NOVA SCOTIA HEMLOCK WOOLLY ADELGID MANAGEMENT PLAN

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ACKNOWLEDGEMENTS

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Additional information about hemlock woolly adelgid in Nova Scotia, including ongoing research updates, is available at: www.nshemlock.ca

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Eastern hemlock (*Tsuga canadensis*) has been called the 'redwood of the east' and is among the largest and the longest lived trees in Nova Scotia. It is very shade resistant, slow growing and forms dark closed canopy forests. Due to its influence on local microclimate and associated species composition, eastern hemlock has been described as an ecological foundation species of the Acadian Forest Region. Eastern hemlock stands form unique habitats and associated biodiversity, help maintain ecological integrity of riparian zones, and generate a suite of ecosystem and economical services, including many social values. Many of the remaining old-growth stands in the Acadian Forest region are eastern hemlock. A destructive insect now threatens hemlock in Nova Scotia (NS): the non-native hemlock woolly adelgid (*Adelges tsugae*; HWA). Introduced to the eastern United States from Japan over 70 years ago, HWA has been decimating hemlock across its southern range before reaching southwestern NS, where it was detected in 2017. Spreading rapidly through the region's significant hemlock resource (present in at least seven counties as of May 2021), HWA is causing tree decline and stand mortality, with all of NS at risk of HWA infestations. HWAs impacts are expected to increase in the coming years, exacerbated by anthropogenic climate change.

This plan outlines HWA suppression and mitigation tactics for NS land managers and landowners with the aim of conservation of select eastern hemlock stands, drawing on information from extensive research and control outcomes from the eastern United States. A single management tactic cannot mitigate HWA impacts beyond individual trees; an adaptive, integrated pest management approach is required to preserve NS hemlock, and the work on developing this control program is ongoing. Importantly, the users of this plan must keep in mind that specific management strategies will vary with infestation levels and across the range of hemlock in NS.

The features described in this plan are situated within a growing context of ongoing research and developing regulatory frameworks, including the *Hemlock Woolly Adelgid Management Plan for Canada* and the *Guidance for Managing Invasive Alien Species in Parks Canada's Protected Areas – Hemlock Woolly Adelgid* document. While the national framework stands as the main guiding document, the provincial plan is intended to be the first step in providing local context and on-the-ground, scientific advice for developing a complete roadmap to manage HWA in NS. Along with the resources on www.nshemlock.ca, these recommendations will continue to be updated and expanded into detailed implementations, and are summarized in the following categories:

1) **PUBLIC OUTREACH:** Broad awareness of the pest and its larger-scale impacts is essential in proactive management. Continued engagement with First Nations communities, the public, woodlot owners, the forest industry, and other stakeholders through education and active involvement is needed to mobilize resources to conserve high-value hemlock stands.
2) **MANAGEMENT APPROACHES:** Monitoring and stand assessment will help identify and apply suppression tactics as appropriate, including insecticides, silvicultural methods, and stand restoration and regeneration. As these tactics continue to be refined and integrated, ongoing evaluation of their outcomes should inform adaptive management strategies and stand prioritization. As treatments may not be feasible in many affected stands, the consequences of not doing active management also need to be considered.
3) **RESEARCH:** Most of the effective suppression tactics for HWA used in the USA, such as biological control and basal bark sprays of insecticides, remain to be developed for Canada. These tactics and their integration will be critical for long-term, landscape-level HWA management and hemlock

conservation and restoration in NS. Continued support and engagement of HWA research will further benefit other Canadian jurisdictions under the threat of HWA.

4) **STAND PRIORITIZATION:** HWA infestations will grow rapidly and cause high levels of tree decline and local extinction of hemlock in NS. These impacts, coupled with the relatively high cost of treatments, will necessitate that resources are invested first to protect trees in high-priority hemlock stands. A prioritization framework is required to identify these stands in NS.

5) **PARTNERSHIPS:** The rate and scale of HWA impacts requires coordination and cooperation among multiple partners and stakeholders to garner sufficient support and resources. Such collaboration is essential for the development and prompt implementation of effective control tactics.

INTRODUCTION

Eastern Hemlock

Eastern hemlock (*Tsuga canadensis* (L.) Carrière) is a long-lived, shade-tolerant conifer native to eastern North America (Figure 1), and a common species in the Acadian Forest Type in Nova Scotia (NS). This species can live for hundreds of years and reach impressive diameters (> 1m) and heights of over 30m in some regions (Ward et al., 2004). Eastern hemlock is drought-intolerant, preferring cool, moist areas such as north-facing slopes, ravines, or riparian zones (Farrar 2007; Ward et al. 2004).

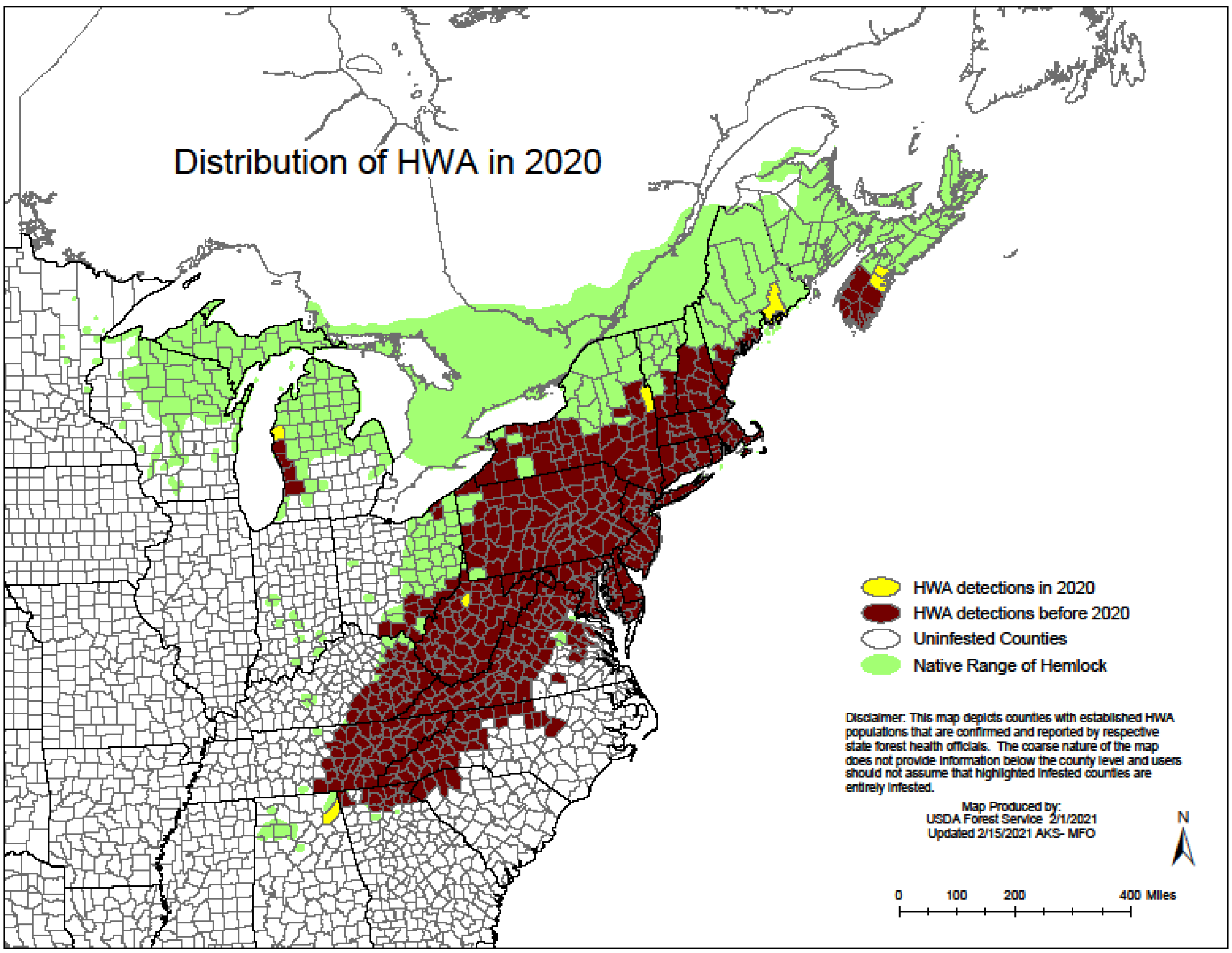

Figure 1. Map of eastern North America showing the range of eastern hemlock (green) and counties in the United States and Canada infested with the hemlock woolly adelgid (red, yellow is new counties for 2020). Source: USDA Forest Service.

Considered a foundation species, hemlock plays a key role in ecosystem function (Ellison et al. 2005). Research from the US shows hemlock supports unique terrestrial arthropod (insects and spiders) communities (Adkins & Rieske 2013) and provides critical habitat for over 120 species of wildlife (Tingley et al. 2002; Ward et al. 2004). Hemlock is a major component of many old-growth forests, contributing to shade provision, moderation of abiotic conditions, and nutrient cycling in these habitats. Furthermore, streams sheltered by hemlock support higher populations and diversity of aquatic species than those sheltered by hardwoods (Evans, 2002).

Hemlock's significance extends beyond these ecological values: this tree provides many social and cultural values as well, including the use of bark to make dyes and traditional medicine to treat a variety of ailments (Arnason et al. 1981; AMEC Environment & Infrastructure 2013). With their unique aesthetic, intact, mature hemlock stands provide humans with a sense of spiritual connection and wellbeing (Owen et al., 2009), and support a range of recreation activities.

Eastern hemlock abundance has likely been reduced by as much as 80% since the pre-colonial time (Loo & Ives 2003; Mosseler et al. 2003*a*). Nevertheless, it remains a widespread and significant component of forests in NS, with approximately 226,000 ha with 10% or more hemlock (NSDLF 2021). Alarmingly, the presence of the hemlock woolly adelgid (HWA) threatens hemlock throughout the entire province.

Hemlock Woolly Adelgid

The HWA (*Adelges tsugae* Annand) is an invasive, aphid-like insect native to eastern Asia and the Pacific Northwest. It was first reported in Virginia in 1951 after being accidentally introduced likely in the 1920s. Initially it spread slowly until about the late 1980s when it reached natural forests and began to spread more rapidly. It is now found in 17 US states (Figure 1) from the Smoky Mountains to southern Maine and has caused significant decline and mortality of native hemlock species (*Tsuga* spp.) in eastern United States.

HWA was discovered in southwestern NS in July 2017; by that point the pest had already spread through at least five counties, and was causing hemlock decline and mortality. These counties (Annapolis, Digby, Queens, Shelburne, and Yarmouth) were designated as HWA-infested and movement of hemlock logs, hemlock nursery stock and other material that might contain HWA was regulated by the Canadian Food Inspection Agency (CFIA 2017*b*) (Figure 2). As of spring 2021, HWA had been detected in two additional counties (Lunenburg and Kings Counties).

In its native range, HWA rarely causes significant tree mortality as natural enemies and host resistance regulate populations to endemic levels. In the invaded range, such population regulators do not exist; consequently, infestations are both rapid and serious. Following a gradual decline in tree health, tree mortality following HWA infestation can occur in 3 to 15 years, depending on site conditions, tree age, weather, and climate (McClure et al. 2001).

