

# The Large Pine Weevil: A Comprehensive Review of Biology, Impact, Management, and Data Resources

## I. Executive Summary

The large pine weevil, *Hylobius abietis*, represents a persistent obstacle to successful regeneration of conifer forests across the Palearctic region. Economic losses arise mainly from adult feeding on the bark of newly planted *Pinus* and *Picea* seedlings, where girdling frequently leads to high mortality. This pressure is sustained by a prolonged and flexible life cycle, larval development within stumps and roots that are difficult to access, and adults may survive several years after a clear cutting.

Although this species is not established in the United States, repeated interceptions linked to wood packaging materials indicate ongoing introduction pressure through international trade. Climate based suitability analyses and host availability suggest that many regions of North America could support establishment if introductions occur. This places *H. abietis* within a clear biosecurity context and supports the need for early detection, monitoring, and risk-based planning rather than reactive control.

Current management is shaped by increasing restrictions on insecticide use and growing emphasis on environmentally responsible forestry. Chemical protection can reduce damage but is insufficient when applied in isolation. Evidence supports integrated approaches that combine silvicultural decisions, biological control, and limited chemical use. Entomopathogenic nematodes and fungi are particularly effective against larval stages developing in stumps, while planting timing and stump management strongly influence subsequent damage levels.

Genetic, genomic, and monitoring advances reinforce a shift toward long term management strategies grounded in species biology. High gene flow across populations informs resistance oriented breeding efforts, while improved monitoring technologies allow more precise intervention. Effective management of *H. abietis* therefore depends on coordinated strategies that address immediate seedling protection and sustained population pressure within regenerating forest systems.

## II. Introduction

The large pine weevil, *Hylobius abietis*, is recognized as a major threat to coniferous forest ecosystems, particularly affecting Pine (*Pinus spp.*) and Spruce (*Picea spp.*) species. Its impact on newly planted seedlings has made the species a persistent concern in forest management and reforestation practices. The biological characteristics of this pest, including its prolonged life span and development within protected substrates, contribute to the difficulty of effective control and justify continued research attention.

Beyond its established range in Europe and North Asia, *H. abietis* also represents a potential biosecurity risk for regions where it has not yet become established. Reports of repeated detections linked to international trade highlight the importance of understanding pathways of introduction and assessing regional vulnerability. These issues underscore the need for early detection, monitoring, and risk assessment frameworks, which are addressed in later sections.

At the same time, changes in regulatory standards and environmental priorities are reshaping management approaches toward Integrated Pest Management (IPM) strategies. A growing body of work examines alternatives to conventional chemical control, including biological agents and sustainable practices that aim to balance seedling protection with reduced environmental impact. Recent advances in genomic resources and monitoring technologies further expand the range of available tools, supporting the development of targeted and long term solutions. Accordingly, this report provides an overview of the species' ecological and economic significance, outlines current and emerging management options, and sets the foundation for a coordinated approach that is explored in detail in the sections that follow.

### III. Biology and Identification of the Large Pine Weevil

*Hylobius abietis*, originally described by Linnaeus in 1758, is a curculionid beetle widely known by the common name large pine weevil.<sup>1</sup> In earlier taxonomic literature, the species has also been reported under several synonyms, including *Hylobitelus abietis*, *Curculio abietis*, and *Curculio pini*, reflecting historical revisions in its classification.<sup>1</sup> Additional common names such as large brown pine weevil and fir tree weevil are used in reference to its characteristic coloration and its close association with coniferous host plants.<sup>1</sup>

#### Life Cycle: Egg, Larval, Pupal and Adult Stages

The life cycle of *Hylobius abietis* is relatively prolonged and variable, typically lasting between one and three years, though development can extend up to five years under unfavorable climatic conditions.<sup>1,2,3,6</sup> In warmer environments, development from egg to adult may be completed in approximately two years, whereas cooler climates generally result in a three-year life cycle.<sup>6</sup> Eggs are laid during late spring and summer, most commonly from June through early August, in stumps, roots, or surrounding soil of recently felled or dead conifer trees.<sup>1,2,6</sup> After hatching, larvae migrate to suitable feeding sites within the bark of roots or stumps and pass through multiple larval instars over an extended period, with development rate strongly influenced by host quality, temperature, and microclimatic conditions.<sup>1,2,3</sup> Pupation occurs within excavated chambers inside the bark, usually one to two years after oviposition, followed by adult emergence either in late summer of the same year or during the subsequent spring.<sup>1,2,6</sup>

