First-Year Research in Earth Sciences: Dunes

Distribution of Eastern Hemlocks and Woolly Adelgid Infestation on a Michigan Coastal Dune System

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FYRES: Dunes Research Report #36
August 2019

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Abstract

Eastern Hemlock (*Tsuga canadensis*), a species of climactic vegetation found in mature forests on dune systems in Michigan, has been preyed upon by hemlock woolly adelgid (*Adelges tsugae*) since the arrival of the insect in coastal Michigan in the twenty-first century. This study investigates the distribution of hemlocks and the prevalence of hemlock woolly adelgid (HWA) on a parabolic dune system in P.J. Hoffmaster State Park. Project researchers recorded the location of individual hemlocks and concentrated hemlock stands using GPS receivers. Data was collected on tree diameter, stand density, health, and environmental characteristics. Particular attention was paid to evidence of symptoms of *Adelges tsugae* infestation throughout the dune system. Hemlocks were only found in mature forests on the arms of the parabolic dune and infrequently on the dune slipface; they were not discovered on the windward slope of the blowout or along the crest of the dune. The hemlocks were found as individual trees among other forest species or concentrated in hemlock stands. Most of the hemlocks were on north-facing slopes. Several trees exhibited symptoms of early stages of HWA infection. Widespread loss of hemlocks on Michigan dune systems could result in diminished soil stability and elevated exposure to wind erosion.

Introduction

Exotic and non-native pests are one of the most critical threats to global forest ecosystems (Pimental *et al.* 2000). North American forests have been subject to repeated waves of infestation that have decimated specific populations, such as Dutch elm disease, emerald ash borer, and oak wilt disease. Hemlock woolly adelgid (HWA) is the most recent infestation to receive attention in Michigan, where forested dunes are vulnerable to the losses of another forest species. Because detection of hemlock woolly adelgid in Michigan is relatively recent (dating only back to 2015), there is little research on the potential impacts of this infestation to dune ecosystems and physical environments. This research project investigates the distribution of hemlock trees, their characteristics, and potential HWA infestations in a Michigan parabolic dune system.

Several research questions provide the framework for this study. How are *Tsuga canadensis* (eastern hemlocks) distributed on a west Michigan parabolic dune system? What are the physical characteristics of *T. canadensis* trees on the dunes? Is *Adelges tsugae* (hemlock woolly adelgid) present in this dune system? If so, how prevalent is the infestation? The investigation specifically targeted a dune area where hemlocks were known to be present, but surveying and treatment for the infestation were not taking place. By doing so, the researchers were able to expand the site-specific knowledge base as well as contribute to the broader understanding of hemlock woolly adelgid on forested dunes.

Based on the research questions, the research objectives were to:

- Identify the location and density of hemlocks in specific dune areas,
- Record characteristics of individual hemlock trees and hemlock stands, and
- Document potential infestations of hemlock woolly adelgid in the study area.

Background

Eastern Hemlock (Tsuga Canadensis) *Characteristics*

Tsuga canadensis (eastern hemlock) is a shade-tolerant, coniferous tree found widespread across the eastern and northern regions of the United States (Figure 1; Orwig *et al.* 2002; Krapfl *et al.* 2011; Letheran *et al.* 2017). The tree features narrow, grey branches covered in singularly distributed needles approximately 15-20 mm long (Figure 2; USDA, NRCS 2002). *Tsuga canadensis* exhibits red-brown bark that is scaly on younger trees and develops ridges and

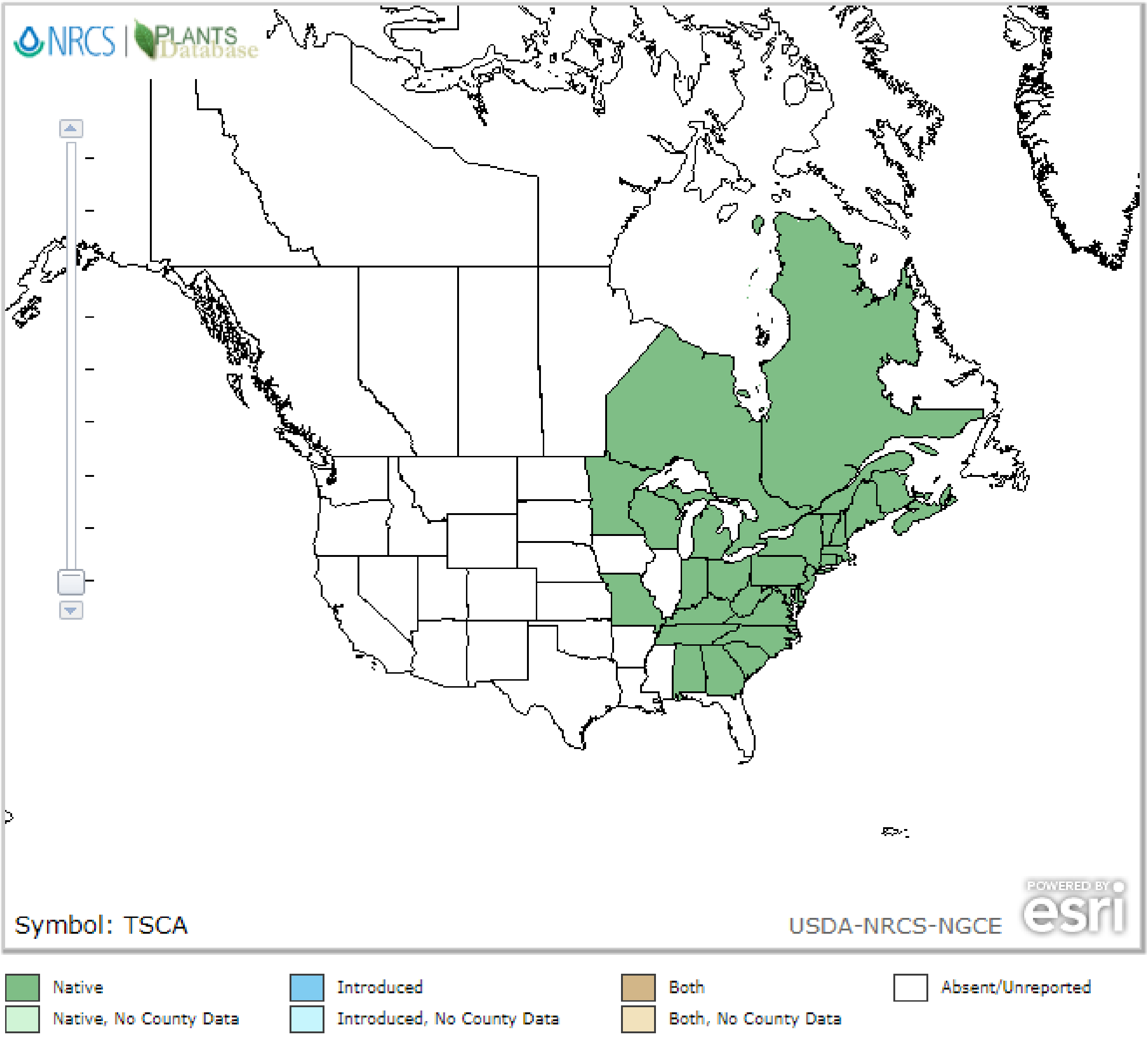

Figure 1. Range for *Tsuga canadensis* (USDA, NRCS 2019)

Figure 2. *Tsuga canadensis* branches with needles (The Morton Arboretum 2019)

furrows as trees grows older (USDA, NRCS 2002; The Morton Arboretum 2019). Hemlocks are slow-growing, with hemlock stands creating environments suitable for expansion by producing shady areas and protecting soil beneath the canopy from drying out (Letheren *et al.* 2017).