The combination of HWA dispersal, its ability to start new populations asexually from a single individual (parthenogenesis), and its cryptic life stages make it a very difficult pest to contain, and virtually impossible to eradicate. During the mobile stage of its life cycle (see below), HWA can spread passively over large distances by wind, birds, and human-assisted movement. In the northeastern US, HWA has progressed at an average rate of approximately 8-12 km per year (Evans & Gregoire 2007).

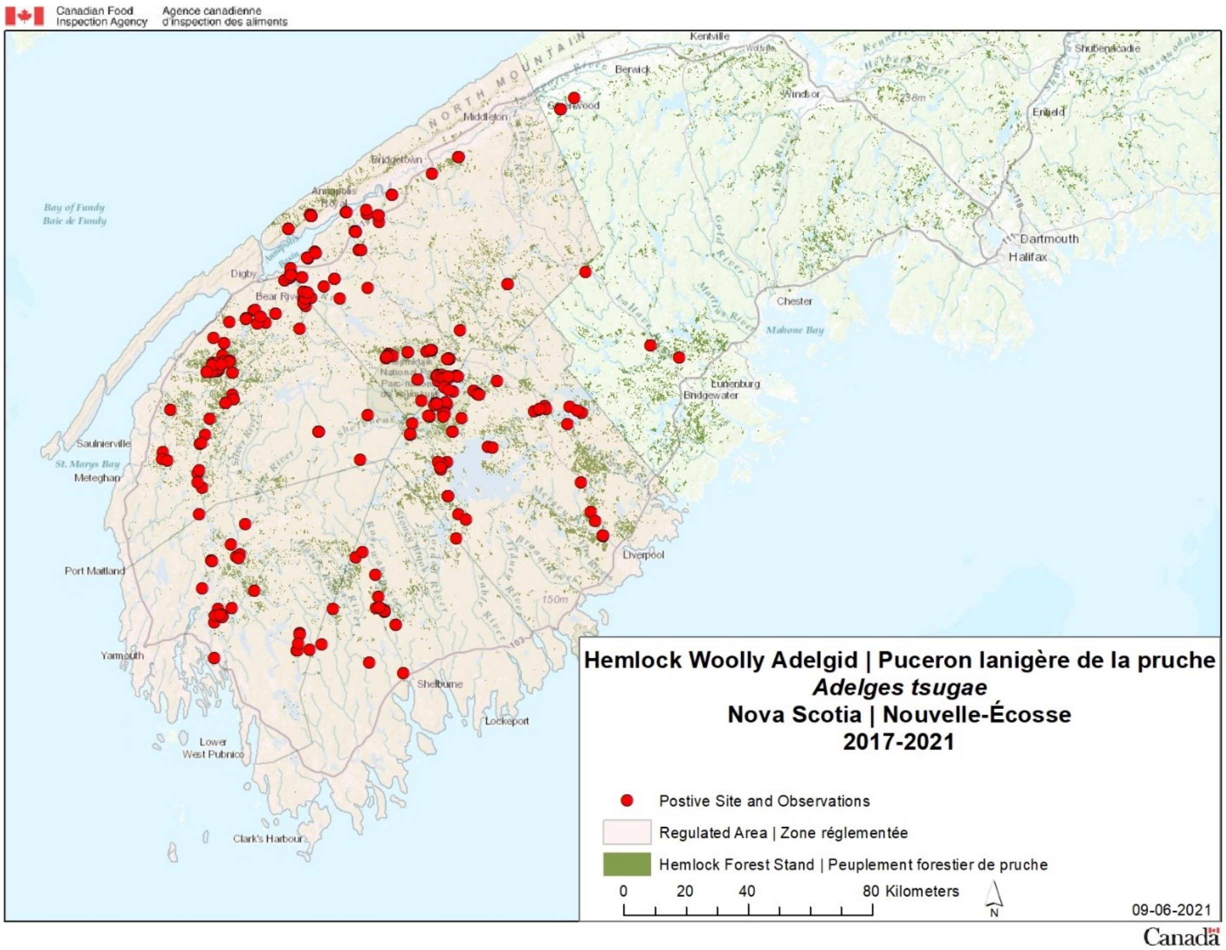

Figure 2. Distribution of hemlock, hemlock woolly adelgid detections, and the five regulated counties of Nova Scotia as of June 9, 2021. Source: Canadian Food Inspection Agency.

Life Cycle: In its native range, HWA completes a two-year sexual life cycle that involves the migration of individuals between hemlock and spruce species (Limbu et al. 2018). In eastern North America, HWA has a shortened one-year asexual life cycle on hemlock, consisting of two all-female generations (sistens, progrediens) (McClure 1987) (Figure 3). Each generation consists of three life-stages: (egg, nymph (which has four instars), and adult), the last of which produces a waxy covering called an 'ovisac' (Figure 4). The sistens generation produces two forms of HWA in spring: the progrediens generation, which recolonize hemlock, and winged sexuparae, that attempt to initiate a sexual generation on spruce (Figure 3). To date, the sexuparae have not successfully attacked spruces native to eastern North America. The progrediens initiate the sistens generation in summer. Upon hatching, the first instar nymphs, referred to as 'crawlers' due to their ability to move independently, attempt to settle on new shoots at branch tips. Upon settling, the crawlers insert their long mouthparts into the shoot to gain access to xylem parenchyma (storage) cells. In doing this, the crawlers become permanently immobile. Following this, crawlers become dormant for the summer (summer aestivation). They resume feeding in the middle of the fall, and continue to feed during winter. The sistens generation matures in spring and then lay progrediens/ sexuparae eggs; these hatch and the crawlers settle amongst their sistens mothers mostly on year-old twigs. Development of these forms is rapid compared to the sistens generation, occurring over a six-week period in NS (Figure 5, Appendix A).

Data from southwest NS suggest that the duration of certain stages differs significantly from previously published studies (McClure 1987, Gray and Salom 1996, Zilahi-Balogh et al. 2003). For example, the progrediens eggs are laid later in NS (NSDLF unpublished data) than in Connecticut, Virginia or British Columbia (note: native strain of HWA in BC) (Figure 5). These results have implications for control strategies, especially the development of effective biological control.

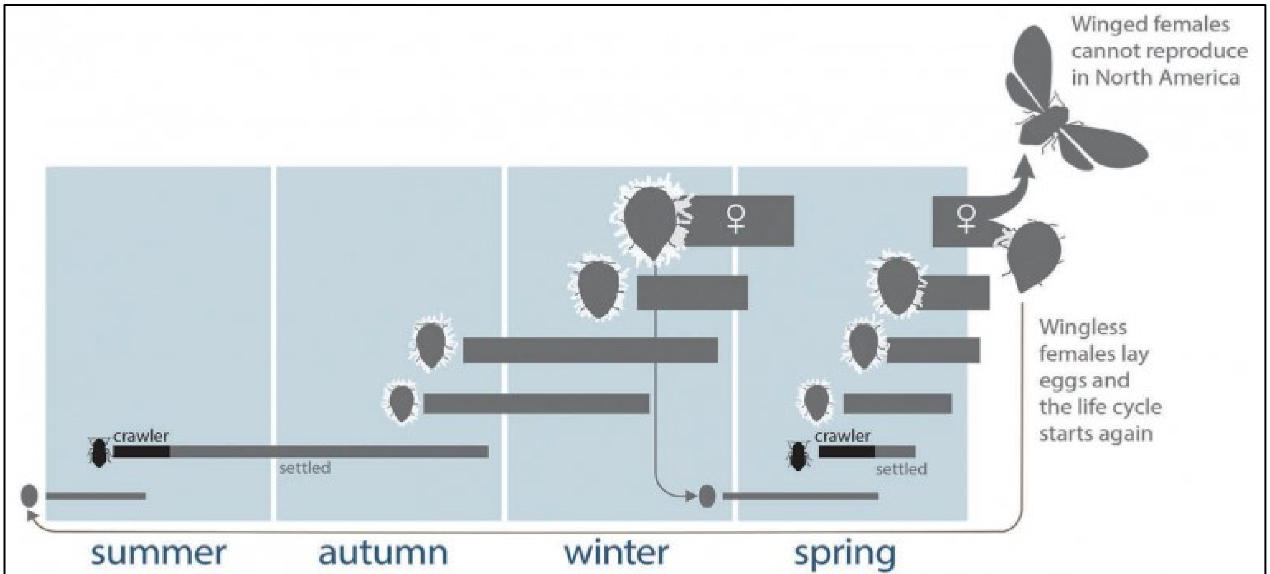

Figure 3. Hemlock woolly adelgid annual lifecycle in hemlock in the eastern United States. Source: Vincent D'Amico and Nathan Havill, USDA Forest Service – Northern Research Station.

Figure 4. Presence of HWA ovisacs on eastern hemlock in Kejimkujik (A) and Annapolis County (B). Sources: Frederica Jacks (A) and Ron Neville (B).

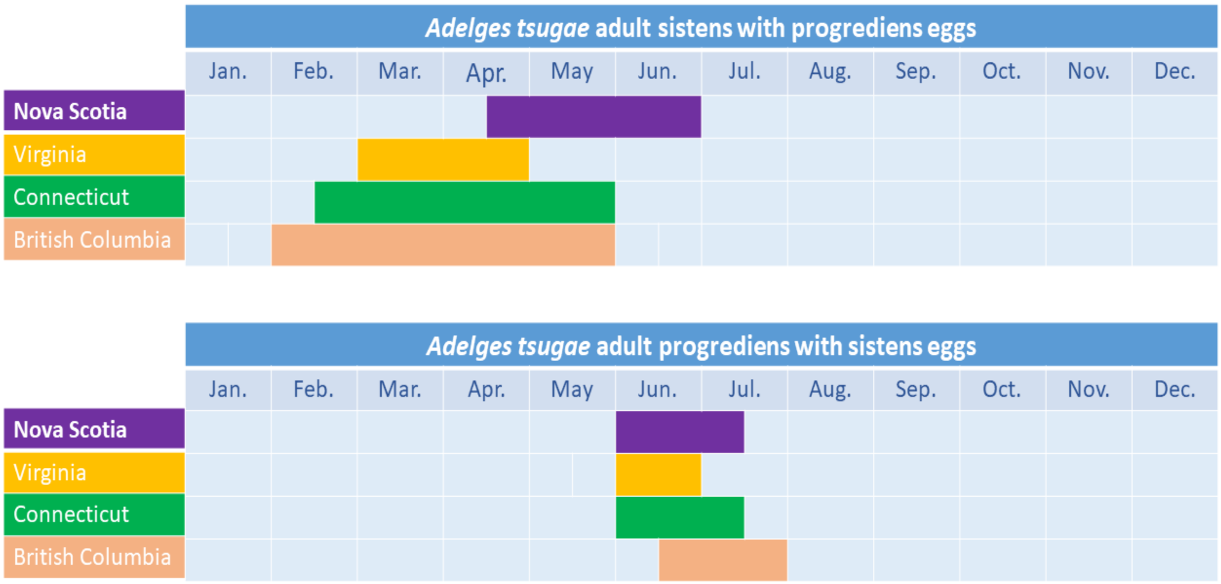

Figure 5. Phenology of hemlock woolly adelgid populations in Nova Scotia (sistens and progrediens) compared to populations in British Columbia (native HWA strain) and the eastern United States. Source: Nova Scotia Department of Lands and Forestry & Canadian Forest Service.

