Ips sexdentatus (Six-Toothed Bark Beetle): A Comprehensive Review of Biology, Impact, Management, and Data Resources

I. Executive Summary

Ips sexdentatus, the six-toothed bark beetle, is a major conifer pest widely distributed across Europe and parts of Asia, with established populations in 24 EU Member States. While its primary hosts are pines (*Pinus* spp.), it also infests Oriental spruce (*Picea orientalis*) in Turkey, Georgia and Southern Russia and occasionally other conifers such as *Larix* and *Abies*. Depending on climate, the beetle produces between one and five generations annually, ranging from a single generation in northern latitudes to multiple in warmer Mediterranean regions. Outbreaks typically originate from wind-thrown or physiologically weakened trees, but under favorable conditions, pheromone-mediated mass attacks can overwhelm healthy hosts. Additionally, the species vectors pathogenic fungi that accelerate tree decline and mortality.

Integrated pest management (IPM) provides the most effective control framework. Core strategies include sanitation measures such as removal of infested, damaged, or fire-affected trees; thinning of dense stands to reduce stress; and, where suitable, the use of trap trees or debarking to prevent beetle emergence. Monitoring relies heavily on pheromone-baited traps using compounds such as ipsdienol, ipsenol, and 2-methyl-3-buten-2-ol to track population dynamics and optimize intervention timing. However, mass trapping has variable success and may affect non-target species, highlighting the need for careful deployment. Quarantine and surveillance remain critical in Protected Zones, including Ireland, Cyprus, and parts of the UK.

Recent advances in detection and research tools strengthen management capacity. Image libraries (Invasive.org, Forestry Images, iNaturalist, GBIF) support field diagnostics, while molecular assays such as real-time PCR enable rapid and precise identification, even from frass samples. Reference gene datasets facilitate robust expression studies, enhancing understanding of beetle physiology and climate adaptability. Emerging technologies like AI-based image recognition, remote sensing, and climate-based modeling can improve early warning and risk assessment capabilities.

In conclusion, *Ips sexdentatus* poses a continuing threat to Eurasian conifer forests due to its wide distribution, ability to mass-attack healthy trees, and association with pathogenic fungi. Sustainable management requires a combination of vigilant monitoring, rapid sanitation, targeted quarantine, and the integration of molecular and digital tools to improve detection and decision-making. Looking ahead, research on climate change effects, natural enemies, and host–pathogen–microbiome interactions will be essential to reduce dependence on chemical methods and to strengthen forest resilience.

II. Introduction

The six-toothed bark beetle, *Ips sexdentatus* (Coleoptera: Curculionidae: Scolytinae), is a major Eurasian pest of conifer forests. Adults typically initiate colonization on fallen or weakened pines, yet under favorable environmental conditions they can mount pheromone-mediated mass attacks that overcome the defenses of healthy trees. In addition to direct phloem disruption, the beetles vector pathogenic fungi into hosts, accelerating decline.

Geographically, *I. sexdentatus* occurs across most of continental Europe and adjacent parts of Western Asia, with the EU recognizing 24 Member States with occurrence and maintaining Protected Zone status for Ireland, Cyprus, and parts of the UK. Population dynamics vary across this range: the species produces from one to five generations per year, with voltinism increasing toward warmer climates (e.g., multivoltinism in Mediterranean climate). These gradients necessitate region-specific surveillance calendars and sanitation schedules.

Biologically, males often initiate attacks and release aggregation pheromones (principally ipsdienol, with ipsenol and 2-methyl-3-buten-2-ol documented as key components) thereby attracting conspecifics of both sexes and coordinating gallery establishment beneath the bark. Such semiochemical ecology supports contemporary monitoring programs and informs operational decisions about trap deployment and bait formulation.

From a management perspective, the most consistently effective tactics are preventive and sanitary: prompt removal of infested, wind-thrown, or fire-damaged material; thinning to reduce stand stress; and, where appropriate, debarking or the use of trap trees prior to adult emergence. Pheromone-baited trapping provides essential population intelligence and can contribute to suppression when carefully configured to local predator communities and phenology. Coupled with targeted quarantine measures in Protected Zones, these strategies frame an IPM approach that reduces outbreak intensity and limits spread.

