PREDICTING INFESTATIONS OF HEMLOCK WOOLLY ADELGID (*Adelges tsugae*) IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE/NORTH CAROLINA, USA

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Scott F. Snider

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This thesis entitled

PREDICTING INFESTATIONS OF HEMLOCK WOOLLY ADELGID

(*Adelges tsugae*) IN GREAT SMOKY MOUNTAINS NATIONAL PARK,

TENNESSEE/NORTH CAROLINA, USA

BY

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Predicting Infestations of Hemlock Woolly Adelgid (*Adelges tsugae*) in Great Smoky Mountains National Park, Tennessee/North Carolina, USA (61pp.)

Director of Thesis: James Dyer

The hemlock woolly adelgid (*Adelges tsugae*) is a non-native, invasive pest killing eastern hemlock (*Tsuga canadensis*) trees in the eastern United States. The purpose of this research is to evaluate wind and people as dispersal mechanisms and the factors limiting the spread of the adelgid in the Great Smoky Mountains National Park. The results from binary discriminant analysis indicate that people have the biggest influence on spreading HWA, wind was not a significant factor of dispersal, and cold temperatures can limit the range to which it will spread. This information can be applied in the fight against the adelgid because it can help to define a search area with a higher probability of infestation and to define monitoring and treatment standards for these areas.

Approved: James Dyer
Associate Professor of Geography

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An Act. No. 233
Declaring and adopting the hemlock (Tsuga Canadensis Linnaeus) as the State tree of Pennsylvania.

Whereas, The hemlock (*Tsuga Canadensis* Linnaeus) is still today, as it was of old, the tree most typical of the forests of Pennsylvania; and

Whereas, The hemlock yielded to our pioneers the wood from which they wrought their cabin homes; and

Whereas, The hemlock gave its bark to found a mighty industry; and

Whereas, The hemlock everywhere lends kindly shelter and sure haven to the wild things of the forests; and

Whereas, The lighted hemlock at Christmas time dazzles the bright eyes of the child with an unguessed hope, and bears to the aged, in its leaves of evergreen, a sign and symbol of faith in immortality; now therefore,

Section 1. Be it enacted, &c., That the hemlock tree (*Tsuga Canadensis* Linnaeus) be adopted as the State tree of Pennsylvania.

Approved-The 22nd day of June, A. D. 1931.

GIFFORD PINCHOT

Chapter 1: Introduction

1.1 Introduction

While working at the Great Smoky Mountains Institute at Tremont I first learned about a non-native, invasive insect plaguing the Great Smoky Mountains National Park (GSMNP). Being in the position where I was about to start a thesis I decided that this invasive insect newly introduced to the park would be a great topic of research. In conducting this research I was motivated by the effort to try and do something to help preserve a place that I am very fond of. Also, the hemlock forests of GSMNP is also one of a number of forest types that combine to make GSMNP a unique American treasure worthy of National Park status.

The eastern deciduous forests of the United States have experienced a barrage of pathogens in recent history. Probably most infamously is the chestnut blight that eliminated nearly the entire population of large reproducing American chestnut (*Castanea dentata*) in the early to mid-1900s. Some other forest pathogens that have reshaped the eastern deciduous forest include balsam woolly adelgid (*Adelges piceae*) affecting Frasier fir (*Abies fraseri*) trees, the gypsy moth (*Lymantria maimaiga*) affecting a multitude of species in this forest type, and Dutch elm disease (caused by a fungus *Ceratocystis ulmi*) negatively affecting native elm (*Ulmus spp.*). Currently we are faced with yet another threat to the eastern forests, the hemlock woolly adelgid (*Adelges tsugae*). Hemlock woolly adelgid (HWA) is attacking a tree of its namesake, the eastern hemlock (*Tsuga canadensis*), and it is spreading at an alarming rate.

The eastern hemlock is a forest evergreen that has a geographic range from Nova Scotia south through Georgia (Harlow 1957). In the past, hemlock has been subject to logging for use as tannin for the tanning industry, but hemlock is not preferred as a lumber source because of undesirable characteristics of the wood (Howard et al. 1999), such as its tendency to be splintery, brittle, and knotty (Harlow 1957). However, hemlock is desirable for landscaping purposes because of its ability to grow in shaded areas and to retain its lowest branches throughout much of its life (Harlow 1957). The use of hemlock as an ornamental includes using species other than the native eastern hemlock. It is because of this ornamental use that we are now faced with the possibility of losing our native eastern hemlock.

It is believed that the non-native invasive insect HWA was introduced from Asia into the United States on nursery stock of hemlocks (McClure and Cheah 1999). HWA was first discovered in the early 1920s in British Columbia where it was found to not have a negative effect on western hemlock (*T. heterphylla*) or mountain hemlock (*T. mertensiana*) (McClure and Cheah 1999). Since the discovery of HWA in Virginia in the early 1950s it has spread throughout much of the native range of the eastern hemlock in a 12-state area from North Carolina to Massachusetts (McClure and Cheah 1999). Since the discovery in the eastern United States, HWA has infested approximately 25% of the 1.3 million hectares of hemlock forests in the eastern United States (Zilahi-Balogh et al. 2002).

1.2 Background on HWA

Hemlock woolly adelgid feeds upon the sap of the hemlock by attaching itself to the base of the needles and injects its piercing-sucking mouthparts into the storage cells. As a result, the tree loses its needles prematurely and new shoots and needles are not developed causing defoliation and eventually death of the tree in as short as 3-5 years (Bonneau et al. 1999). HWA compounds its effect on the hemlock by reproducing at a rate of two generations per year (McClure and Cheah 1999). HWA disperses from site to site by several modes of dispersal: locomotion, wind, birds, mammals, and humans.

Various treatments have been used in attempting to control adelgid infestations, including application of horticultural oils, insecticidal soaps, and injected pesticides. Research has established the presence of native insects that prey on the adelgid, but none has proven to be of great influence on the adelgid populations (Wallace and Hain 2000). Recent measures to control infestations have gone as far as to release a non-native beetle, the coccinellid beetle (*Pseudoscymnus tsugae*), whose primary prey is HWA (McClure and Cheah 1999). In addition to the chemical measures, *Pseudoscymnus tsugae* has been released in large numbers to try and establish biological control on HWA (G. Taylor, GSMNP Biologist, pers. comm. 2002). The use of control measures like these can be better planned with early knowledge of infestation characteristics.

1.3 Objective

Early identification of HWA infestations is key in trying to stop its spread and save the hemlock forests; the objective of this thesis is to develop a method to assess patterns in early HWA infestations to aid in this fight. This study was conducted in GSMNP

Tennessee/North Carolina (Figure 1.1). Infestations of HWA in the GSMNP are under constant observation, and park personnel have been fighting it since its discovery in the park around 2000-2001 (G. Taylor, pers. comm. 2002). Early detection helps personnel to combat the infestations while there is still hope of saving the hemlock.

Within GSMNP there are large areas that are only accessible on foot; in order to locate and treat infestations in these areas of the park more effectively it is essential to develop a method to asses and predict locations of HWA infestations. I have tried to develop such a method utilizing a Geographical Information Systems (GIS) approach to extract environmental information on HWA infestations for GSMNP.

The null hypothesis being used in this research is:

"The locations of HWA infestations in GSMNP are random in occurrence."

Findings that refute the null hypothesis will show that there are relationships between the environmental characteristics and the locations of HWA infestations in the park. I hypothesize that there will be associations between some of the environmental characteristics and locations of HWA infestations.

The research questions being asked in this project are:

"What are the limiting factors of the spread of HWA infestations?"

and

"What are the major dispersal vectors that aid in the dispersal of HWA in GSMNP?"

Determining the limiting factors and the dispersal vectors of the forest pathogen can assist personnel in their search for the insect, and allow them to develop strategies for

