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RESEARCH ARTICLE

Bark Beetle Outbreaks: Economic, Ecological Impacts, and Allelochemicals in Management

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ABSTRACT

Tree-killing bark beetles (Coleoptera: Curculionidae: Scolytinae) are highly devastating insect pests of coniferous trees worldwide. Global warming, drought stress, and poor management of forests favor beetle infestation. Climate change has enhanced the magnitude of bark beetle attacks, causing tree mortality and economic loss. Phloem-feeding beetle genera i.e. Dendroctonus, and Ips have an overwhelming impact on coniferous forests and recently beetle infestation and outbreak escalated. Synthetic pesticides play an important role in protection but cause environmental effects. Thus, there is a dire need for alternative integrated insect pest management methods. Plant secondary metabolites referred to as allelochemicals are biological compounds naturally produced in conifers resin ducts. Coniferous Allelochemicals are the first line of chemical defense against tree-killing bark beetles. Alkaloids, terpenoids, and phenols are the most compelling compounds of secondary metabolites of conifers. In this review, we described the plant-based allelochemicals and their role in pest management of tree-killing beetles. Conifer allelochemicals protect trees by deterring infestation, inhibiting feeding, and poisoning, and by alluring beetles through traps and influencing beetle behavior and physiology. Alleochemuicals offer environmentally friendly, sustainable control of insect pests. In this study, we conclude that allelochemicals provide various promising opportunities for novel and ecologically friendly solutions for the control of tree-killing bark beetles.

INTRODUCTION

The bark beetle is an important biotic factor that significantly alters forest dynamics. Beetles inhabit forests globally (Hulcr et al., 2015), outbreaks of beetles cause tree mortality and due to global climate change bark beetles are expanding their range, elevational distribution, and changing host preferences (Raffa et al., 2015). The structure of the forest ecosystem and its functioning has been disturbed by bark beetle strongly, also affecting species composition, disturbance regimes like wildlife, carbon sink, nutrient cycle, and ecosystem hydrology (Morris et al., 2017). Bark beetle disturbance can have, hence, significant consequences for the preservation of ecosystem services in the future (Hlásny et al., 2019). Scientists have acclaimed the bark beetle outbreak as a significant factor for forest ecosystems worldwide considering the influence of global climate change. These beetles play a crucial part in forest ecosystem processes like surface albedo, carbon water fluxes, and global climate change.

In this review, we focused on the bark beetle species that damaged the coniferous forests and their economic and ecological effects. We explained bark beetle biology, the life cycle, and the effect of climate change on beetles. Then we present the mechanism of host allelochemicals and their role in deterrence and toxicity to beetle.

Bark beetle biology

The bark Beetles are smaller cylindrical insects, taxonomically classified in the Scolytinae (Latreille,1804) subfamily, Curculionidae family, and Coleoptera (Linnaeus,1758) order. 6000 beetle species are identified in the Scolytinae subfamily and less than 1 % can colonize and cause healthy tree mortality (Hulcr et al., 2015). Coniferous tree-killing bark beetles can cause important economic and environmental impacts (Morris et al., 2017). In this review, we mainly focused on North American and European coniferous forest species of *Dendroctonus*, *Tomicus,* and *Ips* genera.

Bark beetles all their life besides the dispersal phase during the adult stage, spend their lives breeding, and feeding gallery chambers inside plant bark tissues (Raffa et al., 2015) also few species overwinter in forest tree debris (Schebeck et al.. 2017). The bark beetle life cycle consists of host tree selection for colonization and reproduction, development through all the larval instars, pupate, and dispersal after maturation (Sauvard, 2004). Still, there are variations among species of tree-killing bark beetles such as reproductive strategies, for example, monogamous or polygamous, number of generations each year, and host selection. It affects the host tree colonization, dispersal, and potential population outbreak.

After the selection of a susceptible host beetle attacks and colonizes the tree for production, the beetle bores through phloem and excavates galleries to select the mating partners. In *Dendroctonus* genera and *Tomicus* which is a monogamous species, females are the pioneers while in the genus *Ips* polygamous males are the ones who initiat galleries (Lieutier et al., 2015; Six and Bracewell 2015 (Cognato, 2015). Pioneer beetles produce aggregation pheromones to attract the matting partner on a new host (Blomquist et al., 2010). Female beetles oviposit eggs in galleries to produce brood. Through mass attack species such as *Dendroctonus rufipennis, D. ponderosae*, and *I. typographus* overwhelm the defense of the host tree (Blomquist et al., 2010). The mass attack counts on factors like the density of the beetle, host tree defensive metabolites, and the health of individual host trees (Boone et al., 2011).

Bark beetled along with associated symbiotic microorganisms (fungi) is capable of causing tree mortality, which also helps in the detoxification of tree secondary metabolites (Chiu et al., 2019). Antiagression pheromones are released to deter further infestation after successful colonization of the host tree to decrease conspecific competition (Wood, 1982). Depending on tree size, the nutritional quality of the host, and bark beetle species infestation, the host tree is typically available for up to two generations of beetle per year (Raffa et al., 2016). Larvae excavate perpendicular galleries to maternal chambers and start eating phloem along with blue fungi. After pupation, individuals bore in phloem i.e. in *Ips sexdentatus* or in *Tomicus piniperda* which bore in outer bark (Lieutier et al., 2015). The maturation period required in beetles before they start reproduction and dispersal in *Ips* and *Dendroctonus* takes place in the natal host (Six and Bracewell, 2015), after maturation beetles disperse to select a new susceptible host tree. However, the *Tomicus* species starts feeding on the same host twigs and shoots. Dispersal of bark trees and selection of hosts are influenced by biotic and abiotic factors like beetle fitness, temperature, tree density, and wind Kautz et al., 2016; Jones et al., 2019). Usually, dispersal happens from a few hundred meters to a few kilometers (Doležal et al., 2016). However, beetles do cover long-distance distances when flight is assisted by wind currents. *D. ponderosae* has been documented more than 24 km from the natal host tree (Evenden et al., 2014) furthermore *I. edentates* and *I. typographus* can fly above 40 km distance (Nilssen, 1984, Jactel and Gaillard, 1991).