Finally, expanding data resources including image libraries for field recognition and probe-based qPCR assays capable of detecting I. sexdentatus from adult tissue or frass (sawdust-like excrement of the insect) are improving early detection and diagnostic accuracy. Together with standardized reference genes for expression studies, these tools support rigorous research pipelines and operational decision-making in forest health programs.

III. Biology and Identification of *Ips sexdentatus*

Ips sexdentatus (Coleoptera: Curculionidae: Scolytinae) is a conifer-feeding bark beetle within the genus *Ips*, defined by its steeply sloped and spined elytral declivity.[1] It is native to Asia and Europe.[2]

Life Cycle: Egg, Larvae, Pupa and Adult Stages

The life cycle of *Ips sexdentatus* consists of four main stages: egg, larva, pupa, and adult.[1] Females start laying eggs one to seven days after mating, creating individual niches along their galleries under the bark.[1] Each female can produce up to 60 offspring with an approximately balanced sex ratio.[1] Eggs typically develop into larvae after around three weeks, and both the larval and pupal stages last roughly two weeks each.[1]

Larvae feed in galleries perpendicular to the maternal gallery, completing their development before pupating in small niches at the ends of their galleries.[2] Pupae display some adult features, including folded wings, and are located within the inner bark.[5] Larvae and pupae are sensitive to temperature, with development accelerating at 27°C, slowing at 22°C, and halting entirely at 12°C.[5] Adults emerge after pupation, overwinter under bark, in stump cracks, or forest litter, with supercooling points of about -19°C for adults and -9°C for larvae.[5]

Adult males initiate attacks by boring into the phloem and releasing an aggregation pheromone mainly composed of ipsdienol.[2,5] One to five females join the male to mate, then each constructs maternal galleries parallel to the fibers and deposits single eggs at regular intervals.[2] Adults can be found under the bark, flying during dispersal, or in the ground while overwintering.[3] The species prefers large trees with thick bark, and the adult beetles share common morphological traits with other Ips species, such as a pill-shaped body, hairy surface, and a sloped, concave elytral declivity with six lateral spines that differentiate I. sexdentatus from other Ips species.[3]

Ips sexdentatus typically produces one generation north of the Arctic Circle, two generations in central Eurasia, and up to four or five generations in the Mediterranean and other regions with long, warm summers.[4,5] In Turkey, for example, the first generation usually begins around April to May, with newly molted adults flying in late June to find new hosts, and a third generation often starting in late September.[1] Tropical populations, such as in Thailand, can produce more generations annually than temperate populations in Western Europe.[1]

Physical Description and Distinguishing Features

Ips sexdentatus exhibits distinctive morphological characteristics at each stage of its life cycle, which are important for correct identification.

- **Adult:** *Ips sexdentatus* is the largest beetle in the Ips genus, measuring 5.5–8.2 mm in length, with a body roughly 2.6–2.8 times longer than wide.[3,8] Its body is shiny, brown to brownish-black, with fine hairs on the head, along the sides, and around the rear of the elytra.[3] Young specimens taken from galleries are usually pale, while mature adults appear darker.[3]
  The antennae are clubbed and bent, with a clearly developed scape and a flat club that has two curved sutures.[7] The head is partially covered by the enlarged front of the pronotum, and the beetle has a large, flat scutellum.[7]
  A key feature for identification is the elytral declivity, the sloped rear part of the beetle, which has six spines on each side.[3,7,8] The fourth spine is the largest and capitate, which helps differentiate *I. sexdentatus* from other *Ips* species[7]. Female beetles also have a short transverse line above the median tubercle on the frons, a feature absent in males and similar species.[7] They live mostly under tree bark, fly to new host trees when swarming, and can also overwinter in the ground.[3] These characteristics make it possible to identify *Ips sexdentatus* clearly at the adult stage.
- **Pupa:** *Ips sexdentatus* pupae are white and resemble small mummies, showing some adult features such as wings that are clearly visible and folded behind the abdomen.[3] Pupation occurs in round chambers at the ends of the larval galleries, providing protection during this developmental stage.[3]
- **Egg:** The eggs are pearly-white and are deposited in the inner bark.[3] They are placed individually in niches along longitudinal egg galleries constructed by the female, which are usually 15–35 cm long and 4–5 mm wide.[9]
- **Larva:** The larvae are legless and possess a dark amber cephalic capsule.[4] When larvae hatch, they feed in galleries perpendicular to the egg galleries, usually found in the inner bark of the lower stem.[2] Larval galleries increase in size as the larvae grow.[9] Mature larvae are 0.1875–0.3125 inches long, c-shaped grubs, with a white body and a distinct amber head[3]. Pupation occurs at the end of each larval gallery in round chambers.[2,9] Maturation feeding is required for sexual maturity[2]

