Technical Note
Science and Research Branch
Ministry of Natural Resources and Forestry

Hemlock woolly adelgid: Management guidelines to increase the resilience of Ontario’s eastern hemlock resource to an exotic, invasive insect

William C. Parker[1], Victoria Derry[2], Ken A. Elliott[1], Chris J.K. MacQuarrie[2] and Sharon Reed[1]

[1] Ontario Ministry of Natural Resources and Forestry
[2] Natural Resources Canada-Canadian Forest Service

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Note: Additional supporting information is available in research article by Parker et al. (2023).

Eastern hemlock

Eastern hemlock (*Tsuga canadensis*) is a long-lived, slow growing, late successional tree species that occurs in pure and mixed stands in cool, humid regions of eastern North America (Figure 1). It is shallow rooted, very intolerant of drought, and most common on sites with a relatively constant soil moisture supply. In Ontario, hemlock is most abundant on sheltered, moist north facing slopes with coarse to medium textured soils in association with eastern white pine (*Pinus strobus*), northern white cedar (*Thuja occidentalis*), yellow birch (*Betula alleghaniensis*), American beech (*Fagus grandifolia*), red oak (*Quercus rubra*), and red (*Acer rubrum*) and sugar (*A. saccharum*) maple. Hemlock is also very shade tolerant and adapted to a disturbance regime characterized by periodic formation of small canopy gaps. It can survive long periods of heavy shade and trees up to 400 years old will grow in response to improved light conditions after gap formation. The largest, most rapid growth response to canopy disturbance occurs in comparatively healthy trees with live crown ratio (LCR) ≥50%.

Hemlock is a foundation species with architectural features and functional traits that define forest structure and drive ecosystem dynamics. Hemlock forest canopies create a cool, shaded understory environment for unique terrestrial and aquatic communities, and provide habitat for white-tailed deer and several bird species (Figure 2). Old growth hemlock stands are highly prized for their aesthetic, recreational, and ecological value. Hemlock is of relatively little economic interest and is commonly processed for lower grade lumber products for limited markets. Hemlock is of cultural importance to Indigenous communities — they use inner bark extracts for tanning and to produce teas and medicines. The abundance and extent of hemlock in Ontario was much reduced during European settlement. Hemlock now occupies about 1 million ha of Crown land, parks and protected areas, and private land, represents about 1% of the total provincial growing stock, and is most extensive in Ecoregion 5E (Figure 3). About 22,000 ha (14%) of hemlock-dominated forests are old growth, most of which is in parks and protected areas.

Figure 1. Profile of mature eastern hemlock in J.W. Wells State Park, Michigan. Photo credit: William Parker.

Figure 2. Canopy of mature eastern hemlock. Photo credit: William Parker.

