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A decision framework for hemlock woolly adelgid management: Review of the most suitable strategies and tactics for eastern Canada

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ABSTRACT

The invasive hemlock woolly adelgid (HWA) has decimated hemlock stands across much of the eastern United States, and presents a significant threat to all eastern hemlock in Canada across Ontario, Quebec, New Brunswick, Nova Scotia, and Prince Edward Island, especially since the recent detection of its widespread establishment in southwest Nova Scotia. The spread and rising infestation level and impacts of HWA in this region serve as a warning for forest managers across eastern Canada to develop appropriate management plans and priorities. The HWA decision framework presented here aims to prepare forest managers in eastern Canada for the decisions and challenges that they will face, from prevention, detection, and control, to hemlock ecosystem restoration and management program evaluation. We review the strategies and tactics that are currently available, that are being developed, and that show the most promise to date. Given the nature of HWA, the long-term outlook for eastern hemlock in Canada will likely feature HWA as a component of hemlock ecosystems across much of the region, necessitating a comprehensive, adaptive management program to mitigate its ecosystem consequences.

1. Background

Hemlock woolly adelgid (Hemiptera: Adelidae, *Adelges tsugae*, Annand, HWA) is an invasive, aphid-like pest introduced from southern Japan that infests and eventually kills eastern and Carolina hemlock (*Tsuga* spp.*)*. Since its discovery in Virginia in the early 1900's, HWA has decimated hemlock stands across much of the eastern United States, spreading at a rate of 7.6–20.4 km $year^{-1}$ (Trotter et al., 2013) from Georgia, north to Nova Scotia (Limbu et al., 2018).

Eastern hemlock (*Tsuga canadensis*) is the species of concern for HWA in Canada, and is distributed throughout southern Ontario, southwestern and eastern Quebec, New Brunswick, Nova Scotia, and Prince Edward Island. Although hemlock is only a minor source of revenue as pulp and lumber in Canada, it is valued as a foundation species providing unique habitat and environmental conditions that support distinct terrestrial and aquatic ecosystems (Ward et al., 2004). For example, year-round shading by hemlock canopy lowers air and water temperatures, shelters the understory from snow and harsh weather, and maintains more consistent hydrology. These conditions provide habitat for species such as brook trout (Ross et al., 2003), and overwintering ground for deer and moose (Yamasaki et al., 2000). Several bird species, including the black-throated green warbler, Blackburnian warbler, and Acadian flycatcher, rely on the dense, multi-layered canopy structure of hemlock (Tingley et al., 2002). The slow decomposing needles of hemlock contribute to soil acidity, build a thick overlaying litter layer, and mediate energy and nutrient cycling that supports distinct biota in forest ecosystems (Stadler et al., 2005), and in aquatic ecosystems where hemlock commonly comprise an important component of the riparian zone (Adkins and Rieske, 2015). Along with its ecological importance, hemlock is also recognized for its longevity, iconic size and stature, and aesthetic appeal that give it great social value among recreationalists and homeowners.

Forest managers in Eastern Canada are now faced with the challenge of managing HWA and its ecological impacts. In June 2017, established HWA populations were discovered in southwest Nova Scotia with evidence of tree decline and mortality (CFIA, 2017). Prior to the discovery of HWA in Nova Scotia, small, localized HWA incursions were found in Ontario in 2012 and 2013 (Fidgen et al., 2014). These populations were controlled by removal of the infested hemlock trees. Delimitation surveys have been ongoing at these locations and no further evidence of HWA has been detected since 2015.

The risk of HWA spread and hemlock mortality exists in all areas of eastern Canada with hemlock. This risk is underscored by the fact that HWA populations have already established in southwest Nova Scotia

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and have caused tree mortality (CFIA, 2017), suggesting that HWA has persisted there for a number of years. HWA has been shown to adapt to cold conditions (Lombardo and Elkinton, 2017), and its survival at the northern edge of its distribution is predicted to continue to increase with winter warming under climate change (McAvoy et al., 2017). Therefore, although the stage and degree of management in each province will vary depending on the rate, context, and impacts of HWA incursions, it is important that forest managers in all provinces with hemlock consider prevention and detection strategies to complement current CFIA efforts, and prepare HWA management plans that include control, restoration and evaluation.

To date, no single management strategy has been identified to control HWA, with HWA causing up to 100% hemlock mortality in some areas of the eastern United States (Brantley et al., 2015). However, much work has been done in the United States describing the pest's biology and life cycle, and in developing and evaluating HWA management practices and their potential impacts (Limbu et al., 2018). We recently reviewed the implications of HWA introduction to Canada in a technical report that outlined the components for an HWA management plan based on research and implementation strategies in the United States (Emilson et al., 2018). Under the assumption that subsequent incursions are probable and HWA will continue its spread, we build on this management plan by identifying the strategies and tactics best suited for use in Canada in the context of a decision framework for forest owners and managers.

2. Review of strategies and tactics

The decision framework presented here is based on a decision framework for HWA management in the eastern United States (Vose et al., 2013), the framework of a pest risk assessment (Scarr and Ryall, 2012), and a review of the issues and decisions faced during the planning and implementation of HWA management programs in eastern North America. The decision framework is summarized below in the context of the stages of HWA currently found across eastern Canada, including: (Stage 1) HWA not detected, (Stage 2) HWA detected, hemlock still healthy, and (Stage 3) HWA causing hemlock decline or mortality (Fig. 1).

The sections that follow include a review of the strategies to provide additional information and context, including detailed tables outlining the tactics available, target outcomes, and the costs and benefits of the strategies and associated tactics presented for use in Canada. Strategies are divided into five main sections including: (2.1) Prevention, (2.2) Detection, (2.3) Control, (2.4) Restoration & Rehabilitation, and (2.5) Evaluation. The "Do Nothing" strategy is included to contrast the costs and benefits of attempting action under each section.

2.1. HWA prevention

Prevention aims to minimize the risk of new HWA introductions and the spread of existing HWA incursions. Prevention efforts are currently being led federally by the CFIA across all eastern provinces at risk through education and outreach, and the implementation of phytosanitary legislation (CFIA, 2015a, 2015b). Additional provincial and regional education and outreach efforts, and regulations have been set in place in Ontario (e.g. Invasive Species Act: Government of Ontario, 2015) and Nova Scotia where HWA has already been detected.

2.1.1. Education & outreach

Education and outreach in their various forms (Table 1.1) can help to reduce pest spread through greater awareness of the risks, pathways, and impacts of the pest (e.g. Gonzales et al., 2015). Education and outreach in pest management programs increase social support helping avoid adverse public reactions due to lack of knowledge or understanding (Klapwijk et al., 2016). They also help to coordinate pest management efforts on private land (Niemiec et al., 2017), facilitate the contributions of citizen science to pest management efforts (Ingwell and Preisser, 2011), and facilitate more effective monitoring via forestry and research staff trained in identification and detection.

While a comprehensive evaluation of education and outreach success in HWA management is still lacking, a review of 104 media articles on HWA in the United States highlights the importance of fairly representing potential risks and uncertainties, along with the benefits of a proposed management tactic when informing the general public (Leppanen et al., 2018). In addition, the Ontario Ministry of Natural Resources and Forestry conducted a survey to examine the importance of aquatic invasive species education and outreach across different provincial, state, international and regional scale programs. Its results highlighted an increased participation in prevention strategies and reporting of incursions with the implementation of a simple, positive message. Strong legislation backed by consistent enforcement, on-the-job training of industry partners, the engagement of partners in the support of pest management programs, and consistent messaging across different regions were also found to be important to increased participation (Fera et al., 2015).

2.1.2. Additional federal, provincial or municipal regulation

Prevention strategies and regulations may vary in their effectiveness due to differences in existing regulations and values, and the degree of coordination and cooperation among federal, provincial, and municipal governments, commercial and industry partners, and the general public. Therefore, scenario-specific regulations may enhance the effectiveness of prevention (Table 1.2). For example, after HWA was found in Nova Scotia in 2017, Parks Canada issued a firewood movement ban for Kejimkujik National Park due to the proximity of established HWA populations in southwest Nova Scotia and the extensive old-growth stands of eastern hemlock located in the park (unfortunately, in 2018, it was confirmed that HWA was already established in the park). Another pathway that presents a risk of new HWA introductions is the purchase and movement of hemlock material (i.e. boughs, logs with bark, and bark chips) from regulated areas in British Columbia (see biological control section for details on the western strain of HWA) and the United States to eastern Canada (CFIA, Belleville, ON, 2017); in this case, education and outreach tactics targeting both the buyers and the distributors of hemlock boughs, logs, and bark chips would help to create greater awareness of CFIA regulations on these forestry-related products, especially where enforcement is complicated by the lack of border control between provinces.