Signs and symptoms: HWA infestation results in several distinct symptoms in affected hemlock. The most obvious sign is the presence of the waxy ovisacs that are primarily found on the underside of current growth at branch tips (Figure 4). Ovisacs may also be found on the forest floor (i.e., twigs snapped off during storms) or adhered to hemlock bark (MacQuarrie et al. 2021). As the HWA density increases on a tree, distinct symptoms begin to appear: an increasing frequency of aborted buds (lack of new shoots), needle yellowing (chlorosis) and needle loss. Symptomatic of the underlying physiological stress on the tree, this progression eventually leads to major limb and crown dieback. In tall stands lacking low branches or hemlock understory, early stages of decline may be difficult to monitor, but eventually, heavily infested trees will begin to appear yellowish- or greyish-green from a distance. As needle loss progresses during the infestation, the crown becomes noticeably thin and more light is able to penetrate the canopy. Heavily impacted trees may undergo a brief period of recovery by producing new shoots after HWA densities drop temporarily due to insufficient food resource. However, trees soon become re-infested and often die shortly after; some may also become infested by the native hemlock borer.

Effects of Climate Change

Climate change is expected to play a role in the outcomes of HWA invasion through NS. Anthropogenic or human caused climate change is expected to elevate stress on hemlock, particularly through increased severity and frequency of drought. In the long-term, increasing portions of the region could become climatically less suitable to hemlock (Taylor et al. 2017), impacting both its survival and regeneration, though riparian habitats may offer critical climate change buffering from drought (Orwig et al. 2002). On the other hand, HWA is predicted to benefit from a warmer climate through enhanced winter survival, accelerating the pest’s impacts and spread in Atlantic Canada.

Adelgid survival is adversely affected by extremes in winter temperature but adaptation to colder winter temperatures has been observed in some populations (Butin et al. 2005; Lombardo & Elkinton 2017). Paradis et al. (2008) found that 91% mortality is required to stabilize HWA populations in specific conditions. However, overwintering mortality of HWA in NS in 2019 and 2020 ranged from only 30–60% (Ogden & Boone 2020), suggesting the HWA populations will continue to increase and spread throughout most of NS.

OBJECTIVES AND APPROACH

Given the large area that already has HWA populations in the Province and the potential for continued rapid spread of this HWA infestation, a collaborative and adaptive management approach is essential to guide the management response to HWA. Such an approach is also critical for recognizing knowledge gaps and allocating resources. Shortly after HWA was identified in NS, the HWA Working Group – Maritimes was founded. This groups includes researchers, representatives of non-government organizations, Mi'kmaq of Nova Scotia and various government departments. Significant outreach has also taken place with the forest industry and private woodlot owners that are affected, all with an interest in protecting local hemlock ecosystems. Additionally, the Maritime HWA Working Group supports a Two-Eyed Seeing approach to the management of this invasive species in Kespukwitk, the Mi'kmaq region of southwestern NS. This approach incorporates the strengths of both Indigenous ways of knowing and the mainstream scientific perspective for the benefit of all (Bartlett et al., 2012). The relationship between Mi'kmaq and scientific communities has been initiated and will continue to be fostered as management activities carry on.

The goal of this document is to build on the *Hemlock Woolly Adelgid Management Plan for Canada* (Emilson & Stastny 2019) and to provide comprehensive, up-to-date information with a specific focus on the HWA in NS. The document seeks to guide the prioritization of treatment options and development of control strategies, identify research and communication gaps, and complement resources found at www.nshemlock.ca. Drawing on both the extensive body of research and implementation of HWA management strategies in the invaded range of the eastern USA, and on the management framework for Canada (Emilson & Stastny 2019), this plan is intended to help launch management actions in the infested regions of the province, as well as offer strategies for all hemlock forests across NS.

The primary objectives of this plan are as follows:

- To compile the best current knowledge to assess the risks posed by HWA to hemlock, and evaluate the potential impacts for NS
- To offer advice on current treatment options for high-value stands of hemlock
- To provide a structured framework for identifying and prioritizing hemlock for protection
- To identify research needs in the development of control tactics
- To mobilize resources, communication and outreach

ASSESSMENT OF INFESTATIONS

Assessment of infestations and their impact on tree health is a fundamental component of managing invasive species. It determines the pest's occurrence and spread and informs decision makers regarding the appropriate management tactics for a given area. Effective assessment is also necessary for accurate evaluation of management actions taken.

Assessment of HWA typically involves three complimentary approaches: detection, delimitation and monitoring; these surveys are generally the responsibility of the landowner. In the case of a cryptic species such as HWA, effective sampling can be challenging.

Detection

Detection surveys typically focus on determining whether HWA is present in an area. Once an area is determined to be infested, other more intensive surveys can be done. Several techniques are available to perform detection surveys for ovisacs (Figure 4). They include visual examination of branch tips within arm's reach (Costa and Onken 2006), ball sampling for adelgid wool (Fidgen et al. 2020), using sticky cards to detect HWA life stages, notably crawlers (Fidgen et al. 2020) and examination of the forest floor and hemlock bark for HWA wool (MacQuarrie et al. 2021). Detection surveys ought to focus on stand edges and perhaps tall trees within the stand as these locations are generally first to become infested by HWA. However, false negatives (i.e., failing to detect HWA when it is present in a stand) are very likely with HWA, especially in tall stands lacking hemlock understory, and therefore all additional means of detection (e.g., inspection of harvested trees, or fallen twigs after wind events) should be encouraged. Despite these techniques, detecting establishing populations of HWA remains a challenge. A new technique that detects the DNA of HWA is showing promise as an HWA detection tool (M. Whitmore, pers. comm.).

The CFIA conducts landscape level detection surveys in areas of Nova Scotia where HWA is not known to be present utilizing a combination of survey techniques outlined in the Hemlock Woolly Adelgid Survey Protocol (Appendix B). Detection surveys and reporting of suspected HWA populations by other members of the HWA Working Group and the public is encouraged through public engagement sessions, social media campaigns, and collaborations. All detections and reports of HWA are tracked to assist with research and management and regulatory decision making. Members of the public are encouraged to report sightings of HWA to their local CFIA office or on iNaturalist.ca (https://inaturalist.ca) where a distribution of many reports can be viewed.

At higher HWA densities, detection of HWA hotspots can also incorporate tree symptoms (e.g. crown thinning, off-color foliage), which are absent in the early stages of infestations and may be detected from aerial or satellite imagery. Resources for regional and stand level detection can be augmented using a regional program of citizen scientists (Mersey Tobeatic Research Institute 2018, 2019) and by encouraging crown inspections by industry professionals during harvest operations, which will aid in detection of isolated hotspots especially in tall, mature stands.

Delimitation

A delimitation survey is more intensive as trees are checked for HWA in all directions surrounding the infested tree. However, survey tools for HWA run the risk of not detecting HWA when it is present on the tree (i.e., false negative). For example, visual surveys have a false negative rate of up to 80% when used to detect low level infestations of HWA (Fidgen et al. 2018). A safe strategy is to stop sampling in each direction once three negative trees are sampled to reduce the likelihood of missing infested trees. Once the extent of the infestation is delimited, HWA populations can be mitigated using approved treatments within this area. Another strategy to reduce the false negative rate is to use two or more detection techniques per tree (MacQuarrie et al. 2021). The techniques used for detection can be used for delimitation. However, more labor-intensive techniques, such as pole pruning of branch tips from the hemlock canopy, can also be used for delimitation. Pole pruning is particularly useful when information on the incidence or density of HWA is required as when for monitoring of HWA populations.

Monitoring

Monitoring is used in stands with known infestations to check on the HWA population level as this is a key feature in the coordination of treatments for HWA (see Treatments section). Removing branch tips from the hemlock canopy with pole pruners is preferred for this task. If the canopy is not accessible, indirect forms (i.e., sticky traps) of monitoring HWA population level are recommended, but this technology requires research to develop the relationship between canopy infestations of HWA and catch of HWA on traps. When it is feasible to collect branch tip samples, the incidence (number of shoots infested by HWA divided by the total number of shoots) or more detailed observation on density (number of ovisacs per cm of shoot) provide a sound basis for making treatment decisions (Fidgen et al. 2006, 2013). Indeed, an incidence of 30% might be a good damage threshold above which tree growth begins to be impacted by HWA (Table 1) (Fidgen et al. 2006). The method described by Fidgen et al. (2006) could be extended to identify trees and stands with high incidence of HWA, helping prioritization of treatments.

Monitoring the health of hemlock is another important measure in the monitoring process. The rate of hemlock decline will vary depending on several factors, such as site conditions and tree susceptibility to HWA, but hemlock health is an important step in the monitoring process. Several techniques exist for the rating of hemlock health, but the one produced by Virginia Tech is recommended (McAvoy et al. 2019). Of note is the census of new shoots at branch tips as these disappear with increasing HWA populations

Table 1. Stop boundaries for binomial sequential sampling of *A. tsugae* infesting *T. canadensis* at the 10 and 30% of new shoots infested with at least one ovisac. Sampling is carried out in early spring when ovisacs contain eggs (Reproduced from Fidgen et al. 2006). The protocol is as follows for a 30% infestation threshold: Sample a branch tip and count the number of infested shoots in the first 20 new shoots per branch tip. Stop sampling if you count 3 or fewer infested shoots or 11 or more infested shoots. If neither threshold is crossed, sample another branch tip from the same tree and repeat the process. If after four tips have been sampled and a threshold has not been crossed, the infestation level is moderate.

Threshold (%)	Sample number	Stop boundaries				
			Lower stop value		Upper stop value	
10	20	Low infestation	---	Continue sampling	6	High infestation
	40		1		8	
	60		2		12	
	80		3		15	
30	20		3		11	
	40		7		19	
	60		12		34	
	80		16		37	

When access to the hemlock canopy is not possible (due to height of live crown), other factors can be assessed to determine tree health (McAvoy et al. 2019). These include crown transparency (e.g., needle loss), crown intactness (e.g., major limb loss) and off-color foliage in addition to scanning for adelgid wool on the forest floor and on the bark of hemlock trees.

PREVENTION

Regulation

The HWA spreads naturally by wind and animals at a rate of 8-12 km per year (McClure 1990; Evans and Gregoire 2007) However, human-assisted movement of HWA can potentially create satellite infestations 100's of km distant from areas regulated for HWA, and regulations combined with education can reduce this risk. The CFIA regulates the movement of potentially infested articles to reduce the risk of long distance spread of HWA, working closely with industry. These regulated articles include firewood, plants, or plant parts containing bark or foliage of hemlock (CFIA 2017*b*) and alternate hosts of HWA from its native range (i.e., Yeddo and Tiger-tail spruces). Prevention efforts should also focus on limiting the spread of HWA by those engaged in recreation, forestry activities, and research in hemlock stands infested with HWA. Strategies could improve awareness and reduce spread from recreationists, including firewood bans, signage and decontamination of clothing, vehicles and other outdoor articles prior to leaving the area regulated for HWA. Signage developed by CFIA are now displayed many parks and recreation areas with hemlock forests (Appendix C).

