phloem (*Scolytinae*), while the others feed on the fungi they cultivate (*Platipodinae*). In both cases, the adult beetle's tunnel into the bark of trees to oviposit beneath it. In some species of both groups only the female digs and in others the male helps her. Once inside the tree and after mating, the females make a vertical tunnel where they oviposit, separating the eggs with a certain distance between them, so that there is no interference between the larvae at the time of feeding. When the larvae emerge as they feed, they dig longitudinal tunnels away from the parental tunnel and eat until they are large enough to metamorphose**,** leave the tree as adults and complete their life cycle. Each species of debarking beetle produces a different pattern of galleries in the wood of the tree[12]. In the case of ambrosial beetles, each species has a mutualistic association with a particular fungus, so when young adults emerge from trees to find a couple and mate, they carry spores of their symbiont fungus with them in order to share with the new generation the fungus that will provide food, thus ensuring the welfare of the new generation[12]. In general, most species of bark beetles attack trees weakened by age, drought, fire, disease or mechanical damage; however, there are aggressive species such as Dendroctonus J. Tontalis (**Figure 1**) and *Dendroctonus ponderosae* that, when their populations are very large, can infest healthy trees by car-

rying out massive attacks on them over large areas[13,14].

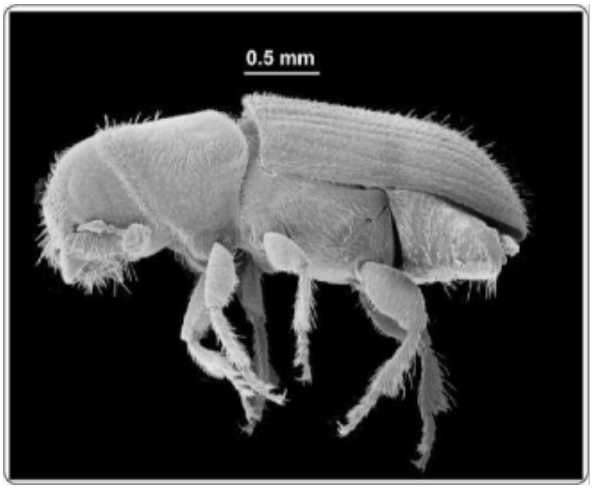

Figure 1. Pine bark beetle, *Dendroctonus frontalis.* Photograph courtesy of Dr. Thomas Atkinson.

Around 3,000 species of bark beetles have been described in the world and in Mexico there are 870 of these distributed in 87 genera, although this number is likely to increase because new species are still being described[15].

Bark removers play a major role in the dynamics of temperate forests by promoting the turnover of plant species, allowing the establishment of other species that are less competitive when they eliminate some dominant individuals. However, few insect species can cause tree mortality by themselves; most do not kill the host tree and remain in small populations as natural forest sanitation agents[16]. In Mexico, the number of species of bark beetles that cause conifer mortality is reduced to less than 20, most of which belong to the genus *Dendroctonus* and some species to the genus *Ips*[17-19].

4. Climate change

The environmental changes that planet Earth is experiencing due to anthropogenic activities have had different repercussions on ecosystems. On average, the global temperature of the planet has increased by 0.5–1 °C and with it extreme meteorological phenomena such as storms or hurricanes[20]. In Mexico, a generalized increase in temperature has also been observed in recent times[21] regardless of the oscillations related to the El Niño meteorological phenomenon[22]. Predictions for the year 2030 indicate that the country will experience an average temperature increase of 1.4°C and a decrease in average precipitation of 5.6%[21]. In some regions the temperature has been even higher and has combined with a reduction in precipitation, leading to unusual drought conditions. In particular, the direct effects of climate change on vegetation are evident worldwide[23,24]. For example, arid and semi-arid zones are expanding[25], the latitudinal limit of temperate forests has shifted poleward[26] and several vegetation types, as well as several species in particular, have migrated altitudinally in recent times[27]. Animal populations have also undergone important changes; for example, in Great Britain, 22 species of butterflies are reported to have expanded their home range towards colder latitudes[28], while in Spain, 16 species of butterflies changed their altitudinal distribution (climbed almost 200 m), representing a considerable increase in their optimal habitat[29].

5. Climate change and bark strippers

In particular, global climate change in temperate forests has led to a decrease in the intensity of winters and a reduction in the number of days with temperatures below zero, making them one of the ecosystems most vulnerable to the phenomenon[30]. Several studies have documented that there is a decoupling between current climatic conditions and the environmental requirements of temperate forests[31-33], and that this decoupling will be accentuated towards the future with climate predictions for temperate regions[34]. In biological terms, this situation of climatic alteration has resulted in tree growth being able to extend for a longer period of time in colder regions[14], while trees in the lower altitudinal and latitudinal distribution limit towards the equator are more stressed by drought causing massive mortalities due to lack of water[35-38]. In these same forests, the regulation of herbivore species related to the presence of low temperatures has decreased considerably resulting in the populations of some herbivorous insects increasing and becoming pests by expanding their populations, in particular *Dendroctonus ponderosae* and *Dendroctonus*