Adult *H. abietis* can live for three to four years, with activity and reproduction closely regulated by temperature and seasonal conditions.<sup>1,2,3</sup> Adults typically emerge from overwintering sites when temperatures rise above 8 to 9°C and undergo a maturation feeding period before reproduction begins.<sup>1,2,3</sup> Oviposition generally starts approximately two weeks after spring emergence and continues through the summer, with peak egg laying occurring in early to mid-June under optimal temperatures.<sup>1,2,6</sup> Depending on environmental conditions, adults may overwinter in pupal chambers, litter, or soil, while overwintering can also occur during late larval instars.<sup>1,3</sup> This extended and flexible life cycle, combined with the long adult lifespan and delayed development of immature stages, allows populations to persist on reforested sites for multiple years and contributes to sustained infestation pressure.<sup>2,3,4</sup>

#### Physical Description and Distinguishing Features

The Large Pine Weevil exhibits distinct morphological characteristics across its life stages, which are important for accurate visual identification.

- **Adults:** Adults are relatively large weevils, measuring approximately 9 to 16 mm in length.<sup>1</sup> The body is dark brown to reddish brown, with elytra marked by irregular patches or rows of yellow to light brown narrow scales that create a mottled appearance.<sup>1,5</sup> The elytral surface is finely punctured, and the pronotum is convex, wrinkled, and broader than long, with additional yellow scale patches.<sup>1</sup> The head is extended into a long cylindrical snout with mandibles located at the tip, and elbowed antennae are inserted near the end of the snout.<sup>1,5</sup> Legs are robust, ending in sharp claws, each femur bearing a distinct inner tooth.<sup>1</sup>
- **Eggs:** Eggs are very small, measuring less than 1 mm in length and less than 0.5 mm in width.<sup>1</sup> They have an oval shape and a pearly white appearance.<sup>1</sup> Eggs are smooth surfaced and lack visible ornamentation, making them difficult to detect without close inspection.<sup>1</sup> They are typically found individually or in small numbers within small holes or notches gnawed into the bark of roots or stumps, usually just below the soil surface.<sup>3</sup>

- **Larvae:** Larvae are soft bodied, legless, and slightly curved, with a creamy white to whitish coloration<sup>1</sup>. Fully developed larvae range from approximately 9.5 to 16 mm in length, though some descriptions report lengths up to 23 mm.<sup>1,5</sup> The head capsule is relatively large and distinctly brown, contrasting with the pale body, and bears flattened mandibles that are clearly visible.<sup>1</sup> The body surface appears smooth and fleshy, lacking segmentation markings that are easily distinguishable to the naked eye.<sup>1</sup>
- **Pupae:** Pupae are pale white, soft, and loosely formed, with a body length of approximately 8 to 10 mm.<sup>1</sup> All appendages are free and unpigmented, and the outlines of future adult structures such as legs, antennae, wings, and the elongated snout are clearly visible through the pupal cuticle.<sup>1,5</sup> The overall appearance is delicate, with narrow and elongated appendages positioned close to the body.<sup>5</sup>

### Host Plants and Feeding Behavior

The large pine weevil is a polyphagous species whose feeding activity is strongly associated with coniferous hosts, particularly within the genera *Pinus* and *Picea*.<sup>1</sup> Adult *Hylobius abietis* shows a marked preference for Norway spruce and Scots pine, although it is capable of feeding on a wide range of other conifer species when preferred hosts are limited.<sup>1,2</sup> While primarily linked to coniferous forestry systems, feeding scars have also been documented on several broadleaved tree species, including birch, oak, ash, willow, and alder, indicating a flexible but clearly conifer oriented host use strategy.<sup>1,2</sup>

Feeding damage is caused by adults gnawing the bark of stems, roots, and young shoots, with a strong preference for seedlings and small diameter plant material.<sup>1,5</sup> This bark feeding can result in partial or complete girdling, which disrupts nutrient transport and often leads to seedling mortality, particularly in newly planted forest stands.<sup>5</sup> Damage intensity is highest in young plantations, where large scale feeding can result in extensive economic losses across European forestry systems.<sup>2</sup> Adults may also feed below ground, targeting roots and subterranean plant parts when conditions allow, further increasing the risk of seedling death.<sup>1</sup>