Education and Outreach

Along with regulatory measures, public education and awareness are at the forefront of proactive HWA management. According to the State of the Forest 2016 report, approximately 59.4% of NS land is privately owned, while 33.6% exists in the provincial Crown land base and 2.8% is federally owned (NSDLF 2017). **With most provincial land belonging to private woodland owners, these groups should be engaged to enlist their involvement in mitigating the impact of HWA in NS**. Engagement might include promoting resources such as www.nshemlock.ca, facilitating workshops, conducting other outreach initiatives and providing financial assistance with treatments in key areas. A centralized HWA fact sheet and a Best Management Practices brochure for woodlot owners should also be developed.

A regional program of monitoring, outreach, and citizen scientist engagement was led by the Mersey Tobeatic Research Institute in recent years, with the support of Parks Canada and other partners.

An eastern US survey study by Poudyal et al. (2016) revealed that even in counties where HWA was affecting hemlocks, the public was largely unaware of HWA infestation. This point, if analogous to NS, could pose significant issues for the containment of the infestation. It should therefore remain a priority to provide HWA education across the province to facilitate stakeholder and community awareness and support, which in turn allows for rapid action to be taken.

Community and stakeholder awareness has already begun across Canada with pest information on HWA being provided and distributed through the CFIA pest fact sheet (CFIA 2016) and signage and CFS publications (Fidgen et al. 2013). However, more focused efforts related to social media and the media are urgently required.

The ongoing work of the HWA working group in NS provides a vital forum for discussion, coordinated actions and communication amongst key interest groups.

Citizen science programs and workshops can continue to be used to educate and increase awareness about HWA prevention and monitoring; web platforms and social media campaigns can be used to target specific demographics to increase impact. In particular, citizen science can be a powerful way to engage and inform the public, while increasing the potential for ongoing HWA detection. iNaturalist is a useful tool that is currently used by citizen scientists and the public in NS.

A number of these initiatives and tools have been developed in Ontario and could be expanded to Nova Scotia. For instance, the Invasive Species Centre (ISC) and Ontario Invasive Plant Council created the Early Detection and Rapid Response (EDRR) Citizen Science network based on the identification and reporting of invasive species. Through such a network, volunteers could be trained in HWA detection in NS. A version of the Early Detection and Distribution Mapping System (EDDMapS) was developed in Ontario for HWA that allows for the reporting and documenting of HWA incursions using a smartphone app and this could have extended to include NS as well.

RISK ASSESSMENT

Nova Scotia's Hemlock Resource

Eastern hemlock has long been a key species of the Acadian Forest Region, especially prior to its decline following large-scale logging and land use change during the European settlement (Loo & Ives 2003; Mosseler et al. 2003*a*). While hemlock is not considered an economically important timber species, there is a market for its wood and mulch products in NS. Woodlot owners and recreationists also value hemlock forests for recreational use and wildlife habitat. In NS, all forests have been estimated to contribute between $869 to $5415 CAD per hectare in ecosystem services on an annual basis, including water filtration, carbon storage, habitat, and recreational services (Gardner Pinfold Consultants Inc. 2017). TD Economics and Nature Conservancy of Canada (2017) have valued old-growth Acadian forests in southwestern NS at $26 250 per hectare per year. The exact economic value of eastern hemlock is not yet agreed upon, but according to analysis from the eastern US, eastern hemlock provides approximately $1366 per hectare per year in ecosystem services (Havill et al. 2016). While many estimates exist, valuation of forests, stands, and trees are subjective and depend on various ecological, economic, spiritual, and cultural factors.

Presently, most remaining old-growth forest in NS contains eastern hemlock due to its undesirable characteristics for the present-day forest industry. Provincial forest inventory analysis by the NSDLF has confirmed 226,011 ha of hemlock forest with at least 10% (regardless of age) of the basal area in the stand in hemlock. To put this in perspective, stands with 10% basal area of hemlock would likely have the hemlock concentrated near wet areas or riparian zones. Only 9,628 ha of Nova Scotia is occupied by stands where eastern hemlock is dominant (≥60% eastern hemlock) and of this a scant 1823 ha is recognized as old growth (NSDLF 2012), with 1,592 ha found in Provincial Protected Areas and 231 ha on Crown Land (P. Bush, personal communication, February 28, 2020). Of grave concern is that 40% of these stands are contained within the current area regulated for HWA. Some states in the US use a 6% basal area cutoff for stands of high importance because most of the hemlock are located along riparian zones (Fajvan & Morin 2021). This would expand the amount of hemlock acreage identified along riparian zones in NS.

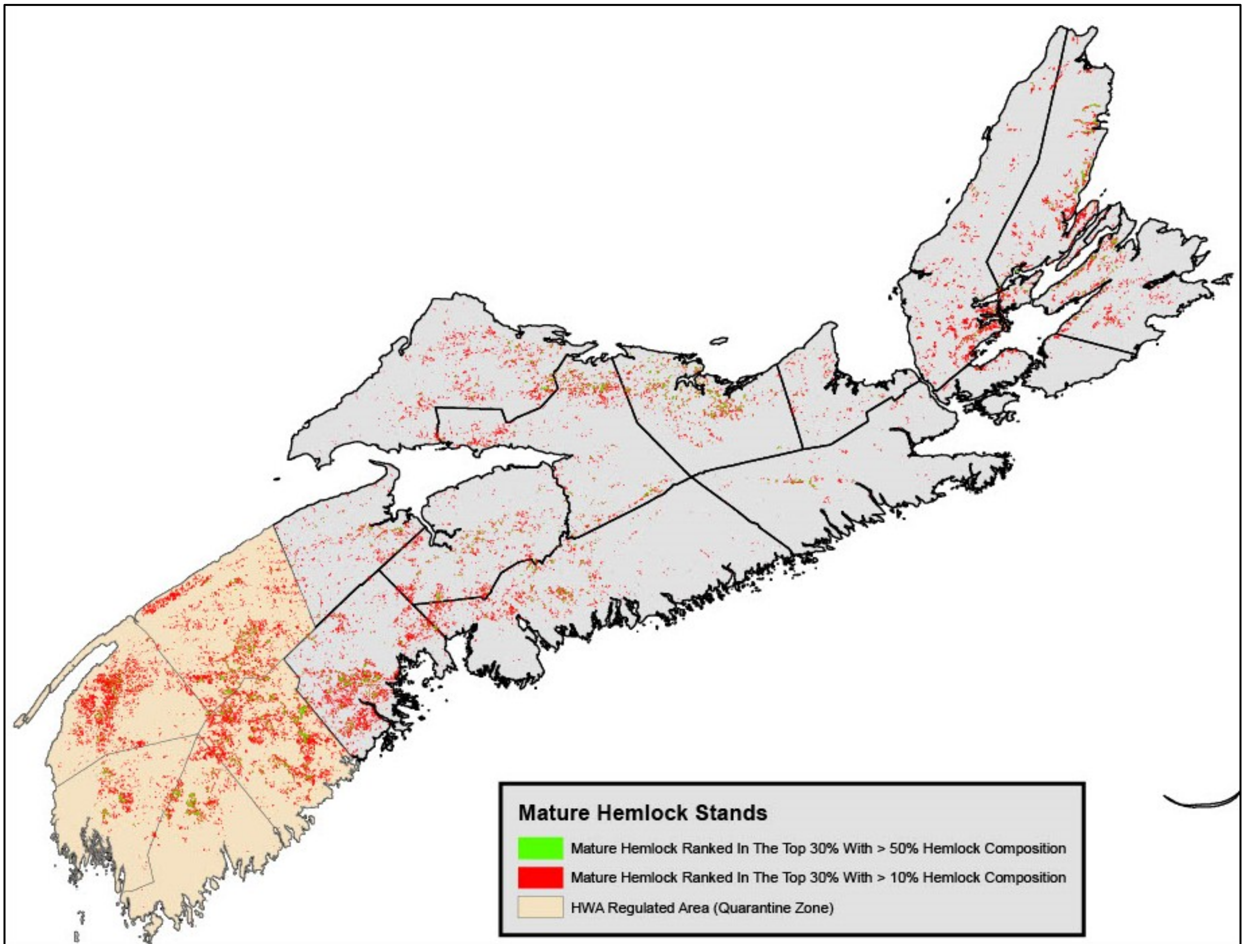

Figure 6. Distribution of potential hemlock stands across NS (2020), including the five counties regulated by the Canadian Food Inspection Agency, ranked in the top 30% with either ≥10% or ≥50% hemlock composition. Source: Nova Scotia Department of Lands and Forestry.

Old-growth forests are known to foster biodiversity (NSDLF 2012; Spies 2004; Ward et al. 2004) and ecosystem services such as carbon storage, soil stability, and water quality (Harmon et al. 1990; Haqen et al. 1992). Hemlock's contribution to these ecological benefits may be significant even in stands where hemlock is a minor component (Figure 6), given its typically clumped occurrence, such as in riparian zones. Along with providing critical animal habitat, old-growth hemlock forests may also support four times more understory vegetation than second-growth hemlock forests (D'Amato et al. 2009). In NS, Lahey (2018) advocates for improved protection and restoration of old-growth forests, citing the need for an integrated approach to prioritizing ecosystems and biodiversity. Similarly, the *Biodiversity Act 2019* describes the essential nature of biodiversity in the province, stating that diverse ecosystems directly contribute to well-being, sustainable prosperity, and sustainable environments within NS. **Considering the significant contributions of hemlock forests to habitats and ecosystems, old-growth and riparian stands should have high weighting in a prioritization scheme.**

Eastern hemlock is a culturally significant species in First Nations communities, used for traditional medicine and crafts (Arnason et al., 1981). Forest conservation within Mi'kmaq culture involves prioritizing ecology and biodiversity over economic objectives, much like the practice of ecological forestry (Lahey, 2018). In Mi'kma'ki, the unceded territory of the Mi'kmaq, it is important to integrate traditional knowledge with ecological knowledge of hemlock and old-growth forest. As such, the identification of culturally significant stands in NS should be continued with all First Nations communities within the province.

After considering the cultural and ecological values of hemlock stands in NS, **high priority stands, or portions of stands, should be defined as those with cultural significance, wildlife habitat value, sensitive riparian areas, rare or otherwise uncommon species, wildlife corridors, ecosystems services, and old-growth forest. It is recommended that an up-to-date eastern hemlock inventory be completed as well as a structured framework to prioritize stands for treatment.**

Although the current infestation in southwest NS lies largely within rural stands, the risk to urban forests will increase as HWA spreads eastward. While eastern hemlock is rarely a street tree, it plays a disproportionate role in urban parks, such as Hemlock Ravine Park (Halifax), Shubie Park (Dartmouth), and Victoria Park (Truro). These patches of old-growth hemlock forest provide critical ecosystem services as well as cultural and aesthetic values to park visitors. **Because of the unique value of these stands, they should be intensively surveyed to detect HWA as early as possible and monitored thereafter in order for appropriate management tactics to be applied.**

Impacts of Hemlock Degradation

Degradation of hemlock due to HWA infestation is unavoidable, regardless of stands being treated or managed. In NS, old-growth forests or riparian stands may be the most impacted by the loss of eastern hemlock due to patterns of historical use and the fact that this species has been largely spared in recent decades of commercial harvesting (Mosseler et al. 2003*a*). As such, the potential cascading effects of hemlock degradation must be understood. Research from the eastern US, where HWA has been present for many decades, can help us predict impacts and best management practices for NS forests.