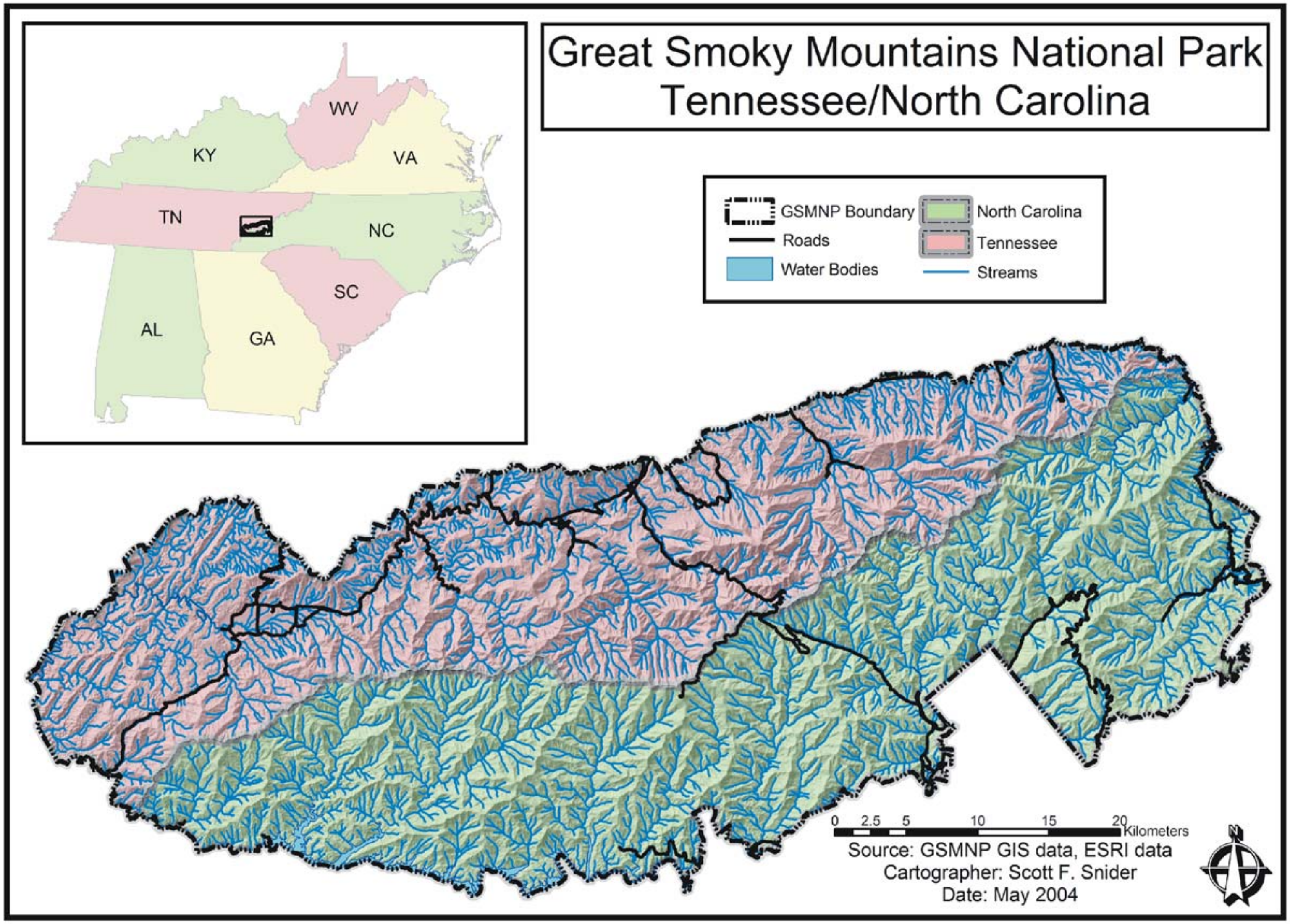

Figure 1.1 Location of GSMNP.

limiting the spread as well as they can. Specifically I examine wind and humans as dispersal mechanisms, and cold temperatures as a limiting factor, to HWA spread.

1.4 Significance

This research has the potential to be applied to any geographic area where HWA has infested, or could infest, and to aid personnel attempting to stop the spread of HWA. Finding significant results of an association, positive or negative, with any class within an environmental variable in this study can help GSMNP personnel to know where infestations are mostly likely or unlikely to occur. Such a finding can help to reduce staff-hours used in the search for HWA, saving resources and money. Application of such a technique can also help to locate areas where control measures would be most effectively applied, maximizing the effect against HWA.

A review of the literature reveals that there have been no studies looking at the link between the geographic location of infestation sites and the associated environmental variables. The majority of the research that has been performed on HWA has focused on its biology and on insects that prey upon it. All of this information is vital to developing a study of the spatial aspects of HWA infestations and is outlined in the literature review chapter of this thesis. Studying the spatial aspects of infestations earlier could have assisted in the time-sensitive fight against HWA.

Chapter 2: Literature Review

2.1 Introduction

In this chapter I first outline what is known about the biology of HWA, including its reproduction cycle and dispersal mechanisms. Then I assess the factors limiting the spread of HWA. After that I move into the characteristics of hemlock forests that could contribute to the discovery of infestations and then into species associations and biodiversity of hemlock forests. Finally I turn to lessons learned from other forest pathogens to see how they can be applied to the fight against HWA.

2.2 Hemlock Woolly Adelgid

The hemlock woolly adelgid was discovered in Honshu, Japan in 1936, but was found to be an innocuous inhabitant of several hemlock species (McClure and Cheah 1999). Since the discovery that HWA was damaging the eastern hemlock, its biology has been thoroughly studied. The hemlock woolly adelgid was discovered to have a polymorphic life cycle, rearing two generations of young per year (McClure and Cheah 1999). One generation of young is a winged progeny that flies away in search of a spruce host in which to rear another generation of HWA, however it has been discovered that there is no such spruce in the eastern United States (McClure and Cheah 1999). The other generation of HWA is a wingless sexuparae known as “crawlers” since their only form of locomotion is crawling (McClure and Cheah 1999)

The crawlers disperse in different ways, the most common method is crawling to a new site on the same tree from which they hatched. The hemlock woolly adelgid can also be dispersed long distances to other sites by birds, mammals, humans, or wind (McClure 1990). McClure (1990) documented that the effect of wind is essential in dispersing HWA within a stand. His results showed that significant numbers of HWA of all life stages were captured 300m downwind from the infested stand and 4 individuals were captured more than 1km from the stand.

McClure (1990) assessed the role of mammals as dispersal vectors of HWA by examining deer browsing. The results showed that browsed hemlock seedlings had significantly higher densities of HWA than unbrowsed seedlings (McClure 1990). He also documented that deer were effective in dispersing HWA long distances because 80% of seedlings that were specifically planted to study the effects of deer were infested beyond 750m from the infested stand, whereas in the wind dispersal study only 25% of traps beyond 750m captured HWA (McClure 1990). The effect of birds in dispersing HWA was documented in the same study; 86% of birds netted in hemlock forests carried HWA and 21% of birds netted in an "old field" site carried HWA (McClure 1990).

McClure (1990) hypothesized about the potential effect of humans as a dispersal vector. He stated that logging operations, such as preemptive logging of hemlock stands to prevent dead trees from injuring people and property, could contribute to the spread of HWA if the trees were not completely cleared of HWA. His findings indicate that HWA can reside in the bark of hemlock, though they do not actively feed there. Laboratory analysis on individuals removed from the bark showed that HWA could survive up to 15 days without sustenance, allowing them ample time to be dispersed by mammals, bird, and humans.

2.3 Limiting Factors of HWA

One factor that has been determined to limit the spread of HWA is cold temperatures (McClure and Cheah 1999; Skinner et al. 2003). In Japan some HWA individuals exist in areas that have extreme daily minimum temperature reaching -35°C during the winter (McClure and Cheah 1999). In the United States it was found that HWA mortality rates ranged between 60-70% in a normal winter in Connecticut, and during one unusually cold winter, temperatures reached below -18°C for four straight days resulting in HWA mortality rates between 90-96% (McClure and Cheah 1999). Skinner et al. (2003) concluded that in the United States cold hardiness varies by geographic location and by time of year. The hemlock woolly adelgid loses its cold tolerance as winter passes and ambient temperatures rise (Skinner et al. 2003). This conclusion indicates that a late season cold spell of lower magnitude could have the same effect of the coldest winter studied by McClure and Cheah (1999).

McClure and Cheah (2002) hypothesized that rain can also be a limiting factor of HWA spread. Any rain event could dislodge moving individuals of HWA from a tree onto the forest floor (McClure and Cheah 2002). Once an adelgid reaches the forest floor it will most likely be preyed upon by other insects, and does not have a chance to make it to a new feeding site (B. Onken, USDA Forest Service Entomologist, pers. comm. 2003).

McClure and Cheah (2002) also observed that interspecific and intraspecific competitions are other limiting factors of HWA infestations. McClure and Cheah (2002) observed that only 14% of progeny were winged on trees sparsely infected with HWA, whereas 90% of progeny were winged on heavily infected trees. This increase in winged progeny guarantees the death of the newly hatched individuals without a suitable spruce host as previously mentioned. One example of interspecific competition (competition from other species) is the gypsy moth, which could defoliate hemlock trees before HWA could infest the tree, effectively killing the tree without an HWA infestation (McClure and Cheah 2002).

2.4 Hemlock in the Great Smoky Mountains

Hemlock is a major forest component in the Appalachian Mountains. Day and Monk (1974) assessed vegetation patterns for watersheds in the southern Appalachian region, including patterns of hemlocks. They found that hemlock basal area had a strong positive relationship with distance from watershed divide and a strong negative relationship with elevation (i.e., hemlock will grow larger in low elevation valleys and conversely smaller at higher elevations). With hemlocks being documented to grow larger in these low valleys the stands would be larger and more noticeable to an observer; if the stand were infested there would be more of a chance for the observer to see it in such a large stand of hemlocks.

Within GSMNP hemlock occurs in a wide variety of forest types, but it is most prominent in cove hardwood forests and hemlock forests (Whittaker 1956). Although it is likely that infestations will occur in all forest types, a higher density of hemlocks in these forest types could lead to a higher concentration of reported HWA infestations in these forests again because of the high visibility of hemlock to an observer.