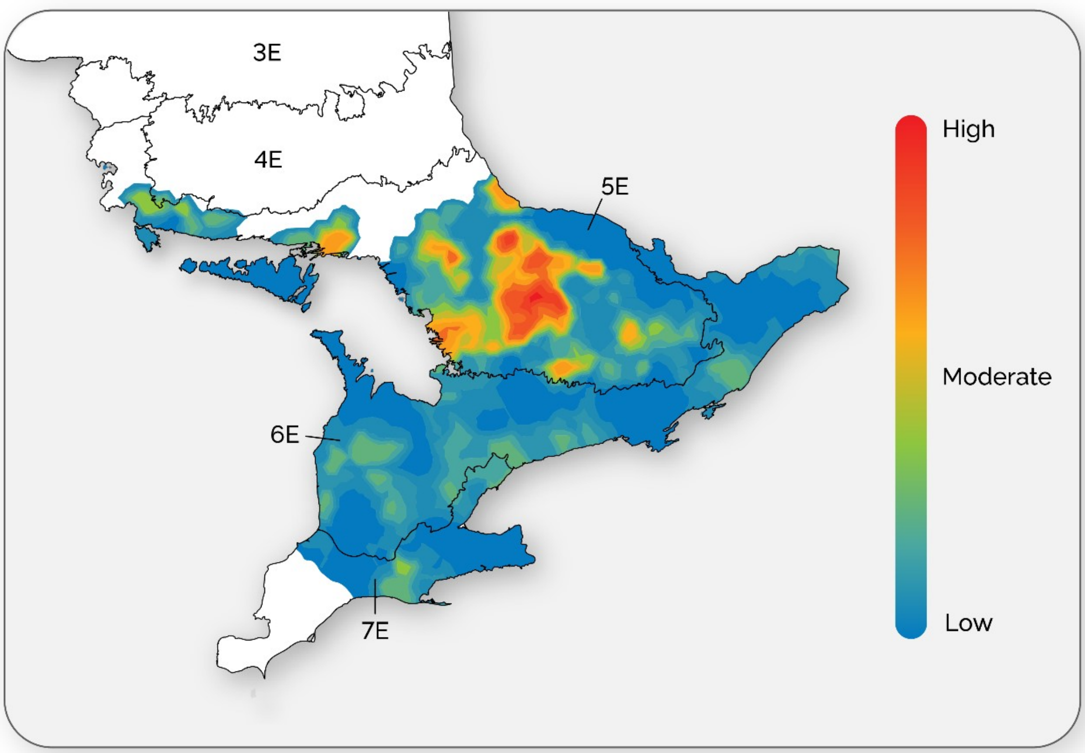

Figure 3. Relative abundance of eastern hemlock in Ontario by ecoregion (Parker et al. 2023). White portion of the map is outside the natural range of hemlock.

Hemlock woolly adelgid

Hemlock woolly adelgid (*Adelges tsugae*) (HWA) is native to Asia and western North America where it is a common inhabitant of hemlock and spruce. Since its accidental introduction to eastern North America more than 70 years ago, HWA has spread and caused considerable damage to eastern hemlock throughout more than half of its natural range in the United States (Figure 4). Within the last 15 years, HWA has become established in the southern half of Nova Scotia and in several small areas in southern Ontario. Hemlock has very little resistance to this sap-feeding insect, and infested trees of all ages and sizes show crown decline, reduced growth, and mortality within 4 to 15 years depending on climate and other factors. Mortality due to HWA has considerable effects on biodiversity, carbon and nutrient cycling, hydrologic processes, and other functions of pure and mixed hemlock forest ecosystems (Figure 5).

