

A REVIEW ON THE STRATEGIES FOR BARK BEETLE MANAGEMENT

Muhammad Sajad^{1*} , Rubab Athar², Sheeraz Malik³, Amir Mughal⁴, Usman Aziz⁵ ,
Humayun Raza¹ , Abdul Rehman¹ , Iftikhar Ali¹ 

¹Department of Plant Breeding and Genetics, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan.

²Institute of Forest Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan.

³Department of Forestry and Range Management, Faculty of Agricultural Sciences and Technology, Bahauddin Zakaria University, Multan, Punjab, Pakistan.

⁴Forestry and Wildlife Department, Lahore Government of the Punjab, Pakistan.

⁵National Cotton Breeding Institute, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan.

Submitted December 3, 2025; Revised March 7, 2026; Accepted March 13, 2026; Published July 20, 2026

ABSTRACT

Global forest decline has accelerated as a result of climate change's increasing sensitivity to forest ecosystems. Bark beetle outbreaks have grown to be a serious biotic hazard over the last century, resulting in extensive tree death. None of the management techniques intended to lower tree mortality and mitigate bark beetle populations have been successful. Furthermore, altered disturbance regimes, driven by a changing climate, have facilitated successful bark beetle attacks, characterized by shorter and multivoltine life cycles. This has resulted in more frequent tree mortality attributed to bark beetles. This paper looks at the dynamics of bark beetle populations in relation to forest stand dynamics, climate change, and different forest management techniques. These varied, cutting-edge approaches have the potential to successfully handle the difficulties of controlling bark beetles and enhancing forest health in reaction to climate change.

Keywords: Review, Strategies, Bark beetle, Management.

*Corresponding Author. E-mail: m.sajad@iub.edu.pk

INTRODUCTION

A change in the climate over the last few decades has made strong windstorms and droughts more frequent, which has encouraged the formation and spread of insect epidemics. Bark beetles are found all over the world, and in the Northern

Hemisphere, several species are responsible for the widespread death of important tree species. For instance, by breaking down dead and dying trees, the Eurasian spruce bark beetle (*Ips typographus*, L.) contributes significantly to forest succession and nutrient

PST is published by AMMANIP Publisher. The authors retain the copyright without restriction. This article is an open access article published under the terms and conditions of [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).



recycling. However, they can cause extensive forest death once their population density reaches epidemic proportions. Beyond their effects on the economy, these outbreaks have disrupted nutrient cycle and forest succession, transforming forests from carbon sinks to sources [1-6]. As the primary host for bark beetle and a major tree species in Eurasian boreal forests, Norway spruce (*Picea abies*) is highly vulnerable to rising temperatures. From 1970 to 2010, frequent drought events and heatwaves led to unprecedented Norway spruce mortality, resulting in an average annual loss of up to 14 million m³, with a staggering 118 million m³ lost in 2019 alone. Furthermore, its primary pest, bark beetle, has benefited from warming temperatures, which has accelerated and extended brood development and led to earlier swarming. The two main goals of bark beetle management are containment and prevention. By removing infected trees, using traps, and clearing fallen trees, prevention tactics seek to maintain beetle populations at low levels. In order to stop or slow the spread of outbreaks, containment measures include salvage and sanitation logging at or near disease areas. However, the efficacy of present management techniques is sometimes questioned because they are frequently insufficient. Therefore, it is critical to investigate novel approaches to bark beetle control that make use of methods developed from functional genomics [7-11]. The usefulness and effectiveness of such molecular methods for controlling bark beetles are highlighted in this paper. These molecular techniques are designed to target particular species, in contrast to many traditional pest management strategies. However, more research and functional validation are needed for bark beetle management [12-15]. There are still a lot of unanswered questions about the primary causes of bark beetle outbreak dynamics and effective

management techniques, even after a century of intensive research on the insect. Furthermore, the latest developments in bark beetle control methods are not well explained. Here, we give a quick summary of bark beetle ecology and population dynamics and talk about the main causes of outbreaks in light of climate change. We talk about various species of eruptive bark beetles while concentrating on bark beetle. We first investigate how temperature regimes impact bark beetle activity, how droughts and water stress impact host tree physiology and vigor, and how changes in forest structure impact initial host colonization and spread. We analyze current management approaches and their efficacy in protecting forests, and we suggest cutting-edge molecular-based approaches to address new challenges that could guide future forest management practices in the Anthropocene.

The bark beetle is a relatively small insect (4.5–5 mm) that exhibits sexual dimorphism. This species is typically univoltine (producing one generation per year) but can become polyvoltine (producing more than two generations per year) in response to warm temperatures, which accelerate development [16-20]. During its endemic phase, bark beetle infests mature trees that are already stressed and weakened by various biotic or abiotic factors such as high temperatures, drought, disease, or herbivory. These beetles are associated with a variety of microbial symbionts, including bacteria and ophiostomoid fungi, which play a significant role in overcoming tree defenses. After then, they scatter, moving anywhere from 100 meters to tens of kilometers in quest of an appropriate host tree. Bark beetles and host trees typically have complex interactions that are shaped by a variety of factors at different temporal and geographical scales. Density-dependent host colonization behavior is also displayed by bark beetle. Beetle populations depend on wind-thrown, dead, or weakened

trees during the endemic period. They do, however, infect healthy trees during the epidemic phase. We shall go over these elements in relation to the population dynamics of bark beetle [21-24].

THE CURRENT AND POTENTIAL FUTURE MANAGEMENT PRACTICES

A variety of techniques are used in bark beetle management tactics. Usually, wind thrown trees and those freshly afflicted with bark beetle are removed first. While techniques like remote sensing and canine detection are used for early detection and minimizing attack damage, anti-attractants or trap trees are frequently used to reduce beetle populations. Additionally, the use of contemporary molecular technologies to manage forest pests is being researched. This section will cover cutting-edge molecular techniques (Sterile Insect Technique (SIT), Clustered Regularly Interspaced Short Palindromic Repeats/Cas9 (CRISPR/Cas9), and RNA interference (RNAi)), as well as conventional approaches (salvage and sanitation harvesting, pheromone or trap-tree use, short-rotation forestry) [25-27].