2.5 Biotic Associations of Hemlock Forests

The loss of the hemlock from HWA could have a drastic effect on the eastern forests. Research has been conducted to determine various organisms that would be affected in the absence of the hemlock. Tingley et al. (2002) conducted bird surveys in Massachusetts to evaluate the associations of bird species with the hemlock forests. They observed that the black-throated green warbler (*Dendroica virens*) had the highest positive relationship with hemlock presence of any bird witnessed in the study because it depends on the hemlock for feeding and nesting sites. Tingley et al. (2002) observed a drastic change with hemlock mortality with a shift from species such as Acadian flycatcher (*Empidonax virescens*), blue-headed vireo (*Vireo solitarius*), and hermit thrush (*Catharus guttatus*) giving way to species such as eastern wood-pewee (*Contopus virens*), white-breasted nuthatch (*Sitta carolinensis*), and red-eyed vireo (*Vireo olivaceus*).

Another response to the loss of hemlock that has been studied is the effect on aquatic ecosystems associated with the eastern hemlock forest. Snyder et al. (2002) compared invertebrate associations between drainage basins dominated by hemlock versus hardwoods in northeastern Pennsylvania and western New Jersey. They observed that streams that drained hemlock stands were observed to have more invertebrate species but less density of invertebrates than hardwood drained streams. They attributed this lower density of invertebrates to the fact that hemlock needles decompose more slowly than hardwood leaves, resulting in less available nutrients and thus support a lower density of species. Also noted in the study was the strong association of 11 species to the hemlock drained streams, with 3 species being found exclusively in the hemlock streams, whereas there were no species strongly associated with the hardwood streams (Snyder et al. 2002). A loss of hemlock forests would result in a loss of the biodiversity of the streams possibly causing some species to be extirpated from the region with the possible increase of hardwoods taking its place.

Hemlock drained and hardwood drained streams yielded similar fish communities in Pennsylvania and New Jersey in a study by Ross et al. (2003). According to the researchers, both types of streams typically supported one to four species of fish in the majority of streams sampled. It was also discovered that eight species were found only in hardwood streams while only a single species, golden shiner (*Notemigonus crysoleucas*), was exclusive to hemlock-drained streams (Ross et al. 2003). Another significant finding by Ross et al. (2003) was that the brook trout (*Salvelinus fontinalis*) was three times more prevalent in hemlock streams than in hardwoods and the brown trout (*Salmo trutta*) was twice as prevalent in hemlock streams (Ross et al. 2003). The finding of less total invertebrates in hemlock streams by Snyder et al. (2002) provides supporting evidence to the finding by Ross et al. (2002) of a decreased presence of insectivorous fish species in hemlock-drained streams.

It has been documented that in stands where hemlock is experiencing death and defoliation other species of trees are increasing in importance (Kizlinski et al. 2002; Orwig and Foster 1998). In Connecticut it has been documented that seedlings in hemlock forests have changed from a maple/hemlock dominance to a maple/birch dominance with a 2.5-fold increase in light levels due to defoliation on hemlocks (Kizlinski et al. 2002). Orwig and Foster (1998) noted the increased presence of oak species in hemlock forests to a lesser extent than other species, although they were reluctant to dismiss the importance of oaks in replacing dying hemlocks. These studies give a small glimpse into the future of what the hemlock forests may look like if they are destroyed by HWA.

2.6 Lessons from Other Pathogens

2.6.1 Balsam Woolly Adelgid

The balsam woolly adelgid (BWA), a congener of HWA, is a pest of the Fraser fir and the effects of BWA infestations are very evident in GSMNP. In the highest elevations of GSMNP exists the spruce-fir forest type, where the Fraser fir was the dominant canopy species above 1890 meters before the introduction of BWA (Smith and Nicholas 1998). Currently all that is left of the Fraser firs is a stand of dead trees that has no dominating canopy trees. The balsam woolly adelgid was first discovered in GSMNP in 1962, and by 1986, 90% of the standing Fraser firs were dead (Smith and Nicholas 1998). BWA was also found in Virginia, but the Fraser firs found there have withstood the effects of BWA and are still alive (Smith and Nicholas 1998).

It is believed that BWA was dispersed by winds into GSMNP and reached the southern limit of the spruce-fir forests by 1976 (Rabenold et al. 1998). Smith and Nicholas (1998) provided an order in which major mortality of Fraser firs occurred from northeast to southwest on the major peaks of GSMNP, which is reflective of the initial date of infestation. Mount Sterling experienced mortality between 1970-72, followed by Mt. Guyot from 1980-82, Mt. LeConte from 1982-1984, Mt. Collins from 1985-1987, and finally Clingman’s Dome from 1990-1992. Figure 2.1 shows the locations of these peaks studied by Smith and Nicholas (1998).

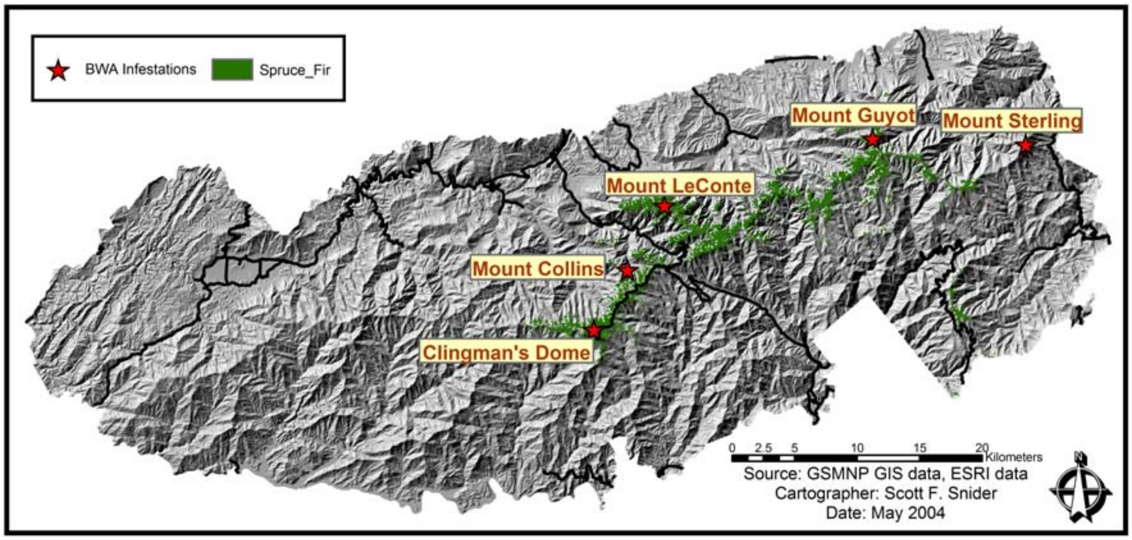

Figure 2.1 Locations of BWA infestations studied by Smith and Nicholas, 1998.

It has been hypothesized that the firs in GSMNP succumbed to the stress of BWA because they were growing in a harsher environment than the firs in Virginia that still exist with BWA (Hollingsworth and Hain 1994). This distinct difference in the two populations of Fraser fir gives hope to the fight against HWA in GSMNP. It is possible that the death of hemlock in other regions could be isolated to those areas and that there could be a difference in some environmental variable within GSMNP that could allow the hemlocks to exist with HWA. Assessing the environmental variables of infestations in GSMNP could not only help to predict further infestations but it could also be used to compare GSMNP to other infested locations to evaluate the differences in environmental characteristics and predict losses in GSMNP.

2.6.2 Chestnut Blight

The American chestnut has been virtually extirpated from the eastern deciduous forest by a fungal pathogen known as the chestnut blight. The chestnut blight was introduced into the United States around 1904 and had infected nearly 100% of chestnuts by 1950 (Jarosz and Davelos 1995). This blight attacks the tree by causing cankers around the tree that expand until they essentially girdle the tree causing the upper leaves to wilt and die (Jarosz and Davelos 1995).

Because the chestnut blight is a fungus it reproduces by releasing spores that are spread by winds (Heald and Walton 1914). In order for the chestnut blight to release spores it has to have moist conditions and warm temperatures (Heald and Walton 1914). The blight has advanced to the point where chestnut exist mostly as sprouts that grow from the roots of fallen chestnut trees (Paillet 2002). Several stands of chestnut in Michigan have survived the blight and are recovering, this survival could provide useful genetic research about how select stands could survive a pandemic outbreak of a pathogen possibly lending itself to the fight against HWA (Jarosz and Davelos 1995).

2.6.3 Gypsy Moth

The gypsy moth was introduced into North America in 1869; it has been expanding its range ever since (Liebhold et al. 2000). Liebhold et al. (2000) suggest that one determining factor of gypsy moth outbreaks can be mast failure. They suggest that a 3-year lag occurs from mast failure to an eruption of gypsy moths because the mast failure results in the loss of predators (such as rodents and small mammals) of gypsy moth that are also dependent on mast. The gypsy moth exists in low densities at all times, but this kind of epidemic outbreak can result in the total defoliation of host trees (Liebhold et al. 2000). This cyclic nature of the pathogen outbreaks demonstrates what could happen if a successful biological control agent is implemented that could keep HWA in check until the control agent populations decline allowing for a rapid advancement of HWA.