Forest Ecosystems

The loss of eastern hemlock can lead to profound effects on forest ecosystems, including changes in biodiversity, increases in nutrient and energy cycling, and altered hydrology (Ellison et al. 2005). In a multi-year study of New England hemlock forests, Orwig et al. (2008) found that even in forests with light HWA infestation, the carbon-to-nitrogen ratio and organic matter within soils were reduced, surface decomposition was slower, and soil pH was higher than in uninfested stands. These variables contribute to soil nutrient availability, risk of water eutrophication, and potentially lower biodiversity.

The loss of genetic diversity of hemlock is another consequence of HWA, especially in the face of climate change. Old-growth forests, in particular, act as reservoirs for genetic material important for species' adaptation to changing conditions (Mosseler et al. 2003*b*). Eastern hemlock forms a large proportion of the remaining old growth forests in NS, and the provincial Old Forest Policy states the directive to *"conserve the remaining old-growth forests on public land and ensure that a network of the best old forest restoration opportunities is established"* (NSDNR 2012). In this context, HWA damage and anthropogenic climate change will cause significant loss of the remaining old forest on conserved public lands.

Following hemlock dieback due to HWA, a shift toward deciduous or mixedwood stands over time will favour earlier seral stages (Orwig and Foster 1998, Vose et al. 2013, Taylor et al. 2017). However, stand mortality resulting from HWA will still involve a more gradual stand turnover compared to dramatic changes associated with salvage logging in response to HWA (Kizlinski et al. 2002). Deer browsing and invasions by non-native or early successional plant species present additional challenges in stand management and restoration in the aftermath of HWA. Excessive browsing by white-tailed deer (*Odocoileous virginianus*) can dramatically shape forest succession rates and trajectories post-HWA infestation (Horsley & Marquis 1983). Non-native shrubs such as glossy buckthorn (*Rhamnus alnifolia*) may invade declining hemlock stands (Frappier et al. 2003). Among the native species, hay-scented fern (*Dennstaedtia punctilobula*) can impede tree or shrub recruitment (Orwig et al. 2002); similar dynamics have been observed in Kejimkujik, where an outbreak of the moth pale-winged grey (*Iridopsis ephyraria*) caused decline of hemlock throughout the early 2000s (Pinault et al. 2007).

Several migratory bird species, including the Hermit thrush (*Catharus guttatus*), Black-throated green warbler (*Dendroica virens*), Acadian flycatcher (*Empidonax virescens*), and Blackburnian warbler (*Dendroica fusca*), may be considered obligate hemlock species and their populations have declined following HWA damage in hemlock dominant stands in southern New England, (Tingley et al., 2002). Mammals that rely on old forest attributes found in hemlock-dominant stands include White-tailed deer, moose (*Alces alces*), fisher (*Martes pennanti*), American marten (*Martes americana*), flying squirrels (*Glaucomys spp*.), and several bat species (Broders et al. 2003). The decline and loss of hemlock will put pressure on neighbouring, less suitable habitat to act as refugia for displaced individuals (Tingley et al. 2002).

Riparian Ecosystems

Hemlock mortality is likely to affect stream health through reduced shading, and increased coarse woody debris inputs. While the influx of coarse woody debris is expected to provide structural habitat as well as support diversity and abundance of benthic invertebrates (Pitt & Baxter 2015), it may also cause streamflow alterations (Emilson & Stastny 2019). The loss of riparian hemlock canopy will lead to warmer surface water temperatures that will threaten fish-bearing streams and their food webs, and cool-water summer refugia for trout species (MacMillan et al. 2008). In addition to cascading ecological impacts of HWA, these changes in hemlock-rich watersheds would could impact recreational anglers in the province, who spent approximately $86 million on sport fishing in 2000 (Nova Scotia Department of Agriculture and Fisheries 2005).

Southern NS is home to several of the last remaining Atlantic salmon (*Salmo salar*) populations in NS, brook trout (*Salvelinus fontinalis*), and the last known population of endangered Atlantic whitefish (*Coregonus huntsmani*). Portions of the Tusket River watershed, a habitat of endangered Atlantic salmon, have already been impacted by HWA (Figure 7). Streams in this province already experience warmer temperatures, which induce stress in native salmonid species (MacMillan et al. 2008); alterations to their critical habitat due to HWA will exacerbate the threat already posed by the warming climate.

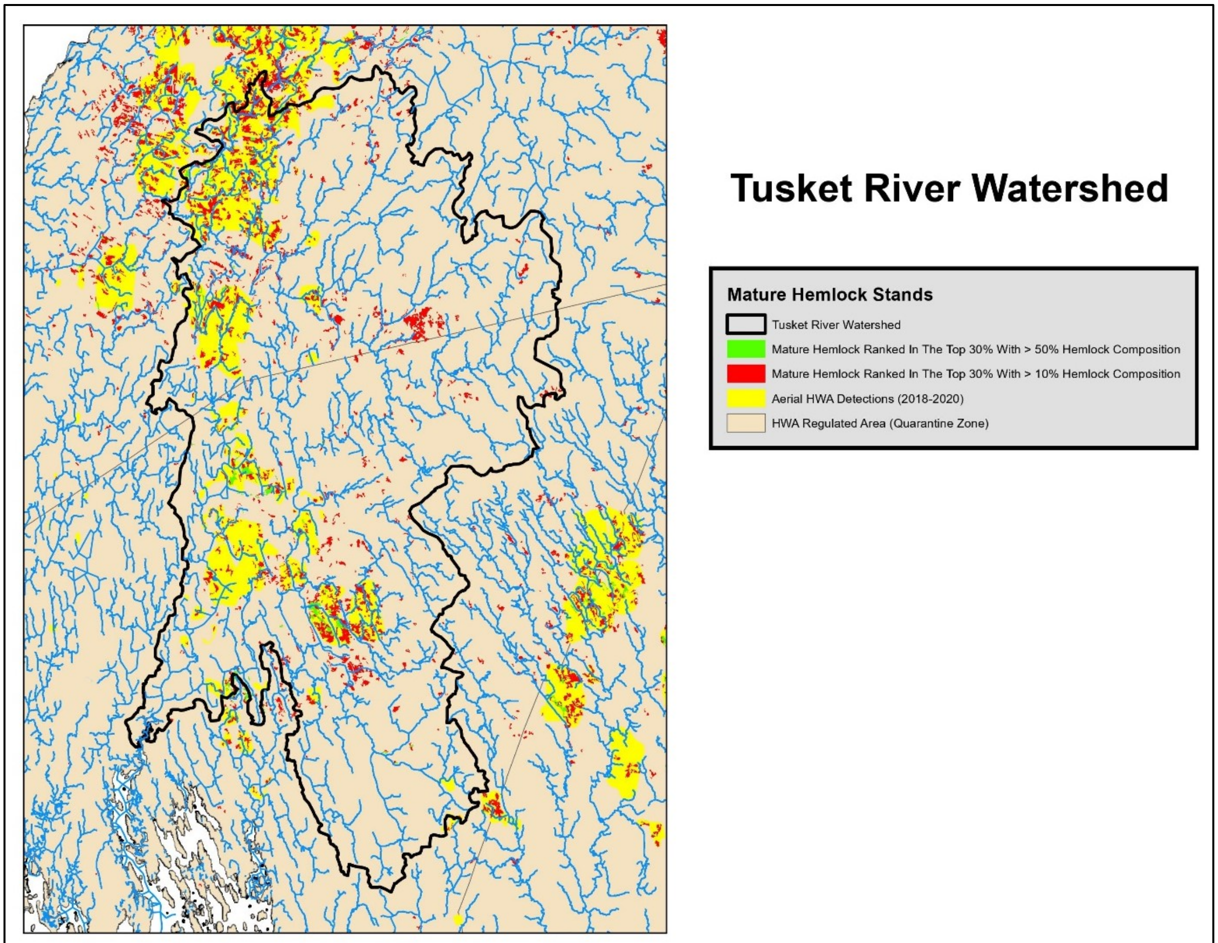

Figure 7. Distribution of hemlock stands and confirmed HWA infestation sites in the Tusket River watershed, within regions regulated by the Canadian Food Inspection Agency in the fiscal year 2020-2021. Hemlock stands are ranked in the top 30% of old-growth forest scoring with either ≥10% or ≥50% hemlock composition. Source: Nova Scotia Department of Lands and Forestry.

Fire Risk

Dead hemlock trees (snags) and accumulating woody debris may elevate the risk of forest fires in regions where HWA is causing hemlock decline. Even prior to tree mortality, in multi-aged stands with ladder fuels especially comprised of softwoods, severe infestations might make a crown fire more likely due to needle desiccation and crown dieback. In mature hemlock stands with few ladder fuels, the eventual loss of canopy is likely to result in drier site conditions and a higher risk of surface fires that can spread to adjacent stands. Southwest NS has experienced light to severe droughts every year since 2016 (Agriculture and Agri-Food Canada 2021), and in combination with hemlock mortality due to HWA, this region may sustain an increased frequency of forest fires under future climate scenarios (Flannigan et al. 1998).

MANAGEMENT OPTIONS

No Management Approach

In many situations, it is not feasible to protect hemlock from HWA; in integrated pest management, this lack of intervention is typically referred to as the “do nothing” strategy or “no management approach”. There are many reasons for this decision. In some cases, the infestation may be too advanced for management to be effective. In other cases, resources required for management may be insufficient, the regulatory framework may not allow other tactics, or the stands may be too remote or intentionally unmanaged (e.g. in protected areas). However, it is important to realize that choosing not to treat certain stands may free up resources to focus management on other stands that may be of higher priority. Therefore, the no management approach is an integral component of an overall HWA management strategy.

Given the scale of Nova Scotia’s hemlock resource, and the nature of HWA and its impacts, it is unavoidable that many stands will fall under a no management approach. Few tools are currently available to mitigate HWA impacts (see below), and the cost of chemical control, in particular is prohibitive for most stands let alone landscape-level intervention. The impossibility of effective delimitation and containment of the pest also pre-empts the utility of focused control along the invasion front. Therefore, the no management approach and its consequences need to be recognized as the default for most hemlock stands, both private and public.

In the absence of management, hemlock would remain untreated and undisturbed in response to HWA infestation, leading to high levels of tree mortality likely within a decade, and cascading ecosystem effects (see Impacts of hemlock degradation). Dead trees will pose a risk to human safety, particularly near private homes, recreational areas, or transportation corridors and infrastructure. Pre-emptive removal of hemlock through salvage cutting may be desirable in this context, but may also initiate more rapid ecosystem changes than the more gradual mortality due to HWA (Foster & Orwig 2006), and potentially make it more difficult to steer stand regeneration in the face of invasive species.

The decision to adopt a no management approach may also occur when stands have been previously treated for HWA and treatments were either unsuccessful or could not be continued. These scenarios are considered explicitly in adaptive management, which involves simultaneous implementation and active assessment of outcomes, including the possibility of ceasing treatments (Emilson & Stastny 2019). To complement this adaptive approach, **managers should consider setting “decision checkpoints” to assess management progress and options.** After all, failing to decide a course of action is a decision nonetheless, and it is not synonymous with a “no management” approach (Rauscher 1999).