Tsuga canadensis is long-lived and often serves as a stabilizing species in forest environments (Orwig *et al.* 2002; Krapfl *et al.* 2011). The trees are commonly the dominant or co-dominant flora species in their respective ecosystems, especially in forest areas featuring deeply-shaded understories (Cobb 2010). The long-lived nature allows the tree to reach great heights, with mature hemlocks commonly reaching 15-25 meters (50-80 feet) above the ground (Krapfl *et al.* 2011). In some mature environments, the trees can reach up to 50 meters in height (Letheren *et al.* 2017). In Michigan and other states in the northern reaches of *Tsuga canadensis,* the average height of a 50-year old individual is 6 meters (20 feet; Lancaster 1985).

Hemlock Woolly Adelgid (Adelges Tsugae) *Characteristics*

The *Adelges tsugae* is an aphid, a type of insect that consumes sap and liquid from plant tissue and is known for carrying diseases that are destructive to many species of biota (Nalam *et al.* 2019). A fully-grown hemlock woolly adelgid is reddish-brown to purplish-black in color, with an ovular shape and soft body less than 1.5 millimeters in length (Abella 2014). The name comes from the woolly white appearance (Figure 3), which develops as the insect "matures and produces a covering of wool-like wax filaments to protect its eggs" (Abella 2014: 21). The insect features a stylet bundle, which it inserts into a hemlock needle for feeding (Young *et al.* 1995); some have referred to the stylet bundle as a "piercing-sucking mouthpart" (e.g., Hoover 2004).

Figure 3. White hemlock woolly adelgid on a hemlock shoot (Photo by Michael Montgomery in McCullough 2015).

Figure 4. *Adelges tsugae* on the base of hemlock needles (Photo by J. Weiferich and D. G. McCullough in McCullough 2015)

The *Adelges tsugae* insect infests hemlock trees by implanting into needles on healthy hemlock branches and feeding on cellular fluids (Krapfl *et al.* 2011; Preisser *et al.* 2014). Each adelgid settles permanently at the base of a hemlock needle (Figure 4) and inserts its styli into xylum ray parenchyma cells (Young *et al.* 1995; Preisser *et al.* 2014). As the insect feeds on the nutrient-rich cellular fluids, researchers hypothesize that it injects phytotoxic saliva into hemlock needles, polluting biological matter in the tree (Young *et al.* 1995; Krapfl *et al.* 2011; Preisser *et al.* 2014). As a result, hemlocks lose their needles, tree growth is stunted, and the trees are unable to recover (Ellison *et al.* 2018). The process renders the tree incapable of responding to other pests and environmental hazards (Letheran *et al.* 2017). Indicators of the decline in tree health following infestation include needle drop, bud abortion, and inhibition of new growth (Preisser *et al.* 2014). Given the extremely rapid rate of reproduction once *Adelges tsugae* infests its hemlock host, the health of infested trees can decline rapidly, with tree mortality occurring in approximately 4-10 years (Preisser *et al.* 2014). The rate of mortality will increase in areas where *Adelges tsugae* is numerous (Paradis *et al.* 2007).

Adelges tsugae is an asexually reproducing species, producing two generations of nymph offspring each year (Preisser *et al.* 2014; Ellison *et al.* 2018). Females from the previous year, who have lain dormant on the hemlock individual since late autumn of the previous year, lay 50-300 eggs in the late winter season to produce the first generation (*progrediens*, plural *progredientes)* of offspring: nymph insects which hatch in mid-spring (Pressier *et al.* 2014; Letheren *et al.* 2017). These nymphs are crawlers and either move to a permanent feeding site on the hemlock of their birth (Preisser *et al.* 2014) or are dispersed to other sites by wind, birds, deer or humans (McClure 1990). Mortality rates for nymphs can approach 90% (Preisser *et al.* 2014). The surviving progredientes will mature by May and produce woolly sacks containing eggs of the next generation of offspring (Letheren *et al.* 2017).

The second generation of *Adelges tsugae* is born from the mature spring nymphs in early summer (Figure 5). This generation (*sistens*, plural *sistentes)* is smaller than the first annual generation of offspring at 20-30 individual insects (Preisser *et al.* 2014; Letheren *et al.* 2017). After searching for newer growth portions of the hemlock host, the *sistentes* nymphs will embed their styli into the host tree and go dormant until late fall, when they begin feeding until the birth cycle restarts with the arrival of the spring *progrediens* generation (Preisser *et al.* 2014). The production of two new generations of *Adelges tsugae* each year leads to greater resiliency between years and a faster spread of the disease in affected hemlock forests (Letheran *et al.* 2017).

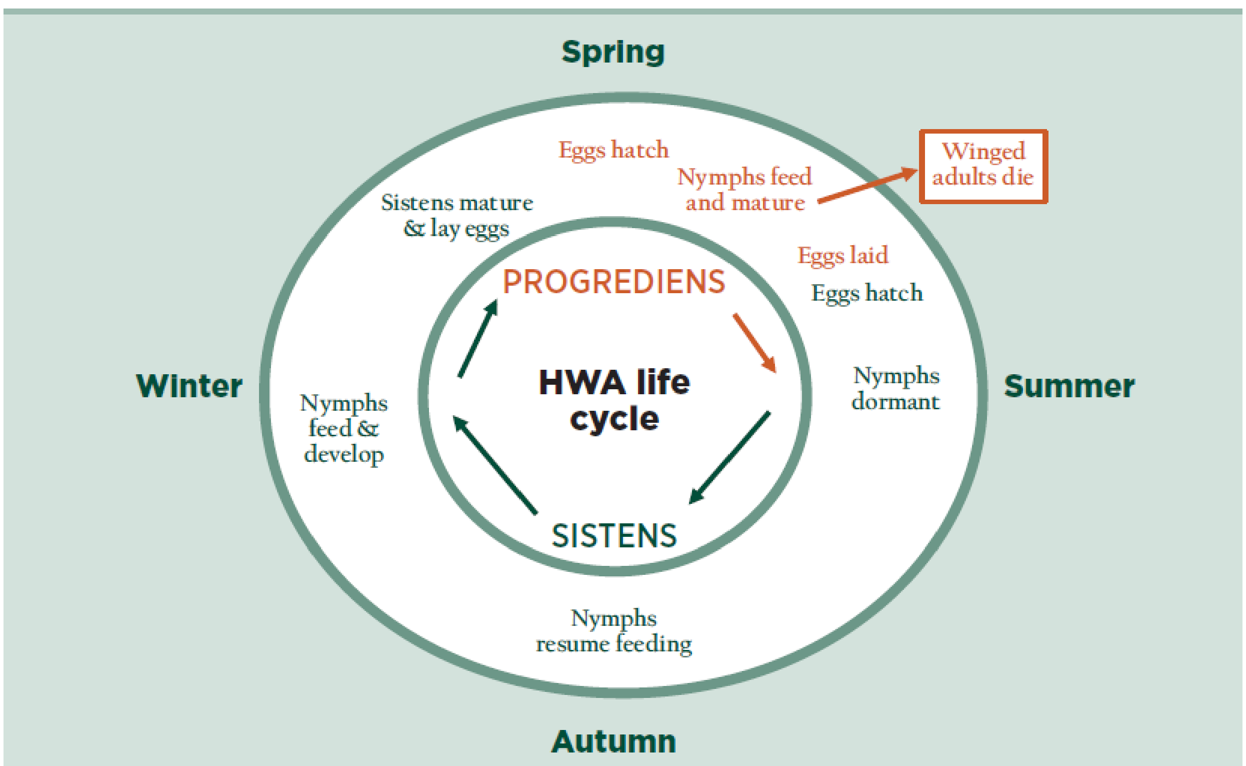

Figure 5. Two generations of hemlock woolly adelgid form the insect’s life cycle each year (McCullough 2015: 2)

The infection of *Tsuga canadensis* by the *Adelges tsugae* insect generally moves from the top of the infected tree to the base (Ellison *et al.* 2018). Both generations of the adelgid feed on new needles, which "leads to progressive needle loss, often first observed in the lower and central portions of tree crowns, then on interior branches and exterior branch tips, and finally at the top of the crowns [Orwig *et al.* 2002]" (Ellison *et al.* 2018: 3). After the adelgid becomes established in a forest stand, tree morbidity and mortality may last until the hemlocks are eliminated (Ellison *et al.* 2018). In New England states, the loss of hemlocks has been followed by a change in forest cover to deciduous stands of mixed hardwoods (Ellison *et al.* 2018). Hemlock mortality may also leave canopy gaps that can be colonized by non-native species including oriental bittersweet (*Celastrus orbiculatus*) (Ellison *et al.* 2018). Animal species that spend part of their life cycle in hemlocks can be adversely affected, as shown by significant declines in some warbler, flycatcher and thrush species in mid-Atlantic and New England forests (Ellison *et al.* 2018). White-tailed deer (*Odocoileus virginianus*) are predicted to be negatively impacted by the loss of hemlocks, but small mammal populations are less likely to be affected (Ellison *et al.* 2018).