Movement of the gypsy moth is very similar to that of HWA. The gypsy moth females are unable to fly, so dispersal is completed through passive movements of the first instar of the species when it is blown by wind (Liebhold et al. 1992). Humans can also disperse gypsy moths accidentally. Liebhold et al. (1992) states that all life stages of the gypsy moth can be dispersed on artificial objects, which will initiate an infestation in an area previously uninfested. In the 1960s the gypsy moth was accidentally introduced in Michigan when it was previously only found in New England. Thus far, the spread of the gypsy moth has been slow, which has allowed forest managers time to plan for future invasions of the moth. Having time to plan is crucial. A memorandum (Appendix A) was distributed to all GSMNP personnel in 1990 cautioning of the impending invasion of HWA. This memo documents the park personnel's desire to attempt to plan for the arrival of HWA and what was known about the insect at that time, including dispersal vectors.

2.6.4 Dutch Elm Disease

Most pathogens do not effectively kill a host species at first, which was the case with the Dutch elm disease. The Dutch elm disease originated as the fungus *Ophiostoma ulmi* when first discovered in the early 1900s in Europe (Jarosz and Davelos 1995). This species was found to be fairly non-aggressive, but it rapidly gave way to a new species *O.*

novo-ulmi, which has been established to be evolved from *O. ulmi* (Jarosz and Davelos 1995). This new species of the pathogen is very aggressive and is resulting in increased death rates of elms all over the northern hemisphere (Jarosz and Davelos 1995). This disease has not yet reached its full potential because it has not yet infected the entire geographic area it may potentially infect (Jarosz and Davelos 1995).

The reproduction and spread of Dutch elm disease is comprised of two steps. The first step of the infestation is initiated by bark beetles that disperse the spores of the fungus (Buck 1988). Once the beetles disperse the spores and they germinate, the fungus attacks the xylem, causing a reaction by the tree that shuts off the xylem, eventually causing death (Buck 1988). The next step is for the fungus to grow outward to the bark where it can be dispersed to other healthy elms by beetles (Buck 1988). Dutch elm disease relies on another species for dispersal, which is one of several methods previously outlined as being a mode of dispersal for HWA.

Chapter 3: Methodology

3.1 Study Area

The Great Smoky Mountains National Park was founded on June 15, 1934, and is the single most visited park in the national park system, receiving over 9 million visitors per year (Dennis 1988). The park is one of two recognized International Biosphere Reserves in the eastern forest. This designation was established by the United Nations Educational Scientific and Cultural Organization (UNESCO) in 1977 (Dennis 1988). The GSMNP has also been designated a "World Heritage Site" by the United Nations for its "outstanding universal value" in conservation of natural systems; GSMNP is one of two U.S. National Parks to receive this honor (Dennis 1988). The GSMNP covers approximately 212,000 hectares between Tennessee and North Carolina (Figure 1.1).

From 1992-1995 park personnel worked to assess and document hemlock resources within the park (Johnson et al. 1999). Results indicated that overstory eastern hemlock forests cover 1546 hectares within the park. Twenty percent of the park has never been harvested for timber, so stands of hemlock that exist within these areas exceed 400 years in age (Johnson et al. 1999). The inventory also showed that hemlocks range in elevation from 450-1,750 meters within the park. Since the highest elevation in the park at 2,025 meters is Clingman's Dome, hemlock exists in a majority of elevations within the park. Hemlocks in lower elevations are predominantly found along watercourses and north-facing slopes whereas in higher elevations they were found along ridges (Johnson et al. 1999). The inventory outlined only contiguous hemlock stands, but also noted hemlock to be a significant component of cove hardwood and northern hardwood forests within the park, and sometimes existing in close proximity with pine and spruce species.

The Tennessee side of GSMNP first experienced HWA infestations during 2002; the North Carolina side of the park experienced infestation up to two years earlier (G. Taylor, pers. comm. 2002). Infestations have been found throughout the entire park, within all of the ranger districts. All of the infestations in the park are indicative of early infestations with no deaths of hemlock individuals attributed to the infestations yet (G. Taylor, pers. comm. 2002). Through correspondence with park personnel I have gained access to a database with information about the locations and distributions of HWA infestations within the park. Figure 3.1 depicts infestation locations within GSMNP.

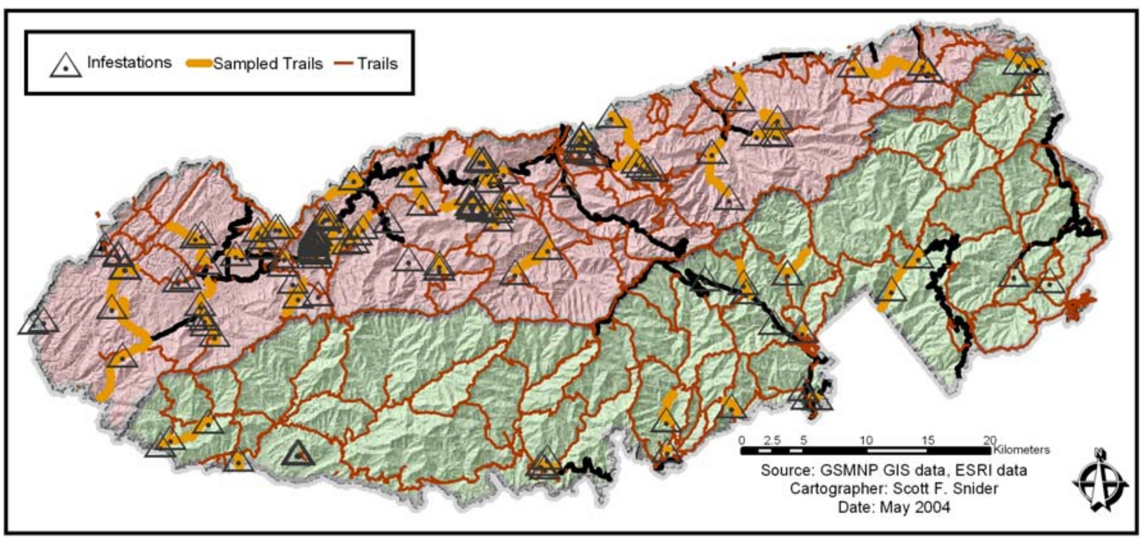

Figure 3.1 HWA infestations in GSMNP (as of 12/20/03).

3.2 Data Sources

Park personnel from GSMNP provided me with an Excel workbook that contained detailed information about the known HWA infestations within the park as of December

20, 2003. Within this workbook are the UTM coordinates for the known infestations (Appendix B), collected using Global Positioning System (GPS) technology. Personnel surveyed for HWA infestations based on reported sightings from park personnel and patrons, which occur mostly along trails and other highly visible areas. The infestations were recorded distinguishing between distinct, non-contiguous infestations and large continuous infestations using starting and ending coordinates. I was also provided with the full complement of GIS layers for the park. Layers included in this dataset are elevation, aspect, slope, vegetation cover, and hemlock distribution developed within the park. The environmental variables that I studied in this research were either included in this dataset or generated from the data.

3.3 Methodology

With the majority of infestation locations being reported along trails I used trails as sample areas for studying the infestations. The GIS methods for this project were derived to extract the environmental variables for known infestation locations. However, in order to perform statistical analysis it is important to get information for areas that are not infested for comparison. To fulfill this requirement trails were divided into segments, and each segment was designated as being infested or not. Environmental characteristics were extracted for both infested and non-infested segments, and a comparison made. To substantiate emergent patterns between infestation sites and environmental variables I performed a field survey for HWA infestations in GSMNP in March 2004.

I imported the coordinates of infestation locations into ArcGIS. Continuously infested areas were delineated with starting and ending coordinates, and were connected.

Trails and roads within the park were buffered to a distance of 25 meters; if an infestation point fell within the buffer, the entire trail or road was selected for further analysis. If the infestation point fell within 25 meters of multiple trail segments, I selected the segment that was closest to the infestation point. Sample trails were then divided into 50-meter segments by overlaying a grid, resulting in a total of 3464 plots for which environmental variables were extracted. The raster layers of environmental variables provided by GSMNP personnel were based on 30-meter grid cells, whereas trail segments are in a 50-meter resolution grid. ArcGIS uses a nearest-neighbor sampling method when combining grids, such that each 50-meter trail segment was assigned the value of the 30-meter grid (elevation, aspect, etc.) that is closest to the center point of the segment.

3.4 Environmental Characteristics

3.4.1 Elevation

Elevation can be a predictor of HWA infestations because of the effect that elevation has on temperature, and McClure and Cheah (1999) documented that cold-hardiness of the species limits its expansion. Elevation for the park ranges from 266-2025 meters, and according to the hemlock inventory completed by Johnson et al. (1999), hemlocks exist at a maximum elevation of 1750 meters. However, there were no infested hemlocks above 1380 meters. Based on this information, I limited the classes for elevation from 266 – 1750 meters and divided elevation into three classes representing low (266-750m), middle (750-1255m), and high (1255-1750m) elevations to include all possible hemlock forests in the study (Figure 3.2).