The ornamental tree nursery industry in Canada and harvesting practices in stands containing hemlock may require increased regulation, or additional legislation. The ornamental tree nursery industry is a known high-risk pathway and HWA has previously been introduced to Ontario on nursery stock from the United States. Active enforcement of phytosanitary measures at different scales specific to identified problem scenarios may help improve compliance to regulations. Additional provincial regulatory measures or legislation for harvest activities in stands containing hemlock at risk to HWA may also prove beneficial, as movement of harvested trees in HWA-infested stands presents another potential pathway for HWA spread. Phytosanitary measures could include mandatory inspection of the stands in regulated counties for HWA prior to or, more effectively, during harvest along with the steps following detection. The creation or updating of Memoranda of Understanding (MOUs) between the CFIA and individual provinces may also prove useful in facilitating active collaboration in relation to the specific needs of each province.

2.2. HWA detection

Detection is central to an invasive pest management program as it contributes not only to early discovery and response to new incursions, but also to documenting and understanding population spread, and the success of management efforts. Monitoring efforts are currently led

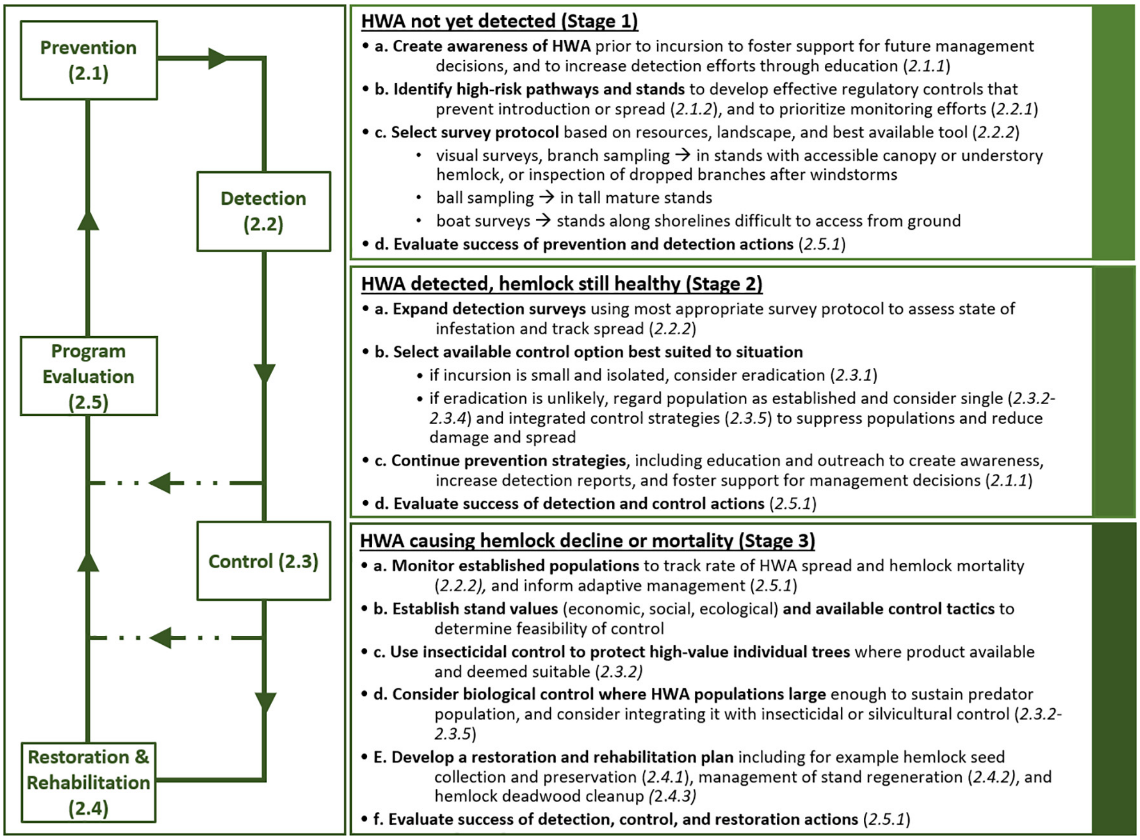

Fig. 1. Summary of decisions framework and suggested strategies for the different stages of HWA incursions across Canada.

federally by the CFIA in all provinces at risk, with visual surveys in 2018 including 75 sites in Ontario, 25 sites in Quebec, 40 sites in New Brunswick, 96 sites in Nova Scotia, and 15 sites in Prince Edward Island. Provincial and local monitoring and detection efforts are also underway in some of these provinces (e.g. at least an additional 60 plots surveyed by partners in Nova Scotia including Parks Canada, Natural Resources Canada – Canadian Forest Service, Nova Scotia Department of Lands and Forestry, and Mersey Tobeatic Research Institute), along with the reporting of HWA detections from forestry staff, conservation groups, woodlot owners, and citizen scientists via web reporting tools where education and outreach efforts have been made.

2.2.1. Allocation of resources for detection

Detection and monitoring efforts that target high risk areas can both increase the chance of early detection, and the efficacy of invested resources (Table 2.1). Data on the distribution of eastern hemlock stands are critical to HWA spatial risk modelling, along with data on the location and extent of current HWA infestations. Recently established HWA populations in the northeastern United States and Nova Scotia have been georeferenced, but will require updating as HWA continues to spread. All eastern provinces would also benefit from more comprehensive and current hemlock inventory data. Outreach to facilitate the reporting of hemlock stands on private land (e.g. efforts in Ontario led by Silv-Econ Ltd.; Emilson et al., 2018), the use of remote sensing techniques and aerial surveys, or modelling approaches using environmental parameters (e.g. Clark et al., 2012) could all be used to improve current hemlock databases across eastern Canada.

In combination with the spatial data on hemlock stands and HWA distribution and abundance, landscape, climate, and bird migratory route information can all be used to spatially model the risk of HWA, allowing for targeted and more efficient detection efforts (Liang et al., 2014). Minimum winter temperatures (Fitzpatrick et al., 2012) and drought stress (Livingston et al., 2017) are known to influence hemlock susceptibility to HWA, and these and additional factors are currently being examined in the context of infestations in Nova Scotia to further assess vulnerability of hemlock stands to HWA. Information on the proximity of hemlock stands to existing HWA infestations, along with the presence of dispersal corridors such as trails, roads, riparian corridors (Koch et al., 2006), and railroads (Liang et al., 2014) may act as additional factors in HWA spread. Finally, incorporation of bird migratory routes may lend to increased predictive power given the ability of HWA to attach to and disperse via birds over long distances (Russo et al., 2019), and the identification of stands with high social and economic value can inform the prioritization of monitoring efforts.

2.2.2. Survey methodology to implement

Detecting HWA as early as possible along with having the ability to accurately delimit infestations is key to the successful prevention of HWA establishment and spread. However, despite the many HWA survey methods available (Table 2.2), no single method currently provides consistent and reliable low-density detection and delimitation of HWA infestations. The small size of HWA (individuals approximately 1–2 mm long) makes it a challenging pest to detect when it is present at low densities. In addition, based on recent detection and delimitation efforts in Nova Scotia, HWA densities can be highly variable within a stand and even among the branches of a single tree making it problematic to conclusively delimit a population once it is discovered.