<u>*Spread of* Adelgis Tsugae *to Michigan Environments*</u>

The *Adelges tsugae* insect is native to southern Japan, one of several similar aphid insect species found across eastern Asia (Krapfl *et al.* 2011; Havill *et al.* 2016). In East Asia, the pest is unable to cause instability in hemlock tree populations because of natural predators, but these predators are not present in North America (Orwig *et al.* 2002; Letheran *et al.* 2017). As a non-native insect to this region, *Adelges tsugae* relies on *Tsuga canadensis* (Eastern hemlock) and, to a lesser extent, *Tsuga caroliniana* (Carolina hemlock) as a food source, species which serve as the dominant or co-dominant species of forests across the eastern United States (Havill *et al.* 2016).

The first confirmed instance of *Adelges tsugae* on the North American continent was discovered in Maymont Park, Virginia near Richmond, Virginia in 1951 with a series of shipments of ornamental foliage (Letheran *et al.* 2017). After being contained for several decades to the region of northern Virginia, in the 1980s the pest began to spread quickly through the hemlock-rich forests of the eastern United States. By 2018, the adelgid had established populations in 19 states and one Canadian province (Ellison *et al.* 2018; see Figure 1). Figure 6 shows the historical spread of *Adelges tsugae* between 1951 and 2006 (Morin *et al.* 2009). Many local areas have been substantially impacted, such as Virginia's Shenandoah National Park which lost approximately 90% of its mature hemlocks (Preisser *et al.* 2014) and Delaware Water Gap National Recreation Area where more than 65% of hemlocks were dead or declining by 2003 (Abella 2014).

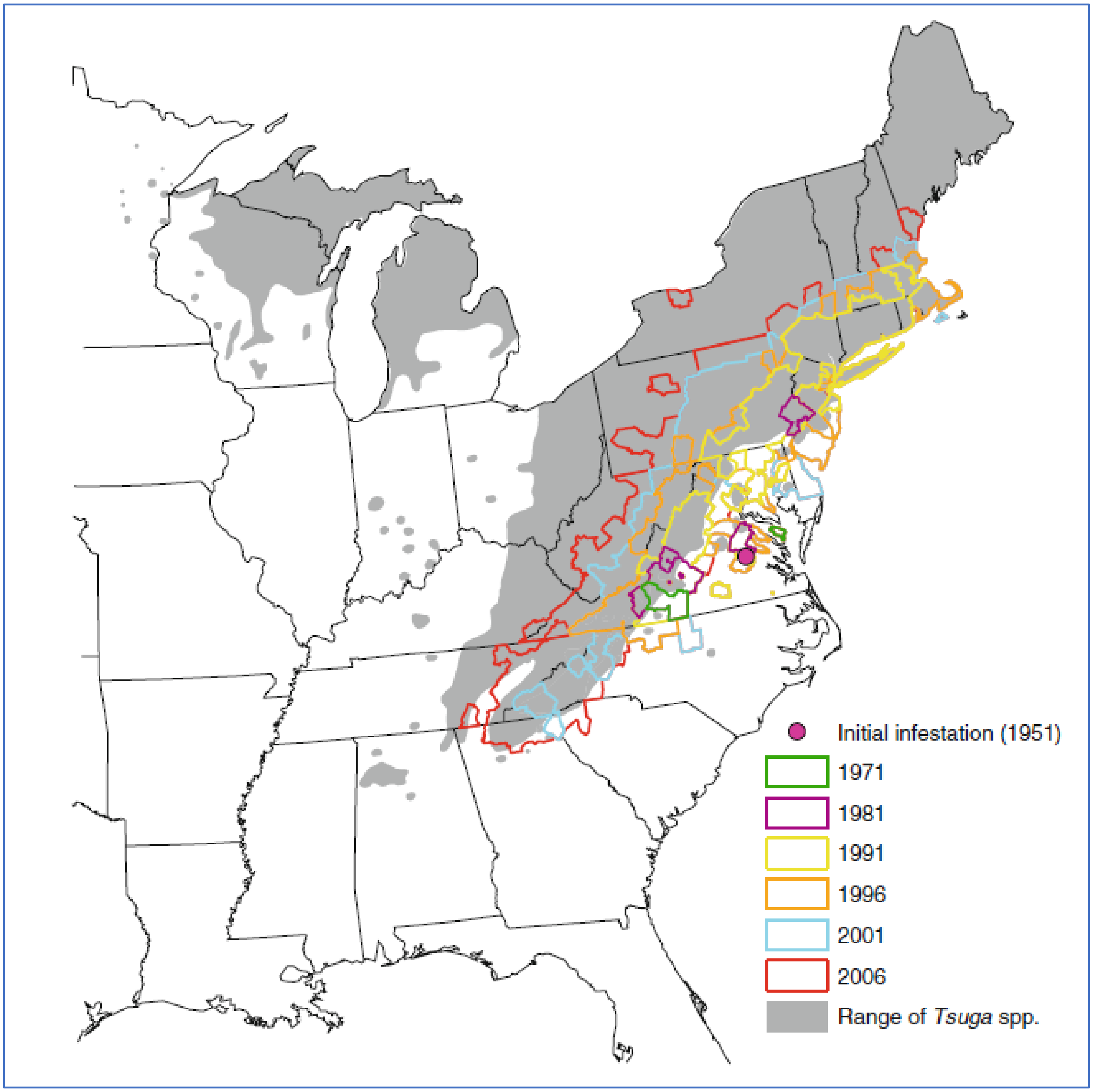

Figure 6. Historical (1951-2006) spread of *adelges tsugae* in the United States (Morin *et al.* 2009)

By 2015, small infestations of *Adelges tsugae* were discovered in western lower Michigan (McCullough 2015). From evidence, McCullough (2015: 1) states that "some of these infestations are at least 10 years old and probably originated when infested hemlock trees from other states were planted in landscapes". Since 2015, *Adelges tsugae* has been detected in additional Michigan counties (Figure 7). The insect is viewed as a significant threat to *Tsuga canadensis* trees across the state (McCullough 2015). A 2014 inventory indicated more than 173 million hemlocks growing in Michigan forests, along with thousands more planted in Michigan landscaping (McCullough 2015). Because of preferential browsing of deer on younger hemlock, much of the hemlocks in Michigan forests are relatively old trees (McCullough 2015).