Optimizing Forest Composition

Rapid population and economic growth are placing increasing pressure on forests to supply wood and related products. Consequently, vast

areas globally are being cleared and converted into plantation forests to meet this demand. The intended purposes of plantation forests vary, and species are chosen accordingly. Monocultures, which emerged in Europe during the 18th and 19th centuries to address timber scarcity and achieve high-quality products, are a common example. For instance, Norway spruce, known for its rapid growth and favorable timber characteristics, was extensively harvested across much of Europe [28-34]. However, frequent drought events now threaten these harvesting plantations. A significant increase in spruce mortality in Europe between 1970 and 2019 was partly attributed to frequent droughts and heatwaves. Alterations in forest structure and composition accounted for approximately half of the documented increase in bark beetle outbreaks during this period. Furthermore, monocultures compromise essential ecosystem services such as carbon sequestration, water regulation, and habitat provision. This is because a greater number of species with diverse functional traits can collectively contribute to a wider range of ecological functions. Beyond the deliberate cultivation of Norway spruce outside its native range, increased growing stocks and altered age-class distributions have also significantly heightened the susceptibility of spruce forests to bark beetle attacks.



Figure 1: Strategies for bark beetle management.

In response to monoculture forest diebacks, increasing tree diversity and age classes has been tested and recommended to enhance forest resilience against biotic and abiotic disturbances. Empirical evidence strongly suggests that planting multiple species offers numerous environmental, economic, and social benefits. Careful selection of species in mixed plantations can promote complementary structural and functional traits, making mixed plantations a more favorable strategy than monocultures. Improved canopy coverage, which lowers solar radiation reaching the forest floor and may lessen ground-level evaporation, is another benefit of including trees of different age classes in mixed forests [35–41]. There are two primary reasons for the claim that promoting tree species diversity reduces the likelihood of bark beetle infestation. First, as was mentioned, mixed forests are more resilient to storm damage and windthrow, two major causes of bark beetle epidemics. Furthermore, a wide variety of tree species support a number of bark beetle natural enemies, such as parasitoids, diseases, and predators, which reduce bark beetle populations. Second, bark beetles rely on multiple cues—olfactory, gustatory, and visual—for host selection, enabling them to discriminate, for instance, defensively compromised trees. However, in mixed forests, these cues may be masked by diverse volatile emissions from non-host trees during host selection. These data highlight how crucial species richness is for reducing bark beetle infestation. However, even when the percentage of host plants in the stand is less than 40%, the richness of tree species simply suppresses bark beetle outbreaks, not prevents them. To completely understand the impact of non-host volatiles on beetle infestation dynamics, more data from field research using choice bioassays are still required [42–46].

Reduction of Rotation Periods

Norway spruce forests in many European regions often have rotation periods exceeding 100 years. This results in extensive forest

areas that are particularly vulnerable to disturbances from wind and bark beetles. For instance, in Slovakia, less than a quarter of Norway spruce trees reached 100 years of age between 1998 and 2009. Due to these vulnerabilities, shortening rotation periods can be an effective adaptation strategy against increasing bark beetle pressures. The optimal rotation period varies based on the forest management system, site productivity, and species mix. Therefore, forest managers should determine the appropriate rotation length considering regional conditions. However, reducing the rotation period might also decrease biodiversity and the amount of carbon stored in forests [47–53].

Early Detection

Detection Dogs

A successful forest protection strategy requires the rapid detection of bark beetle infestations and the removal of recently infested trees. However, human detection typically necessitates close inspection (≤ 1 m) of trees, which is time-consuming, costly, and not always feasible. Consequently, aerial detection of infested trees usually occurs 2–3 months after an infestation, once tree crown color fades and bark begins to fall off. By this point, most bark beetles have already departed the infested trees and may have targeted healthy ones [54–58]. Trained detection dogs offer an effective alternative for locating infested trees. Their primary advantages are an incredible sense of smell and the ability to rapidly cover large areas. Reports indicate that trained sniffer dogs can locate infested trees up to 150 meters away. This capability extends the window for finding and removing infested trees, potentially preventing larger infestations from developing. A limitation, however, is that detection dogs are not suitable for very large or remote areas.

Remote Sensing of Forests

In huge, inaccessible areas, it is still difficult to collect accurate and up-to-date spatial data

on bark beetle infestations. Research groups in North America and Europe have recently concentrated on spatiotemporal assessments of the dynamics of bark beetle populations. Forest managers will probably have to deal with frequent and large infestations, which calls for effective instruments for quick and accurate evaluation of the dynamics and spread of insect outbreaks. Planning protective and hygienic measures (e.g., pheromone or tree trapping) to restrict or limit epidemic intensity requires accurate, current spatial information on bark beetle outbreaks, such as the locations of dead trees. Forest structure plays a major role in identifying and mapping tree death brought on by bark beetle outbreaks. For example, it is quite easy to identify and track forest stands that are exclusively made up of coniferous host species. Since bark beetles mostly target trees that are next to those that have already died, new dead trees in these stands usually emerge in big, obvious clusters. However, in mixed forest systems, which are mosaics of different stands with mixed tree species where typical host species occur in smaller, dispersed groups or as individual trees, identifying individual diseased trees becomes more challenging. It can be difficult to identify individual affected trees under these circumstances, and since fieldwork is expensive, remote sensing (RS) techniques provide a useful substitute and addition to field surveys [59-61]. Insect outbreaks and other forest disturbances have been successfully mapped using multispectral aerial and satellite data in conjunction with artificial intelligence and machine learning. For instance, at the start of the growth season, before new attacks, Enhanced Vegetation Index (EVI) and Visible Atmospherically Resistant Index (VARI) imaging showed notable spectral variations between healthy and stressed trees (e.g., due to dryness). These findings demonstrate the potential for early pest

detection and forest ecosystem management using spectral vegetation indices (SVIs) obtained from high-resolution multispectral photography.