### Geographical Distribution (Global and United States)

The large pine weevil is widely distributed across the Palearctic region, with confirmed presence throughout much of Europe, northern Asia, and parts of western Asia, extending from Scandinavia and the British Isles to Russia, Armenia, and Turkey.<sup>1,4</sup> Additional records exist from East Asia, including China and Japan, as well as Kazakhstan, indicating a broad tolerance to temperate climatic conditions.<sup>1,4</sup> Although the species has been reported from New Zealand, it is now considered absent there based on more recent assessments.<sup>1,4</sup>

The species is not currently established in the United States, but it has been intercepted multiple times at U.S. ports of entry, primarily as adult beetles associated with wood packaging materials, conifer logs, and related cargo.<sup>1,7</sup> These interception records suggest a repeated introduction pressure linked to international trade rather than the transport of immature stages, which typically develop in stumps and root systems of recently cut conifers.<sup>1</sup> Host availability maps indicate that large areas of the United States, particularly the southeastern, northeastern, western, and upper Great Lakes regions, provide suitable environmental conditions and abundant host material for potential establishment.<sup>1,7</sup> The ability of overwintering larvae to survive subzero temperatures further supports the possibility that large portions of temperate North America could sustain viable populations if introduction were to occur.<sup>1</sup>

**Table 1: Key Characteristics of Large Pine Weevil Life Stages**

Life Stage	Size (approx.)	Color/Appearance	Key Distinguishing Features	Typical Location
<b>Eggs</b>	<1 mm	Pearly white	Smooth surfaced, oval shaped, very small and difficult to detect; laid individually or in small numbers	Small holes or notches in bark of roots or stumps, usually just below soil surface
<b>Larvae</b>	9.5 to 16 mm, up to 23 mm reported	Creamy white body with brown head capsule	Soft bodied, legless, slightly curved; large contrasting head with visible flattened mandibles	Beneath bark of roots and stumps of recently felled or dead conifers
<b>Pupae</b>	8 to 10 mm	Pale White	Free and unpigmented appendages; outlines of legs, antennae, wings, and elongated snout clearly visible; delicate appearance	Pupal chambers excavated within bark of roots or stumps
<b>Adults</b>	9 to 16 mm	Dark brown to reddish brown with yellow to light brown scale patches	Elongated cylindrical snout with mandibles at tip; elbowed antennae; robust legs with inner femoral tooth; mottled scaly elytra	On seedlings, stems, roots, soil surface, and litter in conifer plantations and reforested sites
<b>Adult Comparison (<i>Hylobius Pales</i>)</b>	Similar adult size range to <i>Hylobius abietis</i>	Lighter overall coloration than <i>Hylobius abietis</i> , with paler brown to yellowish scaling	Native pine weevil <i>Hylobius pales</i> , similar general morphology and host use, but consistently lighter coloration. Serves as a native reference species when evaluating potential damage from introduced <i>H. abietis</i>	Native North American conifer stands where pine weevils are already present.

The biological features described above directly influence how *Hylobius abietis* can be managed in practice. Larval development inside stumps and roots, long and variable life cycles, and the long survival of adults reduce the effectiveness of short term or single control actions. As a result, damage can continue for several years after clear cutting. Management therefore needs to consider delayed population responses and life stages that are protected from direct intervention. In North America, the native pine weevil *Hylobius pales* provides a useful reference point, as it has a broadly similar body plan and host association but typically causes more limited damage within its native range. This has led to a shift toward integrated approaches that combine monitoring, silvicultural practices, biological control, and limited chemical use, which are outlined in the next section.

#### **IV. Management and Control Strategies**

Effective management of *Hylobius abietis* requires the use of Integrated Pest Management strategies. These strategies rely on monitoring and the combined use of cultural, biological, and chemical control methods.

##### **Integrated and Early Detection Methods**

Measures to reduce and control levels of damage by *Hylobius abietis* are especially necessary in forest systems where clear cutting and subsequent replanting are practiced for regeneration, as these conditions promote high pine weevil pressure.<sup>11</sup> Monitoring of adult populations is therefore considered a core component of integrated management, particularly in newly established plantations where early detection allows timely intervention.<sup>11</sup>

### **Chemical Control Approaches**

Plants may be protected against *Hylobius abietis* through pre planting and post planting applications of insecticides.<sup>3</sup> Pre planting treatments include dipping bare rooted seedlings in high concentration insecticide solutions or spraying seedlings raised in Japanese paperpots at similar concentrations.<sup>3</sup> Post planting applications at lower concentrations can be applied in the field, although they are considered less effective than pre planting treatments.<sup>3</sup>