Host Plants and Feeding Behavior

Ips sexdentatus primarily attacks conifers in the Pinaceae family, with a preference for large trees with thick bark.[1,3,4] In Northern Europe, it is mainly recorded on Scots pine (*Pinus sylvestris*), while in Central and Southern Europe it also infests maritime pine (*P. pinaster*), Bosnian pine (*P. heldreichii*), and black pine (*P. nigra*).[4] In Turkey, Georgia, and Southern Russia, the beetle occurs on Oriental spruce (*Picea orientalis*), and it has occasionally been found on species of Abies, Larix, and other Picea species.[1,3,4] In Asia, *Ips sexdentatus* infests *Pinus armandii* and other *Pinus* species.[4] Preferred hosts with documented outbreaks and economic impact include *Pinus* spp. and *Picea orientalis*.[3] Other reported hosts include *Abies alba, Abies holophylla, Abies nordmanniana, Abies nephrolepis, Abies sachalinensis, Abies sibirica, Larix gmelinii, Larix sibirica, Picea abies, Picea jezoensis, Picea koraiensis, Picea obovata, Pinus brutia, Pinus* *cembra, Pinus densiflora, Pinus halepensis, Pinus pinea, Pinus radiata, Pinus strobus,* and *Pinus tabuliformis*.[4]

Ips sexdentatus generally colonizes stressed, dying, or recently dead trees but can occasionally attack healthy trees under favorable conditions.[3] Epidemics are usually triggered by environmental disturbances such as storms, drought, wildfires, or severe defoliation.[3] Males initiate colonization by boring into the bark and releasing an aggregation pheromone that attracts 2–5 females, which then excavate individual egg galleries.[3] Females deposit 10–60 eggs during their lifetime, laying them in niches along the gallery. After hatching, larvae feed inside the galleries until pupation occurs in round chambers at the gallery ends.[3] Emerging adults feed for 12–14 days before dispersing to new trees to start the next generation.[3]

Geographical Distribution

Ips sexdentatus naturally occurs across a wide range of ecosystems in Eurasia and has been documented in 49 countries.[1] In Europe, it is widespread in Pinus forests but is absent from Ireland, Cyprus, and certain parts of the United Kingdom, including Northern Ireland and the Isle of Man, which are considered Protected Zones.[4] Within Scandinavia, the beetle is only found north of the Arctic Circle, while in southern regions of Europe, including Austria, Bulgaria, Czech Republic, France, Germany, Greece, Hungary, Italy (mainland and Sardinia), Lithuania, Macedonia, Norway, Poland, Portugal, Romania, Russia (central, southern, Western Siberia, Far East), Spain, Sweden, Slovakia, Switzerland, Turkey, UK (England), Ukraine, and the former Yugoslavia, it is widely distributed.[5]

In Asia, *Ips sexdentatus* occurs in Russia (Siberia and the Far East), China (Hebei, Heilongjiang), Japan, Mongolia, Myanmar, Thailand, and both North and South Korea.[4,5] Its presence spans a variety of forest types and climates, showing adaptability to both temperate and subtropical conditions, with populations in northern regions typically having fewer generations per year due to cooler temperatures.[1,4] The species is established throughout the European Union and maintains a continuous distribution wherever suitable conifer hosts are present.[5]