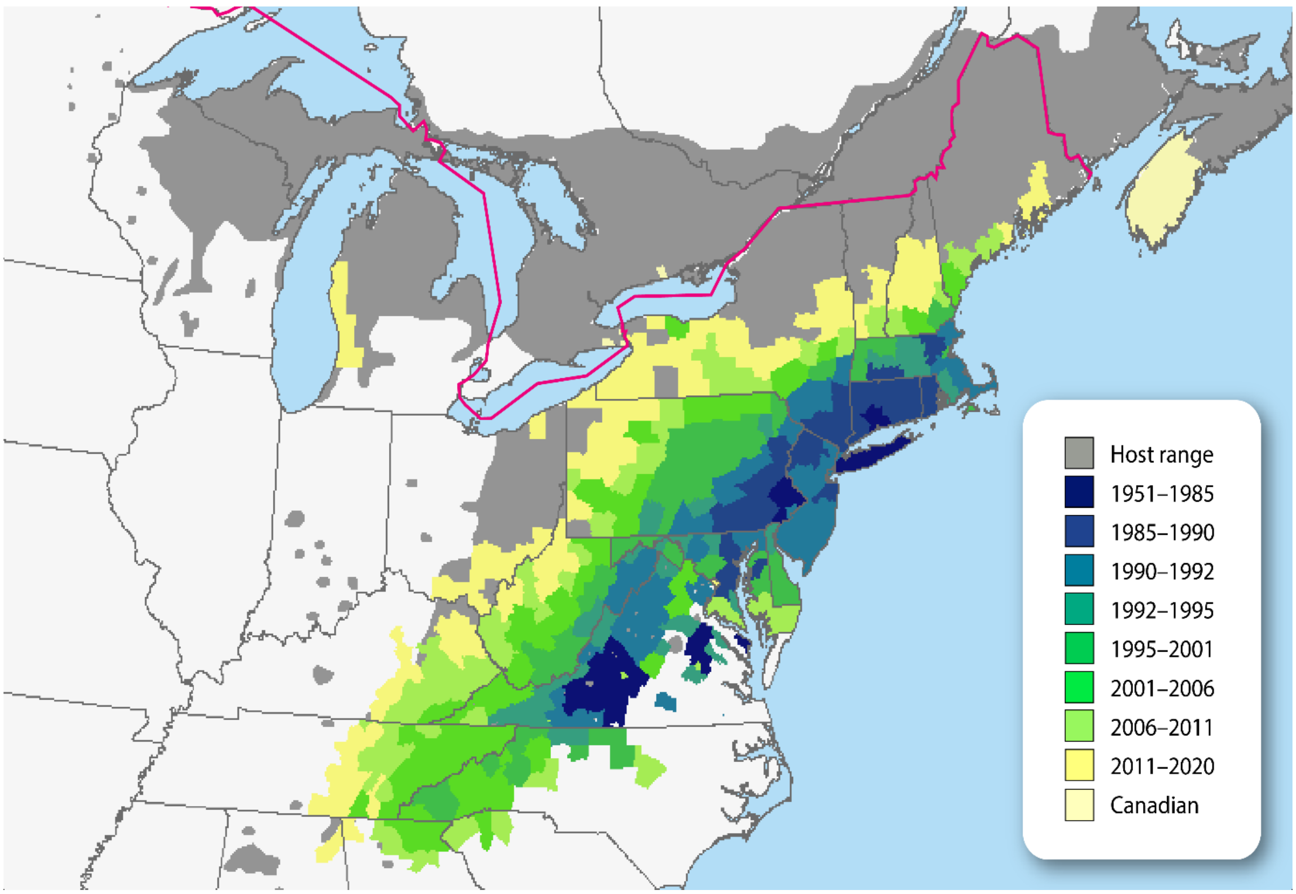

Figure 4. Period of hemlock woolly adelgid establishment in eastern North America (Parker et al. 2023).

Figure 5. Hemlock mortality caused by hemlock woolly adelgid in Nantahala National Forest, North Carolina, USA. Photo credit: William M. Ciesla, Forest Health Management International, Bugwood.org

Hemlock woolly adelgid has a complex life cycle with 2 generations per year each having several larval or nymph stages with alternating periods of movement, settling, and dormancy (Figure 6). Both generations are female and reproduce asexually. The nymphs of the overwintering sistens generation emerge from eggs in summer in a mobile crawler stage that moves short distances in the tree to settle on nearby, newly formed shoots. It pierces the base of needles with specialized mouth parts to access storage cells in the xylem (Figure 7). The nymph then remains stationary and enters a dormant phase. In early autumn, the insect breaks dormancy, begins to feed, and produces a white, woolly wax covering from which it derives its common name. It develops and feeds until early winter and produces 50–175 eggs that hatch in early spring to form the second, short-lived, progrediens, generation. The crawlers of this stage disperse and settle on the previous year's shoots, begin to feed and produce wool, and lay 25–125 eggs in late spring that become the next sistens generation. The progrediens generation also produces a winged, sexual phase that disperses away from the host tree but does not survive in North America. The insect remains stationary for most of its life and is dispersed locally during the crawler stage by birds, wind, mammals, and people. Longer distance dispersal occurs via migrating birds, and human activities such as transport of firewood, harvested logs, and ornamental nursery stock.