Pyrethroid insecticides such as permethrin and deltamethrin have been widely used for protection against pine weevil damage, while older organochlorine and organophosphate compounds were applied historically.<sup>3</sup> A longer term protection method involves slow release systemic carbamate insecticides formulated in polymer granules, which can provide protection for up to 20 months but allow limited feeding before deterrence occurs.<sup>3</sup> This method is currently used in several European countries despite its limitations.<sup>3</sup>

Additional studies have shown that pine weevils preferentially avoid treated seedlings over untreated ones, particularly when insecticides such as imidacloprid and other neonicotinoids are applied, and mortality may occur up to three weeks after exposure rather than immediately.<sup>11</sup> While insecticides such as Decis and Karate Zeon are effective against pine weevils, they have also been associated with potential long term effects on seedling growth and development, highlighting the need for careful selection and application timing.<sup>11</sup>

### **Indirect chemical related approaches**

Chemical attractants such as alpha pinene and ethanol are used in pitfall trapping systems to enhance adult pine weevil capture efficiency, although these compounds function as lures rather than control agents.<sup>5</sup> The combination of alpha pinene and ethanol has been shown to increase trap effectiveness compared to single compound use, supporting their role in monitoring rather than direct population suppression.<sup>5</sup>

Surface treatments such as low friction coatings are sometimes applied to pitfall traps to prevent adult escape, representing another limited chemical use associated with trapping rather than pest mortality.<sup>5</sup> Earlier trapping approaches also relied on bait fluids composed of turpentine and ethanol mixtures, which were shown to be attractive to adult pine weevils and useful for population estimation rather than direct control.<sup>11</sup>

### **Biological Control**

Various natural enemies attack immature and adult pine weevils, including predatory beetles, entomopathogenic fungi, entomopathogenic nematodes, and parasitoid wasps.<sup>9</sup> The parasitoid *Bracon hylobii* attacks pine weevil larvae by locating feeding vibrations under bark, paralyzing the host, and consuming larval tissues during development.<sup>9</sup> Although parasitism rates can reach up to 40 percent at some sites, this level is insufficient to prevent economically significant damage during outbreaks.<sup>9</sup>

Entomopathogenic nematodes infect soil dwelling stages of pine weevils by entering through natural openings and killing the host within days through the release of symbiotic bacteria.<sup>9</sup> These nematodes can

reproduce inside the host and release large numbers of infective juveniles into the soil, contributing to local population suppression.<sup>9</sup> Field applications targeting larvae in stumps 12 to 24 months after felling have shown substantial reductions in adult emergence, although effectiveness depends strongly on environmental conditions and application timing.<sup>9</sup>

Additional biological control research has demonstrated that entomopathogenic nematodes from the families Steinernematidae and Heterorhabditidae are lethal to multiple developmental stages of *H. abietis*, with *Steinernema carpocapsae* showing high efficacy against adults developing in conifer stumps.<sup>11</sup> Entomopathogenic fungi such as *Beauveria bassiana*, *Beauveria caledonica*, and *Metharizium brunneum* have also shown promise, with some species persisting in felling sites for multiple years, although further evaluation under operational conditions is required.<sup>11</sup>

## Trapping

- **Trap barks**

Mass trapping using trap barks has been described in the literature since the nineteenth century and involved placing fresh bark, branches, or logs on clear felled areas to attract adult weevils, which were then collected and destroyed.<sup>5</sup> Trap barks prepared from spruce bark with inserted pine twigs were historically used to reduce adult abundance but required high densities and frequent inspection.<sup>5</sup> Due to high labor demands and operational costs, trap barks are no longer used for population reduction and are now mainly applied for monitoring adult presence before curative spraying.<sup>8</sup> Historical use of toxic bark traps treated with substances such as DDT, HCH, or Arsen based products was common before the widespread regulation of pesticides, although these approaches are no longer acceptable under modern environmental standards.<sup>11</sup>

- **Pitfall traps**

Pitfall traps consist of buried containers that allow adult weevils to enter but prevent escape, often using host material or synthetic attractants.<sup>5</sup> These traps can operate as dry or wet systems, with escape prevention achieved using surface treatments such as Teflon coatings.<sup>5</sup> Attractants such as alpha pinene combined with ethanol significantly increase trap efficiency compared to single compounds.<sup>5</sup> Despite their usefulness for monitoring, large scale trapping using pitfall traps has generally failed to provide sufficient protection for seedlings due to high labor requirements and limited population reduction.<sup>10</sup> Field studies have shown that insufficient trap density, delayed placement, or delayed replacement can severely reduce trapping effectiveness, resulting in continued moderate to very strong attack levels despite protective measures.<sup>11</sup>