Host selection

The Bark beetles widespread infestations and colonization are complex and supported by climate change, and extreme draughts which lead to devastating effects on coniferous forests (Seidl and Rammer, 2017). Host tree response under stress and drought is varied across species. Fallen, stress trees provide breeding material for tree-killing bark beetles to transition from endemic to pandemic situation (Hroššo et al., 2020). Fully grown adult beetles locate a suitable host, bore, mate, and lay eggs in galleries under the bark. Larvae and adult beetles feed to maturity on tree phloem. Brood adults emerge and migrate to fund new hosts (Raffa et al., 2015). Successful beetle infestation results in tree mortality. Hundreds of beetles attack simultaneously to colonize trees and block nutrient transport. Single species of tree-killing beetle can breed on one tree and can breed up to 3 generations before tree bark gets exhausted (Krokene, 2015). Bark beetles attack hosts in intermittent events followed by a non-outbreak phase where they reproduce. In the endemic phase, the beetle population is controlled by host tree defensive chemicals and weather and natural enemies. Due to favorable conditions beetles superpass threshold level and overwhelm the stressed tree defense through an aggression mechanism (willian et al., 2004).

Bark beetle and climate change

Bark beetle outbreaks are facilitated by droughts and wind to some extent (Negrón and Huckaby, 2020). Contemporary, bark beetle outbreaks in North America and Europe are changed than previously observed, suggesting the role of climate change and its role in new infestation patterns (Fettig et al., 2022). Beetle outbreaks are more grave and frequent, and the length of beetle attacks is longer than past (Hlásny et al., 2021). Warmer temperature enhances beetles' generations per year, expanding their dispersal beyond the historical typical range with the risk of becoming an invasive species i.e. *D. ponderosae* (Cudmore et al., 2010). Phloem eating beetle species are colonizing formerly noninfested coniferous species, indicating their expansions in host preferences (Raffa et al., 2013).

Economic impact

Over the past two decades, a huge number of conifer species spanning millions of hectares (ha) in Canada and Mexico have been infested, colonized, and killed by bark beetles (Fettig et al., 2022). 36 million hectares of coniferous forest land have been affected by tree-killing bark beetle in the western USA, belonging to *Ips* and *Dendroctonus* genera (USDA, 2020). US$2 billion annually loss is experienced by the USA due to timber loss due to tree-killing bark beetle infestation. An outbreak of *D. ponderosae* caused the mortality of 14 million ha *Pinus contorta* in British Columbia and converted it to a carbon source from a carbon sink (Woods et al., 2010). Bark Beetles from *Ips* and *Tomicus* genera are the main drivers of tree infestation and outbreaks of beetle which caused recent tree mortality across Europe. *Ips typographous* is the most aggressive species among all tree-killing beetles which affected the spruce forest in Europe in the last decade (Patacca et al., 2023). Between 2017-2019 in the Czech Republic *I. typographus beetles* killed greater than 23 million m3 of spruce forest (Hlásny et al., 2021). 260 million USD worth of economic loss was experienced in the Czech Republic during the year 2018-2019 due to the *Ips typographus* outbreak (Gandhi et al., 2022).

Allelochemicals and Their Role in Insect-Plant Interaction

Insect pests interact and damage plants around the globe which leads to the development of complex defensive systems including chemical mechanisms. This evolution of plants determines insect population diversity. Secondary metabolites play a crucial role in defense mechanisms and Insect-plant interactions are called allelochemicals (Ibanez et al., 2012). Plants counter herbivore attacks through induced defense response. Plants produce defensive metabolites that protect against insect attacks (Yan et al., 2014). Phytoanticipins (stored) and phytoalexins(active) are two metabolites that form in plants. They protect the tree by inhibiting or intoxicating the insects and cause negative effects on the digestion of herbivores. Insects and plants are in continuous interaction. Plants provide food and shelter to insects and in return, they lay eggs and help with pollination (Newman, 2014). Plants evolved multiple resistances to overcome insect pest damage (Schoonhoven et al., 1998). Constitutive and induced defense mechanisms consist of morphological attributes and secondary plant metabolites to protect plants against insects. Anti-feeding compounds are plant secondary metabolites that inhibit insect feeding (Block et al., 2019). Metabolites are divided into subgroups like alkaloids, glucosinolates, cyanogenic glycosides, terpenoids, and phenolics (Polumackanycz et al., 2020). The main groups of allelochemicals are Allomones, Repellents, Suppressants, Deterrents and Toxins. Their main role is to suppress inhibiting, prevent feeding and ovipositing, and produce chronic or acute toxic effects to insect pests. The production of secondary phenolic metabolites varies significantly among tree species, tree parts, ages, and regions (Mbata and Payton, 2013).