To estimate tree health characteristics, we can use a variety of RS data and sources. Sensor technologies based on satellites or airplanes (such as unmanned aerial vehicles) are commonly used in remote sensing. Both active (like LIDAR) and passive (like multi- and hyperspectral sensors) sensors can be utilized in forestry, especially for analyzing the spectral characteristics of trees. The latest techniques for utilizing, processing, and evaluating RS in identifying tree propensity incorporate multitemporal GIS analysis based on hyperspectral and airborne laser scanning data along with sensor data. In order to identify significant forest disturbances in bark beetle outbreak areas and dead trees in the red and grey attack stages, hyperspectral and aerial laser scanning data are frequently utilized. About six to eight months after the infestation begins, infected trees start to show signs of a color shift in their foliage. The progressive loss of moisture and the breakdown of pigments within the foliage are the causes of this change in the crown from green to yellow to red. The "red-attack" and "grey-attack" phases are the names given to these discrete stages of color shift. We may better understand the dynamics of bark beetle outbreaks by analyzing red and grey attack data. By adding more information, such as environmental parameters (temperature, wind speed, precipitation), we can identify the most important causes of these outbreaks. The output data accessible for analysis, particularly from prominent dominating trees in the first forest layer, limits the capacity to identify all attacked trees. The misidentification of dead trees as living ones because of reflection from lower forest layers presents another difficulty. Similarly, the availability of ground truth data is necessary for the early detection of trees afflicted by

bark beetles. However, gathering ground truth data is frequently time-consuming and limited to locations that field teams can reach. Additionally, because of changes in the foliar color of spruce trees at the start of the season, early-attacked trees are challenging to detect with remote sensing when surrounding stressed plants are present. The amount of processing power needed to analyze enormous amounts of data is another drawback.

Pheromone Traps

Various trapping techniques, including sanitation felling and removal of windthrown trees, have been widely employed in bark beetle management. Pheromone traps are used to monitor beetle populations or to reduce their numbers below outbreak density through mass-trapping. This approach utilizes pheromone trap barriers to lower the bark beetle population to a level where trees can successfully defend against attacks. To attract beetles, trapping methods include employing log traps or trap trees baited with pheromones or host substances unique to the species. Beetles can be removed by removing the infected trees or logs or by using insecticides once they have been attracted. However, there is little scientific proof that trap trees can successfully lower beetle populations or the amount of trees that are attacked. Research on the effectiveness of trapping methods, especially in large-scale applications, in lowering epidemic risks and damage rates is also lacking. While pheromone traps typically capture only 3–10% of beetle populations at a relatively high cost, integrating pheromone trap barriers into a forest protection system can significantly reduce tree mortality. Despite this, the relatively high labor costs have led to the discontinuation of pheromone trap use in Scandinavia and most parts of Germany and France. The "spillover effect," in which commercial pheromones draw more beetles than the traps can manage, further restricts the use of pheromone traps for mass trapping by

causing assaults on nearby trees. Therefore, rather than population reduction and outbreak control, the major goal of such traps should continue to be population monitoring. With novel attractant mixes, pheromone trap barriers could be further improved.

Anti-Attractants

Anti-attractants are semiochemicals that disrupt pest host-finding behavior by emitting repelling signals or masking attractive host signals. This protects trees from pest colonization. For bark beetle, several anti-attractant compounds have been identified. Verbenone, derived from the host compound α -pinene or converted from bark beetle main pheromone component cis-verbenol, is a notable example. A second group consists of non-host volatiles (NHVs), including: trans-conophthorin, a synergistic compound found in broad-leaf tree bark; Green leaf volatiles (GLVs) like 1-hexanol, (Z)-3-hexen-1-ol, and 1-2-hexen-1-ol, detected in non-host birch and aspen (*Populus tremula*); and C8 alcohols (3-octanol; 1-octen-3-ol), emitted from the bark of these species. Despite these advances, anti-attractants have not successfully prevented bark beetle attacks, including those by bark beetle, on logs or fallen trees. Currently, the most promising defense for standing spruce trees against bark beetle involves dispensers containing a blend of verbenone and NHV compounds. A recent study observed a strong "switching effect," where beetles were pushed from areas with anti-attractants into unprotected areas [62-64]. Additionally, there was no change in the performance of anti-attractant dispensers installed at different tree heights, indicating that they are useless in regions that are severely impacted by drought and high bark beetle populations. It's interesting to note that (+)-trans-4-thujanol repelled female bark beetle just as successfully as well-known anti-attractants as verbenone and 1,8-cineole, making it a novel compound for forest preservation. The push-pull technique, which combines appealing and

repellent semiochemicals, can lower bark beetle and *Dendroctonus* populations by 66% and 54%, respectively, in comparison to controls, according to a recent meta-analysis.