Ips sexdentatus is not established in the United States.[6,7] Although it has been intercepted multiple times since 1985, survey data confirm that the species has not been found in natural populations, and it remains restricted to its native range in Europe and Asia.[2]

Table 1: Key Characteristics of *Ips sexdentatus* Life Stages

Life Stage	Size (approx.)	Color/Appearance	Key Distinguishing Features	Typical Location
Adult	5.5–8.2 mm (0.22–0.32 in)	Brown to brownish-black, shiny, fine hairs on head, sides, and rear of elytra	Pill-shaped body, elytral declivity with six lateral spines (fourth spine largest and capitate), clubbed antennae, female with transverse line above median tubercle on frons	Under bark, dispersing to new host trees, or in ground during overwintering
Pupa	N/A	White, mummy-like, wings folded behind abdomen	Located at ends of larval galleries	Inner bark at gallery ends

Egg	N/A	Oval, smooth, shiny	Deposited individually in niches along longitudinal egg galleries, galleries 15–35 cm long, 4–5 mm wide	Inner bark along maternal galleries
Larva	3/16–5/16 inch (approx. 0.48–0.79 cm)	White with dark amber head capsule; as they mature, color remains whitish, sometimes darker at older stages	Legless, feed in galleries perpendicular to egg galleries, pupation at gallery ends, maturation feeding required for sexual maturity	Inner bark of lower stem

IV. Management and Control Strategies

Effective management of the *Ips sexdentatus* requires a comprehensive and adaptive strategy, primarily rooted in Integrated Pest Management (IPM) principles.

Integrated Pest Management (IPM) Principles for I. sexdentatus

Integrated Pest Management (IPM) is an approach that integrates cultural, biological, and chemical methods to suppress insect, fungal, and weed populations below levels that cause economic harm.[10] A comprehensive IPM strategy is crucial to limit the spread of the I. sexdentatus and to prevent further damage to pine stands. This strategy focuses on enhancing tree vitality, performing routine checks at key stages of the pest's life cycle, and controlling larvae through insecticides.

Monitoring and Early Detection Methods

Within an IPM framework, monitoring and early detection are essential for limiting the spread and damage caused by *Ips sexdentatus*, as they allow for the prompt identification of infestations and the timely implementation of control measures.

- **Population Monitoring via Pheromone Traps**
  Ips sexdentatus are strongly attracted to aggregation pheromone components such as ipsenol, ipsdienol, and 2-methyl-3-buten-2-ol.[1] This makes pheromone-baited traps a practical tool for monitoring populations. Using these synthetic pheromones, males can be reliably captured, and both seasonal and diurnal flight activity can be assessed, providing critical information on population density and peak activity periods. These data can guide the timing of control measures. Although mass trapping cannot provide definitive control, it is one of the few methods available to limit the destruction of millions of cubic meters of conifer forests caused by bark beetles worldwide.[11] The use of *Ips sexdentatus* pheromones in monitoring and control programs can, however, affect non-target saproxylic insects, including predators.[11] Adding pine volatiles such as (−)-α-pinene and ethanol to pheromone traps may reduce attractiveness to *Ips sexdentatus* while attracting some predator species; therefore, bait composition should be carefully considered.[11] Flight activity differs significantly between *Ips sexdentatus* and its predators, and these differences should be accounted for when planning control measures.[11] Despite these limitations, pheromone

traps remain a reliable method for population monitoring and can contribute effectively to integrated pest management when implemented strategically.