Conifers produce a wide range of allelochemicals that can inhibit the growth or development of other plants and organisms, playing a key role in plant interactions by affecting competition, herbivory, and mutual relationships, with their method of allelochemical production being particularly intricate (Despland et al., 2016).

In coniferous species, tree defense against beetles depends on terpenoids with polyphenols which are produced in resin ducts of the plant xylem (Copolovici et al.,2012). These secondary metabolites are evenly distributed in the roots, shoots, and needles of conifers. Terpenoids comprise different groups e.g., monoterpenoids, sesquiterpenoids, diterpenoids, and triterpenoids. Terpenes protect plants against insect pests indirectly by increasing and luring natural enemies of beetles. They released a blend of volatiles that attract beneficial insects including predators and parasitoids of beetles (Bond et al., 2004). A few Monoterpenoids e.g. D-limonene, pulegone, and myrcene used as the primary ingredients of essential oils which are used against many insects. The toxicity of 10 predominant monoterpenes *of P. contorta* against the bark beetle mountain pine beetle suggested that carene, myrcene, terpinolene, enantiomers of α-pinene, β-pinene, and limonene triggered beetle mortality (Tao et al., 2003). Some plant oils are neurotoxic when beetles feed on them. The most noticeable symptoms include hyperactivity, and hyper-excitation, followed by brisk knockdown and paralysis (Singh et al., 1988).

Due to the attractant behavior of few monoterpenes, I can potent synergist along with pheromones of *Dendroctonus* species which is not influenced by host orders solely. Turpentine can be used in baited traps for *D. frontalis* to increase the catch along with its attractive pheromone (Billings, 1985, Sullivan, 2016). Combinations of monoterpenes result in up to 30 times increase in catches of *D. ponderosae* contrasted to pheromone alone (Borden et al., 2008).

Scots pine shows different concentrations of phenolic compounds in its dried bark, needles, and heartwood are 76.0, 17.5, and 1.1 mg/g, respectively, while wood samples have tannic acid equivalent concentrations ranging from 6.7 to 13.6 mg/g (Kahkonen et al., 1999, Venalainen et al.,2004). Norway spruce's knot wood can have phenolic concentrations ranging from 10-15% to 30% by dry weight (Willfor et al., 2003). Terpenes, which impart the distinctive scent of conifers and can adversely affect plants and insects due to their volatility, and non-volatile phenolics, which inhibit the growth of neighboring plants by disrupting their metabolic processes, are both crucial in plant interactions. Conifer resins, containing toxic substances that deter pests like bark beetles and affect their feeding, development, and reproduction, serve as a defense mechanism that helps minimize damage to conifer foliage and bark (De Silva et al., 2015). The current review is investigating the potential use of conifer allelochemicals for natural pest control in forest management.

Verbenone, is a monoterpene ketone with two enantiomeric forms: (−)-*S*- and (+)-*R*-verbenone. It was initially discovered as an oxidation product in coniferous turpentine oil (Blumann and Zeitschel, 1913). It can be present in various coniferous bark beetle host species (Szmigielski et al., 2012).

Verbenone is produced under aerobic conditions when α-pinene (conifer resin) or verbenol are present (Ramakrishnan et al., 2022). Through autoxidation, the spontaneous conversion of verbenol happens and results in verbenone (Dvořakova et al., 2007) and its irreversible process.

Verbenone is a widely recognized bark beetle repellent which is a well-studied and established phenomenon, and stands as a prominent bark beetle aggregation inhibitor (Mafra-Neto et al., 2022). Verbenone seems to be ubiquitous only among the Scolytinae family. Verbenone inhibitory effect against bark beetle through the baited traps in the field is positively associated with verbenone dosage (Lopez et al., 2013; Byers et al., 2018, 2020).

Table 1: Alleochemical conifer source, Application methods, and their efficacy.

Allelochemical Source	Application Mode	Localization of Compound	Insect Suppression	Reference
Monoterpenes				

α-Pinene	Natural resin, essential oils, spray fumigant, tropical application, pheromone trap	Resin ducts of bark, needles	Deterrence of bark beetle bark beetles. Inhibits feeding and development. In a pheromone trap a lure agent.	(Faccoli et al., 2005 Fang et al., 2021 Chiu et al., 2017 Moliterno et al.,2023 Mamoci et al., 2022)
β-Pinene	Natural resin, essential oils, spray fumigant, tropical application	Resin ducts of bark, needles	Deterrence of bark beetles. Inhibits feeding and development. In the pheromone trap a lure agent.	(Faccoli et al., 2005 Fang et al., 2021 Chiu et al., 2017 Moliterno et al.,2023 Mamoci et al., 2022)
Limonene	Foliar application, essential oils	Resin ducts of bark, needles	Repels beetles and inhibits feeding	(Faccoli et al., 2005 Fang et al., 2021 Chiu et al., 2017 Moliterno et al.,2023 Mamoci et al., 2022)
Myrcene	Natural resin, essential oils, spray fumigant, tropical application	Resin ducts of bark, needles	Repels bark beetles. Inhibits feeding and development. In the pheromone trap a lure agent.	(Faccoli et al., 2005 Fang et al., 2021 Chiu et al., 2017 (Moliterno et al.,2023 Mamoci et al., 2022)
Diterpenes				
Abietic Acid	Resin extraction, topical application	Resin ducts of bark, needles	inhibits feeding and development; effective against bark beetles.	(Kopper et al., 2005 Schiebe et al., 2012 Lopez et al., 2020)
Pimaric Acid	Resin extraction, topical application	Resin ducts of bark, needles	Toxic and deterrent effects on insects; reduces beetle infestations.	(Kopper at al., 2005 Schiebe et al., 2012 Lopez et al., 2020)
Sesquiterpenes				
Farnesene	Foliar application, essential oils	Resin ducts	Repellent to beetles and insects; effective in preventing beetle infestation.	(Gonzalez et al., 1995 Kendra et al., 2014 Gonzalez et al., 2014 Cheney et al.,2019)
Germacrene D	Foliar application, essential oils	Resin ducts	Inhibits feeding and development of various beetles and caterpillars.	(Gonzalez et al., 1995 Kendra et al., 2014 Gonzalez et al., 2014 Cheney et al.,2019)
Tannins				
Catechins	bait trap to lure.	Needles	Repels insects; deters feeding and reduces larval development.	(Solar et al., 2006 Keefover et al., 2016)
Resin Acids				
Resin Acid Esters	Natural resin, topical treatment	Resin ducts, spruce wood	Toxic to bark beetles; reduces infestation rates.	(Chiu et al., 2019)
Phenolic Compounds				