Genetic Approaches

Genetic Information

Rapid climate change has led to an increase in the frequency and intensity of drought events in forests globally. Trees can adapt to these new disturbance regimes at a local, genetic level, with significant selection pressure favoring tolerant phenotypes. For instance, Norway spruce responds to shade by increasing lignin synthesis and expressing defense-related genes, which may enhance its resistance to pest attacks. Heat shock proteins, catalase enzymes, signaling factors (transcription factors and protein kinases), and heat stress factors are all involved in trees' reactions to heat stress. On the other hand, dehydration responsive element binding proteins shield trees from osmotic stress, whereas ascorbate peroxidase and histidine kinases reduce reactive oxygen species under heat stress. Stomatal closure and cuticular wax on needle surfaces can minimize water loss, according to conifer studies that look at spatial and differential gene expression. In comparison to irrigated saplings, cuticular wax and the genes involved in its synthesis were found to be overexpressed in non-irrigated maritime pine (*Pinus pinaster*) and Norway spruce saplings [65, 66]. With advancements in molecular techniques and high-throughput sequencing, molecular tools for pest management, particularly gene targeting, have become widely popular. Since the identification of the cry gene in the 1980s—one of the first unique genes used in genetically modified (GM) crops to combat insect pests—various genes have been employed in agricultural pest management. However, these advancements are still in their early stages for forest applications, limited by factors such as tree size, density, and the challenges of stand-

level application. As a result, research turned to genetic alterations at the insect level, resulting in methods such as the sterile insect technique, CRISPR and RNA interference (RNAi) gene silencing, and other pre- and post-translation level modifications. Breeding bark beetle-resistant trees, diagnosing tree health issues, and protecting forests can all benefit from the identification of genetic markers for tree resistance.

CRISPR/Cas9

Clustered regularly interspaced short palindromic repeats/Cas9 (CRISPR/Cas9) is a groundbreaking genome editing tool that has been widely utilized in numerous studies. This gene editing technology allows for the alteration of an organism's DNA. In the CRISPR/Cas system, CRISPR refers to DNA sequences found in prokaryotic organisms (e.g., bacteria and archaea), while Cas9 is an enzyme that uses these CRISPR sequences as a guide to locate and cleave specific DNA strands. By attaching to and cleaving the target DNA, the Cas9 enzyme deactivates the targeted gene. This process, known as gene "knock-out," is a reliable method for identifying genes of interest or gaining deeper insights into genome complexities. CRISPR is considered a more intuitive and user friendly technology because it requires only a single guide RNA (gRNA) for target identification and the Cas9 nuclease for implementation. A common derivative employs a single chimeric guide RNA (sgRNA) to recognize and bind to the intended target sequence, alongside a CRISPR-associated (Cas) nuclease that cleaves DNA at specific locations by creating site-specific double-strand breaks. Plasmid DNA, RNA, or ribonucleoprotein complexes (RNPCs) are some of the delivery methods that can be used to introduce the CRISPR/Cas components (sgRNA and Cas9 protein) into the target organism. The capacity of CRISPR/Cas9 to cause long lasting and heritable genomic changes gives it an

advantage over RNA interference (RNAi), which usually only has temporary effects unless a steady supply of double-stranded RNA (dsRNA) is maintained. Although CRISPR technology has the potential to completely transform pest management, it is crucial to carefully weigh its benefits and drawbacks. The red flour beetle (*Tribolium castaneum*) and the Colorado potato beetle (*Leptinotarsa decemlineata*) are the only coleopteran insects where CRISPR/Cas9 has been used, despite the fact that it has been applied to a variety of insect species [66, 67].

RNA Interference

By interfering with mRNA breakdown and protein synthesis, insects use RNA interference (RNAi), a conserved biological mechanism, to decrease gene function. Short RNA molecules are used in this process to target and break down particular messenger RNA (mRNA) sequences, stopping the synthesis of the proteins those genes encode. Insects eventually die when genes essential to their existence are silenced. MicroRNA (miRNA), piwiRNA (piRNA), and small interfering RNA (siRNA) are the three different RNA interference processes that have been discovered. For controlling insect pests, the siRNA pathway has received the greatest attention. The siRNA machinery is activated when double-stranded RNA (dsRNA) is successfully delivered into a cell. The enzyme Dicer-2 (ribonuclease type III) then converts the dsRNA into siRNAs (approximately 21–24 base pairs), which are subsequently integrated into the RNA-induced silencing complex (RISC). Argonaute2 eventually cleaves and removes the sense strand of the siRNA. The remaining antisense strand then guides the RISC to target and degrade complementary mRNA sequences, leading to post-transcriptional gene silencing. This sequence-specific RNAi mechanism can be leveraged to effectively target vital genes in insects, including bark

beetles, offering a promising avenue for pest management.

Biological Control Agents

Natural Enemies

Biological control aims to suppress insect pests by introducing naturally occurring antagonists, providing sustainable and ecofriendly pest management. Natural enemies such as predators, parasites, and parasitoids significantly influence the population dynamics and ecology of bark beetles. A wide array of antagonists target bark beetles, including those from the orders Hymenoptera, Coleoptera (beetles), Diptera (flies), Heteroptera (true bugs), Raphidioptera (snakeflies), and Acari (mites). Predators of bark beetles are very varied and can eat them at any stage of life, from eggs to adults, which has a big effect on population dynamics. Only a small number of predator species actively hunt eggs, larvae, pupae, and/or adults, despite the fact that many predator species are linked to bark beetle galleries. The majority of predators that hunt bark beetles are members of the Coleoptera order, which includes Rhizophagidae, Trogossitidae, and Cleridae. The checkered beetles (Cleridae) are the most prominent coleopteran predators of bark beetles. *Thanasimus dubius* (F.) from North America and *Thanasimus formicarius* (L.) from Europe are two early-season predatory species that belong to this tiny family. Shortly after bark beetles arrive at afflicted trees, clerid beetles feed directly on the surface of the bark.