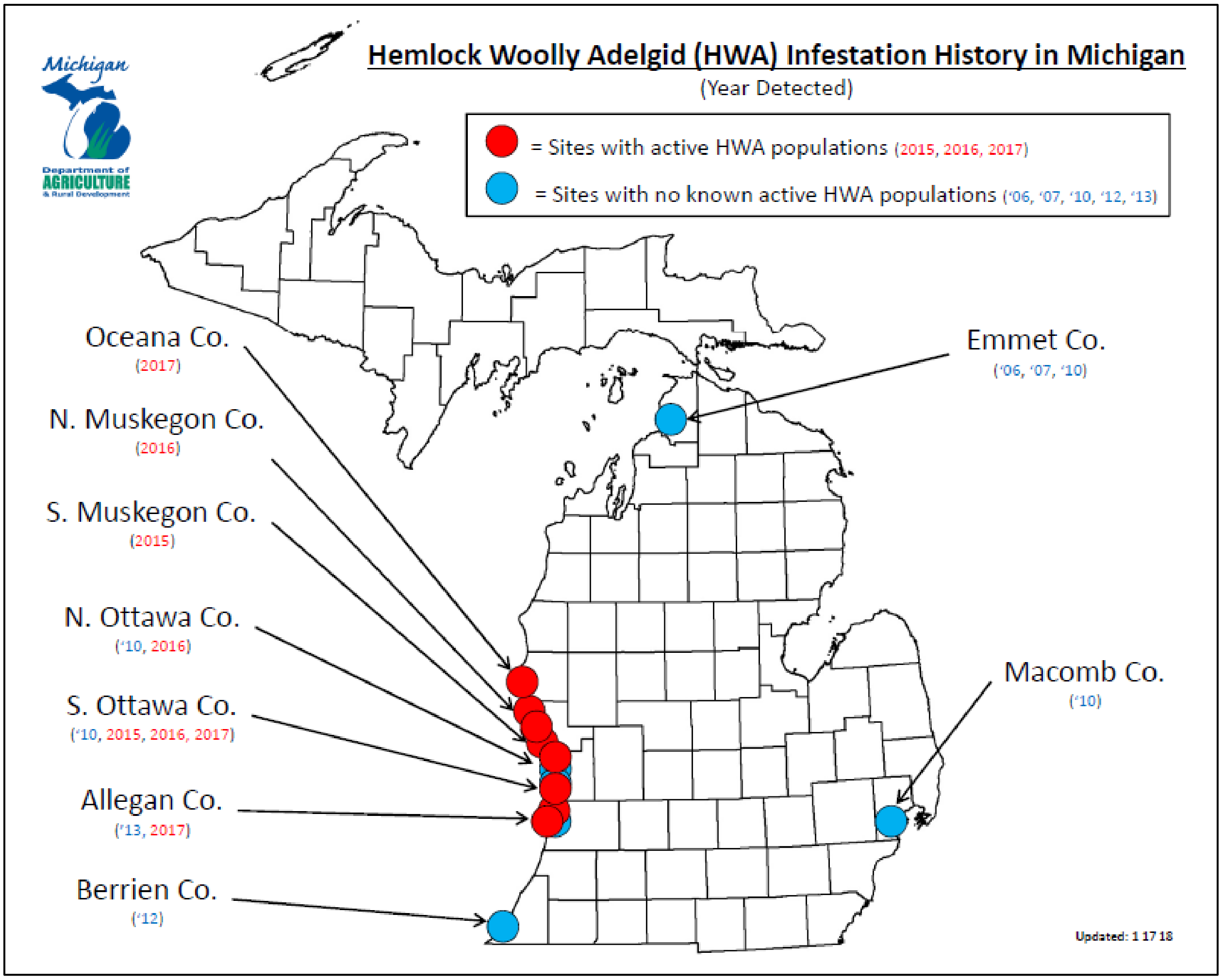

Figure 7. History of A*delges tsugae* detection in Michigan (State of Michigan 2019)

Michigan Dunes, Tsuga Canadensis*, and* Adelges Tsugae

Michigan's coastal environments include more than 230,000 acres of coastal sand dunes (Arbogast *et al.* 2018), with a variety of dune types and sizes. More than half of the dunes (54.7% of the total coastal sand dune area) are in public ownership (local, state or federal) or conservation ownership (local land conservancy or other conservation-based ownership) (Arbogast *et al.* 2018). Approximately 70,000 acres are regulated by the state of Michigan with Part 353 of the Natural Resources and Environmental Protection Act (NREPA 1994) as "critical dunes". Critical dunes are "a unique, irreplaceable, and fragile resource that provide significant recreational, economic, scientific, geological, scenic, botanical, educational, agricultural, and ecological benefits" (NREPA 1994: Part 353). Human changes to dune topography, drainage, vegetation and silviculture are regulated under this law (NREPA 1994), but changes resulting from infestations such as the *Adelges tsugae* may have similar types of impacts to the regulated human changes.

The types, sizes, shapes and activity of dunes vary greatly within and between dune areas in Michigan (Hansen *et al.* 2010). West Michigan dune systems may include some or all of the following dune types: foredune, shore-parallel dune ridge, blowout, parabolic dune, and backdune ridge (Hansen *et al.* 2010; van Dijk 2014). Furthermore, the blowouts, dune ridges and parabolic dunes may be partially or wholly active or stabilized by vegetation. Ecological communities range from pioneering vegetation on more active or recent dune surfaces, through early and secondary succession communities, and to climax forest communities on wooded dunes (Cowles 1899; Olson 1958). *Tsuga canadensis* are present in the forested areas of Michigan's coastal dune systems (Cowles 1899; Olson 1958; Lichter 1998**)**. To date, there has been very little investigation and no peer-reviewed publications focused on the current and potential impacts of *Adelges tsugae* on the hemlocks and surrounding environments of Michigan's coastal dunes.

Study Area

The study area for this investigation was a coastal dune system in P.J. Hoffmaster State Park on the shore of Lake Michigan in Norton Shores, Michigan (Figure 8). P.J. Hoffmaster State Park is a 1200-acre protected area operated by the Michigan Department of Natural Resources, located in Ottawa and Muskegon Counties (MDNR 2019). Our study area is one of eight large active parabolic dune systems along the park shoreline; dune activity is visible on the aerial imagery in Figure 8 where the lighter colors near the shoreline indicate bare sand and pioneering vegetation. The active parabolic dunes have been numbered 1 through 8 from south to north, and our study area is Dune 2. Geomorphic units in our study area included (starting from Lake Michigan and moving inland): beach, foredune, dune ridge, blowouts and ridges on a large parabolic dune (Figure 9).

Figure 8. Aerial image of P. J. Hoffmaster State Park and its location in lower Michigan. The study location is circled on the aerial image. (Sources: Google Maps satellite imagery and Michigan Department of Transportation (MDOT))

Figure 9. Closer view of Dune 2 in Hoffmaster State Park with variety in dune topography and vegetation communities visible. (Source: Google Maps Satellite Imagery)

Low human impacts make the study area attractive for an investigation into the distribution of *Tsuga canadensis* and attributes of the spread of *Adelges tsugae.* The study area is a 20-minute walk from the nearest parking lot in the park. Although the study area is bounded by Homestead Trail to the south and the beach to the west, there are no managed trails within the study area itself. There are several unmanaged trails: along the crests of the dune arm complexes on each side of the parabolic dune, along the center of the windward slope to the dune crest, and along the shore-parallel dune ridge between the beach and the parabolic dune.

The dune systems in the southern portion of Hoffmaster State Park, including the study area, had not been inventoried for the presence of *Adelges tsugae.* The northern part of Hoffmaster State Park, which includes the park campground, a visitor center, and developed beach areas, has been confirmed to have mild to moderate infestations of *Adelges tsugae,* particularly in areas with acute human impacts (Brockwell-Tillman 2018). The areas of the park proximate to the campground and visitor center have been prioritized in disease management strategies by the Michigan Department of Natural Resources (Brockwell-Tillman 2018).

Prior published investigations of the study area have focused on dune geomorphology, including history (Hansen *et al.* 2010) and foredune activity (van Dijk 2004, 2014). Hansen *et al.* (2010) did not collect samples for radiocarbon or optically-stimulated luminescence dating from our study area. From samples collected at other locations in Hoffmaster State Park, they described the age of the shore-parallel dune ridge as roughly 0.5 to 1 thousand years old and the ages of the large active parabolic dunes near the shore as roughly 1.5 to 3.5 thousand years old (Hansen *et al.* 2010). Contemporary measurements of foredune evolution by van Dijk (2004, 2014) identify the following variables as important for dune activity: lake-level variations, patterns of wind speed and direction, and seasonal influences including winter temperatures and processes. Unpublished reports from short-term studies have focused on the importance of storms in dune changes (Swineford *et al.* 2014) and the impacts of deer on different parts of the Dune 2 parabolic dune system (McClellan *et al.* 2018).