Flavonoids	Fumigant, Tropical spray	Tree needles	Repels insects; inhibits feeding and larval growth.	(Pereira et al., 2024 Hammerbacheret al., 2019 Schnarr et al., 2022)
Phenolic Acids	Fumigant, Tropical spray	Bark, wood	Acts as a repellent; reduces feeding and survival rates of insects.	(Pereira et al., 2024 Hammerbacheret al., 2019 Schnarr et al., 2022)
Cinnamic Acid	Fumigant, Tropical spray	Bark, wood	Deterrent to various insects; reduces feeding and development. Inhibits detoxification,	(Pereira et al., 2024 Hammerbacheret al., 2019 Schnarr et al., 2022)

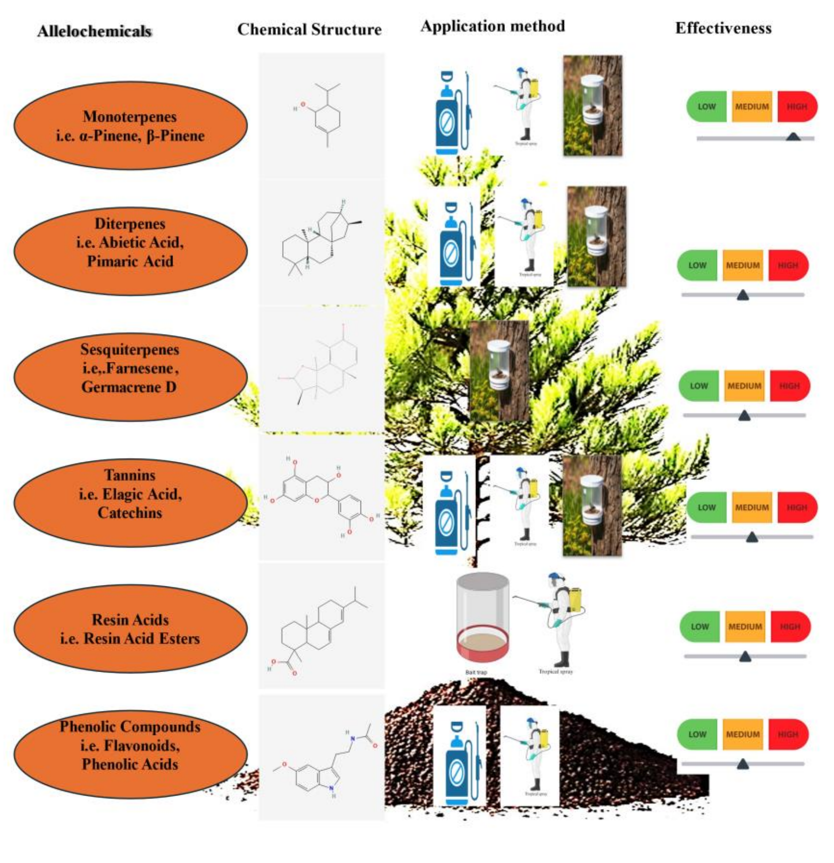

Figure 1: Allelochemicals in conifers

CONCLUSION

Current beetle infestation demands novel, effective, sustainable, and eco-friendly beetle management methodologies. The use of coniferous allelochemicals (secondary metabolites) with toxic and deterrent effects is an environmentally acceptable beetle management strategy. Devastating bark beetle attacks occurred due to stress and rise in temperature. These naturally occurring metabolites play an important role in constituting tree defense. The role and potential of many secondary metabolites of conference have not been investigated yet. Therefore, it is necessary to conduct new experiments concerning beetle inhibiting and deterring the properties of conifer allelochemicals. Additionally, adding these allelochemicals with other Ipm strategies like biological control, using allelochemicals as synergists or habitat modification can enhance overall effectiveness in bark beetle control methodologies. Furthermore, by understanding how climate change and increase in temperature will affect the production and effectiveness of these secondary metabolites bark beetle adaptive control strategies can be developed.

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AMZ conceptualization. AMZ prepared the first draft wiring. AMZ and KM finalized the table and figure and prepared the final draft. All authors read and approved the final version of the draft.

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Conflicts of Interest

The authors disclose no conflicts of interest.