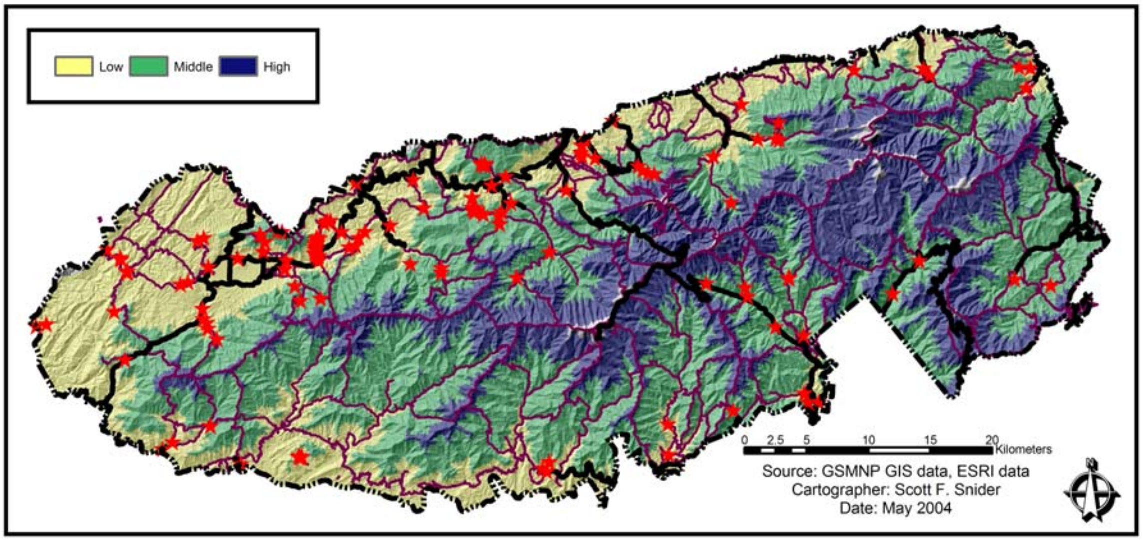

Figure 3.2 Elevation classes for GSMNP.

3.4.2 Aspect

With wind being an important dispersal mechanism for HWA, and most other pathogens, I used aspect as a surrogate to evaluate the effect of wind on HWA infestations. Aspect was divided into eight equal classes for analysis. The classes were groups of 45 degrees of aspect each based on subcardinal directions: NNE (0-45), ENE (45-90), ESE (90-135), SSE (135-180), SSW (180-225), WSW (225-270), WNW (270-315), and NNW (315-360). Figure 3.3 is a diagram showing each of the classes and the range of aspect for each class.

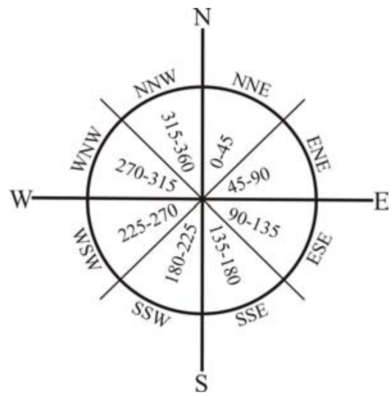

Figure 3.3 Diagram of aspect classes.

3.4.3 Topographic Position

With hemlock being documented to grow heavily in stream valleys (Day and Monk 1974) infestations may be more visible in these areas. Ridges may have the effect of intercepting HWA individuals being transported by wind and may indicate an increased chance of infestation because of this effect. To assess the effect of slope position on the location of infestations I developed a layer of topographic position. Buffering the streams to a distance of 50 meters delineated valleys. To extract ridge-top positions, an accumulation grid was processed from the digital elevation model (DEM). This grid calculated a value of how many cells drained into each 50-meter cell in the grid. From this accumulation grid I selected cells with a value of 0 or 1 and used them to represent ridges. I then combined the valleys and ridges together, and anything that did not fall within these two classes was considered mid-slope.

3.4.4 Vegetation

Park personnel provided me with a vegetation cover grid, in which hemlock occurred in all but two of 14 classes, supporting Whittaker's (1956) observations that hemlock grows in a wide range of forest types. Of the 14 vegetation classes, HWA infestations occurred in 8; these classes were used to evaluate the patterns of the infestations. The classes evaluated are: cove hardwood, mesic oak, mixed mesic hardwood, northern hardwood, tulip poplar, xeric oak, pine-oak, and pine forests. Table 3.1 summarizes the vegetation classes and species found within each class as well as locational descriptions about where the forest types can be found. Classes in which HWA infestations do not occur were: spruce fir, heath bald, grassy bald, grape thicket, treeless, and water.

Table 3.1 Vegetation characteristics of classes evaluated (White et al. 2003).

Vegetation Class	Significant Species	Locational Summary
Cove Hardwood	eastern hemlock, mountain silverbell, American beech, fraser magnolia, yellow buckeye, sugar maple, white ash, American basswood	mid to low elevations (600-1300m), low slopes, protected slopes, coves
Mesic Oak	rock chestnut oak, northern red oak, white oak	moderate elevations (750-1225m), well-drained upland slopes
Mixed Mesic Hardwood	white oak, scarlet oak, southern red oak, northern red oak, red maple, rock chestnut oak, hickory spp., magnolia, sourwood	mid to low elevations (600-1300m), moderately steep to steep slopes, north to southeast aspects
Northern Hardwood	red spruce, yellow birch, yellow buckeye, sugar maple, American beech	high elevations (>1100m), steep slopes, protected ridges, north facing slopes
Tulip Poplar	tuliptree, yellow buckeye, white ash, Appalachian basswood, sweet birch, eastern hemlock	mid to low elevations (<1300m), concave lower slopes, sheltered slopes
Xeric Oak	Rock chestnut oak, scarlet oak	mid to low elevations (<1100m), south to west facing slopes, ridgetops
Pine-Oak	eastern white pine, shortleaf pine, white oak, rock chestnut oak, southern red oak, scarlet oak	low elevations (<900m), protected ridges, mid to upper slopes, and disturbed bottoms
Pine	shortleaf pine, table mountain pine, pitch pine, eastern white pine, eastern hemlock, Virginia pine	low elevations (<1100m), southern to western slopes, ridgetops, flats along streams

3.4.5 Hemlock Distribution

Hemlock distribution is one of the most obvious layers to assess for this project. The hemlock distribution layer for GSMNP delineated the presence of overstory hemlocks into dominance classes. Park personnel that evaluated the dominance from aerial photographs created this layer. The classes that are delineated in the layer are: dominant, co-dominant, subdominant, inclusion, and no overstory hemlock present. Figure 3.4 shows the overstory hemlock classes for GSMNP.

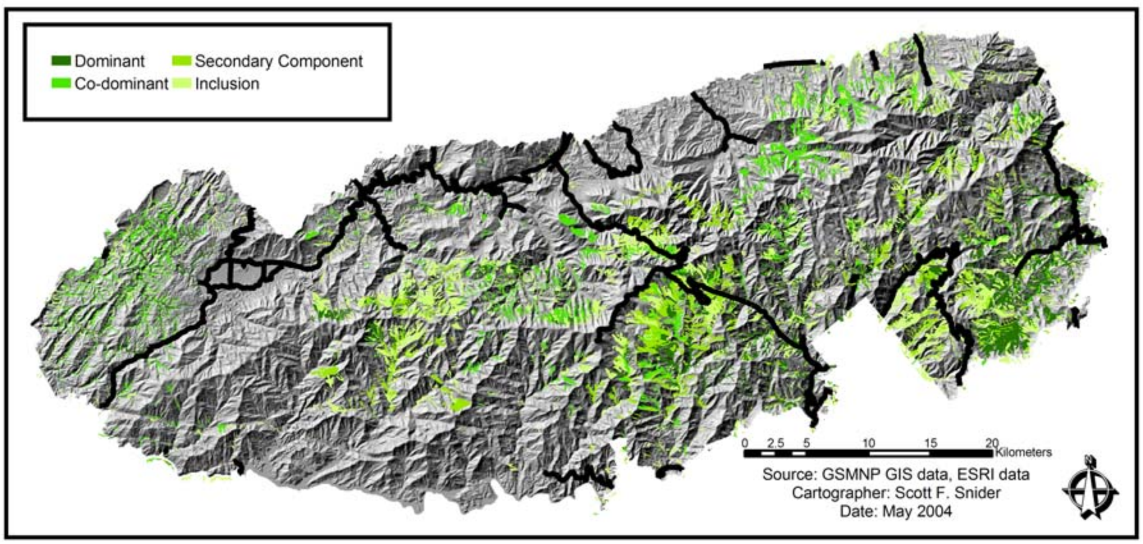

Figure 3.4 Overstory Hemlock Classes for GSMNP.