Methods

Investigate Distribution of Hemlocks in the Study Area

Data on the distribution of *Tsuga canadensis* in the study area was collected through a comprehensive survey of hemlocks. Field data for the survey were collected by researchers during site visits on October 25, November 1 and November 8, 2018.

Before doing the survey, project researchers established study area boundaries to provide comprehensive coverage of all major components of the coastal parabolic dune system. The boundaries were determined from a topographic map of the area. Given that the width of the dune system decreases as distance from the lakeshore increases, boundaries were set tangent to the outer edge of the dune arm to delineate the furthest extent of the dune survey area. These boundary points were recorded as GPS point data during field work. Boundaries were drawn at a perpendicular angle from the lakeshore (approximately N70E) through the boundary points to the tangent line of the furthest extent of the dune slipface. The area enclosed by the rectangular shape created by the boundary lines formed the extent of the dune survey completed in this study.

Within the study area, the researchers observed, mapped and documented *Tsuga canadensis*. The field researchers used a walking survey with visual observation to locate all hemlocks in the study area. In unforested areas (beach, foredune, blowouts on windward slope of parabolic dune), researchers could record the presence or absence of hemlocks from central observation points such as trails through the area or elevated locations. In forested areas (parabolic dune arms), researchers started at the lakeward edge of area and walked back and forth through the forest perpendicular to their main (eastward) trend in direction. In this way, the hemlock survey was completed from the lakeward edge of each dune arm to the eastern edge of the dune slipface.

The sampling method for the hemlock survey identified both individual instances and stands of *Tsuga canadensis.* Individuals were defined as singular instances of hemlocks with no contact with an individual of the same species. Individual trees were named and recorded as GPS point features. Each tree was named with a unique ID number, with many individuals labelled with explanatory text for easier identification in data post-processing. Hemlock stands were defined as areas with two or more individuals clustered together, with some form of continuous contact or near-continuous contact between individuals within the stand. Stands were named and recorded as GPS polygon features. Polygon features were recorded by field researchers with GPS receivers, tracing the perimeter of the most exterior branches of each stand. Each stand was named with a unique ID number, with many stands labelled with unique text to assist in identification during data processing.

Data from each GPS receiver was downloaded and processed at Calvin College. Data was georectified using Pathfinder GPS software and exported into ArcGIS as vector point shapefiles for spatial analysis. The data was collected into geodatabases prepared for use in ArcMap 10.4 and other geospatial analysis tools. Quantitative and qualitative attributes from field notes were added into GIS and assigned to points within the geodatabase.

Analysis of the mapped data included looking for spatial patterns of hemlock distribution, identifying possible variables, and calculating hemlock density. Hemlock locations were compared to dune environments (such as beach, foredune, dune ridge, parabolic dune components) for patterns. Mapped data were compared to LiDAR data for the location to see at what elevations the hemlocks occurred. Using the ArcGIS analysis tools, hemlock locations were compared to aspect to see if there were any patterns. A subsequent visual survey and analysis of qualitative field notes were used to confirm any trends in the data. To quantify hemlock density in stands, researchers counted the number of mapped hemlocks in a 5m x 5m representative area; then researchers divided the count by the area. For average density, researchers did measurements along three transects and calculated the average.

Investigate Hemlock Characteristics

Quantitative and qualitative data were collected for hemlock characteristics (Figure 10). For identified hemlock stands, the characteristics were recorded for three representative individuals located in the stand. Researchers measured tree diameter at breast height (dbh) using a Lufkin dbh tape measure. Visual observations were recorded for the physical appearance and characteristics of individual trees or stands, along with the surrounding soil characteristics. Researchers ranked the health of hemlocks according to a 3-point scale in which 1 indicates poor health, 2 indicates moderate health, and 3 indicates good health.

Figure 10. Researchers mapping a hemlock with GPS and collecting data on the tree's characteristics

Investigate Adelges Tsugae *Presence in the Study Area*

Researchers checked each individual hemlock or hemlock stand for a list of potential symptoms of *Adelges tsugae* infestation. Observations included items such as overall tree health, needle loss, and the presence of any sticky or woolly white masses on tree branches. Recognizing the difficulty of identifying infestation in October and November when *Adelges tsugae* are seasonally dormant, the goal of the observations was to provide a list of trees that more experienced DNR staff could check later. That list, along with a map of the tree locations, was sent to the Hoffmaster State Park Naturalist as soon as it was compiled by researchers.

Results

<u>*Distribution of Eastern Hemlocks*</u>

Tsuga canadensis is selectively distributed on specific components of the dune system (Figure 11 and Table 1). A total of 54 hemlock individuals and 24 hemlock stands are observed in the study area. There were no instances of hemlocks found on the beach, foredune, and the windward slope and dune crest of the large parabolic dune. A lone hemlock individual was located on the slipface of the large parabolic dune. The remaining hemlock trees were found on the parabolic dune arm complexes. Hemlock individuals and stands were distributed along both the north and south dune arm complexes. A total of 29 individual hemlocks and 13 hemlock stands were located on the north arm of the dune system. A total of 24 individual hemlocks and 11 hemlock stands were located on the south arm of the dune complex.