Visual ground surveys looking for HWA nymphs, adults, and white egg sacs, supplemented with branch sampling and climbing, are currently the method of choice used by the CFIA for detection and delimitation surveys (based on: Costa and Onken, 2006). Visual ground surveys have the benefit of requiring little equipment, but are less effective where canopies are too high to assess visually (although broken twigs found on the ground are routinely surveyed for HWA, see below) or where the terrain makes it difficult to access trees (e.g. riparian stands). Climbing and or branch sampling have been implemented to

Table 1.1
HWA prevention using education and outreach. For each strategy requiring action, the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Increase education and outreach about HWA detection and legislation, along with its movement by human mediated pathways	**HWA:** Reduced spread of HWA by human mediated pathways, and improved early detection **Hemlock:** Cases of infestation and mortality decreased	**Costs:** Additional investment in creation of resources and hosting events	Greater awareness that supports legislation and develops social responsibility and participation in the prevention of HWA spread	**PS:** Stakeholder surveys, pest-information sheets and signs, woodlot best management practices, websites, events, media outreach, internal training of staff in HWA identification and detection
Do not invest in further outreach and education	Hemlock mortality remains the same or increases; unmitigated human-assisted range expansion	**Costs:** Less awareness and practice of preventative activities and legislation, and fewer detection reports	No extra investment	No education and outreach tactics required

Table 1.2
HWA Prevention using additional federal, provincial or municipal regulations. For each strategy requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Create and implement additional regulation(s) specific to provincial/ regional situation	**HWA:** Customized regulations improve prevention/ impede movement of HWA within the province/ region **Hemlock:** Cases of infestation and mortality reduced	**Costs:** Additional investment (time & money) in developing, implementing and enforcing new regulations **Obstacles:** Timeline to develop and implement potentially too slow in response to HWA, and potentially challenging to enforce regulations across provinces	Legislation can be better suited and more effective for local situation	**PS:** Firewood movement ban (e.g. National & Provincial Parks, or generally at the provincial level for all untreated firewood), ban on selling of hemlock boughs, logs, and bark, phytosanitary regulation at various scales for ornamental industry, regulations on harvest practices in stands with hemlock at risk, MOUs between CFIA and provinces
Do not add additional provincial/ regional regulations to CFIA regulations in place	**HWA & Hemlock:** No change in prevention capacity and no response to any identified increased threat	**Costs:** Potentially missed opportunity for prevention and increased investment in control	No extra investment in prevention	No additional regulations required

Table 2.1
Resources to allocate to HWA Detection. For each strategy requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Increase monitoring efficiency and efficacy	**HWA:** Earlier and more reliable detection of incursions, and spread **Hemlock:** In combination with other strategies, can lead to a decrease in new infestations and mortality	**Costs:** Additional investment in characterizing risk and prioritizing efforts (time, money, resources) **Obstacles:** Need for data: hemlock inventory and susceptibility, and HWA distribution, and monitoring of hemlock stands on private land	Earlier detection allows for more time to implement management tactics and expands the available options, reducing impacts, and slowing HWA spread	**PS:** Citizen science monitoring program, risk map/modelling to prioritize high risk stands for monitoring
Maintain current monitoring protocol where convenient & most cost-effective	**HWA:** Detection in stands convenient for monitoring **Hemlock:** Greater probability of unknown infestations and mortality	**Costs:** Potentially greater hemlock mortality and spread due to unknown incursions, and less time to implement management tactics the later HWA discovered	No extra investment in detection (time, money, resources)	**PS:** Current visual survey protocol (CFIA, 2018)

Table 2.2
HWA survey methodology to implement. For each strategy requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Adaptive approach selecting survey tool based on stand location and characteristics	**HWA:** Enhanced ability to detect in locations that are less accessible (e.g. riparian stands), and in mature stands with high canopies **Hemlock:** Decreased mortality and infestation with earlier detection providing greater means to treat and control infestation	**Costs:** Detection protocol less standardized and more intensive **Obstacles:** Efficacy of different techniques dependent on situation	Increased flexibility allowing for more effective monitoring in stands where visual surveys inhibited by high canopies or terrain	**PS:** Visual detection, branch sampling, lake-side surveys, ball sampling, sticky trap sampling, detection during harvest, remote sensing, drones and provincial aerial surveys to assess hemlock mortality & health, solicit and support development of new tactics such as potential eDNA analysis techniques
Current visual survey protocol for all stands	**HWA:** Detection methods standardized, but limited where visual inspection inhibited **Hemlock:** Greater probability of infestation and mortality in stands where visual surveys inhibited	**Costs:** Probability of detection greatly reduced in less accessible stands and stands with high canopies	Less expensive (no equipment to buy and maintain, no samples to process, and very little training required), and one existing standardized protocol to implement	**PS:** Current visual protocol (CFIA, 2018)

Table 3.1
HWA control via the eradication of HWA population. For each decision requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Eradicate HWA population	**HWA:** Population eradicated locally with new incursions only potentially occurring from a different source **Hemlock:** Infested tree(s) treated/ removed to prevent or slow further spread	**Costs:** Additional investment (time, resources, money) **Obstacles:** Feasibility depends on spatial extent of incursion, eradication difficult to prove definitively (i.e. removal of last individual)	No threat of further spread or hemlock mortality caused by the eradicated HWA population; Reduces the number of "source" populations	**PS:** Tree removal & destruction, multiple insecticide treatments
Do not attempt eradication	**HWA:** Population will continue to grow and spread **Hemlock:** Infestation and mortality will increase	**Costs:** Need to control HWA populations to low levels (Table 3.2–3.5) to reduce hemlock mortality, or address restoration and rehabilitation needs after hemlock mortality has occurred (Table 4.1–4.3)	No investment (time, resources, money) in eradication	No eradication tactics required

reach upper canopies and are better able to detect low densities of HWA, but these methods quickly become cost- and time-prohibitive.

Other methods that involve sample collection and are not as limited by tall canopies include ball sampling (Fidgen et al., 2018, 2016) and sticky traps (Fidgen et al., 2015). However, retrieving Velcro-fitted balls shot high into the canopy can be time consuming, and the probability of the ball encountering HWA decreases with decreasing HWA abundance, making detection of incipient populations with few individuals unlikely. Sticky traps, on the other hand, integrate sampling over a longer time period, but require more equipment and identification of collected samples where native adelgids on other tree species may be present. An additional opportunity for visual detection is through ground surveys following windstorms, particularly during the sistens stage in winter and early spring, as branches from the upper canopy fall onto the snow or the forest floor, with HWA easily visible on their underside (e.g. Ancient Forest Exploration & Research, 2019; Michigan Department of Agriculture Rural Development (MDARD), 2016). Through education and outreach, recreationalists and the general public may become invaluable in reporting new populations following such weather events.

Detection methods based on the assessment of hemlock health rather than the detection of HWA also exist. These methods rely either on visual identification of hemlock decline, or in the case of lakeside surveys, the absence of new twig growth in the spring. Remote sensing techniques, and aerial surveys with aircraft or drones are being explored. However, unlike the absence of new twig growth that occurs before traditional signs of hemlock decline are apparent, these techniques only have potential to be effective later in an infestations history when a tree or stand has experienced a visual reduction in crown health. Furthermore, such symptoms may be conflated with other causes of tree decline, including old age, native pests (e.g. hemlock looper and hemlock borer), or abiotic stress, such as drought. Further research is needed to demonstrate to what degree visual inspection methods that focus on hemlock health can aid in low density detection and accurate delimitation of HWA populations.

Investment in the improvement of current detection methods along with the development of new methods will lend greatly to low-density detection and accurate delimitation of HWA. Early detection and accurate delimitation provide a greater chance to prevent further HWA spread and establishment. Infestations that are detected late will tend to be more established and wide-spread, raising the costs of control, or of restoration of stands that are beyond control efforts. Improvements to current methods might address identified shortcomings of the most commonly implemented HWA detection methods (i.e. visual surveys, branch sampling, ball sampling, sticky traps), along with the efficacy testing and development of new methods (i.e. lakeside surveys, eDNA analysis, drones and remote sensing,).