One of the most researched predators of bark beetle is *Thanasimus formicarius*. While larvae can eat up to 50 bark beetle larvae during their growth, females lay about 100 eggs, and adults can eat up to three bark beetles daily. Trogossitids are thought to be more specialized predators than clerid beetles, which are often regarded as generalist predators. *Temnochila virescens*, for example, predominantly reacts to

attractants produced by *Ips* species, and its larvae feed on the pupae and larvae of bark beetles in the phloem of the tree. On the other hand, adult *Temnochila* species eat adults of different species of bark beetles. Additionally, the dynamics of bark beetle populations are significantly influenced by parasitoids. Usually, parasitoids favor a certain stage of their host's development. The order Hymenoptera, which includes Braconidae and Pteromalidae, is home to the majority of parasitoids linked to Scolytids. Each parasitoid larva usually eats one beetle larva or pupa, and they can attack bark beetles at different phases of development. *Coeliodes bostrichorum*, which seems to be only connected to bark beetle species that nest in Norway spruce, is the most successful parasitoid of bark beetle [68-70]. Potential enemies of bark beetle include wasps, ants, birds, shrews, mites, and infections like viruses and microsporidia. However, more research is needed to determine how they affect the dynamics of bark beetle populations.

Sterile Insect Technique

The sterile insect technique (SIT) involves releasing a large number of sterile male insects into a target area. These males mate with wild females, producing non-viable offspring and subsequently lowering pest population densities in the next generation. When sex differentiation is impossible, releasing both sterile sexes can enhance the procedure's success and help maintain pest populations below epidemic thresholds. SIT relies on irradiating insects using gamma radiation from isotopic elements (cobalt-60 or cesium-137), high energy electrons, and X-rays [70, 71]. Precise management of the radiation dose is crucial to sterilize reproductive cells effectively while ensuring the insects remain viable enough to compete for mates. Radiation can damage insect sex cells by causing chromosome fragmentation (dominant lethal mutation, translocations, and/or chromosomal

aberrations), leading to unbalanced gametes. The development of fertilized eggs and embryos is hampered by this mechanism, which also prevents mitosis. Higher dosages of gamma radiation shorten the lifetime of both sexes, according to studies on two lepidopteran pests (*Ostrinia nubilalis* and *Phyllocnistis citrella*), while F1 larval emergence was biased towards males. Agricultural insect pests like the pepper weevil (*Anthonomus eugenii*), sweet potato weevil (*Cylas formicarius*), and bark beetle have demonstrated the efficacy of SIT. Although SIT is a cost effective, sustainable, and efficient method, there is currently a barrier to its widespread application in large scale field scenarios.

CONCLUSION

For the management and preservation of ecosystems, it is essential to comprehend the mechanisms behind bark beetle infestation and outbreak dynamics at different geographical scales. Even though bark beetle outbreaks have serious negative effects on the environment and the economy, existing control methods frequently fail to stop their spread. Bark beetle management will continue to benefit from current techniques including pheromone and tree traps, anti-attractants, remote sensing, and dog detection of affected trees, particularly in light of climate change. To control bark beetles in forest management, however, more methods are required and may eventually replace some of the current procedures. These include CRISPR/Cas9-based methods, symbiont-mediated RNAi, nanoparticle-coated RNAi complexes, and SIT. While these novel approaches have shown great success in controlling agricultural pests, their application in forest pest management, particularly for bark beetles, remains relatively underexplored. This is due to various challenges, including the availability of sequenced genomes, difficulties in rearing beetles on artificial diets, and obtaining viable eggs for injection.

Author(s) Contribution: Concept, A. Usman and R. Humayun; supervision, R. Abdul and A. Iftikhar; data collection and analysis, A. Rubab Athar and M. Sheeraz; concept, M. Amir; review and proof-reading, M. Sajad.

Funding: No funding involved.

Ethical Approval: Not applicable

Conflict of Interest: Nil.

Consent for Publication: All authors approved the manuscript for publication.

REFERENCES

1. Boone CK, Aukema BH, Bohlmann J, Carroll AL, Raffa KF (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>
2. Candotti A, De Giglio M, Dubbini M, Tomelleri E (2022) A Sentinel-2 based multi-temporal monitoring framework for wind and bark beetle detection and damage mapping. *Remote Sens* 14:6105. <https://doi.org/10.3390/rs14236105>
3. Ashraf MZ, Mogilicherla K, Sellamuthu G, Siino V, Levan- der F, Roy A (2023) Comparative gut proteomics study revealing adaptive physiology of Eurasian spruce bark beetle, *Ips typographus* (Coleoptera: Scolytinae). *Front Plant Sci*. <https://doi.org/10.3389/fpls.2023.1157455>
4. Bakri A, Mehta K, Lance DR, Dyck VA, Hendrichs J, Robin- son AS (2021) Sterilizing insects with ionizing radiation. *Sterile Insect Tech Princ Pract Area-Wide Integr Pest Manag*. https://doi.org/10.1007/1-4020-4051-2_9
5. Balanyá J, Oller JM, Huey RB, Gilchrist GW, Serra L (2006) Global genetic change tracks global climate warming in *Drosophila subobscura*. *Science* 313:1773–1775. <https://doi.org/10.1126/science.1131002>
6. Carnol M, Baeten L, Branquart E, Grégoire JC, Heughebaert A, Muys B, Ponette Q, Verheyen K (2014) Ecosystem services of mixed species forest stands and monocul- tures: comparing practitioners' and scientists' percep- tions with formal scientific knowledge. *Forestry* 87:639– 653. <https://doi.org/10.1093/forestry/cpu024>
7. Christiaens O, Sweet J, Dzhambazova T, Urru I, Smag- ghe G, Kostov K, Arpaia S (2022) Implementation of RNAi-based arthropod pest control: environmental risks, potential for resistance and regulatory consid- erations. *J Pest Sci* 95:1–15. <https://doi.org/10.1007/s10340-021-01439-3>
8. Blaženec M, Majdák A, Jakuš R (2021) Improvement of *Ips typographus* catches in pheromone trap barriers by altering of sex assigned pheromone blends. *Folia Oecol* 48(1):25–34. <https://doi.org/10.2478/foecol-2021-0003>
9. Devos Y, Mumford JD, Bonsall MB, Camargo AM, Firbank LG, Glandorf DCM et al (2022) Potential use of gene drive modified insects against disease vectors, agricul- tural pests and invasive species poses new challenges for risk assessment. *Crit Rev Biotechnol* 42:254–270. <https://doi.org/10.1080/07388551.2021.1933891>
10. Diallo S, Seck MT, Rayaissé JB, Fall AG, Bassene MD et al (2019) Chilling, irradiation and transport of male *Gloss- ina palpalis gambiensis* pupae: effect on the emergence, flight ability and survival. *PLoS ONE* 14(5):e0216802. <https://doi.org/10.1371/journal.pone.0216802>
11. Egan JM, Jacobi WR, Negron JF, Smith SL, Cluck DR (2010) Forest thinning and subsequent bark beetle- caused mortality in Northeastern California. *For Ecol Manag* 260:1832-1842. <https://doi.org/10.1016/j.foreco.2010.08.030>
12. Sousa M, Birgersson G, Karlsson Green K, Pollet M, Becher PG (2023) Odors attracting the long-legged predator *Medetera signaticornis* Loew to *Ips typographus* L infested Norway spruce trees. *J Chem Ecol*. <https://doi.org/10.1007/s10886-023-01405-6>
13. Sun D, Guo Z, Liu Y, Zhang Y (2017) Progress and prospects of CRISPR/Cas systems in insects and other arthropods.