REFERENCES

Billings RF, 1985. Southern pine bark beetles and associated insects: Effects of rapidly-released host volatiles on response to aggregation pheromones. J Appl Entomol, 99: 483–491. https://doi.org/10.1111/j.1439-0418.1985.tb02015.x

Block AK, Hunter CT, Sattler SE, Rering C, McDonald S, Basset GJ, Christensen SA, 2019. Fighting on two fronts: Elevated insect resistance in flooded maize. Plant Cell Environ, 43: 223–234. https://doi.org/10.1111/pce.13642

Blomquist GJ, Figueroa-Teran R, Aw M et al, 2010. Pheromone production in bark beetles. Insect Biochem Mol Biol, 40: 699–712. https://doi.org/10.1016/j.ibmb.2010.07.013

Blumann A, Zeitschel O, 1913. Ein Beitrag zur Autoxydation des Terpentinols. Ber Dtsch Chem Ges, 46: 1178–1198. https://doi.org/10.1002/cber.19130 46011 54

Bond WJ, Lee WG, Craine JM, 2004. Plant structural defences against browsing birds: A legacy of New Zealand's extinct moas. Oikos, 104: 500–508.

Boone CK, Aukema BH, Bohlmann J et al, 2011. Efficacy of tree defense physiology varies with bark beetle population density: a basis for positive feedback in eruptive species. Can J For Res, 41: 1174–1188. https://doi.org/10.1139/x11-041

Borden JH, Pureswaran DS, Lafontaine JP, 2008. Synergistic blends of monoterpenes for aggregation pheromones of the mountain pine beetle (Coleoptera: Curculionidae). J Econ Entomol, 101: 1266–1275. https://doi.org/10.1093/jee/101.4.1266

Byers JA, Maoz Y, Fefer D, Levi-Zada A, 2020. Semiochemicals affecting attraction of ambrosia beetle Euwallacea fornicatus (Coleoptera: Curculionidae: Scolytinae) to quercivorol: developing push-pull control. J Econ Entomol, 113: 2120–2127. https://doi.org/10.1093/jee/toaa1

Byers JA, Maoz Y, Wakarchuk D, Fefer D, Levi-Zada A, 2018. Inhibitory effects of semiochemicals on the attraction of an ambrosia beetle Euwallacea nr. fornicatus to quercivorol. J Chem Ecol, 44: 565–575. https://doi.org/10.1007/s10886-018-0959-8

Cheney KN, Roy AH, Smith RF, DeWalt RE, 2019. Effects of stream temperature and substrate type on emergence patterns of Plecoptera and Trichoptera from northeastern United States headwater streams. Environmental Entomology, 48: 1349–1359. https://doi.org/10.1093/ee/nvz106

Chiu CC, Keeling CI, Bohlmann J, 2017. Toxicity of pine monoterpenes to mountain pine beetle. Scientific Reports, 7: 8858. https://doi.org/10.1038/s41598-017-08983-y

Chiu CC, Keeling CI, Bohlmann J, 2019. Cytochromes P450 preferentially expressed in antennae of the mountain pine beetle. J Chem Ecol, 45: 178–186. https://doi.org/10.1007/s10886-018-0999-0

Chiu CC, Keeling CI, Henderson HM, Bohlmann J, 2019. Functions of mountain pine beetle cytochromes P450 CYP6DJ1, CYP6BW1 and CYP6BW3 in the oxidation of pine monoterpenes and diterpene resin acids. PLoS One, 14: e0216753. https://doi.org/10.1371/journal.pone.0216753

Cognato AI, 2015. Biology, systematics, and evolution of Ips. In: Vega FE, Hofstetter RW (eds) Bark beetles: biology and ecology of native and invasive species. Academic Press, London, pp 351–370.

Copolovici L, Kännaste A, Pazouki L, Niinemets Ü, 2012. Emissions of green leaf volatiles and terpenoids from Solanum lycopersicum are quantitatively related to the severity of cold and heat shock treatments. J Plant Physiol, 169: 664–672. https://doi.org/10.1016/j.jplph.2011.12.019

Cudmore TJ, Björklund N, Carroll AL, Lindgren SB, 2010. Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naive host tree populations. Journal of Applied Ecology, 47: 1036–1043. https://doi.org/10.1111/j.1365-2664.2010.01848.x

De Silva D, Tu Y-T, Amunts A, Fontanesi F, Barrientos A, 2015. Mitochondrial ribosome assembly in health and disease. Cell Cycle, 14(14): 2226-2250. https://doi.org/10.1080/15384101.2015.1053672

Despland E, Bourdier T, Dion E, Bauce E, 2016. Do white spruce epicuticular wax monoterpenes follow foliar patterns? Canadian Journal of Forest Research, 46: 1051–1058. https://doi.org/10.1139/cjfr-2016-0056

Doležal P, Okrouhlík J, Davídková M, 2016. Fine fluorescent powder marking study of dispersal in the spruce bark beetle, Ips typographus (Coleoptera: Scolytidae). European Journal of Entomology, 113: 1–8. https://doi.org/10.14411/eje.2016.001

Dvořakova M, Valterova I, Vaněk T, 2007. Biotransformation of a monoterpene mixture by in vitro cultures of selected conifer species. Natural Products Communications, 2: 233–238. https://doi.org/10.1177/1934578X0700200302

Evenden ML, Whitehouse CM, Sykes J, 2014. Factors influencing flight capacity of the mountain pine beetle (Coleoptera: Curculionidae: Scolytinae). Environmental Entomology, 43(1): 187–196. https://doi.org/10.1603/EN13244