Active Management Approach

Land managers in NS can benefit from thirty years of research and experience in the US at developing management strategies. Active management includes three categories: 1) chemical control, 2) silvicultural management (tree cutting, planting resistant stock), and 3) classical biological control. In the short term, the main focus of HWA management for NS, based on the outcomes in the US and the tools currently available, is to treat trees with insecticides (chemical control) until longer term, persistent treatments can be developed (i.e., biological, silvicultural). Landowners may not be able or willing to use this approach to managing HWA on their lands; however, they should be aware that the risk of hemlock loss will be high. Only after one or more long-term strategies have been established will hemlock restoration be possible.

Chemical Control

Chemical control is the main short-term tool of the HWA management program in the US. This treatment option has several benefits, the first being its ability to keep trees alive right now until other management strategies can be implemented (Emilson & Stastny 2019). It is important to note that chemical treatment for HWA is applied on a tree-by-tree basis, and not via aerial application as is commonly done for defoliating insects like the spruce budworm.

Two products are currently available for HWA control in Canadian forestry use under the Pest Management Regulatory Agency (PMRA): (1) dormant oil (Plant Products Inc.), and (2) Ima-Jet® (Arborjet Inc. 2020). Dormant oil is only practical for use in treatment of nursery stock. Because this treatment is not 100% effective due to poor coverage, it should not be relied upon to treat trees in preparation for movement to uninfested areas of the country. For forestry use, only Ima-Jet® is currently available for use in NS. The active ingredient in Ima-Jet products is the neonicotinoid imidacloprid, which is a systemic chemical that renders plants temporarily toxic to insects (Kobashi et al. 2017) when used according to instructions. Imidacloprid is most effective when applied to healthy trees (i.e., trees with nil to moderate HWA infestations and no or very limited decline) (Benton et al., 2015), with tree protection lasting up to four years following treatment (Doccola et al. 2021). Ima-Jet® is administered via stem injection. While effective in reducing HWA infestation, stem injections are not the most efficient means of delivery, as some injected material may not reach the parts of the tree fed upon by HWA (Dilling et al. 2010). Traces of imidacloprid have been found in hemlock tissues up to 7 years after application (Mayfield et al. 2017).

Several other more effective formulations and delivery methods exist for HWA mitigation. These include Safari 20SG (dinotefuran) and Xytect® 2F basal bark spray. While their use is permitted in many states in the US, neither product is registered for HWA treatment in Canada. Unlike Ima-Jet®, both dinotefuran and Xytect® 2F are delivered via a basal bark spray, thereby eliminating the risk of product immobility associated with tree injection. These treatments are less costly and can be applied more rapidly than stem injections. Dinotefuran moves rapidly in hemlock and the active ingredient dissipates within a year. Furthermore, it can be used for recovery of trees with advanced impacts from HWA. Indeed, both Safari 20SG and Xytect® 2F are mixed and applied together to provide a quick knock down of HWA (Safari 20SG) and long term (i.e., 5-7 years) protection from reinfestation by HWA (Xytect® 2F). **These products are currently the principal chemical tools for HWA suppression in the U.S.A. and ought to be considered for use on HWA in Canada.** Research will be required to support adoption of these products in Canada.

Because the area treated with chemical insecticides will be small as compared to the total area of hemlock in NS, the anticipated landscape-level risk of these treatments is considered relatively low. Research from the United States has shown that nontarget impacts are outweighed by the impacts of hemlock loss due to HWA. For example, at a local scale, several studies found low or negligible nontarget impacts on soil arthropods, canopy arthropods in treated hemlock stands and on aquatic invertebrates downstream of treated stands (Reynolds 2008; Dilling et al. 2009; Falcone and DeWald 2010; Knoepp et al. 2012; Kung et al. 2015; McCarty 2020).

Among the most sensitive of ecosystems to HWA mitigation products are aquatic environments. At the sub-watershed level, two studies in the US found no differences in the aquatic macroinvertebrate community (mayflies, stoneflies, and caddisflies) in streams running through imidacloprid-treated hemlock stands vs. untreated stands (Churchel et al. 2012) or upstream vs. downstream of imidacloprid-treated stands (Benton et al. 2017).

There has been very little research on impact of imidacloprid use on pollinators in hemlock forests but much research has been done in agricultural settings where imidacloprid is applied to crop plants, soil, and used as a seed coating. Meta-analysis found that field-realistic doses of imidacloprid in nectar and pollen had no lethal effects on honeybees but reduced colony performance by 6 to 20% (Cresswell 2011). Bees and other wild pollinators may be exposed to imidacloprid that is taken up into the pollen and nectar of flowering plants growing directly adjacent to treated hemlocks (McCarty 2020). However, soil imidacloprid concentrations diminish with distance from treated trees so only a small fraction of flowers that pollinators may encounter in a treated stand would potentially have imidacloprid in the nectar or pollen (McCarty 2020). The likelihood of pollinators coming into contact with imidacloprid in treated hemlock stands is likely low, but should be verified empirically, and is currently being studied in Nova Scotia (see *Research* section).

Silvicultural Management

Silviculture includes several stand-level operations such as thinning, tree cultivation, spacing, and harvesting trees (Bauhus et al. 2009). Silvicultural operations aim to meet the unique needs of forest sites while addressing ecological issues such as HWA infestation. In this context, stand thinning has been proposed as the primary silvicultural tactic to promote hemlock resilience to the pest and slow the hemlock decline. However, stand thinning is unlikely to prevent eventual tree mortality in the absence of other pest management tactics, such as chemical or biological control. Therefore, its application is primarily to extend the life expectancy for the treated hemlock stand under HWA threat until other approaches can be developed or implemented – some of which (e.g., insecticides) could also be used in combination with stand thinning.

Stand thinning may enhance hemlock's ability to withstand the negative effects of HWA infestation for several reasons. Diverting the products of photosynthesis from the tree, HWA feeding alters both water relations as well as nutrient dynamics and allocation, effectively leading to water stress and carbon starvation, manifested eventually through needle loss and reduced shoot production. By removing competing trees, thinning improves access to light and water, promoting vigor of the remaining hemlocks (Miniat et al. 2020). Second, opening of the canopy elevates the exposure to light and the elements, suppressing HWA populations (Brantley et al. 2017). Collectively, thinning may thus enhance tolerance or resilience of hemlock to HWA infestations, mitigating the pest's negative impacts on growth and longevity, especially if applied prior to any observed decline in tree health (i.e., before HWA establishment, or under light infestation). However, this selective harvesting is not a viable option for landscape-level control of HWA impacts in NS, and thinning stands with high HWA populations may accelerate hemlock loss.

Stand thinning also provides an opportunity for forest managers and woodlot owners to actively shape stand regeneration and restoration through selection of tree species to retain or succeed hemlock, in addition to protecting their hemlock stands (Emilson & Stastny 2019). Since effective silviculture strategies should emulate natural forest regimes (Lahey 2018), improved awareness and adoption of this management tool will promote strategies towards restoration or rehabilitation of hemlock habitats, their ecological integrity, and ecosystem services. Provincial guidelines for forest management should be updated to incorporate HWA-specific strategies and promote active participation by the forest industry through selection harvesting to promote hemlock resilience and stand regeneration. Finally, thinning offers an alternative for woodlot owners who otherwise may be inclined to pre-emptively clear cut their hemlock stands following or in anticipation of HWA detection. This 'panic harvesting' will cause negative environmental impacts over a dramatically faster time scale than HWA-caused decline and mortality (Kizlinski et al. 2002), as hemlock forests can continue to provide significant habitat and ecosystem services throughout and following the devastation by HWA.

Biological Control

The rapid spread and impacts to trees (including high levels of tree mortality) are indicative of a lack of natural controls of HWA in its invaded range. Indeed, studies in the eastern US indicate native natural enemies of HWA are generalist predators that do not regulate HWA populations below levels injurious to trees (Wallace & Hain 2000; C. Cheah & M. Whitmore, personal communications). Classical biological control (i.e., introducing natural enemies from the native range of HWA into the invaded range of HWA) is therefore regarded as a critical long-term treatment for HWA (Emilson & Stastny 2019; Mayfield et al. 2020; Fidgen et al. 2020). Over the last 25 years, eight predatory insects have been released in the eastern US for biological control of HWA through a well-developed biological control network (Emilson & Stastny, 2018; Fidgen et al., 2020). A key feature of the approach to biological control of HWA is to attack both generations of HWA with biological control agents (Elkinton et al. 2011; Vose et al. 2013; Fidgen et al. 2020). Development and investment in a similar biological control program will be required before HWA biological control can be undertaken in Canada (see *Research* section).

The biological control program consists of scientific and operational components and, as a result, will involve multiple organizations (Fidgen et al. 2020). The scientific component involves research on the biological control agents and scientific review by expert panels to determine whether release of biocontrol agents in the invaded range of HWA in Canada is advisable. This can take up to five years for each agent with additional time needed to develop and test protocols for their release and establishment. Once approved for release, the operational component involves collecting agents from their native range and mass rearing them in dedicated facilities near the invaded range in Canada. In addition, research from the US has suggested it could take 20 or more years of releases before an agent reaches population levels that suppress HWA populations enough to prevent hemlock mortality (Fidgen et al. 2020). Both components will require significant initial investment but once biocontrol agents have established costs reduce significantly. Successful classical biological control programs are among the most cost-effective strategies in pest management with better cost-benefit ratios than those for chemical controls (Kenis et al. 2017).

Restoration and Regeneration of Hemlock Stands

While restoration of mature eastern hemlock stands may take hundreds of years, regeneration tactics (e.g., seed collection and tree hybridization) can provide long-term assistance in rehabilitating ecosystems where hemlock has been lost, once long-term control measures are working (Emilson & Stastny 2019). As such, the *Hemlock Woolly Adelgid Management Plan for Canada* recommends that the **collection and preservation of seeds from southwestern NS should be a management priority** (Emilson et al. 2018). Eastern hemlock is known to have relatively low genetic diversity across its range, particularly in northeastern North America (Prasad & Potter, 2017) and in isolated populations (Potter et al. 2012), with significant gaps in our knowledge for NS and other northern regions. This lack of diversity has important conservation implications both in the context of anticipated HWA impacts and future climate change. Eastern hemlock seed collection efforts are ongoing in the Maritime Provinces (see *Research* section).

The lack of resistance to HWA in eastern hemlock has led to its extensive mortality through the invaded range; however, isolated cases of putatively resistant trees amidst decimated hemlock stands have been reported in Connecticut (Caswell et al. 2008). Notably, a limited number of putatively resistant hemlock have been documented in isolated stands following a citizen science campaign to search for candidate trees. A very limited number of these individuals have been clonally propagated and tested in HWA inoculations (Ingwell & Preisser 2010) and in replicated outdoor trials (Kinahan et al. 2020), and further work is needed to validate the conclusions of these studies. While severe genetic bottlenecks are expected under such circumstances, this approach offers both hope and opportunity to develop an outreach program to search for HWA-resistant hemlock with the goal of starting a tree improvement program. In combination with other management tools, even modest gains in hemlock's ability to resist or tolerate HWA infestation could be instrumental in the restoration and rehabilitation of hemlock forests (Emilson & Stastny 2019).