- Front Physiol 8:608. <https://doi.org/10.3389/fphys.2017.00608>
14. Thomas A, Kolb T, Biederman J, Venturas MD, Ma Q, Yang D, Dore S, Tai X (2024) Mitigating drought mortality by incorporating topography into variable forest thinning strategies. *Environ Res Lett* 19:034035. <https://doi.org/10.1088/1748-9326/ad29aa>
 15. Yan G, Yang J, Li W, Guo A, Guan J, Liu Y (2023) Genome-wide CRISPR screens identify ILF3 as a mediator of mTORC1-dependent amino acid sensing. *Nat Cell Biol* 25:754–764. <https://doi.org/10.1038/s41556-023-01123-x>
 16. Erbilgin N (2019) Phytochemicals as mediators for host range expansion of a native invasive forest insect herbivore. *New Phytol* 221:1268–1278. <https://doi.org/10.1111/nph.15467>
 17. Faccoli M, Stergulc F (2004) *Ips typographus* (L.) pheromone trapping in south Alps: spring catches determine damage thresholds. *J Appl Entomol* 128:307–311. <https://doi.org/10.1111/j.1439-0418.2004.00848.x>
 18. Guevara-Rozo S, Hussain A, Cale JA, Klutsch JG, Rajabzadeh R, Erbilgin N (2020) Nitrogen and ergosterol concentrations varied in live jack pine phloem following inoculations with fungal associates of mountain pine beetle. *Front Microbiol* 11:1703. <https://doi.org/10.3389/fmicb.2020.01703>
 19. Huo L, Lindberg E, Bohlin J, Persson HJ (2023) Assessing the detectability of European spruce bark beetle green attack in multispectral drone images with high spatial and temporal resolutions. *Remote Sens Environ* 15:113484. <https://doi.org/10.1016/j.rse.2023.113484>
 20. Ikegawa Y, Ito K, Himuro C, Honma A (2021) Sterile males and females can synergistically suppress wild pests targeted by sterile insect technique. *J Theor Biol* 530:110878. <https://doi.org/10.1016/j.jtbi.2021.110878>
 21. Jactel H, Brockerhoff EG (2007) Tree diversity reduces herbivory by forest insects. *Ecol Lett* 10:835–848. <https://doi.org/10.1111/j.1461-0248.2007.01073.x>
 22. Jamali S, Olsson PO, Ghorbanian A, Müller M (2023) Examining the potential for early detection of spruce bark beetle attacks using multi-temporal Sentinel-2 and harvester data. *ISPRS J Photogramm Remote Sens* 1:352–366. <https://doi.org/10.1016/j.isprsjprs.2023.10.013>
 23. Cochard H, Hölttä T, Herbette S, Delzon S, Mencuccini M (2009) New insights into the mechanisms of water-stress-induced cavitation in conifers. *Plant Physiol* 151:949–954. <https://doi.org/10.1104/pp.109.138305>
 24. Dalponte M, Solano-Correa YT, Frizzera L, Gianelle D (2022) Mapping a European spruce bark beetle outbreak using sentinel-2 remote sensing data. *Remote Sens* 14:3135. <https://doi.org/10.3390/rs14133135>
 25. De Groot M, Diaci J, Ogris N (2019) Forest management history is an important factor in bark beetle outbreaks: lessons for the future. *For Ecol Manag* 433:467–474. <https://doi.org/10.1016/j.foreco.2018.11.025>
 26. Afzal S, Nahrung HF, Lawson SA, Hayes RA (2024) How effective are push-pull semiochemicals as deterrents for bark beetles? A global meta-analysis of thirty years of research. *InSects* 14:812. <https://doi.org/10.3390/insects14100812>
 27. Ahmad S, Shahzad R, Jamil S, Tabassum J, Chaudhary MA, Atif RM, Iqbal MM, Monsur MB, Lv Y, Sheng Z, Ju L (2021) Regulatory aspects, risk assessment, and toxicity associated with RNAi and CRISPR methods. In: *CRISPR and RNAi Systems*, Elsevier, pp 687–721. <https://doi.org/10.1016/B978-0-12-821910-2.00013-8>
 28. Biedermann PHW, Müller J, Grégoire JC, Gruppe A, Hage J, Hammerbacher A, Hofstetter RW, Kandasamy D, Kolarik M, Kostovcik M, Krokene P, Sallé A, Six DL, Turrini T, Vanderpool D, Wingfield MJ, Bässler C (2019) Bark beetle population dynamics in the anthropocene: challenges

