The Redheaded Pine Sawfly (*Neodiprion lecontei*.) and Its Impact on Conifer Forests: A Review of Biology, Ecological Effects, Management Strategies, and Data Resources

I. Executive Summary

The redheaded pine sawfly (RPS) is a species within the broader sawfly group, containing multiple subspecies, and is native to the United States and Canada. In the U.S., particularly in states like Florida and Texas, RPS directly harms the local vegetation and also causes negative economic impacts on the forestry industry. This species damages many types of pine trees by feeding on their needles in large groups, often stripping entire branches or even whole trees. Severe infestations can lead to reduced tree growth, tree deformities, or in some cases, tree death, especially among young pine stands.

A comprehensive Integrated Pest Management (IPM) approach is required to protect pine forests against the redheaded pine sawfly. This approach should include early detection of larvae activity, regular monitoring of susceptible pine stands, proper tree spacing to reduce favorable conditions for infestation, and the promotion of natural predators such as birds and parasitic wasps. In the long term, effective protection will require combining traditional IPM practices with new tools such as remote sensing, pheromone-based monitoring, and genomic data. These approaches will make detection faster, help predict outbreak risks more accurately, and reduce the need for heavy chemical use. By building on both ecological knowledge and technological advances, it will be possible to manage RPS populations in a more sustainable way.

This report provides an overview of the biology of the redheaded pine sawfly, examines existing management strategies, and presents key datasets and resources that support continued research and effective control measures.

II. Introduction

The redheaded pine sawfly (RPS) poses a significant threat to the pine industry due to its ability to utilize a wide range of host tree species, including various commercially important southern yellow pines and ornamental pines.[4,5] This species is particularly damaging during outbreak years, when larvae can defoliate entire young pine plantations or commercial stands, sometimes over large areas and for multiple seasons.[4,5] The larvae are initially whitish with a brown head capsule, later becoming yellow to green with distinctive rows of black spots along the body and a red to reddish-orange head.[2] They feed in dense groups and cause highly recognizable damage. Younger larvae consume the outer portions of pine needles, leaving the central tissue intact, which then wilts and dries into straw-like remnants. As they mature, they consume entire needles, and when foliage becomes limited, they may even feed on the soft bark tissue of defoliated trees.[1,5] This progressive and aggressive feeding behavior, combined with their host flexibility and seasonal persistence, makes RPS a potentially destructive pest in both forest and landscape settings.

This comprehensive report aims to provide a review of RPS. The report examines the complex biology of the sawfly and the existing integrated management strategies used to address the threat. It also gathers and describes the available datasets and resources, including essential image datasets necessary for research and control measures. Lastly, it considers ongoing research directions and future opportunities to support the long-term sustainability and protection of pine forests.

III. Biology and Identification of the Redheaded Pine Sawfly

The redheaded pine sawfly, *Neodiprion lecontei* (Hymenoptera: *Diprionidae*), is a native North American defoliator with a broad distribution. Among the 35 species classified within the genus Neodiprion, RPS is distinguished from the others by its unique morphological traits and life history characteristics.[2]

Life Cycle: Egg, Larvae, Cocoon (Pupa) and Adult Stages

The life cycle of *Neodiprion lecontei* consists of four main stages: egg, larva, cocoon (pupa), and adult. The adult sawfly is rarely seen and causes little damage when laying eggs, while the larvae feed on needles and cause most of the harm.[4] Females deposit 100 or more eggs by creating rows of slits along the edges of needles, typically placing one egg per slit. Eggs remain viable even if the female is unmated; fertilized eggs give rise to both male and female offspring, whereas unfertilized eggs produce only males.[5] As they mature, larvae drop to the ground and spin cocoons in the soil, where they pupate before emerging as adults.[1]

Larvae hatch from eggs in 15 to 30 days and feed together on pine needles.[4] They usually eat one branch completely from top to bottom before moving to the next. Sometimes, they also feed on the soft bark of young twigs.[4]

The speed of larval development depends on the air temperature the cooler it is, the slower they grow and it may complete between 1 and 5 generations per year.[3,4] Larvae are typically present from late May through late October, with peak activity occurring between late July and September.[3] However, this pattern varies significantly with geography. In Canadian populations, only one generation occurs annually, and larvae are generally absent by mid-September.[3] In contrast, southern populations, such as those in Florida, may remain active year-round and bypass overwintering entirely.[3] This variation has direct implications for pest control strategies, as the timing and frequency of interventions must align with local population dynamics.