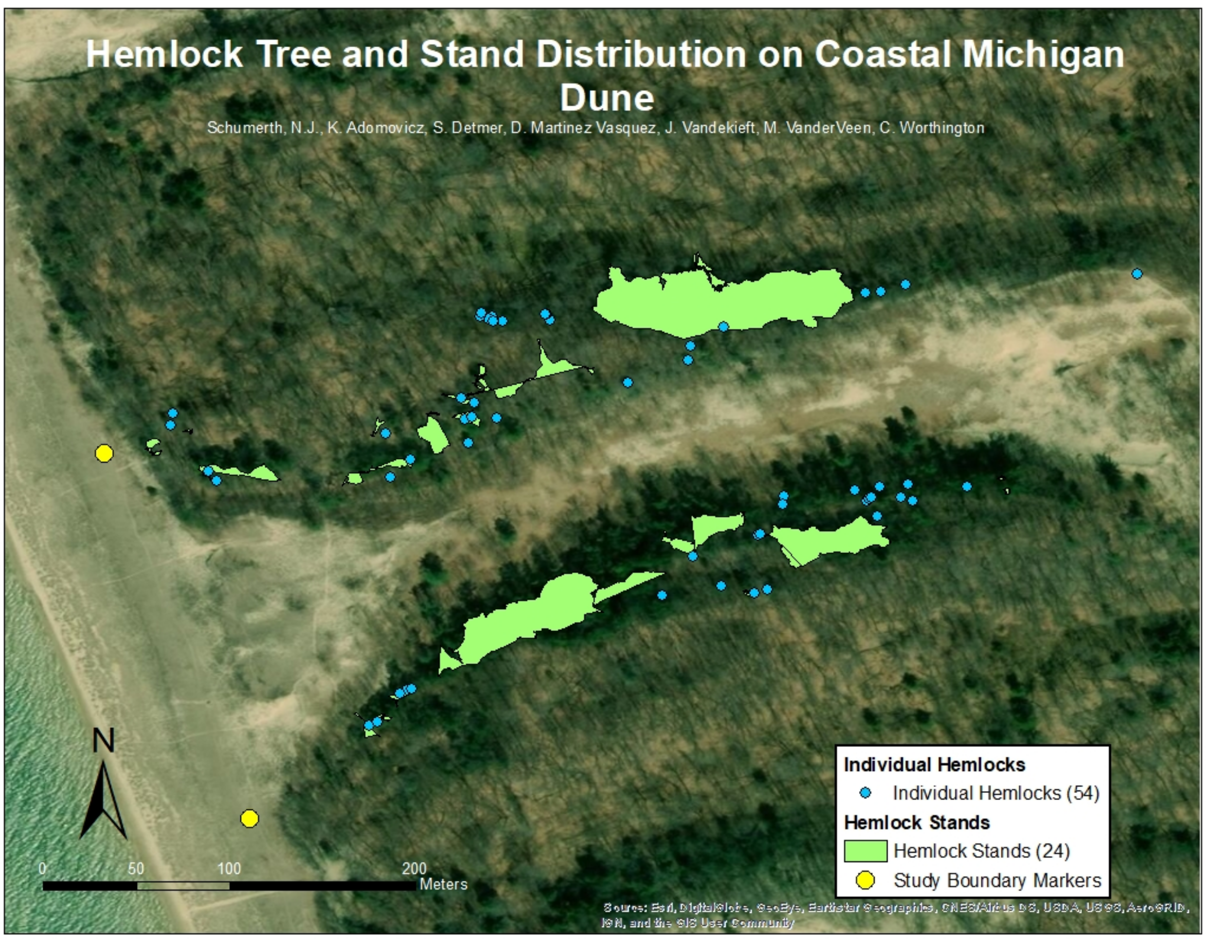

Figure 11. Distribution of *Tsuga canadensis* in the study area

Dune Environment	Individual Hemlocks	Hemlock Stands
Beach	none	none
Foredune	none	none
Dune ridge	none	none
Parabolic dune - windward slope	none	none
Parabolic dune – north arm	29	13
Parabolic dune – south arm	24	11
Parabolic dune - crest	none	none
Parabolic dune - slipface	1	none

Table 1. Counts of *Tsuga canadensis* in dune environments in the study area

Based on elevation mapping from LiDAR data (Figure 12), only three hemlock individuals appeared at elevations above 221 meters above sea level (m.a.s.l.; 725 feet). No hemlock individuals were located below 183 m.a.s.l. (600 feet). Many hemlock individuals were present between 189 m.a.s.l. (620 feet) and 213 m.a.s.l. (700 feet). For reference, the average level of Lake Michigan-Huron is 176.5 m.a.s.l. (USACE 2019).

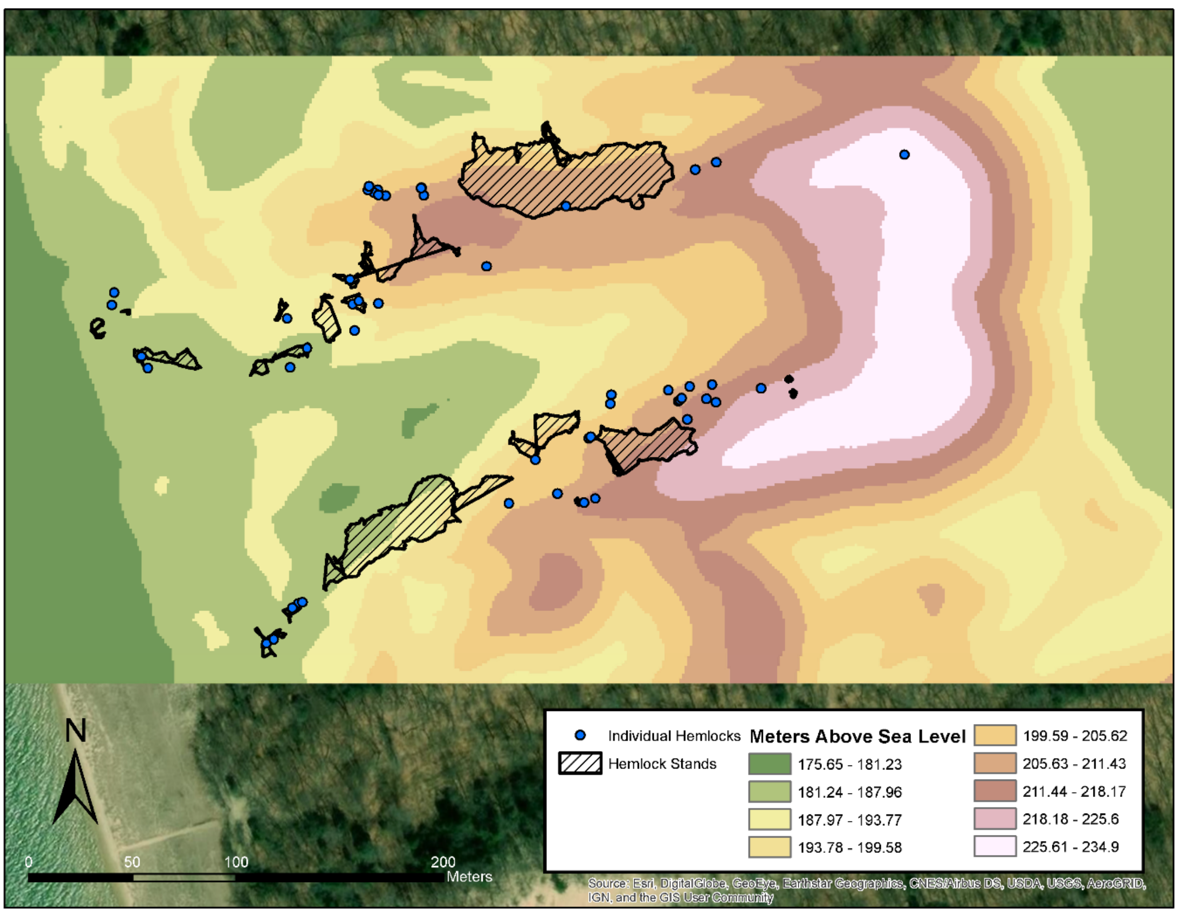

Figure 12. *Tsuga canadensis* mapped by elevation

The average density of hemlocks in stands on the dune arms was calculated at 0.44 trees per square meter. This calculation was based on an average of 11 hemlock trees in a 25 square meter zone.

Most of the *Tsuga canadensis* individuals and stands were found on northern slopes of the dune system (Figure 13). This pattern was visible even on the complex arms of the parabolic dune, which included many folds perpendicular to the lakeshore at the western ends of the arms.