- and solutions. *Trends Ecol Evol* 34:914–924. <https://doi.org/10.1016/j.tree.2019.06.002>
29. Joga MR, Zotti MJ, Smagghe G, Christiaens O (2016) RNAi efficiency, systemic properties, and novel delivery methods for pest insect control: what we know so far. *Front Physiol* 7:553. <https://doi.org/10.3389/fphys.2016.00553>
 30. Joga MR, Mogilicherla K, Smagghe G, Roy A (2021) RNA interference-based forest protection products (FPPs) against wood-boring coleopterans: Hope or hype? *Front Plant Sci* 12:733608. <https://doi.org/10.3389/fpls.2021.733608>
 31. Desprez-Loustau ML, Marçais B, Nageleisen LM, Piou D, Vannini A (2006) Interactive effects of drought and pathogens in forest trees. *Ann for Sci* 63:597–612. <https://doi.org/10.1051/forest:2006040>
 32. Abdullah H, Skidmore AK, Darvishzadeh R, Heurich M (2019) Sentinel-2 accurately maps green-attack stage of European spruce bark beetle (*Ips typographus* L.) compared with Landsat-8. *Remote Sens Ecol Conserv* 5:87–106. <https://doi.org/10.1002/rse2.93>
 33. Johansson AM, Birgersson G, Schlyter F (2019) Using synthetic semiochemicals to train canines to detect bark beetle-infested trees. *Ann Forest Sci* 76:262386. <https://doi.org/10.1007/s13595-019-0841-z>
 34. Kautz M, Schopf R, Imron MA (2014) Individual traits as drivers of spatial dispersal and infestation patterns in a host–bark beetle system. *Ecol Model* 273:264–276. <https://doi.org/10.1016/j.ecolmodel.2013.11.022>
 35. Kenis M, Wermelinger B, Grégoire JC (2007) Research on parasitoids and predators of Scolytidae—a review. In: *Bark and wood boring insects in living trees in Europe, a synthesis*. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-2241-8_11
 36. Lausch A, Fahse L, Heurich M (2011) Factors affecting the spatio-temporal dispersion of *Ips typographus* (L.) in Bavarian Forest National Park: a long-term quantitative landscape-level analysis. *For Ecol Manag* 261:233–245. <https://doi.org/10.1016/j.foreco.2010.10.012>
 37. Le Provost G, Domergue F, Lalanne C, Ramos Campos P, Grosbois A, Bert D, Meredieu C, Danjon F, Plomion C, Gion JM (2013) Soil water stress affects both cuticular wax content and cuticle-related gene expression in young saplings of maritime pine (*Pinus pinaster* Ait). *BMC Plant Biol* 13:1–12. <https://doi.org/10.1186/1471-2229-13-95>
 38. Aldea J, Dahlgren J, Holmström E, Löf M (2023) Current and future drought vulnerability for three dominant boreal tree species. *Glob Change Biol* 30:e17079. <https://doi.org/10.1111/gcb.17079>
 39. Alem S, Pavlis J, Urban J, Kucera J (2015) Pure and mixed plantations of *Eucalyptus camaldulensis* and *Cupressus lusitanica*: their growth interactions and effect on diversity and density of undergrowth woody plants in relation to light. *Open J for* 5:375–386. <https://doi.org/10.4236/ojf.2015.54032>
 40. Barrette J, Achim A, Auty D (2023) Impact of intensive forest management practices on wood quality from conifers: literature review and reflection on future challenges. *Curr for Rep* 9:101–130. <https://doi.org/10.1007/s40725-023-00181-6>
 41. Lefcheck J, Byrnes J, Isbell F, Gamfeldt L, Griffin JN, Eisenhauer N, Hensel M, Hector A, Cardinale BJ, Duffy E (2015) Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nat Commun* 6:6936. <https://doi.org/10.1038/ncomms7936>
 42. Hajek AE, Bauer LS (2009) Use of entomopathogens against invasive wood boring beetles in North America. In: Hajek AE, Glare TR, O’Callaghan M (eds) *Use of microbes for control and eradication of invasive arthropods*. Springer, Dordrecht, pp 159–179. <https://doi.org/10.1016/j.jip.2012.05.008>
 43. Hanson JJ, Lorimer CG (2007) Forest structure and light regimes following moderate wind storms: Implications for multi-cohort management. *Ecol Appl* 17:1325–1340. <https://doi.org/10.1890/06-1067.1>