3.4.6 Distance from Trail Junction

To evaluate the effect of people as dispersal agents for HWA, I estimated the distance of each trail segment from trail junctions. I placed a point everywhere that a trail crossed a road because this would provide access to the trails and there would be a high concentration of people accessing the trails from the junctions along roads. I evaluated the distance from trail junctions into three classes: nearest (0-500m), middle (500-

2000m), and farthest (2000-6000m). These classes were selected to represent distances that people would travel (1) a short distance and return to the junction, (2) far enough for a day-hike, and (3) leaving for the backcountry, respectively. Figure 3.5 is a map showing the distance classes from trail junctions.

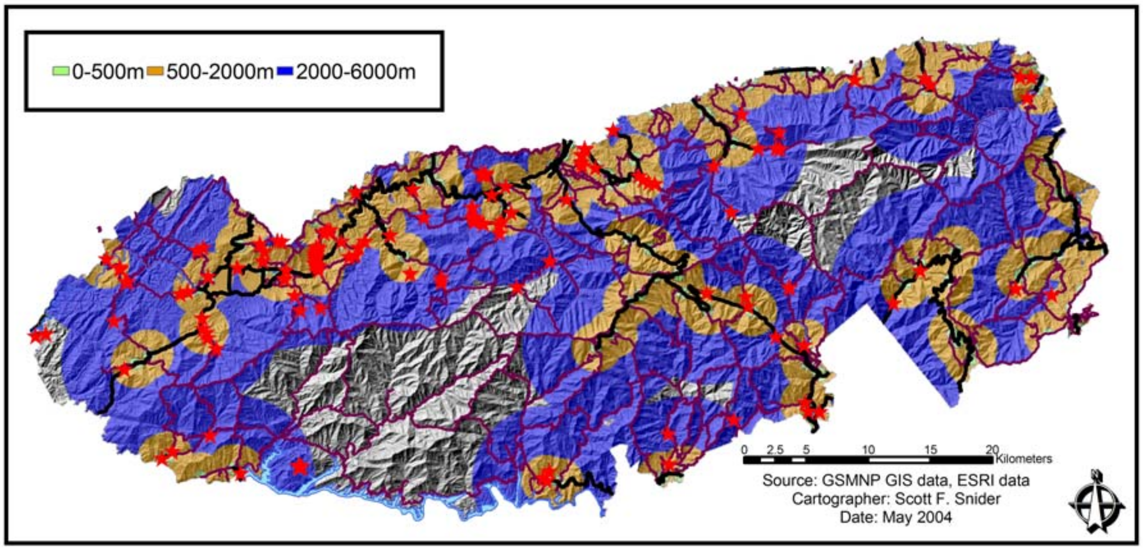

Figure 3.5 Distance from Trail Junction Classes for GSMNP.

3.4.7 Frequency of Trail Use

A second means of evaluating people as dispersal vectors of HWA was to evaluate infestations by the frequency of trail use. GSMNP personnel provided a list of high-, medium-, and low-use trails. The classification only covered a portion of the trails in the park; this analysis was performed with a set of 5132 50-meter cells different from the original 3464 cells. I used these trails to evaluate the influence of hiker traffic on infestation occurrence. Figure 3.6 shows the trails used for classifying the frequency of trail use.

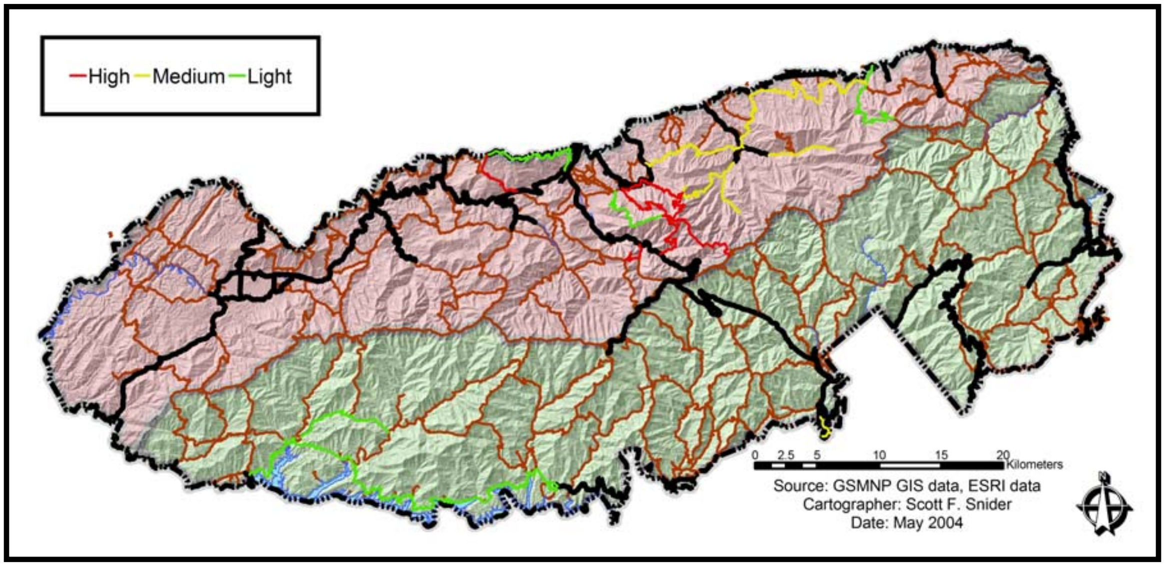

Figure 3.6 Trails evaluated for frequency of use.

3.5 Statistical Analysis

Binary discriminant analysis (BDA) (Strahler 1978) was used to assess the degree of association between infestation sites and the various environmental characteristic categories. This method calls for each variable to first be analyzed using a G-test statistic to determine if the characteristic is significant (Strahler 1978). A G-test is an approximation of a chi-squared test (Sokal and Rohlf 1969) and is applicable when assumptions of the chi-squared test are not met (such as the sum of observed frequencies must equal the sum of expected frequencies). For this study the null hypothesis is that there is no association between environmental characteristics and infestation locations. A finding of statistical significance will result in the rejection of the null hypothesis, indicating a relationship between the infestations and the variables measured. For this study an alpha level of .05 was used to determine significance.

Significant variables were then subjected to residual analysis in order to determine the strength and sign of that relationship (Strahler 1978). A large positive residual indicates a preference toward the class whereas a large negative residual indicates an avoidance of the group (Strahler 1978). From the residual analysis it was possible to identify those sites where infestations were likely (positive residuals for environmental characteristics) or unlikely (negative residuals) to occur.

3.6 Verification of Associations

To substantiate the patterns of the predictive tool I visited GSMNP to perform a field check. Sample trails were selected based on accessibility; since the field work was carried out in March, several roads and campgrounds in the park were still closed for the winter, but March was a prime time to search for infestations because HWA would still be in the woolly ovisacs that help to protect them while they overwinter. Sample trails were selected to cover a wide range of environmental variables.

I used a GPS receiver to obtain the coordinates of all the infestations I encountered while hiking the sample trails. I recorded the infestation information using the GSMNP HWA site report form. The same format used in the Excel worksheet for the known infestations was followed for recording the field-verified infestation coordinates, including starting and ending UTM coordinates for each infestation (Appendix C). These coordinates were then brought into the GIS for analysis. Figure 3.7 shows the trails I surveyed and the infestations that I recorded.

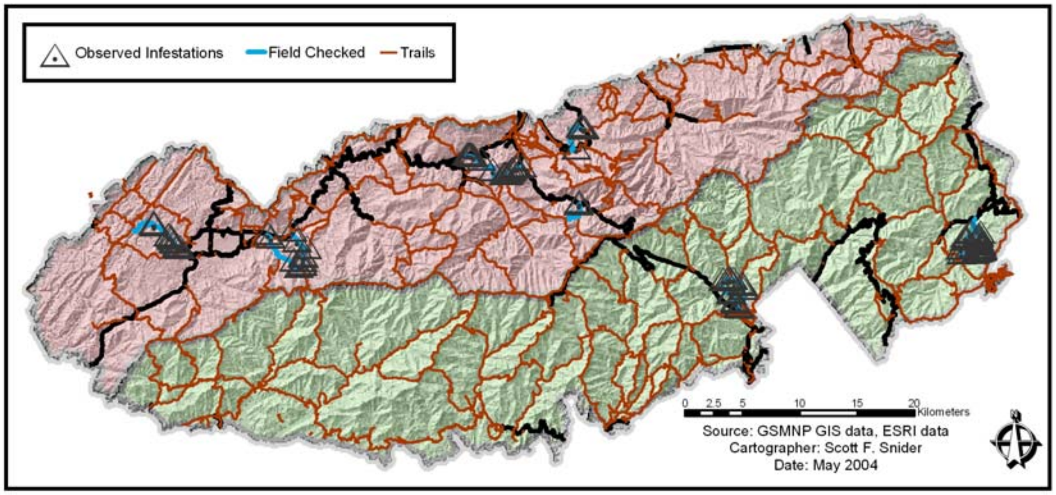

Figure 3.7 Field sampled trails and infestations.