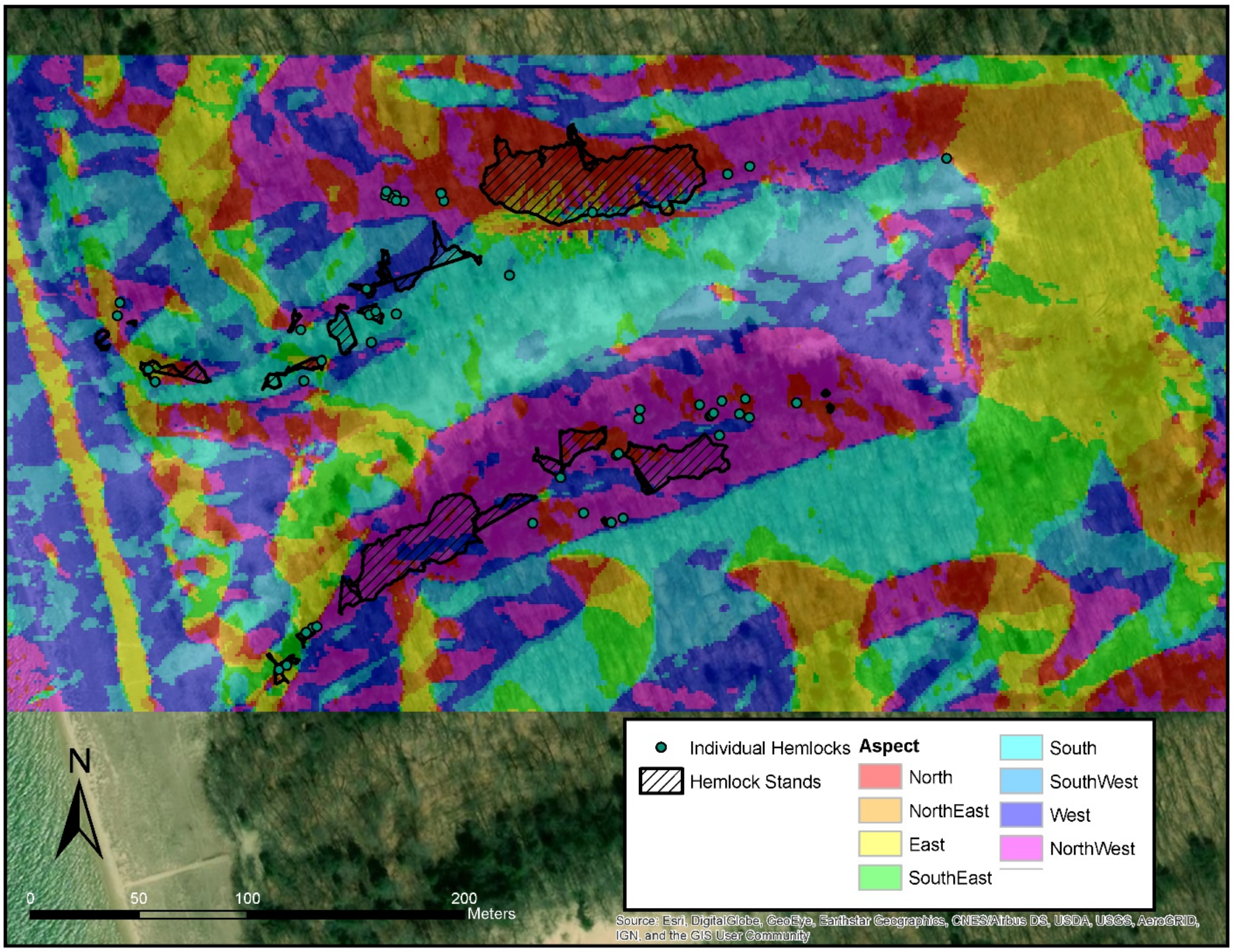

Figure 13. *Tsuga canadensis* mapped by aspect

Hemlock Characteristics

Most *Tsuga canadensis* in the study area were mature trees, but the health assessment showed mixed results. Tree diameter at breast height (dbh) ranged from 5 to 54 cm, with an average dbh of 20 cm. Our sample size was 50 trees, including trees from both dune arms as individuals and in stands. It appeared that hemlocks on the north arm had larger dbh, but our sampling and analysis were not statistically robust. Hemlock health, based on visual observation, ranged from poor (1) to very healthy (3) (Figure 14). Evidence of poor health included dead branches; discolored, clumped or sparse needles; and white substances on branches (Figure 15).

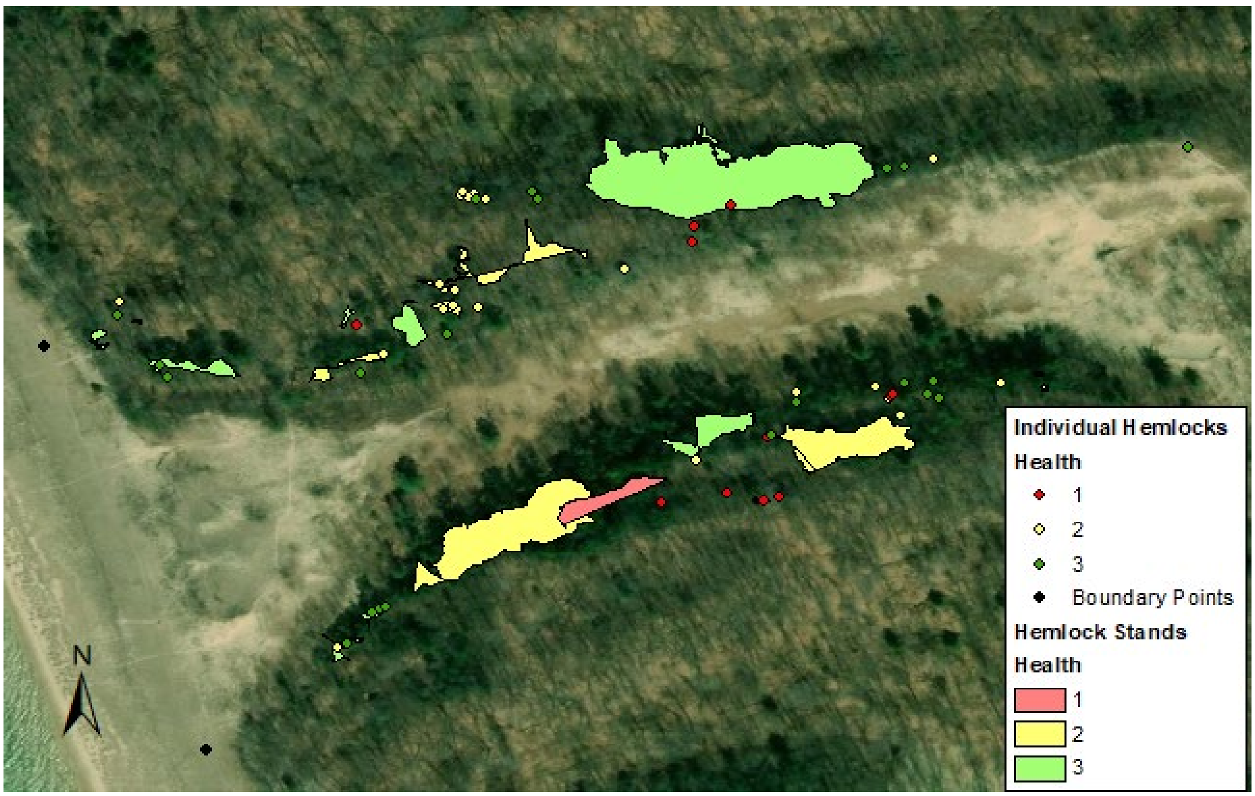

Figure 14. Health characteristics of *Tsuga canadensis* in the study area

Figure 15. *Tsuga canadensis* in poor health on south dune arm shows many gaps in upper foliage when seen from bottom

Presence of Adelges Tsugae *in the Study Area*

Out of 54 individual *Tsuga canadensis* and 24 stands, researchers identified 15 trees as potentially infested with *Adelges tsugae* (Figure 16). Symptoms ranged from poor health of trees (such as needle loss) to whitish substances visible on needles (Figure 17). Appendix A identifies the specific locations of the 15 trees. More potentially-infested trees were identified on the south arm compared to the north arm. Five hemlock stands contained trees showing symptoms of the infestation: two stands on the north arm and three stands on the right arm. The spatial pattern of potentially-infested tree locations shows the trees to be located at lower and middle elevations in the dune complex.