Faccoli M, Blaženec M, Schlyter F, 2005. Feeding response to host and nonhost compounds by males and females of the spruce bark beetle Ips typographus in a tunneling microassay. Journal of Chemical Ecology, 31: 745–759. https://doi.org/10.1007/s10886-005-3542-z

Fang JX, Zhang SF, Liu F, Cheng B, Zhang Z, Zhang QH, Kong XB, 2021. Functional investigation of monoterpenes for improved understanding of the relationship between hosts and bark beetles. Journal of Applied Entomology, 145(4): 303-311. https://doi.org/10.1111/jen.12850

Fettig CJ, Klepzig KD, Billings RF et al, 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. Forest Ecology and Management, 238: 24–53. https://doi.org/10.1016/j.foreco.2006.10.011

Gandhi KJ, Hofstetter R, 2022. Introduction: Bark beetles, management, and climate change. In: Bark Beetle Management, Ecology, and Climate Change; Elsevier: Amsterdam, The Netherlands; pp. xix–xxvi.

Gonzalez-Coloma A, Reina M, Cabrera R, Castañera P, Gutierrez C, 1995. Antifeedant and toxic effects of sesquiterpenes from Senecio palmensis to Colorado potato beetle. Journal of Chemical Ecology, 21: 1255-1270. https://doi.org/10.1007/BF02027560

González-Coloma A, Valencia F, Martín N, Hoffmann JJ, Hutter L, Marco JA, Reina M, 2002. Silphinene sesquiterpenes as model insect antifeedants. Journal of Chemical Ecology, 28: 117-129. https://doi.org/10.1023/A:1013566919874

Hammerbacher A, Kandasamy D, Ullah C, Schmidt A, Wright LP, Gershenzon J, 2019. Flavanone-3-hydroxylase plays an important role in the biosynthesis of spruce phenolic defenses against bark beetles and their fungal associates. Frontiers in Plant Science, 10: 208. https://doi.org/10.3389/fpls.2019.00208

Hlásný T, Krokene P, Liebhold A, Montagné-Huck C, Müller J, Qin H, Rafa K, Schelhaas M, Seidl R, Svoboda M, Viiri H, 2019. Living with bark beetles: impacts, outlook and management options. (From Science to Policy; No. 8). European Forest Institute. https://www.ef.int/sites/default/files/publication-bank/2019/ef_fstp_8_2019.pdf

Hlásný T, Zimová S, Merganičová K et al, 2021. Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts, and management implications. Forest Ecology and Management. https://doi.org/10.1016/j.foreco.2021.119075

Hlásný T, Zimová S, Merganičová K et al, 2021. Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts, and management implications. Forest Ecology and Management. https://doi.org/10.1016/j.foreco.2021.119075

Hroššo B, Mezei P, Potterf M et al, 2020. Drivers of spruce bark beetle (Ips typographus) infestations on downed trees after severe windthrow. Forests, 11: 1–15. https://doi.org/10.3390/f11121229

Hulcr J, Atkinson TH, Cognato AI et al, 2015. Morphology, taxonomy and phylogenetics of bark beetles. In: Vega FE, Hofstetter RW (eds) Bark beetles: biology and ecology of native and invasive species. Academic Press, London, pp 41–84.

Ibanez S, Gallet C, Després L, 2012. Plant insecticidal toxins in ecological networks. Toxins, 4: 228–243. https://doi.org/10.3390/toxins4040228

Jactel H, 1991. Dispersal and flight behaviour of Ips sexdentatus (Coleoptera: Scolytidae) in pine forest. Annals of Forest Science, 48: 417–428. https://doi.org/10.1051/forest:19910405

Jones KL, Shegelski VA, Marculis NG et al, 2019. Factors influencing dispersal by flight in bark beetles (Coleoptera: Curculionidae: Scolytinae): from genes to landscapes. Canadian Journal of Forest Research, 49: 1024–1041. https://doi.org/10.1139/cjfr-2018-0304

Kähkönen MP, Hopia AI, Vuorela HJ, Rauha JP, Pihlaja K, Kujala TS, Heinonen M, 1999. Antioxidant activity of plant extracts containing phenolic compounds. Journal of Agricultural and Food Chemistry, 47(10): 3954-3962. https://doi.org/10.1021/jf990146l

Kautz M, Imron MA, Dworschak K, Schopf R, 2016. Dispersal variability and associated population-level consequences in tree-killing bark beetles. Movement Ecology. https://doi.org/10.1186/s40462-016-0074-9

Keefover-Ring K, Trowbridge A, Mason CJ, Raffa KF, 2016. Rapid induction of multiple terpenoid groups by ponderosa pine in response to bark beetle-associated fungi. Journal of Chemical Ecology, 42: 1-12. https://doi.org/10.1007/s10886-015-0659-6

Kendra PE, Montgomery WS, Niogret J, Schnell EQ, Deyrup MA, Epsky ND, 2014. Evaluation of seven essential oils identifies cubeb oil as most effective attractant for detection of Xyleborus glabratus. Journal of Pest Science, 87: 681-689. https://doi.org/10.1007/s10340-014-0561-y

Kopper BJ, Illman BL, Kersten PJ, Klepzig KD, Raffa KF, 2005. Effects of diterpene acids on components of a conifer bark beetle–fungal interaction: tolerance by Ips pini and sensitivity by its associate Ophiostoma ips. Environmental Entomology, 34(2): 486-493. https://doi.org/10.1603/0046-225X-34.2.486

Krokene P, 2015. Conifer defense and resistance to bark beetles. In: Bark beetles, pp. 177-207. Academic Press.