In order to substantiate the patterns of the environmental characteristics of the infestations I used the data collected from the field portion of this project to analyze the environmental characteristics in the GIS. The same procedures of establishing 50-m trail segments and assigning environmental characteristics were used to substantiate the results; there were 1286 total sample trail segments. BDA was used to assess degree of association between these sites and environmental variables.

Chapter 4: Results

4.1 Introduction

In this section I present the results of my analysis on HWA infestation patterns. I present the results for each environmental variable separately: elevation, aspect, topographic position, vegetation classes, distance from trail junctions, frequency of trail use, and overstory hemlock distribution. Within each variable I show the residuals for the analysis of environmental characteristics (from GSMNP records) and for the verification analysis (from personal field observations). A graphical summary of the results is provided at the end of this chapter.

4.2 Elevation

Table 4.1 shows the residuals for the three classes of elevation from both the characterization process and the field verified data. Both sets of residuals indicate a positive association of infestations toward the low elevation class (266-750 meters). The table also shows negative residuals for the remaining two classes indicating that the infestations occur less frequently than expected if they were randomly distributed. Figure 4.1 at the end of this section is a compiled set of graphs showing the residuals of the environmental variables; elevation is included in the figure.

Table 4.1 Elevation Residuals .

Elevation Class	Park Records	Field Verified	% Hemlock
Low (266-750m)	1.77	10.782	15.6
Medium (750-1255m)	-0.959	-9.417	50.0
High (1255-1750m)	-4.092	-3.749	34.4

To assess whether this is an association with elevation or indirectly caused by hemlock abundance being correlated with elevation I looked at the hemlock layer, which depicts the location of overstory hemlock trees. I treated each class as “hemlock present” and extracted the percentage of this layer for each of the classes for the environmental characteristics in the analysis. The percentage of hemlock for the low elevation class shows that only 16% of the hemlock-presence cells are in the low elevation class, which has the highest positive association with HWA infestations (Table 4.1). The highest percentage of “hemlock-present” cells (50%) is in the middle elevation class. Combined, the two classes with negative associations have a total of 84% of the hemlock cells. This indicated that the relationship between elevation and HWA infestations are not dictated by the presence of hemlock.

4.3 Aspect

To evaluate wind as a dispersal vector, aspect was divided into 8 classes. Table 4.2 shows the residuals for aspect, and aspect is also included in Figure 4.1. The results indicate that NNE and NNW-facing slopes have positive residuals for both preliminary and verified calculations, whereas the other classes either do not show an association, the associations are not very large, or the signs of the preliminary and verified residuals contradict one another. Normal monthly wind data for GSMNP indicates that the average wind direction for April-July, the period HWA is dispersing, is 232.5° (WSW) (Rob Ellis, North Carolina Climate Office, pers. comm. 2004). Therefore the association of infestations being positively correlated to NNE and NNW-facing slopes does not seem attributable to wind.

Hemlock presence on NNE and NNW-facing classes shows that 15% of the "hemlock-presence" cells were in both of these categories. Combining these two classes with the two remaining classes of north-facing slopes accounts for 60% of the possible hemlock cells in the analysis. This association is not a surprise since hemlock is documented to grow preferentially on northern-facing slopes (Harlow 1957).

Table 4.2 Aspect Residuals.

Aspect Class	Park Records	Field Verified	% Hemlock
WNW	0.124	0.01	14.4
NNW	1.105	3.014	15.2
NNE	1.647	3.23	15.3
ENE	-1.598	-1.255	14.2
ESE	2.478	-4.143	11.0
SSE	0.222	-3.861	9.8
SSW	-3.406	0.982	8.8
WSW	-1.035	0.25	11.3

4.4 Topographic Position

The data for topographic position show that HWA infestations have a high positive residual for the valley class, while the mid-slopes and ridges have negative residuals (Table 4.3). The indication that infestations are clustering near streams is not explained by the percentage of the hemlock-presence layer because the majority (41.6%) of the cells occur in the mid-slope category. A graph of residuals for topographic position is included in Figure 4.1.

Table 4.3 Topographic Position Residuals.

Topographic Class	Park Records	Field Verified	% Hemlock
Ridge	-5.000	-5.877	34.8
Mid-slope	-0.071	-3.782	41.6
Valley	5.461	9.818	23.6

4.5 Vegetation

Table 4.4 shows the residuals for the 8 vegetation classes containing hemlock that were analyzed. Some of the classes in this analysis show contradicting residuals between the preliminary data and the field verified data. Three classes, cove hardwood, northern hardwood, and mesic oak all show an agreement between the two datasets, with negative residuals for both preliminary and verified classes. The cove hardwood forest classification contains the majority (47%) of the possible hemlock cells, the northern hardwood classification contains 12%, and the mesic oak forests contain 8%.

Table 4.4 Vegetation Classification Residuals.

Vegetation Class	Park Records	Field Verified	% Hemlock
Northern Hardwood	-1.411	-1.567	12.2
Cove Hardwood	-3.116	-4.434	47.3
Mesic Oak	-0.174	-2.95	7.9
Mixed Mesic Hardwood	4.768	-2.026	15.7
Tulip Poplar	-2.391	5.355	2.3
Xeric Oak	-0.959	5.808	5.2
Pine-Oak	1.227	-3.598	0.7
Pine	-0.506	2.838	8.7

4.6 Overstory Hemlock Distribution

Hemlock distribution is an obvious layer to pursue in trying to determine the characteristics of HWA infestations. This layer is limited in the results because it only delineates overstory hemlock layers and the known infestations in the park are mostly within sight of trails where only understory hemlock and lower branches of taller hemlocks can be evaluated. The result of this analysis shows that the amount of hemlock in a forest is not a predictor of infestation locations because all of the classes show contradictory residuals between the park records and the field collected data. Table 4.7 shows the residuals of this analysis and the graph is included in Figure 4.1.

Figure 4.5 Overstory Hemlock Distribution Residuals.

Hemlock Class	Park Records	Field Collected
Dominant	-4.430	0.137
Co-Dominant	1.005	-1.990
Secondary	2.448	-3.634
Inclusion	6.241	-0.899
Not Present	-3.112	2.850

4.7 Distance from Trail Junctions

A great number of trail users in GSMNP will start hiking a trail and turn around and return to the point from where they started (Glenn Taylor, pers. comm. 2004); the effect of this increased trail use could cause increased infestations close to trail junctions. Table 4.5 shows the residuals for this classification. The class closest to the trail junctions shows positive residuals for both the park records (2.057) and the field verified data (2.601) indicating a concentration of infestations nearest to the trail junctions. This result is evidence that people are one of the main dispersal vectors of HWA. The graph of these residuals is also included in Figure 4.1.

Table 4.6 Distance from Trail Junctions Residuals.

Distance Class	Park Records	Field Verified
Nearest	2.057	2.601
Middle	2.396	-2.921
Farthest	-3.879	1.206

4.8 Intensity of Trail Use

Assessing the effect of the frequency of trail use in relation to infestations resulted in a distinct pattern. The trails defined as “low use” showed a significant negative residual, –12.980. Whereas the “high” and “medium-use” trails showed significant positive residuals of 7.076 and 7.741, respectively. These results were the largest residuals (strongest relationship) of any environmental characteristic examined in this study.

I also evaluated the effect of intensity of trail use by taking out one of the defined low intensity trails, the Lakeshore Trail. This trail was removed because it is mainly accessible by water from Fontana Lake on the southern edge of GSMNP. I felt that this could have skewed the results for this interpretation because of the lack of access. Although removing the Lakeshore Trail resulted in a smaller residual there is still a strong negative association with the “low use” trails, which shows that low use trails do have very low infestation rates. Table 4.6 shows the residuals for both analyses of this characteristic and the graph of these residuals is included in Figure 4.1

Table 4.7 Frequency of Trail Use Residuals.

Intensity Class	With Lakeshore	Without Lakeshore
High	7.076	2.867
Medium	7.741	3.509
Low	-12.98	-7.024