The species composition of infested hemlock stands in NS can also be expected to shift naturally to other conifer species or mixedwood stands as hemlock trees die (Emilson & Stastny 2019; Case et al. 2017). As such, one rehabilitation strategy involves replacing eastern hemlock with other evergreen, albeit not ecologically equivalent, species (e.g., red spruce (*Picea rubens*) or eastern white pine (*Pinus strobus*). Unfortunately, these species may struggle with their own health issues under climate change. While replacement would not directly conserve eastern hemlock, it would support the recovery and restoration of at least some of the ecosystem services (Emilson & Stastny 2019). This tactic would therefore help to maintain some of the characteristics of evergreen overstory, and discourage effects of over-browsing by deer or the establishment of invasive shrub species such as glossy buckthorn (Vose et al. 2013; Ward et al. 2004).

Integrated Approach - Pest Management Strategy

No single approach is advisable for the management of HWA (Emilson & Stastny 2019 Mayfield et al. 2020). To support stand survival during the initial wave of HWA, where HWA populations will be high due to host abundance over the landscape, a combination of short- and long-term treatments have been used in the eastern US. In other words, short term treatments are designed to help trees cope with HWA until long term treatments begin to take effect. Given that the efficacy of treatments and the rate of HWA impacts are not yet fully known in NS, an adaptive approach using an integrated pest management strategy is encouraged (Emilson & Stastny 2019).

Optimum short-term tactics should aim to temporarily reduce HWA density followed by treatments to improve tree vigor (Miniat et al. 2020), e.g., use of insecticides followed by stand thinning. Long-term treatments aim to stabilize HWA populations below levels that cause severe impacts or tree mortality. Research suggests that importation of natural enemies from the native range of HWA and development of tree resistance provide much needed, self-sustaining coping mechanisms to HWA infestations.

RESEARCH

Research will play a key role in the delivery of the biocontrol program and will provide support for registration of insecticides needed to effectively combat HWA, amongst development of other tools. While a variety of management options exist to mitigate HWA, research will support future management planning and allow landowners and land managers to make sound decisions. Current and future research topics include the following:

HWA Biology and Monitoring: Studies must continue to fill in fundamental knowledge gaps on the population dynamics and phenology of HWA to assess its seasonal mortality and survey native natural enemies of HWA in NS. Recent advances in genetic tools (i.e., environmental DNA) may provide additional solutions for detection of incipient HWA populations. The propagule pressure from HWA is expected to be very high in NS, and further research is needed to examine the risk of continued tree damage by re-establishing crawlers on treated trees in spite of chemical treatment. This aspect of the biology of HWA should be investigated. Moreover, long-term monitoring of HWA will provide insight into the impacts to hemlock health over time, allowing fine-tuning of the timing of treatments.

Dendrochronology: With support from Mount Allison University and Parks Canada, dendrochronological studies are underway to determine the beginning of HWA-induced hemlock decline in this region (B. Phillips, personal communication, 2020). This will improve the understanding of HWA's arrival in the province and how quickly infested stands decline in NS.

Chemical Control: Research trials are underway in southwestern NS to test the efficacy and nontarget impacts of several chemical control options, including TreeAzin®, Xytect 2F, and Ima-Jet. TreeAzin®, an azadirachtin-based insecticide derived from neem oil extract, has been tested for control of HWA in research trials in southwestern NS (BioForest Technologies Inc., 2018). This chemical significantly reduced live adelgids on treated trees compared to the controls (Sweeney et al. 2020) and also acted more quickly than Ima-Jet or Xytect (Sweeney, unpublished data). However, TreeAzin® is an expensive insecticide, costing on average $2.21 CAD per cm diameter-at-breast-height (DBH) per tree, compared to an average cost of $0.60 per cm DBH for Ima-Jet® (J. Sweeney, personal communication, February 26, 2021). Another imidacloprid-based option, Xytect® 2F, is also being studied in southwestern NS as a potential treatment option. This chemical is cheaper than both TreeAzin® and Ima-Jet®, costing just $0.12 per cm DBH on average and requiring a fraction of the application time (J. Sweeney, personal communication, February 26, 2021). Pending the results of formal consultation with the Mi'kmaq nations of Nova Scotia, the Province will potentially support a federal application for emergency registration of Xytect® 2F from the PMRA to expedite the short-term protection of high priority eastern hemlock stands.

The impacts from HWA will accrue so quickly that many priority stands will have advanced infestations and sustain heavy impacts from HWA. Experience in the USA has found that often imidacloprid acts too slowly to prevent mortality of heavily infested hemlocks. When stands reach this point, managers in the USA usually use a tank mix of dinotefuran (another neonicotinoid) and imidacloprid; the dinotefuran moves into hemlocks quickly, rapidly suppressing HWA and allowing time for the imidacloprid to provide longer term protection (Vose et al., 2013, Webb et al., 2003). Dinotefuran is not registered for outdoor use in Canada and appeals to the manufacturers to support research trials in Canada have been unsuccessful. Recent research with TreeAzin® suggests that it may offer an alternative to dinotefuran as a tool to rapidly suppress HWA populations, and this will be tested in research trials in NS and ON.

Biocontrol: As recommended by the *Hemlock Woolly Adelgid Management Plan for Canada* (Emilson et al., 2018), field and research trials for the rearing of biological control predators should continue to be pursued in southwestern NS. These trials should focus on insect risk and mortality assessments and will be key to CFIA approval. Considering this research, the first release of HWA specific predators could occur within 5 years (Fidgen et al. 2020) and it may take 20 years or more for populations to build to levels where suppression of local populations is observed.

Research has focused mainly on the predatory beetle *Laricobius nigrinus* as a natural HWA predator and an aggressive biocontrol program has been built in the US using this species and a congener, *Laricobius osakensis* that together attack the sistens nymphs and progrediens / sexuparae eggs of HWA. Recently, silverflies (*Leucopis spp*.) (Kohler et al. 2016) that attack both generations of HWA, but attenuate during the progredien nymphs to sistens egg stages, are being pursued for mitigation of this second generation of HWA (Kirtane et al. *in press*).

Silvicultural Management: Early outcomes of several field trials in the US show promising results of stand thinning conducted at the scale of canopy gaps created around focal trees (Fajvan 2008; Piatek et al. 2017), including through trials in combination with biological control (Miniat et al. 2020). Following the initial acclimation, competitively released trees under HWA infestations showed improved photosynthesis, carbon balance, shoot allocation, and up to 9-fold greater growth than those without thinning (Miniat et al. 2020).

To test the potential of this silvicultural approach under NS conditions, stand thinning is currently being tested in eight replicated stands (30–70% hemlock) across southwest NS. The experiment is conducted at an operational scale (2–4 ha treatment blocks), in both private woodlots and on Crown Land, and involves removal of 20–40% basal area through selection harvest or shelterwood cut that leaves vigorous hemlock (20–50 cm DBH). In addition to monitoring tree growth and HWA levels inside the thinned research plots (1 ha) as well as in the adjacent control plots that remain intact, this research is also examining the longer-term effects of thinning on stand regeneration, biodiversity, and soil abiotic conditions under HWA infestation.

Restoration and Regeneration of Hemlock Stands: Research on hemlock restoration and HWA resistance in Canada is needed to determine its feasibility in NS (Emilson & Stastny 2019; Vose et al. 2013). Eastern hemlock seed collection is currently underway as part of an initiative by the National Tree Seed Center, a repository for seed of tree species at risk in Canada located at the Atlantic Forestry Center, Canadian Forest Service, in Fredericton, New Brunswick. Seed collection is carried out by trained partners of the National Tree Seed Center including teams from local non-government organizations, NSDLF, Parks Canada, and the Acadia University Seed Center.

Several options exist to rehabilitate eastern hemlock habitat (e.g., tree species replacement), but information is needed to determine NS-specific restoration tactics. First, genetic diversity of local hemlock populations should be examined. In addition, research should examine the likelihood of stand colonization by invasive plant species (e.g., glossy buckthorn).

Regeneration programs, including those aimed at improving genetic resistance, should focus on using native, non-hybridized hemlock species (with some level of HWA resistance) before considering exotic hemlock replacements. Harper and Weston (2016) suggest the northeastern US may support plantings of

Chinese hemlock (*T. chinensis*) to benefit from that species' resistance to HWA; this could eventually be examined for replacement of eastern hemlock in NS. In time, regions in NS may become suitable for Carolina hemlock (*T. caroliniana*), a hemlock species that can be crossed with HWA-resistant Chinese hemlock (Harper & Weston, 2016).

MANAGEMENT FRAMEWORK FOR NS

Stand Prioritization

As of yet, no landscape-level management tactics are available to protect hemlock in NS against the impacts of HWA, or effectively contain further spread of the pest. Until a biological control program is developed and eventually implemented broadly, the current limitations of HWA management in NS necessitate the following approach: 1) targeting specific, high-value hemlock stands, and 2) applying appropriate treatments given the stand condition, infestation levels, and site-specific considerations. A stand prioritization framework for the province is not yet fully developed, and priorities will vary depending on resources and management context (e.g. private woodlot versus a protected old-growth stand). This section outlines some of the factors, decisions and end goals involved in selecting hemlock stands and individual trees for treatments. As additional information and tools become available, prioritization and treatment options will continue to evolve, and should adapt in response to management outcomes and the changing context of HWA impacts.

The prioritization exercise must be a key feature of the management of HWA and conservation of hemlock resource in NS as it will identify high value stands. Such a practice will be critical given the limited resources, as the cost of the treatments will allow targeting of only a fraction of hemlock stands or individual trees within a stand. A stand prioritization framework will need to consider many criteria to assign a relative value to hemlock stands, which will also depend on the relative abundance and condition of hemlock in an area or region; in other words, a stand prioritized in one context may not be given a high ranking in another context. In addition to assessing the risk of heavy damage from HWA, questions that will guide prioritization will range from those examining stand characteristics (Is the stand old-growth, or hemlock-dominated?), ecological or ecosystem context (Is the stand in a protected area, or a sensitive habitat?), socio-economic values (Is the stand in proximity to recreational areas or private homes?), silvicultural plans (Does the stand need to be thinned to promote tree growth or regeneration?). Depending on the objectives of the treatments, protecting an entire stand may be desirable when the goal is the retention of habitat characteristics and ecosystem function; in other instances, individual trees may need to be selected, requiring additional assessments of tree health and infestations. However, even in treated stands, it may not be possible to include all hemlock trees. In addition, regulatory context may further limit what selection and tactic can be used in a given area (e.g. riparian zone). Managers and woodlot owners will also need to consider the long-term cost feasibility of future treatments when using chemical control.

Small-scale Management

Stand prioritization will serve as a guide for small-scale HWA management aimed at protecting individual stands. This management approach considers the challenging nature of this pest: impossible to eradicate, very difficult to contain, with a highly patchy distribution and variable rate of impacts. The stand-level focus of this approach gives considerable flexibility to forest managers and woodlot owners and lends itself well to adaptive integrated pest management and proactive action. While this strategy is not readily scalable to larger areas due to its resource intensiveness, its recommendations and implementation could be the same for similar stands in different regions of the province. For instance, a lightly infested stand located deep within the area of heaviest infestations may be selected for the same treatments as a healthy stand outside of an affected region. This approach thus allows for fine-tuned management action while complementing larger-scale regulatory action (e.g. regions regulated by CFIA), and regional forest management plans and priorities.