2.3. HWA control

Similar to other invasive species, HWA causes host mortality in eastern North America due to the absence of host resistance and natural enemies, specifically predators, that keep HWA populations in check in its native range (Havill et al., 2014). In addition to these missing top-down and bottom-up population controls, aspects of HWA's biology and life cycle make it a particularly challenging pest to control. In North America, HWA reproduces rapidly with two asexually produced generations per year (McClure, 1989), negating the ability to control HWA via disrupting sexual reproduction (e.g. sterile insect technique, mating disruption). This allows for the potential establishment of a new population from a single parthenogenetic individual (Tobin et al., 2013). HWA dispersal, which occurs mainly during the crawler stage from March to August, is passive and can occur over long distances (e.g. by wind, animals, and humans) (McClure, 1990), negating the control strategy of trap and kill, and making it far more difficult to track and predict dispersal. Finally, HWA's small size (1–2 mm) makes it difficult

Table 3.2–3.4
Single strategy implementation for HWA population suppression. For each decision requiring action the potential tactics are listed. PS = potentially suitable, and NA = not currently available for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
3.2 Insecticidal control	**HWA:** Short-term (3–5yrs) control **Hemlock:** Individual high-value trees protected or kept alive	**Costs:** High investment (time, money, resources), re-application required **Obstacles:** Environmental impacts restrict products, application methods and quantities (not a viable long-term, or large-scale solution)	Provides rapid, short-term protection for individual high value trees, and buys time for other more long-term control tactics to become available or effective	**PS:** Topical oil or soap based treatments for homeowners, injectable imidacloprid systemic insecticide (IMA-jet) **NA:** Botanical azadirachtin (TreeAzin)
3.3 Silvicultural control	**HWA:** Population growth inhibited by tree or stand vigour **Hemlock:** Decreased or slowed mortality and infestation, and increased health	**Costs:** High investment (time, resources, money) **Obstacles:** Limited-scale, requires knowledge of hemlock inventory and value, efficacy not conclusive, broader effects on habitat/ecosystem unknown	Techniques to improve hemlock health can help to slow HWA caused hemlock mortality and spread	**PS:** Thinning, or selection harvest to increase light exposure
3.4 Biological control	**HWA:** Long-term suppression in stands where biological control established **Hemlock:** Long-term survival with infestation levels kept low	**Costs:** High initial investment (time, resources, money) **Obstacles:** Achieving successful biological control complex and not guaranteed, time (years) required for research, non-target testing, controlled trials, certification, followed by agent rearing and release, monitoring of establishment and assessing impacts on HWA populations	Biological control agents that successfully establish and suppress pest populations provide long-term protection, and continue through time requiring little to no further investment (time, resources, money)	**NA:** Identified western North American biological control agents *Laricobius nigrinus*, *Leucopis argenticollis* and *Leucopis piniperda*, identified Asian predators (Havill et al., 2014; Toland et al., 2018), entomopathogenic fungi
Do nothing	**HWA:** Spread, grow, and cause mortality unchecked **Hemlock:** Eventual eliminated from the landscape	**Costs:** Loss of eastern hemlock in Canada, loss of eastern hemlock specific ecosystem services and biota, need to address restoration and rehabilitation (Table 4.1- 4.3)	No investment in control required. Shift in stand composition may favour different desirable biota and result in development of new ecosystem depending on site/stand characteristics	No control tactics required.

to detect at low densities, particularly in mature hemlock canopies, impeding early detection and confirmation of eradication (CFIA, 2018). On the other hand, the crawler and egg stages are very vulnerable to being displaced from their host with little chance of finding their way back, and once the stylet is inserted into the twig, nymph and adult stages remain sessile, making them vulnerable to changes in abiotic conditions, competition, predators and insecticides (McClure and Cheah, 2002).

Once HWA is detected, managers face a variety of decisions depending on the extent, severity, and location of the infestation, and the strategies and tactics currently at their disposal along with those potentially available in the future. The suite of strategies used in HWA population control can be divided into three target outcomes: (1) eradication of HWA (Table 3.1), (2) control of HWA populations at low enough levels so as to reduce spread and hemlock mortality (Table 3.2–3.4), and (3) a do- nothing strategy that relies on abiotic and biotic mortality factors to regulate populations.

2.3.1. Eradication of HWA

Eradication programs are implemented with the aim of completely removing the threat. However, the many factors that influence the success of an eradication program require careful consideration before proceeding (Table 3.1). Eradication is a biological and economic challenge, and the more extensive the infestation the lower the probability of success. Additionally, continued introductions, detectability of the pest (Tobin et al., 2014), and the speed of response (Suckling et al., 2014) affect the suitability of implementing eradication efforts. A meta analysis by Tobin et al. (2014) of 672 arthropod eradication programs across 91 countries showed that host removal and destruction was common for Hemiptera taxa (e.g. adelgids), but that host removal was less successful than mass trapping or lure and kill eradication programs when considering all orders of arthropods reported. Furthermore, eradication programs of sap feeding insects (e.g. adelgids), followed by those of wood and phloem feeders, had significantly less success than the eradication programs of leaf and fruit feeding pests.

Efforts to eradicate HWA in Etobicoke and the Niagara Gorge in Ontario were deemed successful based on ongoing negative detection survey results following removal and destruction of the small number of infested trees. However, the removal of every single HWA individual is near impossible to ascertain in natural stands (Tobin et al., 2014), and low densities of HWA may continue to persist in these areas undetected. In Michigan, frequent and re-occurring HWA introductions diminished the utility of eradication efforts, where repeated insecticide treatments (2006, 2007, 2010, 2012, 2013) were unable to keep up with new incursions that now span four counties (MDARD, 2018).

When the success of an eradication program is improbable, slowing the spread of HWA by reducing potential dispersal opportunities may be considered. Some localities in the United States have attempted the use of barriers or physical pruning to reduce the amount of contact between HWA and known dispersal vectors, such as animals, humans, and vehicles, especially during the crawler phase (McClure, 1995). However, given that HWA dispersal occurs over long distances via wind and birds and that only one individual is needed for parthenogenetic reproduction, these tactics are unlikely to be effective in slowing the spread. Instead, efforts to suppress HWA populations to levels that can be tolerated by hemlock, thereby reducing host mortality, are a more promising pursuit. The two broad strategies of pest population suppression include implementation of a single management tactic (i.e. insecticidal, silvicultural, or biological control individually; Tables 3.2–3.4) or the development of an integrated control program using multiple tactics best suited to the situation (e.g. insecticidal and biological control together; Table 3.5).

2.3.2. Insecticidal control

Insecticides may be a viable tactic to protect high value hemlock and slow spread, while buying time for other tactics to become

Table 3.5
Integrated HWA population suppression strategies. For each decision requiring action, the potential tactics are listed. NA = not currently available for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Develop integrated control based on action thresholds, and favouring non-toxic tactics over insecticides where possible	**HWA:** Complementary tactics sustain population control over the short- and long-term, and use of insecticides reduced **Hemlock:** Stand infestation and mortality decreased	**Costs:** Additional initial investment (time, resources, money) **Obstacles:** Complexity in design, implementation, and coordination	Integrating control tactics allows for a more comprehensive and effective response to HWA incursions based on location specific factors, while synergistically planning for both short and long-term control of HWA populations & hemlock survival	**NA:** Insecticidal short-term control + biological long-term control + silvicultural promotion of hemlock health and tolerance
Do nothing	**HWA:** Spread, grow, and cause mortality unchecked **Hemlock:** Eventually eliminated from the landscape	**Costs:** Loss of eastern hemlock in Canada, loss of eastern hemlock specific ecosystem services and biota, need to address restoration and rehabilitation (Tables 4.1–4.3)	Shift in stand composition may favour different desirable biota and result in development of new ecosystem depending on the site characteristics	No control tactics required

available or effective (Table 3.2). However, due to the high resource and time investment, and significant environmental concerns associated with the use of insecticides in Canadian forests (eg. Holmes and MacQuarrie, 2016), currently identified insecticidal control agents of HWA, including neonicotinoids and tree injections, are unlikely to be feasible or desirable at the stand scale for hemlock.

Two neonicotinoid based systemic insecticides (i.e. dinotefuran applied as a bark spray and imidacloprid applied as a soil drench, or applied together as a tank mix, basal bark spray) are widely used to control HWA in the United States with the target outcome of either sustaining individual high-value hemlocks in parks and urban areas, or slowing HWA spread by suppressing outlier infestations. In Canada, the Pest Management Regulatory Agency (PMRA) is unlikely to approve the registration of a neonicotinoid-based insecticide applied to the soil or as a basal bark spray due to the potential risk to pollinators and of contamination to the aquatic environment (PMRA, 2018, 2016). However, IMA-jet, an injectable imidacloprid product, has recently been registered for use against HWA in Canada. Trunk injections of insecticidal control agents, although more expensive, slower acting, and limited by the number of wounds that a single tree can sustain, have been shown to reduce HWA populations on hemlock, while reducing environmental risks (Doccola et al., 2007).