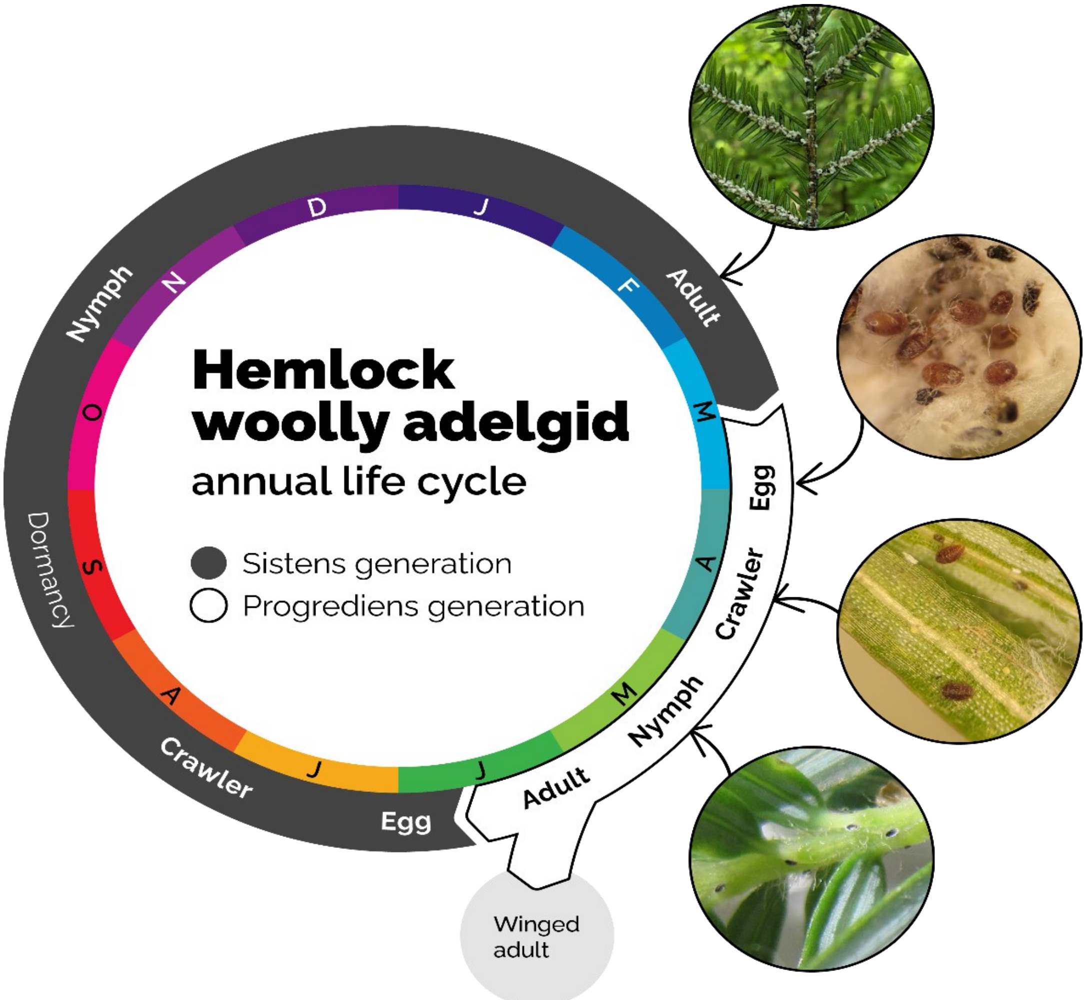

Figure 6. The life cycle of hemlock woolly adelgid by season in eastern Canada (Parker et al. 2023).

The resistance of hemlock to HWA attack is limited to a so-called hypersensitive response that induces the synthesis of chemical defences to increase the resistance of injured and nearby tissues. This response is largely ineffective and is the primary cause of needle shedding and progressive crown decline observed in infested trees (Figure 8). Insect feeding coupled with reduced leaf area and photosynthetic capacity depletes carbohydrate reserves, gradually erodes a tree's carbon balance, and results in mortality. The rate at which infested trees decline and die depends on climate and stand, tree, and site factors that affect both hemlock vigour and HWA population size (Table 1). Stands and trees on cool, mesic sites with deep, fertile soils and a continuous supply of soil moisture are more resilient to (i.e., tolerant of) infestation, while those occupying drought prone sites rapidly decline and die. Slow growing, overstocked stands are also less resilient to HWA due to increased competition for resources and lower tree vigour. Regardless of stand and site conditions, dominant and co-dominant hemlock trees with large crowns (LCR $\geq$50%) are more resilient than damaged and suppressed trees with small crowns (LCR $\leq$30%). Discovery of surviving trees in infested areas where most hemlock trees died suggests that some hemlock populations may be genetically resistant. Research is being directed towards the propagation and testing of these apparently resistant individuals.

Figure 7. Scanning electron microscope image of hemlock woolly adelgid. Note stylet feeding tube used to penetrate hemlock needles. Photo credit: Kelly Oten, North Carolina State University, Bugwood.org.

At the tree and stand scales, HWA prefers comparatively sheltered environmental conditions. HWA density is higher in cooler, shaded crown locations and higher density undisturbed stands. Regional climate also influences HWA population size and infestation severity. Population growth of HWA is strongly influenced by overwinter mortality of the sistens generation, and the current northern range limit of this insect coincides with average annual minimum temperatures of −23.4 to −26.1°C (Figure 2). Low to moderate mortality of the sistens generation during its dormant phase also occurs after exposure to relatively brief periods of high summer temperatures. Despite climatic controls on population growth, the high fecundity of HWA and the lack of specialized natural predators allows populations to quickly recover from periodic exposure to lethal climatic extremes. Although the comparatively cold winters of hemlock's northern range has slowed the spread of HWA, continued climatic change and other factors threaten to facilitate its further dispersal and establishment in Canada. HWA establishment throughout southern Nova Scotia is thought to be linked to warming winter climate and transport by migrating birds.