## Cultural Control Practices

Silvicultural practices play an important role in reducing pine weevil damage. Removal or debarking of stumps after clear cutting has been shown to reduce available breeding substrates, although full stump removal is often economically prohibitive.<sup>11</sup> Adjustments in planting time, such as early autumn planting or planting after adult emigration from clear cut areas, can improve seedling tolerance and reduce damage levels.<sup>11</sup> Practices such as residue removal, mounding with mineral soil, and the use of over stories have also been associated with improved seedling growth and reduced herbivory by *H. abietis* under certain conditions.<sup>11</sup>

## Regulatory Frameworks and Quarantine Programs

Although pine weevil management relies primarily on local silvicultural and operational measures, regional regulatory frameworks governing pesticide use and forest regeneration practices influence which control strategies are permitted. Integrated approaches that combine monitoring, cultural practices, and limited

chemical or biological interventions are increasingly emphasized to balance effectiveness with environmental protection.<sup>11</sup>

## V. Available Datasets and Resources

Available datasets provide the information needed to identify *Hylobius abietis*, monitor its population levels over time, and support research on its biology, distribution, and management and control strategies.

### Image Datasets

- The platform *inaturalist.org*<sup>13</sup> provides publicly available, user submitted photographs of *Hylobius abietis*. These images document observed individuals in natural settings and cover different appearances of the species, supporting basic visual identification and distribution awareness.
- Additional visual material is available through *invasive.org*<sup>14</sup>, where curated images related to *Hylobius abietis* are presented. This resource includes representative photographs useful for recognizing the species and understanding its external characteristics in applied pest management contexts.
- The bark and wood boring beetle database *barkbeetles.info*<sup>19</sup>, maintained by T. H. Atkinson, provides diagnostic images and host association information for *Hylobius* species and related conifer pests, complementing both community sourced and applied pest management image resources.

### Genetic and Genomic Datasets

- ***Hylobius abietis* Transcriptomic Dataset:** A publicly available transcriptome sequencing project for *Hylobius abietis* is accessible through the NCBI BioProject database under accession number PRJNA435679.<sup>12</sup> This dataset contains high throughput RNA sequencing reads generated to characterize gene expression profiles of the species. The data enable transcriptome assembly, functional gene annotation, and the identification of genes involved in key biological processes such as neuropeptide signaling, metabolic regulation, and receptor mediated pathways. These molecular insights are relevant for understanding feeding behavior, development, and potential vulnerabilities that may be exploited in future pest management approaches.
- **Population Genetic Structure Based on Genome Wide Molecular Markers:** A population genetic dataset for *Hylobius abietis* was generated using amplified fragment length polymorphism markers from 367 individuals sampled across 20 European sites.<sup>17</sup> Genome wide marker analysis indicated low genetic differentiation among populations, with most genetic variation occurring within populations, consistent with high dispersal capacity and extensive gene flow across regions.<sup>17</sup> Larval host plant effects on genetic structure were weak and limited to a small number of loci, suggesting that host association does not represent a significant barrier to gene flow in this species.<sup>17</sup> Although the study provides robust insights into population structure and dispersal dynamics, the underlying AFLP marker dataset is not deposited in a public repository and is only described within the article, limiting direct data reuse.<sup>17</sup>

### Population Monitoring Data

- **Seasonal Population Monitoring in Forest Environments:** A detailed field-based monitoring study has investigated the seasonal occurrence and population dynamics of *Hylobius abietis* across different forest environments. This work relied on systematic trapping and repeated observations to quantify adult activity levels throughout the year, allowing the identification of clear seasonal peaks associated with forest structure and environmental conditions. The results demonstrate that

population density varies substantially between habitat types, with higher abundance observed in recently disturbed or regenerated forest stands. Such long term and environment specific monitoring data are essential for understanding population fluctuations, timing control interventions, and assessing the risk of damage following silvicultural practices such as clear cutting and replanting.<sup>15</sup>

- **Climate Based Distribution and Population Risk Modeling:** In addition to direct field monitoring, climate driven modeling approaches have been used to assess the potential distribution and population risk of *Hylobius abietis* at broader spatial scales. A recent study employed ecological niche modeling techniques to identify climatically suitable areas for the species, integrating temperature and precipitation variables to estimate present and future habitat suitability. These results provide indirect but valuable population level insights by highlighting regions where sustained or increasing population pressure is likely to occur. When combined with empirical monitoring data, climate suitability models support proactive surveillance strategies and improve long term planning for forest pest management under changing environmental conditions.<sup>16</sup>

## **VI. Ongoing Research and Future Prospects**

Ongoing research on *Hylobius abietis* increasingly focuses on long term, integrated solutions that move beyond single method control approaches. Current efforts span host resistance, monitoring technologies, biological control, and coordinated industry initiatives, reflecting a broader shift toward sustainable and adaptive forest pest management strategy.