44. Hedgren PO, Schroeder LM (2004) Reproductive success of the spruce bark beetle *Ips typographus* (L.) and occurrence of associated species: a comparison between standing beetle-killed trees and cut trees. *For Ecol Manag* 203:241–250. <https://doi.org/10.1016/j.foreco.2004.07.055>
45. Long JA, Lawrence RL (2016) Mapping percent tree mortality due to mountain pine beetle damage. *For Sci* 62:392–402. <https://doi.org/10.5849/forsci.15-046>
46. Meddens AJH, Hicke JA (2014) Spatial and temporal patterns of landsat-based detection of tree mortality caused by a mountain pine beetle outbreak in Colorado, USA. *For Ecol Manag* 322:78–88. <https://doi.org/10.1016/j.foreco.2014.02.037>
47. Muratoğlu H, Sezem K, Demirbağ Z (2011) Determination and pathogenicity of the bacterial flora associated with the spruce bark beetle, *Ips typographus* (L.) (Coleoptera: Curculionidae: Scolytinae). *Turk J Biol* 35:9–20. <https://doi.org/10.3906/biy-0902-12>
48. Nardi D, Bozzini A, Morgante G, Gaccione A, Finozzi V, Battisti A (2023) Participatory ground data are complementary to satellite bark beetle detection. *Ann for Sci* 80:46. <https://doi.org/10.1186/s13595-023-01216-5>
49. Naseer A, Mogilicherla K, Sellamuthu G, Roy A (2023) Age matters: life-stage, tissue, and sex-specific gene expression dynamics in *Ips typographus* (Coleoptera: Curculionidae: Scolytinae). *Front for Glob Change*. <https://doi.org/10.3389/ffgc.2023.1124754>
50. Öhrn P, Långström B, Lindelöw Å, Björklund N (2014) Seasonal flight patterns of *Ips typographus* in southern Sweden and thermal sums required for emergence. *Agric for Entomol* 16:147–157. <https://doi.org/10.1111/afe.12044>
51. Hepper P, Wells D (2015) Olfaction in the order Carnivora: family Canidae. In: *Handbook of olfaction and gustation*. pp 591–604. <https://doi.org/10.1002/9781118971758.ch26>
52. Fares S, Mugnozza GS, Corona P, Palahí M (2015) Sustainability: five steps for managing Europe's forests. *Nature* 519:407–409. <https://doi.org/10.1038/519407a>
53. Raffa KF, Aukema BH, Bentz BJ, Carroll AL, Hicke JA, Turner MG, Romme WH (2008) Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *Bioscience* 58:501–517. <https://doi.org/10.1641/B580607>
54. Lubojacký J, Holuša J (2014) Attraction of *Ips typographus* (Coleoptera: Curculionidae) beetles by lure-baited insecticide-treated tripod trap logs and trap trees. *Int J Pest Manag* 60:153–159. <https://doi.org/10.1080/09670874.2014.944610>
55. Mann AJ, Davis TS (2021) Entomopathogenic fungi to control bark beetles: a review of ecological recommendations. *Pest Manag Sci* 77:3841–3846. <https://doi.org/10.1002/ps.6364>
56. Marini L, Ayres MP, Battisti A, Faccoli M (2012) Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle. *Clim Change* 115:327–341. <https://doi.org/10.1007/s10584-012-0463-z>
57. Li S, Kim DS, Zhang J (2023) Plastid-mediated RNA interference: a potential strategy for efficient pest control. *Plant Cell Environ*. <https://doi.org/10.1111/pce.14652>
58. Pawson SM, Brin A, Bockerhoff EG, Lamb D, Payn TW, Paquette A, Parrotta JA (2013) Plantation forests, climate change and biodiversity. *Biodivers Conserv* 22:1203–1227. <https://doi.org/10.1007/s10531-013-0458-8>
59. Perkin LC, Adrianos SL, Oppert B (2016) Gene disruption technologies have the potential to transform stored product insect pest control. *InSects* 7:46. <https://doi.org/10.3390/insects7030046>
60. Mat Jalaluddin NS, Othman RY, Harikrishna JA (2019) Global trends in research and commercialization of exogenous and endogenous RNAi technologies for crops. *Crit Rev Biotechnol* 39:67–78.

- <https://doi.org/10.1080/07388551.2018.1496064>
61. Rank AP, Koch A (2021) Lab-to-field transition of RNA spray applications—How far are we? *Front Plant Sci* 12:755203. <https://doi.org/10.3389/fpls.2021.755203>
 62. Ulrich H (2004) Predation by adult *Dolichopodidae* (Diptera): a review of literature with an annotated prey-predator list. *Studia Dipterologica*. 11(2):369–403
 63. Wiedenheft B, Sternberg SH, Doudna JA (2012) RNA-guided genetic silencing systems in bacteria and archaea. *Nature* 482:331–338. <https://doi.org/10.1038/nature10886>
 64. Xu L, Lou Q, Cheng C, Lu M, Sun J (2015) Gut-associated bacteria of *Dendroctonus valens* and their involvement in verbenone production. *Microb Ecol* 70:1012–1023. <https://doi.org/10.1007/s00248-015-0625-4>
 65. Ruel JC, Wermelinger B, Gauthier S, Burton PJ, Waldron K, Shorohova E (2023) Selected examples of interactions between natural disturbances. In: Girona MM, Morin H, Gauthier S, Bergeron Y (eds) *Boreal forests in the face of climate change: advances in global change research*, vol 74. Springer. https://doi.org/10.1007/978-3-031-15988-6_4
 66. Safonova A, Hamad Y, Alekhina A, Kaplun D (2022) Detection of Norway spruce trees (*Picea abies*) infested by bark beetle in UAV images using YOLOs architectures. *IEEE Access* 10:10384–10392. <https://doi.org/10.1109/ACCESS.2022.3144433>
 67. Safranyik L, Carroll AL (2007) The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. The mountain pine beetle: a synthesis of biology, management and impacts on lodgepole pine, 3–66. <https://www.cabdirect.org/cabdirect/abstract/20073248170>
 68. Fassnacht FE, Latifi H, Ghosh A, Joshi PK, Koch B (2014) Assessing the potential of hyperspectral imagery to map bark beetle-induced tree mortality. *Remote Sens Environ* 140:533–548. <https://doi.org/10.1016/j.rse.2013.09.014>
 69. Gao B, Yu L, Ren L, Zhan Z, Luo Y (2023) Early detection of *Dendroctonus valens* infestation at tree level with a Hyperspectral UAV image. *Remote Sens* 15:407. <https://doi.org/10.3390/rs15020407>
 70. Hinze J, John R (2020) Effects of heat on the dispersal performance of *Ips typographus*. *J Appl Entomol* 144:144–151. <https://doi.org/10.1111/jen.12718>
 71. Yoon JS, Mogilicherla K, Gurusamy D, Chen X, Cherreddy SC, Palli SR (2018) Double-stranded RNA binding protein, Staufin, is required for the initiation of RNAi in coleopteran insects. *Proc Natl Acad Sci* 115:8334–8339. <https://doi.org/10.1073/pnas.1809381115>