TreeAzin©, an injectable botanical-based systemic insecticide derived from the neem tree extract azadirachtin, is a promising insecticidal control alternative with fewer environmental concerns than neonicotinoid-based products. TreeAzin© has been used for the control of emerald ash borer (EAB) in Canada, and is currently certified for use against HWA in the United States. However, little is known about the efficacy of TreeAzin© against HWA. Its demonstrated efficacy to control EAB in Canada (1–2 years, BioForest Technologies Inc., 2011) suggests that it is unlikely to be as effective as imidacloprid, which can provide HWA control for 4–7 years before re-application is required (Benton et al., 2016). Efficacy testing of TreeAzin© for HWA control was initiated in 2018 as a precursor step to registering the product in Canada. Insecticidal soaps and horticultural oils can be an option for nursery stock and for homeowners treating single trees, but these treatments need to be re-applied yearly and require complete coverage, making them impractical in the long-term or on tall trees (Ward et al., 2004).

2.3.3. Silvicultural control

Silvicultural tactics for control of HWA focus on using stand thinning to open canopy through partial harvest (e.g. shelterwood, strip or patch cut), but are still largely at a research stage, with limited evidence of successful implementation (Table 3.3). As a drought-intolerant species, water stress created by HWA infestations makes hemlock particularly susceptible to tree decline and mortality, especially in combination with drought (Domec et al., 2013). HWA also impacts the carbon balance of infested hemlock, since the dense, shaded canopy of hemlock stands limits photosynthesis and carbon sequestration (Brantley et al., 2017). Research suggests that improving hemlock vigour through stand thinning can increase tolerance to HWA and extend tree survival, especially in areas where HWA infestations are countered by winter mortality (Fajvan and Wood, 2010).

However, the responses of hemlock to stand or abiotic conditions in the context of HWA feeding are complex. Foliar nitrogen concentrations have been found to be negatively associated with hemlock survival and positively associated with HWA densities (Pontius et al., 2006), re-enforcing the conclusion that hemlock should not be fertilized with nitrogen to stimulate tree growth (McClure, 1991). Hemlock growth may also be enhanced through negative effects of light exposure on HWA, attributed to aestivating sistens mortality in the late summer months, as high light conditions lead to stress in this shade-adapted insect (Brantley et al., 2017). Unfortunately, most of the studies that have examined the responses of hemlock and HWA to reduced shading have been conducted on seedlings or saplings.

Trials in mature stands are underway, but the evaluation of potential longer term benefits of increased tolerance of hemlock to HWA needs to account for the initial stress responses of hemlock to the changes in abiotic conditions triggered by partial harvesting. The broader ecological impacts of stand thinning on the understory habitat and the species associated with hemlock, as well as biogeochemical and hydrological processes, also remain to be examined. Despite these unknowns, thinning remains a viable tactic for further investigation, as even modest improvements in hemlock health under HWA infestations may contribute to outcomes of other management tactics, and stand thinning could be relatively easily incorporated into operational and harvesting plans of stand management in general.

2.3.4. Biological control

Predators show promise for biological control of HWA in eastern Canada, but, as with any biological control program, require a large initial investment to identify and certify the appropriate agent or agents for release (i.e. collection, identification, prey specificity testing, field testing), to successfully collect and rear the selected agent in high enough numbers, and to track and ensure establishment and successful control once released (Table 3.4). Since the initiation of the HWA biological control program in the United States in 1992, the establishment of biocontrol agents and their suppression of HWA populations have been achieved in some locations (e.g. Mausel et al., 2010; Mayfield et al., 2015; Heminger, 2017; Motley et al., 2017; Toland et al., 2018). However, the consistent and large-scale control of HWA has not yet been achieved through any single biocontrol agent. Simultaneous employment of a complex of predators that collectively feed on the different life stages of HWA year round is currently being explored as the next step. Although the potential future use of biological control against HWA in Canada can build on the body of work already done by our American counterparts (Onken and Reardon, 2011), development of this tactic in Canada will require substantial investment.

In the absence of known parasitoids or pathogens of HWA, and the risk of non-target impacts by entomopathogenic fungi, predators are the most suitable agents for HWA biological control programs. The demonstrated absence of native predators that consistently feed on HWA on hemlock in the eastern United States (Wallace and Hain, 2000) highlights the need to introduce more effective predators for population regulation. HWA predators originating from western North America (e.g. *Leucopis* spp.; Motley et al., 2017, *Laricobius nigrinus*; Mausel et al., 2011) and from across HWA's home range in Asia (e.g. *Laricobius osakensis*; Toland et al., 2018, *Scymnus* spp.; Montgomery and Keena, 2011) have been collected and released in the United States.

The predators from western North America hold the greatest potential for certification and use in Canada given the ease of access for collection (Table 3.2). The Pacific Northwest region is an especially promising source of candidate biological control agents because the native predators have co-evolved with a closely related, but genetically distinct strain of HWA that arrived from Asia approximately twenty-three thousand years ago (Havill et al., 2016). This western strain of HWA feeds on the native western hemlock and to a lesser extent mountain hemlock without causing significant mortality (Havill et al., 2014). Research examining its predator communities has identified dominant species from the genera *Laricobius* (Coleoptera: Derodontidae) and *Leucopis* (Diptera: Chamaemyiidae) that show promise for establishment on and control of eastern HWA (Kohler et al., 2008).

*Laricobius nigrinus*is is currently one of the most promising biological control agents for HWA in eastern North America thanks to its significant specificity to and control of western HWA (Mausel et al., 2017), and demonstrated establishment on eastern HWA (Mausel et al., 2010). Since its first release in Virginia in 2003 (Lamb et al., 2006), *L. nigrinus* has been introduced at more than 200 sites over the following decade (Havill et al., 2014), with continued rearing and release programs in the United States to date totalling around 400 000 individuals. However, obstacles remain in confirming *L. nigrinus* as an effective biological control agent of eastern HWA. For example, rearing techniques for *L. nigrinus* are continually being improved in Virginia, Tennessee, Georgia, New York, and New Jersey laboratories, but lab rearing is expensive (Lamb et al., 2005) and can be prohibitive for large-scale releases. Coastal strains of *L. nigrinus* have also been found to be less cold hardy during winter than interior *L. nigrinus*, suggesting that eastern HWA, and especially the most northerly populations, may be better controlled by *L. nigrinus* collected from interior western populations with a more continental climate (Havill et al., 2014). Finally, hybridization between *L. nigrinus* and the native *Laricobius rubidus* LeConte, a predator that primarily feeds on the pine bark adelgid in eastern North America, has been well documented. However, hybridization appears to be stabilizing, with the proportion of hybrids between *L. nigrinus* and *L. rubidus* consistently around 11% across years, reducing concerns about its potential ecological risks, including non-target effects on other adelgid species via their native predators (Mayfield et al., 2015).

Two species of silverflies (Diptera: Chamaemyiidae) from the Pacific Northwest, *Leucopis argenticollis* Zetterstedt and *Leucopis piniperda* Malloch, may complement *L. nigrinus* in the control of HWA populations in eastern North America. However, far less is known about the biology of these predators, and only about 1800 individuals have been released in the United States to date. *Leucopis argenticollis* and *L. piniperda* are significantly associated with HWA population densities (Grubin et al., 2011), and their feeding is highly synchronous with HWA progrediens and sistens eggs. Cage field releases on HWA-infested eastern hemlock have demonstrated successful development and reproduction (Motley et al., 2017), and a recent study found that *L. argenticollis* and *L. piniperda* that feed on western HWA are genetically distinct from eastern *Leucopis* spp. (Havill et al., 2018). However, a risk of hybridization between the western and eastern *Leucopis* strains needs to be determined (Havill et al., 2018).

The base of a sound biological control program is detailed knowledge of the target pest and biocontrol agent's biology and population dynamics. Despite the many criticisms of biological control programs over time, examples of successful biocontrol in Canadian forests include the larch casebearer, browntail moth, and European spruce sawfly (MacQuarrie et al., 2016; Table 3). On the other hand, the history of unsuccessful programs offers a cautionary tale: notably, biocontrol agents against a related pest, the balsam woolly adelgid, failed to achieve control despite many species being released over many years. Presently in Canada, there is only one classical biological control program currently underway against a forestry pest in response to emerald ash borer (MacQuarrie et al., 2016). Much of the foundational research on the phenology and population regulation of HWA required to assess the potential effect of a biological control program is lacking in the context of the HWA infestation under the climatic conditions of southwest Nova Scotia, although this research has been initiated. Collaboration between Canadian and American counterparts in the collection and rearing of HWA biological control agents, such as the western *Laricobius* and *Leucopis* species, will be essential in the development and implementation of a biological control program for HWA in Canada.