### **Host Resistance and Breeding Based Strategies**

Recent studies suggest that integrating host resistance traits into existing forest breeding programs may offer a viable long-term approach to reducing damage caused by *Hylobius abietis*. Progeny trials conducted on Norway spruce have shown consistent family level genetic variation in resistance to pine weevil damage across sites with differing infestation pressure. Although resistance traits exhibited low heritability at the individual level, moderate family heritability indicates that backward selection of resistant parent trees could be used to lower damage risk in planting stock. This approach supports resistance based management as a complementary strategy to biological and non-chemical control methods within sustainable reforestation frameworks.<sup>19</sup>

### **Advanced Detection and Monitoring Methods**

Recent advances in pest monitoring technologies demonstrate the potential of real time detection systems to support integrated *Hylobius abietis* management. Commercially developed monitoring platforms capable of continuously tracking insect activity across forest sites provide early warning information that can improve the timing and precision of control measures. By enabling targeted interventions and reducing unnecessary chemical applications, such systems complement biological and non-chemical control approaches and highlight the growing role of technology driven surveillance in sustainable forest pest management strategies.<sup>18</sup>

### **Industry Led Integrated Research Initiatives**

Current research on *Hylobius abietis* increasingly emphasizes coordinated, industry led programs that aim to reduce reliance on chemical control and promote integrated management strategies. The Hylobius Industry Research Programme reflects this direction by defining short, medium, and long term research priorities focused on population prediction, alternative non chemical control options, biological control

agents, and host resistance through tree genetics. Within this approach, chemical interventions are framed as a final option under regulatory and environmental constraints. Such initiatives illustrate a structured pathway toward sustainable forest restocking while addressing the limitations of single method control strategies.<sup>17</sup>

### **Biological Control Agents**

Recent field-based research further supports the inclusion of biological control agents as practical components of integrated *Hylobius abietis* management strategies. A 2024 study reports that applications of entomopathogenic fungi and commercially available entomopathogenic nematodes can significantly reduce adult emergence of *H. abietis* under plantation conditions, while causing minimal disruption to non-target invertebrate communities. These findings provide experimental validation for biologically oriented control approaches and complement industry led integrated research frameworks by demonstrating that non chemical methods can achieve measurable population suppression in real forest settings.<sup>8</sup>

## **VII. Conclusions**

*Hylobius abietis* remains a persistent and structurally challenging pest in coniferous forestry due to its life history traits, its close association with silvicultural practices, and its capacity to maintain population pressure over multiple years. High mortality in newly planted stands is not the result of isolated events but rather the outcome of predictable interactions between clear cutting, stump availability, and the prolonged survival of adult beetles. Larval development within protected root and stump tissues, combined with extended adult longevity, limits the effectiveness of short term or single method interventions and necessitates management approaches that operate at the system level rather than the individual treatment level.

The evidence reviewed here indicates that effective control cannot rely solely on chemical protection. While insecticides have historically reduced damage levels, increasing regulatory restrictions and environmental considerations have narrowed their role within operational forestry. Biological control agents, particularly entomopathogenic nematodes and fungi, offer practical alternatives when applied with appropriate timing and environmental awareness, especially against larval stages developing in stumps. Cultural practices such as planting schedule adjustments, stump management, and site preparation further influence damage outcomes and can substantially improve seedling survival when integrated into broader management plans. Genetic and genomic studies showing high gene flow and limited population structuring provide additional guidance, suggesting that resistance based planting material and targeted strategies must be designed with dispersal dynamics in mind.

Taken together, the findings support a management framework for *H. abietis* that is integrated, adaptive, and informed by biological understanding and long-term monitoring. For regions where the species is not yet established, particularly North America, the combination of suitable climate conditions, host availability, and repeated interception records underscores the importance of proactive surveillance and risk assessment. Future research should prioritize the operational refinement of biological control methods, the incorporation of host resistance into breeding programs, and the linkage of climate based models with empirical population data. Such efforts are essential to reduce economic losses while maintaining environmentally responsible forest regeneration practices.

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