Adults usually emerge within one to two weeks after pupation.[11] Shortly after eclosion and drying, females begin calling males through a strong long-range sex pheromone, which ensures efficient mate attraction.[11] While females are monogamous, males may mate with more than one partner, and oviposition from virgin females appears to be rare.[11] Adult longevity varies depending on sex, with females living on average 4.5 days, ranging from 2 to 17 days, while males average 3.2 days, with a range of 1 to 17 days.[11] The adult flight period also differs geographically, lasting about 2 to 3 weeks in the South and extending up to 5 to 6 weeks in the North.[11]

Physical Description and Distinguishing Features

The redheaded pine sawfly (RPS) exhibits distinct morphological characteristics across its life stages. It is important to understand these stages for accurate identification.

- **Adults:** Adult sawflies have a broad waist in contrast with many other hymenopterans, and have two pairs of membranous wings.[2] Adults are 0.5–0.85 cm (1/5–1/3 inch) in length, possess two pair of wings, with the females being approximately two-thirds larger than the males.[2,5] Females are mostly black with a reddish brown head, and occasionally white on the sides of the abdomen. Females have 19-segmented, serrated (saw-toothed) antennae, and male antennae are featherlike.[2]
- **Cocoon (Pupa):** Pupation typically begins shortly after warm spring temperatures arrive.[11] The cocoon is spun in the upper layer of the soil and is approximately 1.25 cm (approx. 1/2 in) in length.[2] The cocoon is a reddish-brown paper-like cylinder with rounded ends.[2] Prepupae overwinter in cocoons and, once adults emerge, the cocoons are left behind with a large circular hole in one end.[2]

- **Eggs:** The eggs are oval, smooth and shiny, translucent white and approximately 1.8 mm (1/12 in) long and 0.6 mm (approx.1/40 in) wide when ready to hatch.[2] Each egg is deposited into a separate slit incised by the female's ovipositor along the pine needle tissue, oviposited eggs are evident by small discolored patches in a row on the needle.[2] Unlike some other *Neodiprion* species, eggs of *Neodiprion lecontei* are typically laid on a single branch tip.[3] Eggs appear as brown spots on needles.[7]
- **Larvae:** Larvae emerge after two to three weeks and are whitish with a brown head capsule.[2] As larvae mature, they become yellow to green with brown heads.[2] Mature larvae are approximately 2.5 cm (1 in) long and have a red to reddish-orange head.[2] The mature larvae are yellow to yellow-green in color and have four to eight rows of black spots lengthwise along the body.[2] Each larva has three pairs of thoracic legs and six to seven pairs of prolegs.[2] At first glance, sawfly larvae look like caterpillars of moths or butterflies. The key difference is that sawfly larvae have more than five pairs of fleshy legs on their abdomen and only one eye on each side of the head, while moth and butterfly larvae have five or fewer pairs of fleshy legs and six eyes on each side.[4] Redheaded pine sawfly larvae may lift the front and rear portions of their bodies in a defensive mechanism if threatened and regurgitate a chemical sequestered from the pine needles in an attempt to thwart potential predators.[2] Although larvae generally feed within the same area of a single tree, *Neodiprion lecontei* larvae may travel several yards across the ground in search of new feeding sites.[4]

Host Plants and Feeding Behavior

RPS primarily feeds on a variety of pine species using chewing mouthparts adapted for consuming needles. It usually feeds on young trees, preferably 0.3-4.6 m tall and under moisture stress.[6,3] Trees growing under stress in shallow soils, very wet or dry sites, or under stress from competing vegetation are especially susceptible to infestation and heavy defoliation.[6] Its primary hosts include native pines such as jack pine, red pine, shortleaf pine, Virginia pine, slash pine, and loblolly pine.[3] Additionally, it can infest nonnative species like pond pine, sand pine, and pitch pine, while less commonly affecting eastern white pine, Scots pine, Norway spruce, and larches.[3] Infestations by RPS larvae can cause significant needle defoliation, which may weaken the host tree and reduce growth.[3]