2.3.5. Integrated HWA control

Single-tactic control strategies can be used to elicit immediate action and protection when resources are limited or narrowly defined, rapid response is required, or alternative control tactics are not yet available for use. However, no single tactic of pest management can be universally implemented without its respective limitations. Therefore, an integrated control strategy (Table 3.5) that considers all tactics available currently, in the near future, and that are being explored for future use, and addresses specific needs and situations, is critical to long-term HWA control and hemlock conservation in eastern Canada.

Integrated insecticidal and biological control strategies that combine the short-term, rapid protection of insecticide treatment with the long-term population regulation through released predators show promise for HWA management (Mayfield et al., 2015). These two control strategies can work together where insecticidal control prevents immediate hemlock mortality while biological control has a chance to become available or effective. If successful, biological control can provide long-term control reducing and potentially eliminating the need for insecticidal control all together. However, the implementation of integrated insecticidal and biological control is complicated by timing of implementation and the fragile nature of released predator populations that may require augmentative releases following extreme weather conditions (Sumpter et al., 2018). In addition, insecticidal control to prevent hemlock mortality, may compromise predator survival and establishment either through direct toxicity from the ingested, insecticide treated HWA, or indirectly through the paucity of their prey. One potential strategy to address this problem may involve simultaneous releases of HWA predators on infested understory hemlock while protecting large, over-story hemlock with insecticide treatment until the establishment and subsequent dispersal of the biocontrol agent (Havill et al., 2014). Stand thinning may also be integrated to supplement insecticidal control by slowing hemlock mortality and giving biological control more time to become available or effective (Brantley et al., 2017).

2.4. Hemlock ecosystem restoration & rehabilitation

Eventual local disappearance of hemlock will result in major shifts in the terrestrial, riparian, and aquatic ecosystems in formerly hemlock-dominated stands (Spaulding and Rieske, 2010). Ecosystem restoration and rehabilitation will need to be considered to manage issues ranging from an increase in the abundance of deadwood (Vose et al., 2013), habitat alteration having negative effects on hemlock-associated species, invasion of the former stand by undesirable plant species (Eschtruth et al., 2006), to the loss of social and economic value (Poudyal et al., 2016). The magnitude and spatial and temporal scale of these shifts will vary across the landscape depending on the hemlock content, the spread and severity of HWA infestations, control measures, and the rate of tree decline (Case et al., 2017); however, they will likely be most dramatic in mature, hemlock-dominated stands (Ellison et al., 2005). Widespread tree mortality in the extreme southwest of Nova Scotia, where first HWA infestations likely became established, suggests that hemlock collapse may be rapid. It is therefore critical that a restoration and rehabilitation plan and its desired outcomes are considered in parallel with control measures, both at the landscape scale (e.g. seed collection and preservation) and in management of individual woodlots (e.g. stand regeneration).

2.4.1. Conserve eastern hemlock seed

The conservation of hemlock diversity in eastern Canada via seed collection and preservation is beneficial for a couple of reasons (Table 4.1). Firstly, the collected seed will provide the means of reintroducing the species in case of the regional collapse of hemlock in eastern Canada. Although mature stand hemlock regeneration takes hundreds of years (Jonas et al., 2012), a well-developed seed bank along with restoration tactics could provide a long-term alternative to the loss of hemlock stands from eastern Canada. Secondly, seed collection offers the opportunity for tree improvement programs and genetic manipulation (Oten et al., 2014) in the northern part of the species range where little is known about the variation in responses of hemlock to HWA. Collectively, these efforts could lend to both the preservation and restoration of eastern hemlock, although it should be noted that the very little research or active tree breeding outside of the horticulture industry may impede this restoration effort.

In the face of decreasing hemlock reproduction under HWA infestations, systematic seed collection can capture the genetic diversity of eastern hemlock (Prasad and Potter, 2017), especially in areas where hemlock is at risk (e.g. southwest Nova Scotia). In these regions, the

Table 4.1
HWA restoration and rehabilitation via seed conservation. For each strategy requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Actively collect and preserve eastern hemlock seed	**HWA:** Cause irreversible damage unchecked **Hemlock:** Species and genetic diversity preserved	**Costs:** Additional investment (time, money, resources) associated with collection and proper preservation **Obstacles:** Complete hemlock inventory data required to prioritize and diversify collection	If eastern hemlock removed from landscape by HWA, potential for restoration of hemlock with the preserved collection; Opportunity to preserve and study tolerant individuals	**PS:** Prioritize seed collection to preserve genetic diversity, to preserve and study naturally resistant/tolerant individuals, and to areas at high risk of losing hemlock
Do not actively collect and preserve eastern hemlock seed	**HWA:** Cause irreversible damage unchecked **Hemlock:** Permanently eliminated from landscape if control efforts unsuccessful	**Costs:** Seed not available for potential restoration or study of natural resistance/tolerance	No investment in seed conservation (time, money, resources)	No seed conservation tactics required

Table 4.2
HWA restoration and rehabilitation via management of stand regeneration. For each strategy requiring action the potential tactics are listed. PS = potentially suitable, and NA = not currently available for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Manage stand regeneration following eastern hemlock decline / mortality	**HWA:** Cause irreversible damage to hemlock unchecked **Hemlock:** Recover some ecosystem services following stand level mortality, and prevent invasion of undesirable plant species (native or invasive)	**Costs:** Additional investment (time, money, resources) **Obstacles:** Complex, as management strategy will differ based on specific stand characteristics and value, and regeneration trajectories will be difficult to predict; Regeneration with non-native hemlock species controversial; Only some ecosystem services can be retained	Stand re-generated with some ecosystem services retained, or with desirable native species composition instead of by undesirable species (native or invasive)	**PS:** Replace with conserved eastern hemlock, native evergreen, or supress undesirable species to promote desirable native species already present **NA:** replace with resistant eastern hemlock individuals, or cross-breeds between eastern hemlock and resistant non-native hemlock
Do nothing	**HWA:** Cause irreversible damage unchecked **Hemlock:** The ecosystem is completely altered, with potentially undesirable fast growing species (native or invasive) outcompeting other species and dominating the system	**Costs:** Entirely different ecosystem with different ecosystem services and biota, and potential for undesirable species with competitive advantage to dominate	No extra investment (time, money, resources); Long-term natural regeneration trajectory may be acceptable based on desired outcome	No tactics required to manage stand regeneration

prioritization of collecting seed from trees that show some resistance or tolerance to HWA will provide the means to study and assess the characteristics that make hemlock less susceptible or vulnerable to HWA (Oten et al., 2014). Resources are available in eastern Canada to facilitate the preservation of eastern hemlock seed (i.e. National Tree Seed Centre with the Canadian Forest Service in Fredericton, NB), but would require investment in seed collection and support of preservation activities. The coordinated investment into these efforts across all the provinces at risk, potentially including citizen science programs, would strengthen this effort, spread the cost, and allow for collective advancements to be made.

2.4.2. Management of stand regeneration

The target outcome of managing stand regeneration is to preserve some of the ecological, social and economic services provided by hemlock stands, prevent a shift to undesirable species, and speed-up the recovery process (Table 4.2). The loss of hemlock in a stand is particularly devastating because of its foundational role as a long-lived, late-successional species. Its unique shaded habitat is replaced by a distinctly different ecosystem via the regeneration of other, early-succession, tree species and vegetation. These changes can be long-lasting, as demonstrated by paleoecological studies examining the impacts of hemlock decline in Ontario on lake (Hall and Smol, 1993) and forest (Fuller, 1998) communities in the Mid-Holocene. Currently, the complex patterns of hemlock stand replacement in the aftermath of HWA infestations in the eastern USA (Case et al., 2017) reflects the many factors that potentially influence regeneration trajectories, including climate, site and stand biotic and abiotic characteristics, and rate of hemlock decline (Abella, 2018). Stand regeneration following hemlock mortality has been examined across a variety of ecosystems, ranging from the southern high-elevation Appalachians to the mixed forests of New England (Jonas et al., 2012); however, the differences in forest composition and abiotic conditions make it difficult to apply these findings to the Canadian context. More generally, shifts in vegetation and the associated ecosystem will be particularly detrimental in cases involving undesirable dominant species during regeneration (Eschtruth and Battles, 2009), the loss of specialized habitat and sensitive species (e.g. forest stand vegetation and invertebrate communities; Ingwell et al., 2012, riparian corridors and stream trophic dynamics; Webster et al., 2012), or associated reductions in carbon storage (Ignace et al., 2018) and water yields (Brantley et al., 2015).