Biological Control

Management of *Ips sexdentatus* relies on combining natural biological agents with preventive cultural practices.[1,9] In its natural range, predators such as *Thanasimus formicarius Linnaeus* (Coleoptera: Cleridae) and *Temnoscheila caerulea Olivier* (Coleoptera: Trogossitidae) feed on both larvae and adult beetles, significantly reducing population levels.[1] In regions where these predators are not present, related generalist subcortical predators, already common in North America, could provide similar ecological benefits.[1] Maintaining tree health through thinning and stand diversification is critical, as stressed trees in plantations are more vulnerable to beetle attacks and less able to cope with environmental pressures.[1] Preventive measures must be coupled with direct control strategies: removing infested trees before the new generation of adult beetles emerges is the most effective approach, while debarking and the use of trap trees can further reduce beetle densities.[9] By integrating biological control with proactive forest management, these strategies collectively ensure sustainable suppression of *Ips sexdentatus* populations, limit the spread of infestations, and reduce dependence on chemical treatments.

Cultural Control Practices

Maintaining stand health and minimizing stress are essential components of managing *Ips sexdentatus*. Outbreaks typically occur in unmanaged, overstocked, or environmentally stressed pine stands, which underlines the importance of preventive silvicultural practices.[12] Unhealthy, wind-thrown, or fire-damaged trees should be removed quickly, and beetle-infested materials should be cut, piled, and burned. As an alternative, slash can be scattered in open sunny areas where developing beetles are exposed to desiccation.[12] The timely removal of infested trees before the emergence of a new generation of adults remains the most effective single measure to prevent population growth.[5]

Traditional cultural control also relies on sanitation cutting, salvage logging, and the use of trap trees, which can be employed to attract beetles and then eliminated before brood emergence.[13] These strategies are particularly important during large-scale outbreaks, where rapid intervention can limit beetle reproduction and reduce the risk of further spread. Taken together, such practices form the basis of cultural control against *I. sexdentatus*, emphasizing the role of proactive forest management in maintaining resilience and lowering susceptibility to infestation.

Chemical Control

Chemical control of *Ips sexdentatus* primarily relies on pheromone-based traps and insecticide-treated trap trees rather than broad-spectrum pesticide applications.[12,13] Semio-chemicals are commonly used to monitor beetle populations and attract individuals to specific trap locations.[12] Insecticide-baited trap trees have been employed to capture beetles before they establish and reproduce, although the presence of windfalls can compete with these traps and allow some beetles to escape.[13]

Studies on related species, such as *I. cembrae*, indicate that different trapping methods, including insecticide-treated traps, can negatively affect non-target predators, highlighting the need for careful deployment to minimize ecological impacts.[14] While chemical treatments can reduce local beetle densities, they are most effective when integrated with timely removal of infested trees and proper trap placement, ensuring that new generations are intercepted before emergence.[12,14]

V. Available Datasets and Resources

Datasets and resources on *Ips sexdentatus* are crucial for understanding its biological characteristics, potential economic and ecological impacts, and patterns of spread. They provide a solid foundation for studying the species and facilitating future research efforts.

Image Datasets for *I. sexdentatus*

Image datasets are a key resource for training machine learning and deep learning models, which can be used to automatically identify the presence and damage of *Ips sexdentatus* and other invasive species.

- **General Visual Resources:**
  - The websites invasive.org[15] and forestryimages.com[16] provide valuable visual resources on *Ips sexdentatus*. They include images of all life stages of the species, such as eggs, larvae, pupae, and adults, along with clear examples of the damage observed on host trees.
  - The platform inaturalist.org[17] and gbif.org[18] offers community-contributed records and photographs of *Ips sexdentatus*. It presents examples from different life stages and occurrences, together with general information on the species' biology and ecology.

Table 2: Overview of Image Datasets for *Ips sexdentatus*

Dataset Name	Primary Focus	Number of Images (approx.)	Key Features / Purpose
Invasive.org[15]	Invasive and pest species	142	High-quality diagnostic photos, all life stages, examples of tree damage, educational resource for pest ID
Forestry Images[16]	Forest pests and management	142	Focus on forestry damage, larvae galleries, pupae and adult morphology, host interactions
iNaturalist[17]	Biodiversity observations	59	Crowdsourced observations, photos of various life stages, user-contributed data
GBIF[18]	Georeferenced observations	58	Verified occurrence records with location data, images for identification, study of species distribution

Genetic and Genomic Datasets

Genetic and genomic resources are essential for understanding the biology, morphology, and evolution of *Ips sexdentatus*. Currently, several datasets on I. sexdentatus are publicly available.