Feeding begins soon after larvae emerge, typically two to three weeks after egg deposition. At this early stage, the larvae are whitish with brown head capsules and begin feeding in gregarious groups.[2] Initial feeding behavior is characterized by younger larvae consuming only the outer edges of pine needles, leaving behind the central tissue, which subsequently wilts and turns straw-like in appearance.[2,5] As they mature, larvae change in color to yellow or yellow-green, develop rows of black spots along their bodies, and grow up to 2.5 cm in length, eventually gaining the capability to consume entire needles.[2] In cases of heavy infestation, this complete defoliation leads the larvae to migrate to nearby trees in search of new foliage. When foliage becomes scarce, they can resort to feeding on the soft bark tissues of previously defoliated trees, further compounding the damage.[2] This progressive feeding behavior, from partial needle removal to complete defoliation and bark feeding, especially on stressed or young trees, makes RPS an aggressive and structurally damaging pest.[2,5,4]

Geographical Distribution

The redheaded pine sawfly is native to the United States and found primarily east of the Great Plains, north into Canada, and south into Florida and Texas.[2]

Table 1: Key Characteristics of Redheaded Pine Sawfly Life Stages

Life Stage	Size (approx.)	Color/Appearance	Key Distinguishing Features	Typical Location

Adults	0.5–0.85 cm	Black with a reddish brown head	Two pairs of membranous wings	
Pupae	1.25 cm	Reddish-brown paper-like cylinder with rounded ends		On pine needles or beneath the tree
Eggs	1.8 mm	Oval, smooth and shiny, translucent white	Typically laid on a single branch tip, causing brown spots	Pine needle tissue
Larvae	2.5 cm	Whitish with a brown head capsule, as they mature yellow to yellow-green in color and have four to eight rows of black spots lengthwise along the body	Have more than five pairs of fleshy legs on their abdomen and only one eye on each side of the head	Pine needle

IV. Management and Control Strategies

Effective management of the redheaded pine sawfly requires a comprehensive and adaptive strategy, primarily rooted in Integrated Pest Management (IPM) principles.

Integrated Pest Management (IPM) Principles for RPS

Integrated Pest Management is a system that combines cultural, biological and chemical technologies to reduce insect, fungal and weed populations to levels below those that result in economic damage.[8] A holistic IPM approach is essential to prevent the redheaded pine sawfly from spreading to larger areas and causing further damage to pine trees. This approach primarily involves improving the overall health of the tree, conducting regular inspections during specific stages of the insect's life cycle, and when necessary, removing larvae with water or terminating them using insecticides.[9]

Monitoring and Early Detection Methods

Within the IPM framework, monitoring and early detection represent one of the most important measures for reducing RPS spread and damage, as they allow for timely identification of infestations and prompt implementation of control actions.

- **Population Monitoring via Aerial Imagery**
  Aerial imagery has long been employed as a method for detecting invasive species and forest defoliation. Decades ago, this method relied on manually drawn maps, whereas today it is applied through the processing of images obtained from satellites or drones.[3] More recently, machine learning models capable of performing invasive species detection using imagery captured by unmanned aerial vehicles have been developed.[12] Although there is no direct aerial imagery study for RPS, the body of research conducted to date demonstrates both the value of aerial imagery in detecting harmful species and its potential to remain a widely used approach in the future.
- **Population Monitoring via Pheromone Traps**

  Redheaded pine sawfly males are strongly attracted to female sex pheromones, which makes pheromone-baited traps a practical tool for both monitoring and management.[1,3,10] Using synthetic pheromone blends, researchers can reliably capture male sawflies and determine their diurnal and seasonal flight activity, providing important information about local population densities and periods of peak activity.[3] In addition, pre-exposure of host pine trees to sawfly pheromones has been shown to reduce egg survival, indicating that pheromone-based strategies can enhance tree defenses and further limit larval emergence.[10] Pheromone traps are not only useful for monitoring but can also be applied in attract-and-kill approaches, where males are lured into traps to disrupt mating and reduce the reproductive potential of local populations.[3] The effectiveness of these traps, however, can be influenced by environmental conditions such as temperature, wind, and rainfall, and pheromones have a limited effective range, which means that their impact is generally restricted to local or isolated stands.[2,3] Despite these limitations, when implemented strategically within an IPM framework, pheromone traps offer the dual benefit of providing accurate population data while actively contributing to population suppression, making them an important component in controlling RPS outbreaks.

Biological Control

Redheaded pine sawfly populations are regulated by a wide range of natural enemies, including vertebrates, invertebrates, and microbial agents.[2,3] Birds and small mammals commonly prey on larger larvae and cocoons, contributing significantly to mortality rates, sometimes up to 70%.[3] Among invertebrate predators, arachnids, hemipterans, hymenopterans, and dipterans attack eggs, larvae, pupae, and adults. Fungal pathogens and nucleopolyhedroviruses (NPVs) have been documented to reduce RPS populations effectively.[3] Additionally, environmental factors such as extreme heat or cold can further decrease larval survival.[2] The combined impact of these natural enemies maintains RPS populations at manageable levels, though the intensity of these effects varies depending on location, season, and sawfly life stage.