In order to restore ecological function, the full regeneration of eastern hemlock and its associated ecosystem following mortality due to HWA would be desirable, but very unlikely due to several factors. Because all age cohorts succumb to HWA, hemlock seedlings would first need to be grown in a non-infested area in preparation for re-planting (Jonas et al., 2012). In addition, regeneration of this slow-growing, late-successional species is complicated by a long time frame for full establishment of mature stands, especially under competition with faster growing tree species, such as hardwoods (Jonas et al., 2012). Silvicultural tactics that create small gaps for hemlock planting followed by long-term removal of competitors may prove beneficial (Jonas et al., 2012). These efforts may still be insufficient in sites well-suited for hardwood species or prone to drought stress, and plantings should therefore prioritize sites that are optimal for hemlock growth. However, in the absence of successful HWA control tactics or host resistance, vulnerability to HWA will continue to compromise the longevity of the new hemlock stands.

In addition to the absence of an effective predator complex, the lack of resistance of eastern hemlock to HWA makes the survival of hemlock following HWA infestation very unlikely. Altering this characteristic would present an opportunity for more successful regeneration. Replacement of eastern hemlock with a cross between eastern hemlock and a non-native hemlock species resistant to HWA is one option. However, hybridization between eastern hemlock and Asian hemlock species (i.e. *T. chinensis*, *T. sieboldii*, and *T. diversifolia*) through

Table 4.3
HWA restoration and rehabilitation via hemlock deadwood clean up. For each strategy requiring action the potential tactics are listed. PS = potentially suitable for use in Canada.

Strategy	Predicted Outcome	Costs & Obstacles	Benefits	Potential Tactics
Move hazardous standing and fallen deadwood in recreational and accessible areas	**HWA:** Cause irreversible damage unchecked **Hemlock:** Prevention of deadwood caused flooding, reduced accessibility, and human injury in inhabited and recreational areas	**Costs:** Additional investment (time, money, resources), potentially accelerated re-establishment of stand by other plant species	Prevention of injury and avoidance of increased cost related to flooding and emergencies	**PS:** Assess inhabited and recreational areas with significant hemlock mortality, and move or remove hazardous fallen and potentially hazardous standing eastern hemlock deadwood
Do nothing	**HWA:** Cause irreversible damage unchecked **Hemlock:** Large amounts of downed and standing deadwood alter terrestrial and aquatic ecosystems, and present potential hazard in inhabited and recreational areas	**Costs:** Potential injury and cost (time, money, resources) associated with hazards arising in inhabited and recreational areas	Potentially more time to manage how the stand regenerates	No deadwood cleanup tactics required

controlled pollinations has been largely unsuccessful, most likely due to zygote failure (Bentz et al., 2005, 2002). A search for host resistance in individuals or provenances of the native eastern hemlock in eastern Canada may be a more promising pursuit. Research in the United States has identified putative resistance to HWA in both Carolina and eastern hemlock individuals (Oten et al., 2014), and explored the potential underlying biophysical (Oten et al., 2012) and chemical characteristics (McKenzie et al., 2014). Further work on resistant genotypes of eastern hemlock is being pursued by the Forest Restoration Alliance in the United States (Forest Restoration Alliance, 2017) and at the University of Rhode Island (Roberts, 2015), and their performance under HWA infestations tested in replicate reforestation plots across six eastern US states (Kinahan, 2019). The current infestations and spread of HWA in Nova Scotia present an opportunity to search a new region for hemlock genotypes that may exhibit resistance, or tolerance, against HWA, and to examine the interaction between host defenses and environmental conditions.

Another rehabilitation tactic could rely on the replacement of eastern hemlock with another, substitute, tree species in an attempt to restore some of its original ecological services (e.g. year round canopy cover and stream shading; Vose et al., 2013). Although such replacement does not contribute to the conservation of eastern hemlock, it may be the best immediate rehabilitation plan in the presence or continued threat of HWA. The choice of the substitute species will depend on a number of factors, including its growth rate, region of origin, competitive ability, resistance to browsing, sensitivity to site characteristics, and availability for planting (Jonas et al., 2012). Additional key considerations will include the scale of hemlock replacement, and the priorities for the site, which range from restoration of aesthetic and recreational value, to maintenance of riparian buffer zones, and terrestrial and aquatic habitat for wildlife, including species of concern.

Among the potential substitute species, Asian hemlocks resistant to HWA (e.g. *T. chinensis*; Harper and Weston, 2016) are notable candidates for replacement as their growth characteristics best match the aesthetic and recreational value of eastern hemlock. However, the planting of non-native tree species is usually only considered in ornamental landscapes (Jonas et al., 2012), or in commercial forestry after careful consideration. The long-term establishment and regeneration of Asian hemlocks in Canadian forests remain uncertain, and their provision of ecosystem services is unlikely to fully replace that of the eastern hemlock (eg. Rogers et al., 2018). In addition, introducing a non-native species at the scale of stands or landscapes also increases the risk of invasion by its associated non-native species (Simberloff and Von Holle, 1999). Instead, native evergreens may offer a better alternative by providing year-round shade, and although hardwood species generally dominate the early stages of regeneration (Jonas et al., 2012), simulations have suggested that eastern white pine, for example, has a high probability of becoming dominant in later successional stages (Case et al., 2017).

Where re-planting to restore stands impacted by HWA is not the chosen or feasible management strategy, preventing undesirable species from taking over the stand may be necessary. Following hemlock decline and mortality, invasive plant species may affect tree regeneration or lead to shifts in understory vegetation (Ward et al., 2004), further exacerbated by existing pests or diseases of the native trees, such as beech bark disease (Case et al., 2017). Therefore, stand monitoring following hemlock decline and mortality is necessary to examine the best approach to stand restoration. The suppression of undesirable species may be required to guide the trajectory of succession to a desired outcome based on the social, economic, and ecological goals for restoration.

2.4.3. Hemlock deadwood cleanup

Following the widespread mortality of hemlock in stands where HWA control tactics are not used or unsuccessful, the ecosystem will experience a large pulse of deadwood. While some of these changes may be positive in the short term (e.g. increase in saproxylic beetles, nesting cavities in large snags; Pollock and Beechie 2014), increased coarse woody debris can dam culverts and change hydrologic pathways in watersheds. Particularly in mature and old-growth stands, dead hemlock trees will block paths and roadways, and pose a risk to the public when snags or branches fall (Vose et al., 2013). Given these risks, management actions may need to be taken in areas used for recreation or those with potential for flooding (Table 4.3).

Proactive salvage cutting of hemlock before significant mortality mitigates some of the hazards associated with large quantities of deadwood (Vose et al., 2013). However, it also precludes the opportunity to identify natural resistance in local hemlock, removes carbon and nutrients from the ecosystem, and abruptly alters the ecosystem services (e.g., habitat, shade) provided by declining but still standing hemlock. In addition, regeneration may be accelerated by the removal of hemlock biomass, which in turn would limit opportunities for management of stand regeneration and potentially alter its trajectory (Case et al., 2017). Alternatively, removing deadwood only where necessary might be the best option to mitigate identified hazards while more optimally managing time and resources to investigate potential restoration strategies.

2.5. Evaluation of HWA management program

Evaluation of all tactics implemented in HWA management, from HWA prevention and detection, to HWA control and hemlock ecosystem restoration and rehabilitation (Table 5.1), will be invaluable to the future of eastern hemlock and its ecological role in Canadian forests. In spite of the significant advances in the understanding of HWA and its management strategies in the eastern United States, the pest has continued its spread with devastating impacts. The management of HWA in Canada thus brings with it considerable uncertainties and challenges, including those unique to Canadian forest types and ecosystems, climate, regulations, and values.