In small-scale HWA management, the suite of treatments for HWA suppression and mitigation depends on the level of infestation and health status of trees in the stand. With this approach, HWA populations and hemlock conditions would be monitored in high-value stands and treatments applied proactively to improve hemlock resiliency and/or suppress HWA. A central feature of this management will be communication with stakeholders. As the number of HWA-managed stands grows, they will provide invaluable information on the application and efficacy of treatments, success stories, and foster further training on tools and techniques used to manage HWA and hemlock. In addition to the involvement of the HWA Working Group and its partners at all levels, an effective component of this communication should include installing signage and other messaging at key areas explaining the threat of HWA and the need for focused management to protect the hemlock resource.

Stands prior to detection of HWA

Before HWA arrives in an area, or when HWA is suspected in a stand but populations are too low or localized to detect, several options exist for proactive treatment plans. This advance preparation for the eventual arrival and impacts from HWA should prioritize techniques to boost hemlock vigour and involve ongoing pest monitoring to guide further action as needed. In practice, the lack of immediate threat to the hemlock may often lead to delays in treatment implementation as other more affected stands in the area may take priority. However, proactive HWA management may be particularly well-suited to some woodlot owners and can be incorporated within existing selective harvesting plans.

- Use stand thinning or other proactive methods of improving tree resilience;
- Designate stand for long-term monitoring of stand impacts by HWA;
- If risk of HWA invasion is imminent (e.g. due to proximity to known infestations), consider treating prophylactically with imidacloprid-based insecticides.

Stands with low to moderate HWA infestations, trees still healthy and vigorous

Stands with these characteristics (Table 2; low to moderate classification) may be best suited for active treatments, as their tree condition is more likely to result in good management outcomes, and ensure the preservation of ecological function of the habitat before it is impaired. These stands are suitable for treatments with imidacloprid as well as biological control (once available). The chemical and biological treatments could be applied singly or together; however, the requirements for biocontrol treatment are very specific to ensure the released natural enemies have a high likelihood of establishing and growing their populations.

- Consider application of imidacloprid-based insecticides.
- A portion of the untreated trees could be thinned once insecticides are working to improve stand vigour.
- Release biocontrol agents, once available.
- Designate stands for long term monitoring of impacts by HWA.

Stands with moderate to high HWA infestations, trees at varied levels of decline

Because HWA densities tend to be highly variable (but see Table 2; high classification), considerable differences in the pest impacts will often be observed within a stand, with some trees declining much faster than others. This situation may make it difficult to attempt HWA treatments at the level of the entire stand as directed by applicable regulations, especially when resources are limited, but selective action with a greater emphasis on individual tree prioritization may still be possible (but see Table 2 for classification of infestation levels).

- Designate stands for long-term monitoring of impacts by HWA
- Salvage-harvest trees showing severe decline if possible; other forms of silviculture recommended, such as underplanting with other tree species to promote regeneration, or thinning to select replacement trees
- Consider applying a fast-acting insecticide such as TreeAzin® or dinotefuran, if/when these become available, to recover select vigorous trees that still retain crown growth. This could be coupled with the use of chemical treatments using imidacloprid to provide longer-term control. Once available, biocontrol agents could be also released on trees with low to moderate infestations of HWA.

Stands with high HWA infestations, trees in advanced decline.

Once HWA densities cause a marked decline in hemlock health, management strategies become more limited, and may need to focus on individual trees that may still be salvageable. Stand restoration and regeneration after loss of hemlock should become a priority. In many situations, these stands are likely to rank low in management prioritization if other, healthier stands exist in the same area. Note, however, that some trees may be showing recovery as the HWA populations crash due to depletion of their food resource.

- Similar to the previous stand condition, treatment may be appropriate on trees where HWA populations have crashed locally, provided there is enough time for chemicals to become effective. Some trees may also be recoverable by applying TreeAzin or dinotefuran if/when they become available.
- Tree cutting to remove dead and dying hemlock if deemed a public safety hazard or for salvage harvesting if desired by the landowner.
- Monitoring for trees showing notable resistance/resilience; collection of seed material or cuttings for potential propagation

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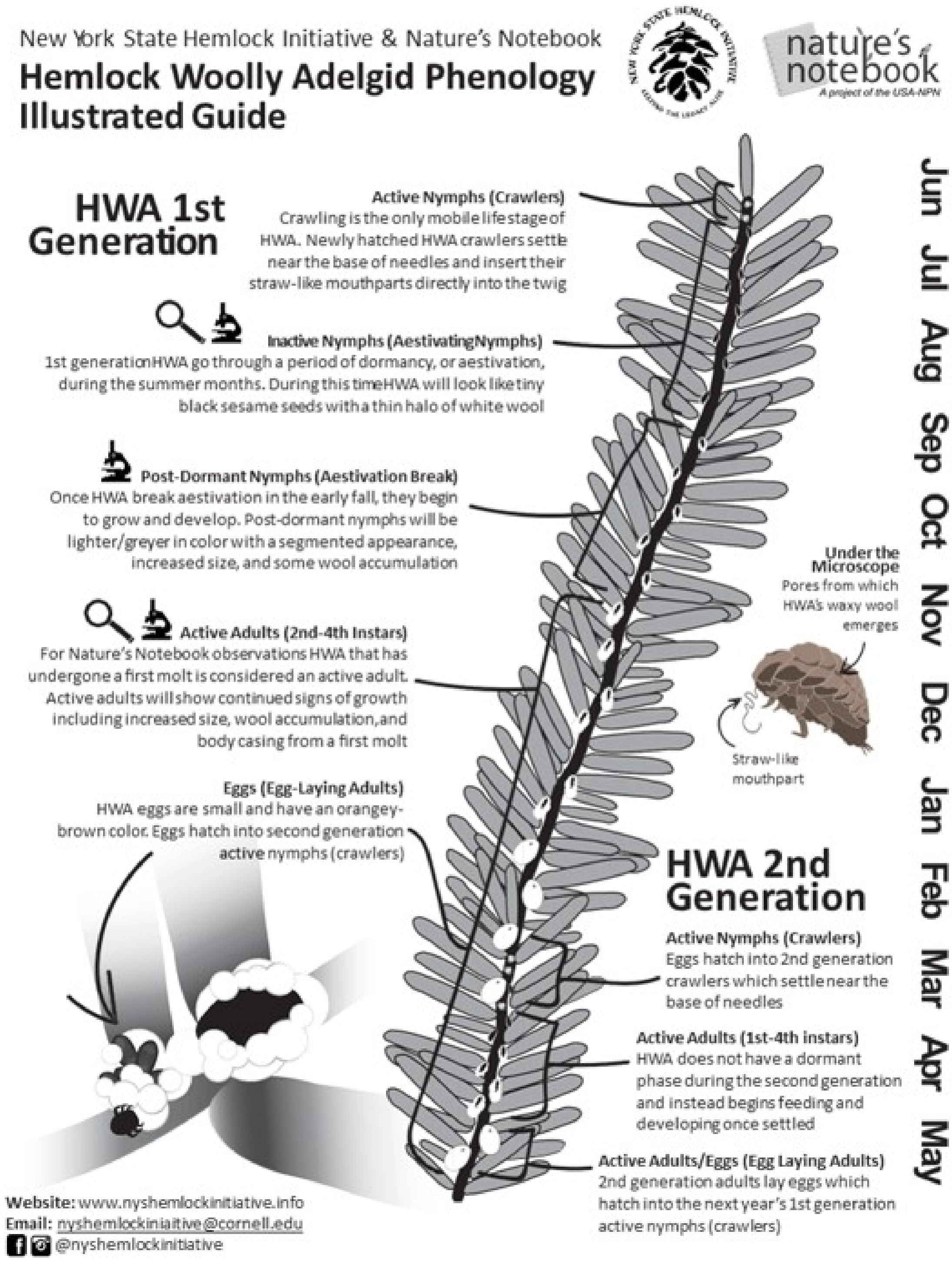
APPENDIX A: Illustrated guide to HWA phenology

(Source: New York State Hemlock Initiative)



APPENDIX B: CFIA Detection Protocol

(to be attached)

APPENDIX C: HWA fact sheet. (Source: Canadian Food Inspection Agency).

HEMLOCK WOOLLY ADELGID
PUCERON LANIGÈRE DE LA PRUCHE

Crown dieback / Dépérissement de la cime

Actual Size / Taille Réelle

Hemlock cone / Cône de pruche

Infested hemlock / Pruche infestée

The hemlock woolly adelgid (HWA, *Adelges tsugae*) is a destructive pest of eastern hemlock, an ecologically significant tree species in eastern Canada. Eastern hemlock provides nutrients, soil stability and habitat for animals and plants.

HWA feeding removes plant fluids, causing needle drop, twig dieback and tree mortality in as few as 4 years. Early detection of HWA is critical to protecting Canada's forests and environment.

Signs and symptoms of this pest include:

- Cottony, white egg sacs at base of needles
- As infestations advance, swelling at twig tips, twig dieback, grey foliage, stand level defoliation will occur

You can help protect natural areas from this invasive insect:

- Check hemlock trees for evidence of HWA
- Collect or photograph suspect HWA specimens if found
- Report suspect HWA or HWA damage

Actual Size / Taille Réelle

Cottony sacs at base of needles, 3–6 mm / Ovisacs d'aspect cotonneux à la base des aiguilles, 3–6 mm)

For more information on this subject or to report sightings please visit our website at: **www.inspection.gc.ca**

Le puceron lanigère de la pruche (PLP, *Adelges tsugae*) est un ravageur destructeur de la pruche du Canada, une essence d'importance écologique dans l'est du Canada. La pruche du Canada fournit des éléments nutritifs, contribue à la stabilité des sols et procure un habitat à diverses espèces végétales et animales.

Not HWA / Pas un PLP

Spittle bug / Cercope

Spider egg sac / Sac ovigère d'araignée

Le PLP aspire les liquides des pruches qu'il infeste, provoquant ainsi la chute des aiguilles, le dépérissement des rameaux et la mort des sujets infestés en aussi peu que quatre ans. La détection précoce du ravageur joue un rôle critique dans la protection des forêts et de l'environnement du Canada.

Les signes et les symptômes d'une infestation par le ravageur sont les suivants :

- présence d'ovisacs (sac d'œufs) blancs d'aspect cotonneux à la base des aiguilles;
- stade plus avancé de l'infestation : boursouflures à l'extrémité des rameaux, dépérissement des rameaux, feuillage virant au gris, défoliation généralisée à l'échelle du peuplement.

Vous pouvez nous aider à protéger nos régions naturelles contre cet insecte envahissant en :

- inspectant des pruches afin de vérifier si elles sont infestées par le PLP;
- récoltant ou en photographiant des spécimens soupçonnés d'être des PLP;
- signalant la présence présumée de PLP ou de dommages potentiellement infligés par le ravageur

Pour de plus amples renseignements sur ce ravageur, veuillez consulter notre site Web à : **www.inspection.gc.ca**

Canadian Food Inspection Agency / Agence canadienne d'inspection des aliments

www.inspection.gc.ca

Canada