Support for native natural enemies can enhance control efficiency and reduce the need for chemical interventions.[11] For example, parasitoid Hymenoptera, which feed on nectar, pollen, or honeydew, show increased parasitism rates when these food resources are available near pine stands. The nuclear polyhedrosis virus (NPV) occurs naturally in RPS populations and can be applied deliberately to accelerate mortality, acting as an effective microbial control agent.[11] While the introduction of new natural enemies is costly and logistically complex, optimizing the habitat for existing predators and parasitoids provides a sustainable and practical approach. These strategies highlight how ecological management can leverage the full potential of biological control within integrated pest management programs for RPS.

Cultural Control Practices

Maintaining tree health and vigor is a fundamental component of managing redheaded pine sawfly populations, particularly in commercial, natural, or managed landscapes. Healthy trees can tolerate levels of defoliation typically caused by sawflies, and improving overall tree resilience reduces susceptibility to infestation.[3] Silvicultural practices that minimize competition for resources, such as selective thinning and appropriate spacing, help maintain tree vigor. Trees under moisture stress or in highly competitive environments are more likely to suffer damage from sawfly attacks, making the optimization of stand conditions a key preventive measure.[3] Prescribed fire can also serve as a cultural control method, killing eggs on needles and pupae near the ground, thereby reducing overall larval populations.[3] In addition, heterogeneous forest environments that increase structural and floral diversity can enhance predation on sawfly cocoons by small mammals and generalist arthropods, further supporting natural population suppression.[3]

For small-scale or localized control, mechanical removal of larvae or eggs remains a practical approach. Larvae can be hand-picked or dislodged from foliage by shaking branches, then collected in a bucket of soapy water, ensuring immediate removal from the environment.[2,3] Historical and contemporary recommendations emphasize the importance of proper tree placement and stand composition to reduce infestation risks. For example, planting pines away from overtopping hardwoods, avoiding high-stress sites, and selecting host species less susceptible to sawfly damage can all contribute to decreased vulnerability.[11] Soil management practices, including fertilization and composting, have also shown promise in reducing larval feeding and mortality, further supporting the integration of cultural control strategies alongside biological and chemical management within an IPM framework.[11]

Chemical Control

The management practices described above have often succeeded in limiting the spread and damage of RPS without relying heavily on pesticides.[3] Still, several active ingredients are known to be effective against sawflies. Systemic and contact insecticides such as pyrethroids, carbamates, and organophosphates have historically been applied and remain effective in controlling larvae.[3] When monitoring indicates the presence of young larvae, spot treatments with products like azadirachtin, horticultural oils, insecticidal soaps, organophosphates, pyrethroids, or spinosyns are recommended.[9] Correct application is essential because larvae can be hard to reach while feeding deep within host foliage. For large forested or natural areas, aerial spraying may be required, whereas tree injection methods are more practical for individual trees or urban sites.[3]

In ornamental plantings and Christmas tree production, localized sprays with a registered insecticide should be applied as soon as new colonies are detected, since infestations typically appear sporadically between May and September.[6] As with any pesticide use, label directions on dosage and safety must be followed precisely.[6]

V. Available Datasets and Resources

Datasets and resources on the redheaded pine sawfly are important for understanding its potential economic and ecological impacts, its biology, and its spread. They provide a foundation for studying the species and supporting future research efforts.

Image Datasets for RPS

Image datasets are essential for training machine learning and deep learning models to automatically detect presence and damage of RPS and other invasive species.

- **General Visual Resources:**
    - The websites invasive.org[13], bugguide.net[14] and forestryimages.com[16] can be regarded as comprehensive visual resources for *Neodiprion lecontei*. They contain images depicting all life stages of the species, including eggs, larvae, pupae, and adults, as well as detailed examples of the damage they inflict on pine trees.
    - Additionally, inaturalist.org[17] provides community-contributed observations and photographs of Neodiprion lecontei, covering various life stages and occurrences, alongside general information about the species' biology and ecology.