- A dataset has been developed for *Ips sexdentatus* to support gene expression and functional genomics studies, helping to understand how this pest adapts to toxic compounds in its host trees.[20] Twelve reference genes commonly used in Coleopterans were tested under different conditions to allow accurate normalization of gene expression data.[20] Most genes showed stable expression across developmental stages, sexes, and tissues, though some variation appeared under different temperature treatments.[20] In developmental stages, β-Tubulin was the most stable gene, followed by translation elongation factor (eEF2) and ribosomal protein S3 (RPS3).[20] For sex-specific conditions, RPS3, β-Tubulin, and eEF2 were the most stable, while tissue-specific analyses showed RPS3 and eEF2 stable in the head, V-ATPase-A and eEF2 in the fat body, and V-ATPase-A and eEF2 in the gut.[20] Under varying temperatures, β-Tubulin and V-ATPase-A were most stable, and ubiquitin (UbiQ) with V-ATPase-A were most stable after Juvenile Hormone III treatment.[20] These results were validated with RT-qPCR, and the dataset provides a reliable list of reference genes for future gene expression and functional genomics research on I. sexdentatus.[20]

- A molecular dataset has been developed for the identification of *Ips sexdentatus*, providing a reliable tool for both direct and indirect detection of this six-toothed bark beetle.[21] The dataset is based on a real-time PCR protocol using TaqMan probe technology and has been validated on whole adult beetles as well as on artificial frass contaminated with beetle DNA.[21] This molecular tool demonstrates high analytical specificity and sensitivity, and it is reproducible and reliable across different sample types.[21] It allows rapid identification of *I. sexdentatus* even in the presence of biological traces from other xylophagous pests, which is critical for phytosanitary monitoring and early detection in countries where the beetle is treated as a quarantine species.[21] The dataset also supports epidemiological studies and quantitative assessments of population pressure, providing a foundation for effective pest management and surveillance.[21]

Population Monitoring Data

Population monitoring resources are critical for understanding the distribution, host range, and life cycle dynamics of *Ips sexdentatus*.

- The Panel on Plant Health performed a pest categorization for the European Union, identifying *I. sexdentatus* as a clearly defined species native to Eurasia and primarily associated with pine (*Pinus* spp.) and spruce (*Picea orientalis* in Turkey and Georgia).[19] The species can occasionally infest Larix spp. and Abies spp.[19] It occurs across 24 EU Member States, while Ireland, Cyprus, and the United Kingdom (Northern Ireland, Isle of Man) are designated as protected zone quarantine areas.[19] Adults typically colonize fallen or weakened trees but are capable of mass-attacking healthy hosts, facilitated by aggregation pheromones that attract both sexes.[19] The beetles inoculate pathogenic fungi into their hosts, and they produce between one and five generations annually.[19] The extensive current distribution suggests the species can establish wherever suitable hosts are present within the EU.[19] Control and monitoring strategies, including sanitary thinning, clear-felling, and localized pheromone mass-trapping, along with quarantine measures, provide essential tools for managing populations and preventing establishment in protected zones.[19] This dataset constitutes a foundational resource for population surveillance, risk assessment, and management planning of *I. sexdentatus*.[19]

VI. Ongoing Research and Future Prospects

Ongoing ecological changes and technological innovations are guiding future research. Upcoming studies are expected to examine the effects of climate change on insect-host and insect-pathogen-bacteria relationships, investigate the natural defense strategies of host trees, and use advanced pest detection methods.