Figure 8. Infested hemlock showing leaf loss and crown decline in Nantahala National Forest, North Carolina, USA. Photo credit: William M. Ciesla, Forest Health Management International, Bugwood.org

Table 1. Stand, site, and environmental conditions that favour (a) hemlock survival and (b) hemlock woolly adelgid population growth.

(a) Favour hemlock survival	(b) Favour hemlock woolly adelgid
• Minimum stocking level with 70% crown closure • Live crown ratio ≥50% • Continuous supply of growing season soil moisture • Cool, mesic topographic positions • Deep, fertile, loamy soil	• High leaf nitrogen concentration • Cool, shaded crown locations (≤30% sunlight) • Warmer, minimum winter temperature • Cooler, maximum summer temperatures

Managing hemlock woolly adelgid

Over the past three decades, much basic and applied research on the biology, spread, effects, and control of HWA has been conducted in the eastern United States. The ultimate objective of this research effort is to develop effective integrated pest management approaches to mitigate the impact of this insect at the landscape scale. Although hemlock forests in this part of its natural range may differ in structure, climate, soils, and physiography from Ontario's hemlock forests, these results can be used to develop science-informed management recommendations to increase hemlock resilience and reduce future effects of HWA in the province.

Biological control is a crucial component of integrated pest management of HWA. The most promising approach is the use of complexes of the beetle *Laricobius nigrinis* and 2 species of silver fly (*Leucotaraxis argenticollis* and *L. piniperda)* native to western North America that provide effective population control of HWA due to their prey specificity and feeding during both the progrediens and sistens generations. Potential deployment of these insects for stand to landscape scale control of HWA in Canada and more northern regions of hemlock's range is currently being tested. Chemical control of HWA at tree and stand scale with foliar and systemic insecticides is an effective but relatively expensive and time consuming method of temporarily reducing HWA damage. Three systemic insecticides applied through stem injection of individual trees are registered in Canada for use against HWA. These compounds differ in the speed and longevity of effective control. TreeAzin (azadirachtin 5%) works relatively quickly, becomes effective within 1 month of application, and provides protection for 1–2 years. IMA-jet (imidacloprid 5%) and IMA-jet 10 (imidacloprid 10%) require 6–9 months to provide insect control but remain effective for 4–7 years. A third systemic insecticide applied via basal bark spray to individual trees is also registered. Xytect is also an imidacloprid formulation, with properties similar to IMA-jet, and is available under emergency registration in Ontario and Nova Scotia until August 2024 at a minimum. Given the lack of biological control agents and the limits of insecticides, silvicultural intervention is an important tool for managing HWA and its impacts. Chemical control options can be considered for use alone or in combination with silviculture, and biological control can be used in infested stands when available.

Stand management treatment options differ among 4 general stages of HWA invasion defined by the relative abundance of this insect in stands and across the landscape (Table 2). Before HWA establishes, intervention consists of proactive, timely application of sustainable management practices to increase the health, growth, and resilience of the hemlock resource as described in regional silviculture guides. Because slow growing, suppressed hemlock trees exhibit more rapid decline and mortality after infestation, intervention could focus on stand density regulation to (1) reduce competition and improve the vigour of larger, residual hemlock canopy trees, (2) remove damaged and suppressed hemlock trees with little probability of exhibiting a positive growth response and surviving HWA, and (3) to create a suboptimal microclimate for HWA. Where hemlock is a dominant stand component, partial harvest to minimum acceptable stocking levels should increase tree vigour and residual tree crown size. In stands with a minor hemlock component, crown release on 2 to 3 sides of codominant and dominant hemlock is a viable approach. These management actions could be undertaken a decade or more before HWA arrival, given the slow hemlock growth response to reduced stand density. Importantly, these practices will also help adapt hemlock to climate change stresses, particularly where species and structural diversity are enhanced.

After successful HWA dispersal and establishment, management could shift to a sequence of 3 discrete but interrelated stages: (1) sanitation to minimize spread, (2) stand conversion and mitigation of the ecological effects of hemlock mortality, and (3) restoration of hemlock and evergreen conifer to the so-called aftermath forest. The specific silvicultural approaches used will depend on the abundance and distribution of hemlock and other species present in the affected stand. In all 3 stages, management practices can include canopy retention and regeneration of evergreen conifers such as white (*Picea glauca*) and red spruce (*P. rubens*), white pine, white cedar, and balsam fir (*Abies balsamea*) to restore some of the ecological functions of hemlock to the stand. The aftermath forest will provide areas for future restoration programs that may span decades.