Latreille PA, 1804. Tableau méthodique des insectes. In: Nouveau dictionnaire d'histoire naturelle, 24?: tableaux méthodiques d'histoire naturelle. Appliquée aux Arts, Principalement à l'Agriculture et à l'Economie Rurale et Domestique, 24, pp. 129–200.

Lieutier F, Langström B, Faccoli M, 2015. The genus Tomicus. In: Vega FE, Hofstetter RW (eds) Bark beetles: biology and ecology of native and invasive species. Academic Press, London, pp. 371–426.

Linnaeus C, 1758. Systema naturae per regna tria naturae, secundum classes, ordines, genera, spacies, cum characteribus, differentiis, synonymis, locis. L. Salvii, Stockholm.

Lopez S, Quero C, Iturrondobeitia JC, Guerrero A, Goldarazena A, 2013. Electrophysiological and behavioural responses of Pityophthorus pubescens (Coleoptera: Scolytinae) to (E, E)-α-farnesene, (R)-(+)-limonene and (S)-(-)-verbenone in Pinus radiata (Pinaceae) stands in northern Spain. Pest Management Science, 69: 40-47. https://doi.org/10.1002/ps.3359

López-Goldar X, Lundborg L, Borg-Karlson AK, Zas R, Sampedro L, 2020. Resin acids as inducible chemical defences of pine seedlings against chewing insects. PLoS One, 15(5), e0232692. https://doi.org/10.1371/journal.pone.0232692

Mafra-Neto A et al, 2022. CHAPTER 15-Repellent semiochemical solutions to mitigate the impacts of global climate change on arthropod pests. In: Corona C, Debboun M, Coats J (eds) Advances in arthropod repellents. Academic Press, Cambridge, Massachusetts, pp 279–322. https://doi.org/10.1016/B978-0-323-85411-5.00010-8

Mamoci E, Andrés MF, Olmeda S, González-Coloma A, 2022. Chemical composition and activity of essential oils of Albanian coniferous plants on plant pests. Chemistry Proceedings, 10(1), 15. https://doi.org/10.3390/IOCAG2022-12260

Mbata GN, Payton ME, 2013. Effect of monoterpenoids on oviposition and mortality of Callosobruchus maculatus (F.) (Coleoptera: Bruchidae) under hermetic conditions. Journal of Stored Products Research, 53: 43–47. https://doi.org/10.1016/j.jspr.2013.02.001

Moliterno AAC, Jakuš R, Modlinger R, Unelius CR, Schlyter F, Jirošová A, 2023. Field effects of oxygenated monoterpenes and estragole combined with pheromone on attraction of Ips typographus and its natural enemies. Frontiers in Forests and Global Change, 6, 1292581. https://doi.org/10.3389/ffgc.2023.1292581

Morris JL, Cottrell S, Fettig CJ et al, 2017. Managing bark beetle impacts on ecosystems and society: priority questions to motivate future research. Journal of Applied Ecology, 54: 750–760. https://doi.org/10.1111/1365-2664.12782

Negrón JF, Huckaby L, 2020. Reconstructing historical outbreaks of mountain pine beetle in lodgepole pine forests in the Colorado Front Range. Forest Ecology and Management, 473: 118270. https://doi.org/10.1016/j.foreco.2020.118270

Newman K, 2014. Feeding and oviposition preferences of the diamondback moth Plutella xylostella (Lepidoptera: Plutellidae) on six Brassicaceae host plant species. Master's Thesis, Department of Biological Sciences, Brock University St. Catharines, Ontario, ON, Canada. http://hdl.handle.net/10464/5759

Nilssen AC, 1984. Long-range aerial dispersal of bark beetles and bark weevils (Coleoptera, Scolytidae and Curculionidae) in northern Finland. Annales Entomologici Fennici, 50: 37–42.

Patacca M, Lindner M, Lucas-Borja ME et al, 2023. Significant increase in natural disturbance impacts on European forests since 1950. Global Change Biology, 29: 1359–1376. https://doi.org/10.1111/gcb.16531

Pereira V, Figueira O, Castilho PC, 2024. Flavonoids as insecticides in crop protection—A review of current research and future prospects. Plants, 13(6): 776. https://doi.org/10.3390/plants13060776

Polumackanycz M, Kaszuba M, Konopacka A et al, 2020. Phenolic composition and biological properties of wild and commercial dog rose fruits and leaves. Molecules, 25: 5272. https://doi.org/10.3390/molecules25225272

Raffa KF, Andersson MN, Schlyter F, 2016. Host selection by bark beetles: playing the odds in a high-stakes game. Advances in Insect Physiology, 50: 1–74. https://doi.org/10.1016/bs.aiip.2016.02.001

Raffa KF, Grégoire JC, Lindgren BS, 2015. Natural history and ecology of bark beetles. In: Vega FE, Hofstetter RW (eds) Bark beetles: biology and ecology of native and invasive species. Academic Press, London, pp 1–40.