Climate Effects

In the coming years, climate change may drive shifts in the behavior of *I. sexdentatus*.[24] Rising temperatures can shorten development time and allow the beetle to produce more generations per year, which increases the risk of frequent outbreaks.[22] In addition, climate change brings multiple pressures like elevated CO2, droughts, and storms that can directly affect the beetle or indirectly influence it through changes in host trees and natural enemies.[23] While higher temperatures can increase brood size and survival, they may also reduce offspring quality at the upper thermal limits, creating trade-offs between productivity and fitness.[22] The overall outcome is shaped by complex interactions among abiotic stress, hosts, and natural enemies, making it challenging to predict long-term impacts on forest health. This highlights the need for models that simulate *I. sexdentatus* population dynamics under different climate scenarios.[23]

Parasites, Fungi and Bacteria Affecting *Ips sexdentatus* Populations

Ips sexdentatus carries a variety of parasites and pathogens that affect its populations.[25,26] Protozoans like *Gregarina typographi* are often found in the gut of adult beetles, with infection rates ranging from 15% to 71.9% depending on location and beetle age.[25,26] Nematode larvae live in the gut and body cavity, sometimes reaching very high numbers, and some use the beetles to move between trees.[25] Fungi that can kill insects, such as *Beauveria bassiana* and *Metschnikowia* cf. *typographi*, infect different parts of the beetle and can reduce survival, though their prevalence is usually low.[25,26] The beetle also spreads several ophiostomatoid fungi, including *Graphium* and *Leptographium*, which can damage or kill pine trees.[27] In addition, *I. sexdentatus* hosts bacteria with insect-killing ability, like *Pseudomonas fluorescens*, which has shown high lethality against its larvae and could be used as a biocontrol agent.[28] Overall, these parasites, fungi, and bacteria form a complex community that affects the beetle and the forest, and they should be considered when planning pest management.

Advanced Detection Methods

Integrating artificial intelligence and computer vision into detection provides a practical way to identify insects automatically and accurately from large image datasets.[29,30] Deep learning methods, especially convolutional neural networks, classify insects based on visual features, increasing speed in identification.[29] As mentioned before in this report, molecular tools, such as real-time PCR with TaqMan probes, offer highly specific and sensitive detection, able to identify *I. sexdentatus* from whole insects or traces of frass containing beetle DNA.[21] Although AI systems face challenges like limited labeled data, cost, and scalability, combining them with molecular diagnostics may strengthen monitoring programs and support effective integrated pest management.

VII. Conclusions

Ips sexdentatus is a bark beetle found widely across Eurasia. It can attack stressed or wind-thrown trees and, through pheromone-driven mass attacks, can also overwhelm healthy trees. The number of generations depends on the climate, ranging from one per year in cooler areas to up to five in warmer Mediterranean regions. Fungi carried during colonization worsen tree health and increase mortality. The species is found across most of continental Europe and parts of Western Asia, is absent in the United States, and is regulated in some EU Protected Zones.

Effective management depends on integrated pest management focusing on sanitation and stand health. Removing and processing infested, wind-thrown, or fire-damaged trees before adult beetles emerge, thinning crowded stands to reduce stress, and using trap trees or debarking where suitable are the most reliable control methods. Pheromone traps with species-specific blends (like ipsdienol, ipsenol, and 2-methyl-3-buten-2-ol) help monitor beetle activity and can support control if used carefully, considering non-target species and predators. Selective chemical methods, such as insecticide-treated trap trees, work best when combined with timely sanitation and proper trap placement. Quarantine and surveillance are essential in Protected Zones.

Data resources are improving early detection and decision-making. Image libraries like Invasive.org, Forestry Images, iNaturalist, and GBIF help identify beetles and map their presence. Real-time PCR allows accurate detection from adults or frass. Standard reference genes support molecular studies on traits like detoxification and thermal response. These tools strengthen early warning systems and guide management actions.

Key research areas include climate-based models to predict beetle emergence, optimizing semiochemical blends while protecting natural enemies, remote sensing, and machine learning for large-scale detection and impact assessment. Studying tree defenses, vector–pathogen–microbiome interactions, and the role of predators and microbial control agents can help reduce reliance on broad chemicals and improve forest resilience. In short, strong monitoring, fast sanitation, and careful use of biological and technological tools are crucial to limit *Ips sexdentatus* impacts.

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