Forest managers will need to use a triage approach to guide identification of stands for intervention as tempered by other objectives for a given land base. For example, intervention could be focused on more vulnerable stands such as those in ecoregions 6E and 7E with warmer, winter temperatures or sites with nutrient and moisture limitation. Alternatively, priority could be based on the likelihood of stands exhibiting a timely, positive response to treatment, such as those on more mesic, fertile sites and in riparian areas where hemlock grows best. Less vulnerable but higher value areas such as old growth stands and conservation reserves might be identified for priority treatment. Timing of intervention may also be based on the probability of HWA becoming established due to nearby stand scale features that favour its dispersal, such as deer yards or high public use areas that concentrate human activity. Some stands may not receive any treatment due to poor access and other factors but will instead be left to respond through natural processes. Regardless of management options selected, we caution against pre-emptive salvage of hemlock for short-term economic benefit. This approach can have more adverse ecological effects than mortality by HWA alone and may hamper the identification of genetically resistant hemlock for use in breeding programs that may contribute to restoration efforts.

Monitoring is a key component of integrated management responses selected to reduce the stand- and landscape-scale effects of HWA. It can be used to determine if management objectives are being met, to test the science-based management guidelines applied, and to adjust management plans as needed based on observations of hemlock response to treatments. Monitoring is also essential for early detection of the presence and potential establishment and spread of HWA.

Please report possible HWA detections to EDDMapS (Early Detection and Distribution Mapping System) at www.eddmaps.org.

Table 2. General management recommendations for hemlock stands at four stages of hemlock woolly adelgid invasion.

Stage of invasion:	**Not present**	**Low abundance, isolated populations**	**High abundance or widely established**	**High abundance or endemic**
Management objective:	Increase resilience	Minimize spread	Minimize effects	Minimize effects
Strategy:	Density regulation	Sanitation	Stand conversion	Restoration
Canopy recommendations:	Remove damaged, weakened, and suppressed hemlock of all crown classes with live crown ratio<30% Retain healthy trees of other species to maintain hemlock ecological function and increase stand resilience to multiple stressors	Selectively remove and destroy infested trees Restore ecological function by retaining evergreen conifer in canopy Consider chemical control	Selectively remove infested trees for economic return or public safety concerns Restore ecological function by retaining evergreen conifer in canopy Retain potentially resistant hemlock	Manage according to new stand structure Identify potentially resistant hemlock
Understory recommendations:	Protect hemlock and evergreen conifer advance regeneration	Protect hemlock and evergreen conifer advance regeneration	Protect evergreen conifer advance regeneration Plant climate adapted evergreen conifers	Facilitate evergreen conifer development Plant climate adapted evergreen conifers, hemlock, or resistant hemlock
Best management practices:	Avoid pre-emptive salvage harvesting of healthy hemlock Avoid harvesting infested hemlock until >60% needle loss to retain potentially resistant trees Minimize soil disturbance and logging damage to maintain residual canopy tree vigour Minimize spread by human activity			

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Résumé

Puceron lanigère de la pruche : Lignes directrices de gestion pour accroître la résilience de la ressource de pruches de l'Est de l'Ontario pour faire face à un insecte exotique envahissant

Le puceron lanigère de la pruche (*Adelges tsugae* Annand) exotique et envahissant s'est établi et a causé une diminution et une mortalité considérables chez la pruche de l'Est (*Tsuga canadensis* (L.) Carr.) dans une partie importante de l'étendue naturelle de l'espèce. L'infestation par cet insecte succivore donne lieu à une diminution progressive de la couronne et à la mortalité des arbres. La propagation continue vers le nord de cet insecte représente une grave menace pour la ressource de pruches de l'Ontario. Nous présentons un survol de la biologie de l'insecte, des interactions entre l'arbre et l'insecte ainsi que des options actuelles pour lutter contre l'insecte et l'atténuation des dommages. Nous concluons par des recommandations en matière de lutte afin 1) d'accroître la résilience de la ressource forestière de la pruche pour faire face à cet insecte avant qu'il se propage, 2) d'atténuer les dommages causés par le puceron lanigère de la pruche une fois qu'il s'est établi et 3) de faciliter le rétablissement de la forêt de pruches dégradée.

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