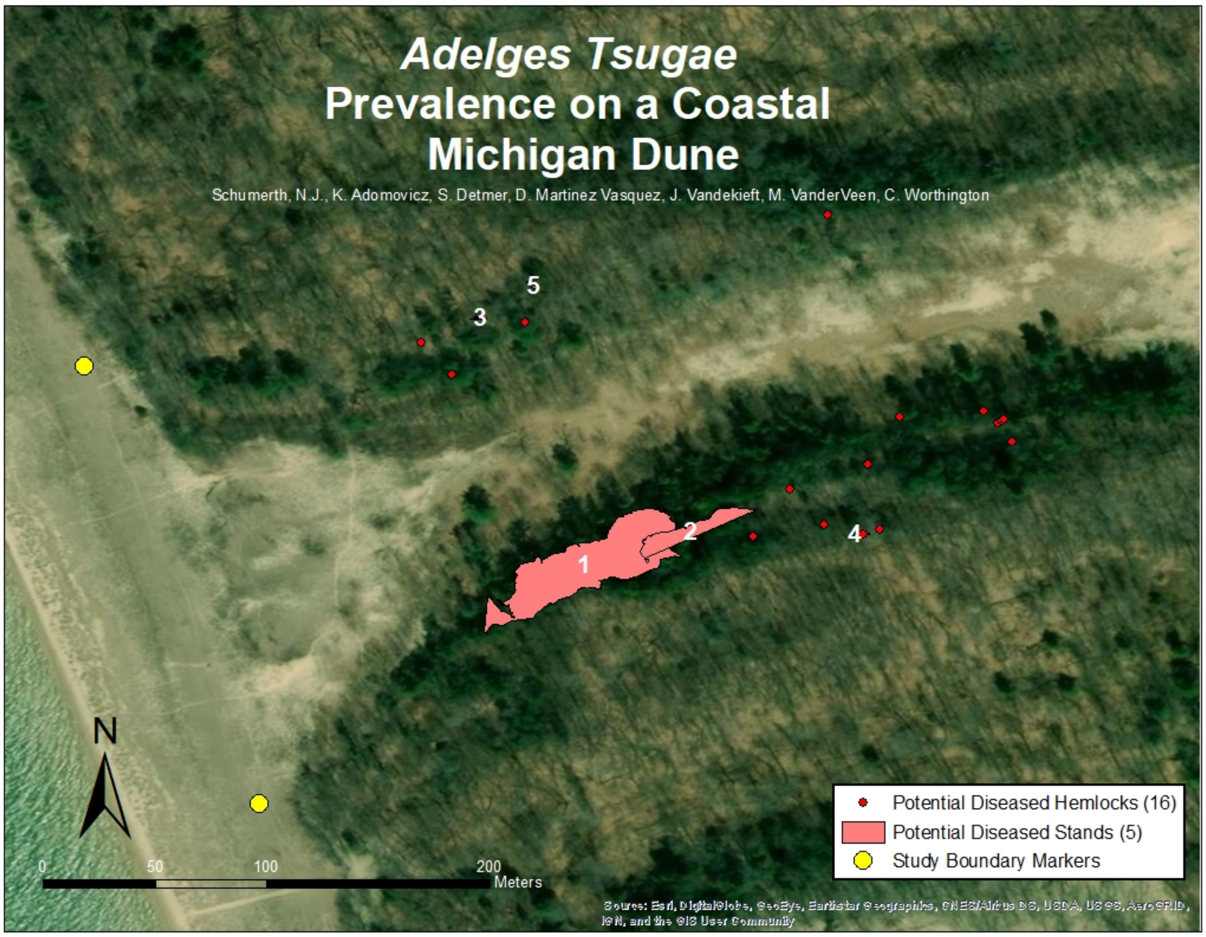

Figure 16. Distribution of *Tsuga canadensis* that are potentially-infested with *Adelges tsugae*

Figure 17. *Tsuga canadensis* in poor health exhibiting potential symptoms of *Adelges tsugae* infestation

Discussion

The distribution of *Tsuga canadensis* in the parabolic dune system is consistent with the patterns seen in other North American locations. On the dune, hemlocks were found in stands as well as individuals mixed with other dune forest species. Abella (2014) notes the ability of hemlocks to form pure stands of their species and to grow in mixtures of species, with the other tree species varying according to what is appropriate in that particular region. In the Hoffmaster study area, most of the hemlocks were found on north-facing slopes of the ridges comprising the lower to middle arms of the large parabolic dune. Krapfl *et al.* (2011: 93) indicated that hemlocks do best on "steep, undisturbed, northerly facing sites". Abella (2014: 18) further explains that one of the environments where hemlocks are most dominant are "north aspects with damp, cool microclimates".

The loss of hemlocks from these dune areas will have impacts on the ecological community. Hemlocks are not easily replaced by other tree species because they have a unique combination of shade tolerance, longevity, large size, and evergreen growth (Abella 2014). Northern red oak (*Quercus rubra* L.) has been identified as a common replacement species in the eastern USA (Letheren *et al.* 2017). However, the red oaks may grow more slowly than usual because of changed mycorrhizal conditions where infested hemlocks were (Letheren *et al.* 2017).

Once established, the red oaks may consume twice as much water as established hemlocks (Letheren *et al.* 2017). Other ecological impacts of losing hemlocks include increases in understory light levels, increases in vascular plant cover, and colonization of the area by invasive species (Preisser *et al.* 2014). Hemlocks provide important microclimates for a number of bird species and protection for vertebrates such as salamanders (Preisser *et al.* 2014; Letheren *et al.* 2017).

The loss of hemlocks from dune environments may also impact dune slope stability, although there is little research on this topic. Orwig *et al.* (2002) suggest that topography may influence impacts of infestation, with ridgetop and topographically-exposed sites both more susceptible to decline from adelgids and harder to protect because of location and stressful growing conditions. Ridgetop and topographically-exposed sites are also the locations in dune environments that are most susceptible to wind erosion and blowouts. However, the north-facing slopes that hemlocks favor are parallel, rather than directly-facing, the west winds that dominate sand transport on the Michigan coast of Lake Michigan. Increased slope erosion by water and gravity may be the more likely outcomes for the dune locations where hemlocks were recorded in this study. The steeper slope angles (Figure 18) where hemlocks do well is a factor that increases the susceptibility to erosion if the hemlocks die.

Figure 18. Hemlocks on a steep north-facing slope in the study area

Conclusions

The distribution of *Tsuga canadensis* in the large parabolic dune system known as Dune 2 in Hoffmaster State Park is primarily on north-facing slopes of the complex ridge systems that form the north and south arms of the parabolic dune. Hemlocks are most-often present in stands, but also present as individuals mixed with other forest species. The hemlocks are mature, have diameter-at-breast-heights ranging from 5-55 cm, and were categorized as having mixed health ranging from poor to very good. Possible symptoms of *Adelges tsugae* infestation were recorded for 15 hemlocks in the study area. Locations were reported to Department of Natural Resources staff so they can follow up with a more robust survey for the infestation in a season when the insects/infestation can be more easily identified.

If the *Adelges tsugae* infestation is present in the study area, or moves into the area in the future, the loss of hemlocks will impact the ecology and slope stability of the dune system. Dune managers can use these study results to plan for treatment of infested areas or mitigation of the impacts of the infestation. Knowledge of the hemlock patterns at this dune location may also to focus investigations and management actions in other Michigan dune systems. Additional research would be valuable, including investigating other dune systems to see how widespread the patterns of hemlock distribution on dunes are, comparing these dune results with sites where there are greater human impacts to see if tree distribution or infestation spread are affected, and investigating the role of hemlocks in dune slope stability.

Acknowledgements

We would like to give special thanks to the following:

- Michigan Department of Natural Resources for permission to do this research in P.J. Hoffmaster State Park.
- Park Naturalist Elizabeth Brockwell-Tillman for information about hemlocks and hemlock woolly adelgid in Hoffmaster State Park.
- Michigan Space Grant Consortium for funding transportation to the study area and other components of the research.
- Calvin University and the Department of Geology, Geography, and Environmental Studies for supporting the research with equipment, facilities, and other resources.
- Liam Ferraby for providing valuable assistance with GIS mapping.
- Dr. Deanna van Dijk for providing and mentoring this research experience.

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Appendix A. Locations of Hemlocks Potentially Infected with *Adelges Tsugae*

Coordinates and map of hemlocks potentially infected with *Adelges Tsugae* in the study area. Trees were identified from visual indicators during field work in October-November 2018.

Latitude	Longitude
43.114353	-86.267726
43.113699	-86.266510
43.113890	-86.266360
43.113989	-86.266046
43.114181	-86.265920
43.114206	-86.265580
43.114480	-86.267848
43.114563	-86.267427
43.11371	-86.266066
43.113729	-86.266
43.113746	-86.266226
43.114081	-86.265467
43.114159	-86.265522
43.114166	-86.265512
43.114173	-86.265501