Raffa KF, Powell EN, Townsend PA, 2013. Temperature-driven range expansion of an irruptive insect heightened by weakly coevolved plant defenses. Proceedings of the National Academy of Sciences, 110: 2193–2198. https://doi.org/10.1073/pnas.121666110

Ramakrishnan R et al, 2022. Metabolomics and transcriptomics of pheromone biosynthesis in an aggressive forest pest Ips typographus. Insect Biochemistry and Molecular Biology, 140: 103680. https://doi.org/10.1016/j.ibmb.2021.103680

Sauvard D, 2004. General biology of bark beetles. In: Lieutier F, Day KR, Battisti A, Grégoire JC, Evans HF (eds) Bark and wood boring insects in living trees in Europe, a synthesis. Springer, Dordrecht, pp 63–88. https://doi.org/10.1007/978-1-4020-2241-8_7

Schebeck M, Hansen EM, Schopf A et al, 2017. Diapause and overwintering of two spruce bark beetle species. Physiological Entomology, 42: 200–210. https://doi.org/10.1111/phen.12200

Schiebe C, Hammerbacher A, Birgersson G et al, 2012. Inducibility of chemical defenses in Norway spruce bark is correlated with unsuccessful mass attacks by the spruce bark beetle. Oecologia, 170: 183–198. https://doi.org/10.1007/s00442-012-2298-8

Schnarr L, Segatto ML, Olsson O, Zuin VG, Kümmerer K, 2022. Flavonoids as biopesticides—Systematic assessment of sources, structures, activities and environmental fate. Science of the Total Environment, 824: 153781. https://doi.org/10.1016/j.scitotenv.2022.153781

Schoonhoven LM, Jermy T, van Loon JJA, 1998. Insect-Plant Biology. Springer International Publishing, Berlin/Heidelberg, Germany.

Seidl R, Rammer W, 2017. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. Landscape Ecology, 32: 1485–1498. https://doi.org/10.1007/s10980-016-0396-4

Singh R, Agarwal RA, 1988. Role of chemical components of resistant and susceptible genotypes of cotton and okra in ovipositional preference of cotton leafhopper. Proceedings of the Animal Sciences, 97: 545–550. https://doi.org/10.1007/BF03179556

Six DL, Bracewell R, 2015. Dendroctonus. In: Vega FE, Hofstetter RW (eds) Bark beetles: biology and ecology of native and invasive species. Academic Press, London, pp 305–350.

Solar A, Colarič M, Usenik V, Stampar F, 2006. Seasonal variations of selected flavonoids, phenolic acids and quinones in annual shoots of common walnut (Juglans regia L.). Plant Science, 170(3): 453–461. https://doi.org/10.1016/j.plantsci.2005.09.012

Sullivan BT, 2016. Chapter Four—Semiochemicals in the natural history of southern pine beetle Dendroctonus frontalis Zimmermann and their role in pest management. Advances in Insect Physiology, 50: 129–193. https://doi.org/10.1016/bs.aiip.2015.12.002

Szmigielski R, Cieslak M, Rudziński KJ, Maciejewska B, 2012. Identification of volatiles from Pinus silvestris attractive for Monochamus galloprovincialis using a SPME-GC/MS platform. Environmental Science and Pollution Research, 19: 2860–2869. https://doi.org/10.1007/s11356-012-0792-5

Tao YZ, Hardy A, Drenth J et al, 2003. Identifications of two different mechanisms for sorghum midge resistance through QTL mapping. Theoretical and Applied Genetics, 107: 116–122. https://doi.org/10.1007/s00122-003-1217-0

USDA, 2020. Major forest insect and disease conditions in the United States: 2018. FS-1155. United States Department of Agriculture: Forest Service.

Venäläinen M, Harju AM, Saranpää P et al, 2004. The concentration of phenolics in brown-rot decay resistant and susceptible Scots pine heartwood. Wood Science and Technology, 38: 109–118. https://doi.org/10.1007/s00226-004-0226-8

Wallin K, Raffa K, 2004. Feedback between individual host selection behavior and population dynamics in an eruptive herbivore. Ecological Monographs, 74: 101–116.

Willför S, Hemming J, Reunanen M et al, 2003. Lignans and lipophilic extractives in Norway spruce knots and stemwood. Holzforschung, 57: 27–36. https://doi.org/10.1515/HF.2003.005

Wood DL, 1982. The role of pheromones, kairomones, and allomones in the host selection and colonization behavior of bark beetles. Annual Review of Entomology, 27: 411–446. https://doi.org/10.5558/tfc86

Woods AJ, Heppner D, Kope HH et al, 2010. Forest health and climate change: a British Columbia perspective. Forestry Chronicle, 86: 412–422.

Yan J, Lipka AE, Schmelz EA, Buckler ES, Jander G, 2014. Accumulation of 5-hydroxynorvaline in maize (Zea mays) leaves is induced by insect feeding and abiotic stress. Journal of Experimental Botany, 66: 593–602. https://doi.org/10.1093/jxb/eru385

Yolla Margaretha, Popo Suryana, (2023). The Effect of Market Orientation, Entrepreneurial Orientation, and Learning Orientation on Marketing Innovations and their Implications on the Marketing Performance of Micro Actors in Bandung Metropolitan Area. *Pakistan Journal of Life and Social Sciences.* E-ISSN: 2221-7630; P-ISSN: 1727-4915, Pak. j. life soc. Sci. (2023), 21(1): 478-498. https://www.pjlss.edu.pk/pdf_files/2023_1/478-498.pdf

Zyoud, O. (2021b). Attitudes of BA Students in the Faculty of Engineering and Information Technology in the Arab American University in Palestine towards carrying out online Projects in Courses during the Coronavirus Crisis*. International Journal of All Research Education and Scientific Methods*, 9(5), 115-230.