frontalis[38-41]. This is the case of bark beetles that has been well documented in the United States, Canada and Europe[42]. In Canada alone, in 2008 an epidemic infestation was reported in the forests of the Province of British Columbia, with an outbreak of *Dendroctonus ponderosae* that in less than 10 years accumulated 14 million hectares affected where there was a disproportionate mortality in five pine species[43]. In Colorado and Arizona, the research group of Negrón *et al.*[44] modeled in the landscape the determinants that resulted in increased mortality of Pinus ponderosa associated with bark strippers (*Dendroctonus ponderosae*, *Ips lecontei*, *I. pini*, *I. calligraphus*, *I. latidens*, *I. knausi* and *I. integer*) and found that sites with greater drought located at lower altitudes had higher tree mortalities[44,45]. Similar situations have been experienced in Europe, particularly between 1980 and 1985, there were recurrent droughts in the center of the continent that triggered an important infestation of several genera (*Ips*, *Dendroctonus*, *Scolytus* and *Tomicus*), on several conifers (*Picea* spp., *Pinus* spp., *Abies* spp.), with an unusual mortality of trees located in lower altitudinal ranges[46].

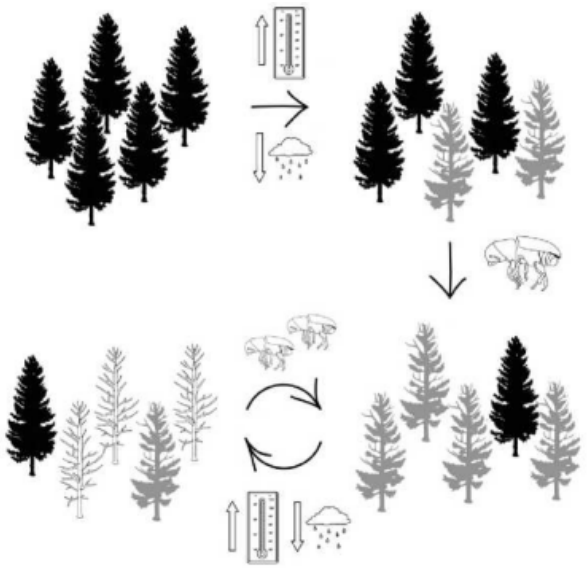

Figure 2. Negative feedback loop between climatic changes and the incidence of debarking on forest health. Carried out by Regina González.

The problems that bark beetles represent for temperate forests, under current conditions of climate change, are a negative feedback loop with a very strong impact on temperate ecosystems that continues to increase as temperatures and drought increase[47,48]. That is, as temperature increases, natural populations of bark strippers increase the number of individuals and their infestation capacity, while trees are stressed by drought and decrease their ability to defend themselves from attack by these insects (**Figure 2**). As explained above, trees at the xeric limits of distribution of these ecosystems are regularly subjected to abnormal stress and are therefore physiologically diminished, which implies that they have a lower capacity to defend themselves from attack by herbivorous insects and under extreme conditions die. Pines defend themselves from them through the production of resins, so that a healthy tree when pierced by an insect, releases a torrent of resin that prevents them from penetrating its tissues (**Figure 3**); however, when the tree is weak it presents less resin as it is reduced in the ducts through which it passes in the xylem or even stops producing it and insects penetrate and easily access the phloem, ending up killing the tree[49]. On the other hand, the increase in environmental temperature in addition to decreasing insect mortality in winter[50,51], accelerates their metabolic rate, inhibits diapause and has allowed them to increase the number of generations they have per year[14,19]. Some studies have reported, for example, that in southern Italy, where the climate is less extreme than in the north, *Ips typographus* has two generations per year instead of the usual one[51]. Other studies have found that *Pinuscontorta* populations in northern British Columbia that have not been exposed to population increases of *Dendroctonus ponderosae* are more susceptible to new attacks than populations where the two species overlapped, and therefore expect population explosions to continue to have very important effects on northern populations[52]. In recent times, studies related to large outbreaks of *Dendroctonus ponderosae* in Canada estimated the modification in the carbon sink that temperate forests normally represent when massive tree mortality occurs. Kurz *et al.*[53], calculated that forests in British Columbia, in years of heavy infestation, not only stopped absorbing atmospheric carbon dioxide, but became a major source of carbon dioxide production equivalent to ~75% of the gases emitted annually across

Canada, due to forest fires. On the other hand, in California, Etaough Jones *et al.*[54], found that pines on sites with high nitrogen pollution are more susceptible to attack by bark strippers. So, the negative feedback, with increasing greenhouse gas emissions due to massive tree mortality and global warming, will also tend to increase along with nitrogen deposition.