Table 2: Overview of Image Datasets for RPS

Dataset Name	Primary Focus	Number of Images	Key Features / Purpose
Invasive.org[13]	Invasive and pest species (including RPS)	~350	High-quality diagnostic photos, educational resource for pest ID
Forestry Images[16]	Forest pests and management	~350	Focus on forestry damage, life stages, host interactions

Bugguide[14]	Community-curated insect ID	~70	Wide coverage of life stages, location data from citizen scientists
iNaturalist[17]	Biodiversity observations	~500	Crowdsourced images, geotagged occurrences

Genetic and Genomic Datasets

Genetic and genomic resources are key to understanding the biology, morphology, and evolution of the redheaded pine sawfly. Currently, several datasets on RPS are publicly available.

- Vertacnik et al. (2023) have shared a dataset on Dryad that examines the evolution of five environmentally responsive gene families in the *Neodiprion lecontei.*[17] This dataset includes multiple sequence alignment files and manually curated gene annotations for CYP450, gustatory receptors (GR), odorant receptors (OR), odorant binding proteins (OBP), and Hisnavicin sequences.[17] Researchers can use these data to study how *N. lecontei* adapts to pine hosts, analyze genetic responses to environmental factors, and investigate the evolutionary processes shaping these gene families.[17] The dataset provides a valuable resource for comparative genomics studies, functional analyses of gene families, and research on adaptive evolution.[17]
- Bagley et al. (2016) have shared a dataset on Dryad that examines genome-wide patterns of genetic variation in the *Neodiprion lecontei* across eastern North America.[18] The dataset includes raw VCF files, input files for ADMIXTURE and DAPC analyses, and demographic modeling data for fastsimcoal2.[18] These data were generated using double-digest restriction-associated DNA (ddRAD) sequencing and are intended to assess the effects of history, geography, and host use on population structure.[18] Researchers can use this dataset to study genetic differentiation among populations, analyze isolation-by-distance and isolation-by-environment patterns, and investigate demographic history.[18] Overall, the dataset provides a comprehensive resource for understanding how divergent host use and geographic factors contribute to genetic variation in *N. lecontei*.[18]
- The NCBI Annotation Release 101 provides a comprehensive gene annotation for *Neodiprion lecontei*.[19] This dataset includes the iyNeoLeco1.1 assembly and annotates a total of 14,732 genes, of which 11,969 are protein-coding and 2,631 are non-coding.[19] The dataset contains mRNA sequences, non-coding RNA sequences, gene lengths, and exon-intron structures, and the completeness of the annotation has been assessed using BUSCO.19 Researchers can use these data to study gene functions in *N. lecontei*, support gene expression analyses, and perform comparative genomics.[19] This resource provides an essential foundation for understanding the genome structure of the redheaded pine sawfly and for addressing biological, functional, and evolutionary questions.[19]

Table 3: Key Genetic and Genomic Datasets for RPS

Dataset Name	**Type of Data**	**Key Contents / Purpose**	**Access Information**
Evolution of five environmentally responsive gene families in	Genomic	Multiple sequence alignments and manually curated gene annotations for CYP450, GR, OR, OBP, and Hisnavicin; used to study adaptation to pine hosts, genetic responses to	Dryad, (https://doi.org/10.5061/dryad.n8pk0p320)[17]

redheaded pine sawfly		environmental factors, and evolution of gene families	
Genomic patterns of population structure in the redheaded pine sawfly (*Neodiprion lecontei*): effects of history, geography, and host use	Population Genetic	Raw VCF files, input files for ADMIXTURE and DAPC analyses, demographic modeling data for fastsimcoal2; used to study population structure, isolation-by-distance, isolation-by-environment, and demographic history	Dryad, (https://doi.org/10.5061/dryad.vh75r)[18]
NCBI *Neodiprion lecontei* Annotation Release 101	Genomic	Gene annotations for iyNeoLeco1.1 assembly; 11,969 protein-coding genes, 2,631 non-coding genes; includes mRNA and non-coding RNA sequences, exon-intron structures, and BUSCO completeness assessment; used for functional genomics, gene expression analysis, and comparative genomics	NCBI, (https://www.ncbi.nlm.nih.gov/refseq/annotation_euk/Neodiprion_lecontei/101/)[19]

Population Monitoring Data

Population monitoring data, in addition to genetic and image-based resources, play an important role in understanding how redheaded pine sawfly populations spread, estimating potential risks, and assessing how well different management approaches work.