2.5.1. Adaptive management

The evaluation of decisions on issues raised by HWA in Canada can be best achieved by using an adaptive management approach. Adaptive management evaluates decisions by simultaneously implementing them while actively learning from their outcomes. This ongoing integration of management and continued learning then informs and improves the implementation of management tactics through time (Walters and Holling, 1990). Adaptive management strategies can vary from the monitoring and assessment of why (or why not) an implemented tactic was successful, to experimental management that utilizes a scientific study design to directly compare a number of management tactics occurring simultaneously. Due to the many biological, ecological and environmental uncertainties, adaptive management approaches are invaluable in pest management programs, particularly those involving novel pests. They also allow for opportunities to make improvements in management decisions as the demands of the program continue to evolve through time and across different spatial scales (Shea et al., 2002).

The key steps to adaptive management include: (1) the assessment of needs and outline of priorities and objectives, (2) the identification of critical uncertainties and hypotheses, (3) the evaluation of options and recommendations, (4) the design and implementation of management experiments or actions to produce results with power for evaluation, and (5) the monitoring and evaluation of responses to management actions (Puddister et al., 2011). These principles of adaptive management can be applied to any management tactic implemented, and will be especially useful where significant uncertainty is identified or emerges. Due to the biology of HWA, its management faces significant uncertainties particularly regarding the efficacy of current tools to detect HWA at low densities and effectively delimit the size and extent of an infestation (a prerequisite for eradication efforts), and the relative

Table 5.1
HWA management program evaluation. For each strategy requiring action the potential tactics are listed. PS = Potentially suitable for use in Canada.

Strategy	Predicted Outcome	Obstacles & Costs	Benefits	Potential Tactics
Plan and implement monitoring and assessment of actual versus predicted outcomes and use information gained to make improvements to future management decisions	Allows for adaptive management moving forward where certain decisions can be favoured or changed based on analysis of predicted outcomes versus actual outcomes	**Costs:** Additional investment (time, money, resources) in short-term **Obstacles:** Planning required to design the evaluation in relation to the tactic being implemented and the known uncertainties being explored	Adaptive management allows for learning from management actions to better understand processes and improve HWA management over time	**PS:** Plan and implement monitoring that allows for assessment of outcome, or an experimental study design and data collection that compares and tests the success of different tactics
Do not assess if predicted outcomes achieved	Decisions made and tactics applied based on best guess without gaining an understanding of why or why not successful implementation was achieved, and therefore without potential for improving management actions moving forward	**Costs:** Difficult to improve HWA management and better inform decision making; Less information and result obtained from investment made	No additional cost (time, money, resources) to obtain further information	No adaptive management planning or implementation required

impact of natural versus human mediated HWA spread. Other uncertainties unique to the Canadian context include the many unknowns surrounding the most effective biological control agent or a combination of biological control agents, the efficacy of silvicultural tactics, the potential for host defenses to counter HWA impacts, and the trajectory of ecosystem rehabilitation following hemlock collapse.

An early and comprehensive identification of such uncertainties can facilitate more informed management decisions and strategies, and enhance their success. Despite an increase in the short-term cost of simultaneous management and learning approaches, the long-term benefit of an adaptable management program will far outweigh the cost of implementing a management program that will be unable to improve or adapt through time (Shea et al., 2002).

3. Summary and future prospects

Key challenges faced by HWA management in eastern Canada are due to uncertainties, short timelines and limited resources, and the unavailability of certain tactics. In particular, eradication, although potentially viable for new incursions, is confounded by the lack of a reliable low-density detection method to delimit the extent of an HWA infestation, and confirm the removal of the last individual. In addition, effectively slowing the spread of HWA via implementation of preventative regulations and increased education and outreach is constrained by the time and resources needed to create effective awareness and enforcement, along with HWA's passive dispersal over long-distances and parthenogenetic reproduction. The suppression of HWA populations to reduce hemlock mortality is also impeded by the current lack of available biological control tactics for use against HWA in Canada. Finally, uncertainties around the nature of the site-specific ecosystems that will emerge following hemlock mortality, along with the unknown consequences for terrestrial and aquatic ecosystem services, habitats and food webs, complicate comparisons between a do-nothing strategy and an intervention strategy.

In light of the challenges and uncertainties around HWA management, significant investments into research and capacity building in Canada will be necessary, with HWA infestations in Nova Scotia offering both opportunities and impetus for a diversity of studies and approaches. To evaluate and advance potential management tactics, federal and provincial agencies have begun exploring new detection methods (i.e. trap-lure tactic), the role of environmental factors that mediate hemlock tolerance to HWA, the efficacy of TreeAzin© for insecticidal control of HWA, and the use of stand thinning for silvicultural mitigation of HWA impacts. A detailed investigation of the phenology of HWA under the climate of Atlantic Canada is paving the way for the future use of biological control, the development of which presents a unique opportunity for inter-agency collaboration. Research and experimental management efforts in Nova Scotia will be invaluable in the preparation for HWA and its impacts on eastern hemlock in the rest of eastern Canada.

While many of the HWA infestations in Nova Scotia are in the early stages and others likely still undetected, at least 17,000 ha of private and public forest lands are already showing hemlock decline due to HWA, ranging from crown thinning and branch dieback to tree mortality of both mature hemlock and its regeneration (Nova Scotia Department of Lands and Forestry, 2018). In spite of the quarantine imposed by CFIA on the movement of hemlock articles and all species of firewood outside the five affected counties, it is highly probable that new HWA populations will be discovered in the adjacent region in the very near future, given the pest's passive dispersal and difficulties in its detection at low density. After the initial discovery of HWA in the region, the proactive investment of Parks Canada into outreach about HWA and its risks through movement of firewood undoubtedly raised the awareness about the pest, but were quickly followed by the discovery of HWA infestations at several locations of Kejimkujik National Park, including the campground. Initial emphasis on prevention, and on early detection and possible eradication, was replaced by prioritization of HWA suppression in select stands (e.g. campground), and farsighted restoration and rehabilitation plans as the Park likely faces hemlock decline of unknown rate and magnitude within the next decade. This management approach may be the current necessity for many of the private woodlot owners and public land managers in the region, given the spatial extent of HWA infestations and the limited availability and efficacy of control tactics.

Ideally, the best prevention and monitoring strategies will include targeted and consistent education and outreach, along with prioritized detection efforts based on risk analysis that includes natural pathways such as bird migration and wind, and updated eastern hemlock distribution maps. Visual surveys of stands with canopies visible from the ground, in combination with examination of fallen twigs, and branch and ball sampling of taller canopies are the best detection tools currently available, but improvements towards accurate low-density detection should be pursued. For control tactics, investment in insecticidal control in the short-term in combination with the establishment of biological control for long-term suppression of HWA shows the most promise and efforts should prioritize their further development for the Canadian context. The utility of eradication is less certain, but for small, incipient HWA incursions an eradication strategy may present a viable option for consideration. Finally, ecosystem restoration may be the best strategy to focus on in some situations, especially in southwest Nova Scotia. Replacement of eastern hemlock with a native evergreen species, or the monitoring of stands recovering from hemlock mortality to prevent undesirable species from dominating and to remove hazardous deadwood are the best restoration options currently available. Other important considerations that are showing promise for the future include silvicultural tactics to promote hemlock health, conservation of eastern hemlock seed, and the identification and breeding of natural resistance in eastern hemlock.

When developing an HWA management plan, managers in eastern Canada will have to consider all the available and soon to be available strategies and tactics given their situation and desired outcomes. In addition, an adaptive management approach should be integrated wherever possible, as there are several reasons to believe it may be key to the success of HWA management in Canada. Firstly, unlike other invasive pests that necessitate a fire-fighting initial response due to their alien biology and unknown impacts, a wealth of information on HWA biology, impacts, and management is available as a starting point for management program planning and iterative learning. In fact, the biology of HWA is problematic for eradication efforts that are often adopted and effective following the first detection of invasive pests. Secondly, the very limited success of currently implemented tactics to control HWA in eastern North America necessitates iterative learning to better understand the uncertainties associated with HWA management and improve its success rate. As the management tactics available in Canada continue to evolve in response to the presence of HWA in Nova Scotia, their implementation and integration across increasing spatial and temporal scales will provide new insights on the status of this pest and hemlock in eastern Canada. Finally, defining values, priorities, and desired outcomes prior to implementing management tactics will greatly facilitate the success of the decision-making process by providing the criteria to select the best available tactic and assess their outcome, along with the direction for improvements. Given the nature of HWA, the long-term outlook for eastern hemlock in Canada will likely feature HWA as a component of the hemlock ecosystems across much of the region, necessitating a comprehensive, adaptive management program to mitigate its ecosystem consequences.

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None.

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