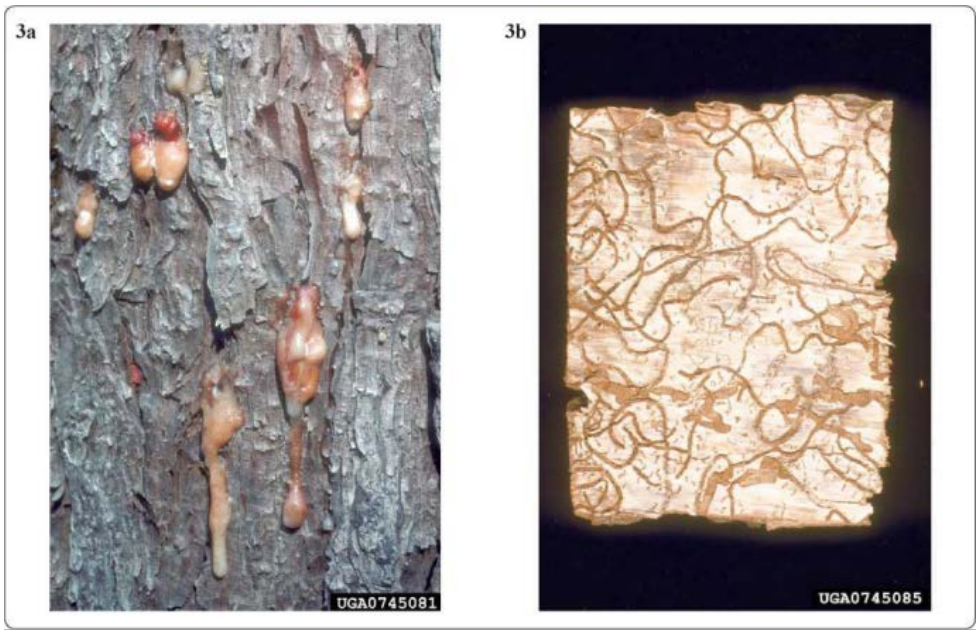

Figure 3. (**a**) Pine trunk attacked by bark beetles. Resin clumps produced by the tree when pierced by the beetles are shown, photograph courtesy of Erich G. Vallery, USDA Forest Service - SRS-4552, Bugwood.org. (**b**) Galleries formed by *D. frontalis* under the bark of pine trees, photograph courtesy of W.H. Bennett, USDA Forest Service, Bugwood.org.

6. Debarkers in Mexico in the face of global climate change

In view of the above, Mexico's temperate forests are no exception to the consequences of climate change and its relationship with forest pests[55]. In recent times, outbreaks of bark beetles have been documented affecting large areas of forests. For example, in 2013, 12% of pine forests had outbreaks (Sistema Nacional de Información Ambiental), in particular in that same year, 25% of the forests of Durango and 18% of the forests of Chihuahua were significantly affected.

Historically, the largest outbreaks of bark beetles in Mexico have occurred in the transverse Neovolcanic Axis, an area that coincides with the greatest diversity of pine trees, but not with the greatest diversity of bark beetle species of the genus Dendroctonus[56]. In Michoacán, an increase in the incidence of outbreaks of these insects has been reported: in the Monarch Butterfly Biosphere Reserve in the years 2007–2008, when there was a significant drought, infestations of *Scolytus mundus* were recorded causing high mortality on oyamel trees[57]. In the forest community of Nuevo San Juan Parangaricutiro, an increase in the number of bark stripper outbreaks was also identified, so a study was conducted to evaluate both the incidence of bark strippers in the forest and the damage. This study found a significant relationship between the abundance of this type of insects and maximum temperatures[58]; in the community where the study was conducted, there is a greater richness and abundance of secondary bark strippers at low altitudes (mediated by maximum temperatures) and also greater damage to the trees. This pattern provides information to interpret the increase of bark strippers at lower altitudes in pine forests, as well as to corroborate that pines are weakened at sites with higher temperatures and also that the abundance of insects is higher at low altitudes, resulting in an increase in the probability of infestation hotspots, especially if this pattern is corroborated with more aggressive bark strippers. Additionally, it is im-

portant to highlight that the abundance and distribution of bark strippers is also closely related to biotic factors such as the predator community at each site[59,60], as well as the vegetation composition of each particular forest[61,62]. In Mexico, there are very few studies that have conducted evaluations on these factors, so they undoubtedly represent a significant area of opportunity.

7. Conclusions

Climate change predictions in Mexico are drastic for temperate forests and there are few studies documenting the spatio-temporal distribution of infestation, magnitude of bark stripper outbreaks in them and their possible association with the increase in temperature and change in rainfall patterns. Due to the evident negative consequences that have been registered in other countries such as: massive tree mortality, increase in greenhouse gas emissions, as well as the repercussions for the communities that live from the forests with the consequent loss of their livelihood, it is essential to direct efforts to better understand the dynamics of bark strippers in the country and to be able to propose management strategies to prevent and control their incidence, as well as to reduce the costs of damages at present and in the near future.

Conflict of interest

The authors declared no conflict of interest.

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