RPS Population Data

- Across the United States, redheaded pine sawfly populations show a consistent latitudinal cline in voltinism: populations are typically univoltine (~1 generation per year) in the northern U.S. and southern Canada, increase to 1–2 generations at mid-latitudes, reach 2–3 generations in the Mid-Atlantic/Southeast (e.g., Virginia), and can attain up to five generations in the Deep South during warm years.[4,11] This gradient, governed primarily by growing-season length and thermal accumulation, necessitates region-specific monitoring designs. In multivoltine regions, higher sampling frequency and explicit phenology tracking are warranted, and the timing of treatments should account for diapause and overlapping cohorts to maintain efficacy.[11,20]

VI. Ongoing Research and Future Prospects

While current management strategies provide a significant foundation for the control of the red-headed pine sawfly (RPS), ongoing ecological shifts and technological advances are shaping future research directions. Future research focuses include the potential impacts of climate change on insect-host interactions, understanding the natural defense mechanisms of host trees and utilizing advanced pest detection technologies.

Climate effects

Climate change is a critical area of research that could have significant impacts on the population dynamics and geographic distribution of RPS. Rising temperatures has direct affect on the physiological development rates and geographic distributions of insects.[21] As noted earlier in this report, the number of generations per year (voltinism) of RPS varies with latitude; warming climates may allow the insect to produce multiple generations per year in more northern regions. This could increase the frequency of outbreaks, putting larger areas of forest at risk. Future research should focus on modeling RPS population dynamics using regional climate projections and assessing the vulnerability of forests to these changes.

Advanced Detection Methods

Unmanned aerial vehicles (UAVs) and machine learning, as discussed earlier in the report, offer significant potential for RPS detection.[12] These tools allow large forest areas to be monitored efficiently, providing early identification of pest infestations before outbreaks reach critical levels. Recent studies have shown that integrating UAV imagery with computer vision models can accurately detect affected trees and estimate infestation severity in real time.[24] Implementing these advanced detection methods could improve early warning systems and reduce reliance on chemical controls while supporting sustainable forest management strategies.

Sustainable Management Integration and Long-Term Vision

To reduce reliance on chemical methods to combat RPS, understanding and utilizing the natural defense mechanisms of host trees is gaining importance. Conifers are known to possess integrated defense systems that combine anatomical barriers with chemical compounds such as resins and terpenoids.[22] Future studies should focus on identifying the specific defense compounds most effective against RPS larvae and the genetic mechanisms that trigger their production. Furthermore, the role of environmental stressors such as drought in weakening trees' defensive capacity, making them more vulnerable to insect attacks, is an important research topic.[23] Therefore, understanding these mechanisms and considering the effects of environmental stressors will be a crucial step in reducing reliance on chemical methods and strengthening the natural defenses of trees against RPS.

VII. Conclusions

Neodiprion lecontei is a significant defoliator of young and stressed pine stands, occurring throughout North America and extending into Mexico. The species' voltinus division varies with latitude and temperature conditions, reflecting temperature fluctuations and direct temperatures that contribute to its damage. The information presented in this report is integrated with current literature, including a review of host preferences, biological cycles, damage patterns, and available management methods.

Early detection and timely intervention are crucial for management. Regular control of eggs and early-stage larvae, reducing heavy infestations in small seedlings by hand or pruning, protecting natural enemies, and carefully applying selective insecticides when economic damage thresholds are exceeded are key steps for integrated management. The use of pheromone traps validated at the species level facilitates early warning and population monitoring, while natural mortality from nucleopolyhedrovirus contributes to population suppression. In nurseries and plantations, maintaining healthy seedlings through irrigation and feeding during dry periods is crucial to limiting the species' potential for multiple generation.

Research priorities can be summarized in several directions. First, there is a clear need for reliable phenology models that can show how many generations occur in different regions and how long each developmental stage lasts. These models should be based on local temperature and photoperiod data so that they reflect field conditions more accurately. Second, pheromones specific to *N. lecontei* should be tested and standardized under real field conditions. This includes not only identifying the most effective pheromone blends but also determining how many traps should be placed per area and what level of trap catch should be considered as a warning threshold. Third, large-scale detection systems should be developed to monitor damage across forests and plantations. Remote sensing tools, combined with machine learning approaches, can make it possible to identify outbreaks earlier and with less labor. Finally, the growing amount of genomic data provides an important opportunity. By using these resources, it is possible to study host defense mechanisms, larval detoxification processes, and how the insect interacts with biological control agents in greater depth.

Consequently, management of *N. lecontei* relies on regular monitoring, protection of beneficial organisms, and appropriate chemical interventions. Filling these information gaps will both improve timing accuracy and reduce unnecessary input use, resulting in more sustainable outcomes in forestry and nursery systems.

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