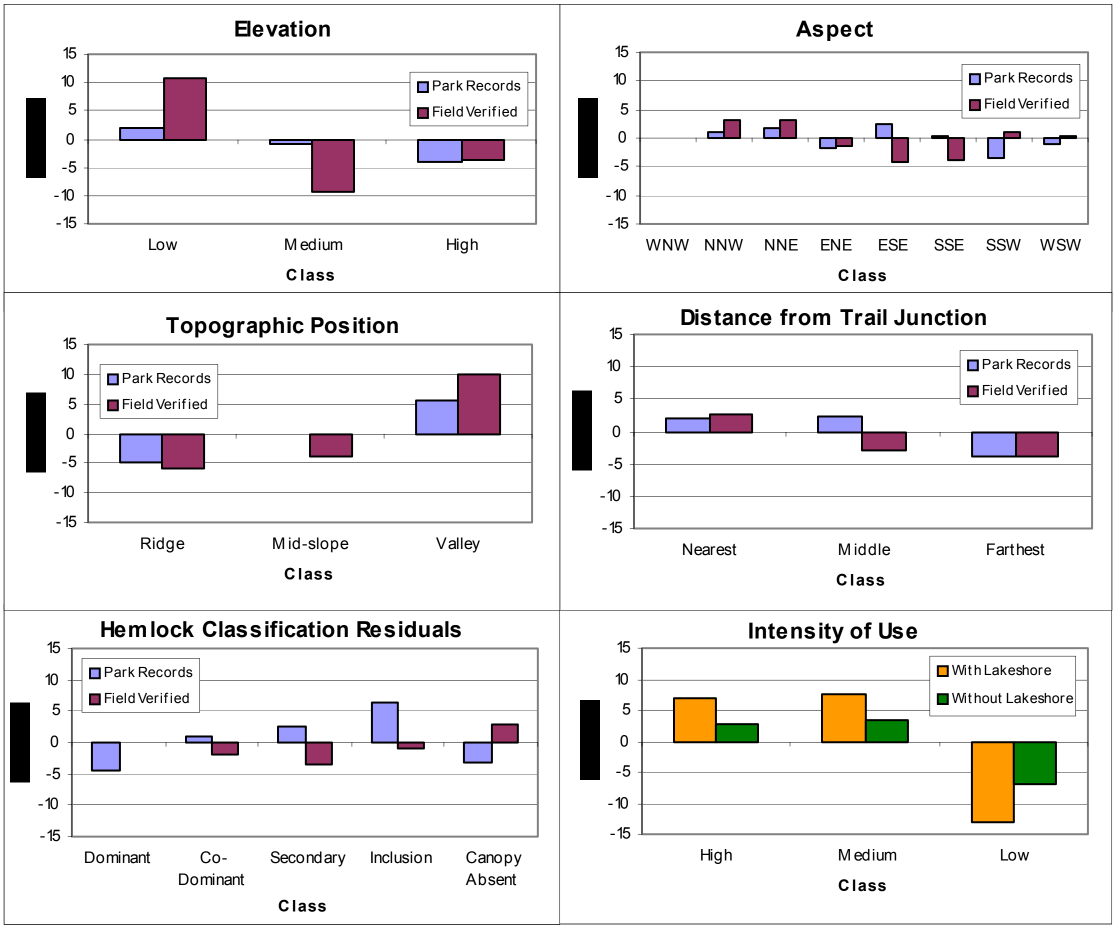

Figure 4.1 Residual graphs for environmental variables.

5.0 Discussion

I must insist that a degree of caution be used in interpreting the results of this research. The methods that I used to study the associations of infestations were surrogates for the environmental characteristics, not a study of the actual characteristics of infestations. However, the variables reported in this study were all significant at the level of $p = .05$. Also, during the field portion of the research I reported an infestation if there was even a single woolly ovisac present. Not being limited by time and money in my search for HWA allowed for me to perform a more thorough search than park personnel would be able to perform with these limitations.

In the research I addressed the cold hardiness of HWA by evaluating elevation. The results of my research show that the infestations have positive residuals with the lowest elevation class and negative residuals above 750 meters. This result shows that HWA infestations within the park are avoiding the higher elevations; I can infer that this could be an effect of temperature decreasing with elevation. This result can help park personnel in their search for HWA to focus their search efforts in lower elevations.

I also assessed two of the dispersal mechanisms of HWA, wind and humans. To address the effect of wind in dispersing HWA I looked at aspect. The results of aspect show that the infestations have positive residuals with the NNW and NNE-facing slopes. The predominant wind direction for the park during the months that HWA is dispersing was WSW, which causes me to infer that wind is not the dominant factor in the spread of HWA in GSMNP because this falls away from the dominant wind patterns. The results show that wind could not be used to predict the locations of infestations. Another possible explanation for infestations being located on NNE and NNW-facing slopes is the abundance of hemlock, since it has been documented that hemlocks have a tendency to grow on north facing slopes. The residuals for this classification were all fairly low (below ±5), indicating that although aspect is statistically significant it is not an especially strong relationship with HWA spread.

I assessed the effect of humans as dispersal vectors with two of the analyses, distance from trail junction and frequency of trail use. Distance from trail junction was assessed in order to see if a higher concentration of people leads to an increased concentration of HWA infestations. The results showed that infestations were clustered to the closest one-half kilometer from the trail junctions. Many patrons of the park use the trails in limited amounts, possibly just walking out a few meters and returning to their vehicles. It is this type of use that can increase the chances of HWA being accidentally attached to a person and dispersed to either a previously uninfested location on the trail or to another area where they stop to get out. Once again, these residuals are all below ±5, indicating this also is not an especially strong relationship despite being statistically significant.

However, the effect of intensity of trail use shows a profoundly stronger result than distance from trail junction in evaluating the effect of people as a dispersal vector. The results show that infestations show positive residuals with high- and medium-use trails, and very strong negative residuals with low-use trails. This positive association can be used to focus search efforts on the higher use trails. If all of the trails in the park have not been assessed for the intensity of use it is certain that park personnel will have personal observations about which trails are more popular in the park. Combining this result with the distance from trail junctions it is clear that humans are a major influence in the dispersal of HWA. I interpret this result as a possibility that high-use leads to an increase in the spread of HWA close to trail junctions, but it cannot be ruled out that there could also be an increase in the chance of observations nearest to trail junctions.

Evaluating the effect of topographic position on HWA infestations showed that infestations had large positive residuals with respect to stream valleys, even though it had the lowest percentage of overstory hemlock. This association could possibly be due to a higher density of birds, deer, or other small mammals that prefer this habitat, or preferentially travel through these sites; or the result could be another factor altogether that was not assessed in this project. Birds and mammals as dispersal vectors is a topic worthy of future research in the park. Stream valleys are sensitive to chemicals so it is not possible to spray pesticides on infestations along streams, but releasing the predator beetle, *Pseudoscymnus tsugae* would be a good option here. With the high residuals it would be very likely that the predator would be able to establish a viable population along streams.

The results of the analysis on vegetation class were less interpretable than the other results. The majority of the classes in this variable showed residuals that did not agree; the residuals that did agree were all negative residuals. The class with the highest negative residuals is cove hardwood, which also has the highest amount of "hemlock-present" at 47%. Between the three classes showing negative residuals (cove hardwood, northern hardwood, and mesic oak), 60% of the "hemlock-present" layer is accounted for. This indicates that the amount of hemlock is not a good indicator of infestation potential. Assessing the presence of hemlock in the canopy did not yield any residuals that agree with one another; I conclude that this layer needs further evaluation.

During the field work there was one major observation that I made that must be addressed. The two densest infestations I observed in the field were in canopy trees that had recently fallen near trails. The first was along Boogerman Trail in the Cataloochee area of North Carolina. I estimate that the tree was over a foot in diameter where it had fallen across the trail and had to be cut to allow passage of the trail. On this tree nearly every needle had a woolly ovisac at the base of it. The other large infestation that I recorded was on Smokemont Loop Trail also in North Carolina. This tree was considerably smaller than the previous. I estimate it to be only four inches in diameter where it fell across the trail, but the level of infestation was nearly as thick as the previous infestation. The presence of these highly concentrated infestations that I observed in these canopy trees causes me to think that the situation in the park is worse than I originally perceived it to be. I also saw some hemlocks along the Smokemont Loop Trail in North Carolina that were missing a great deal of needles, which is a sign of damage due to HWA.

From a discussion with Kris Johnson, Glenn Taylor, and Scott Kitchman of GSMNP, there is not an effective way, short of climbing into the canopy of a tree, to assess these infestations. However doing this would not be cost effective and it would also jeopardize the hemlocks in the park because this action would increase the chance that the personnel that are working to fight it could disperse HWA. Without a method to assess infestations in canopy trees it is going to be difficult to fully assess the situation in GSMNP. Park personnel have attempted several methods in their attempt to assess canopy trees in the park, including using a spotting scope mounted on a tripod in an attempt to view the upper limbs from the ground, but have not come up with a viable method.

Being able to assess canopy infestations could change the results of the hemlock distribution layer analysis because this layer depicts only the canopy hemlock component. It is my belief that the hemlock distribution layer is not the only analysis that could change with evaluating the canopy infestations. Canopy infestation data could also result in a stronger association between HWA infestations and the importance of wind as a transportation vector. If HWA is transporting long distances on the wind it is likely that overstory trees would intercept them and they would begin feeding at these sites, establishing infestations in the canopy. Topographic position could also hypothetically show a change in the results with canopy infestation data. I predict that ridgetop positions would be more likely to intercept HWA that is being transported via wind, causing an increased association between HWA and ridgetop positions.

Assessing the state of all hemlocks within the park is essential to success in saving them from elimination by this pest. The methods that I used here were limited in the scope of this fight because it only takes into account infestations in trees and limbs that are visible from the ground. However, finding infestations and delineating where they may possibly be located is very valuable because it allows for park personnel to establish a treatment method for infested areas in the park as well as establishing areas where they can focus efforts for public awareness so that patrons can give feedback on infestations locations that may not have been assessed yet. Overall, it is my observation that the staff of GSMNP is doing an excellent job with HWA, but the fate of the eastern hemlock in GSMNP may be out of their hands.

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Appendix A: Memo Concerning the Approach of HWA

United States Department of the Interior

NATIONAL PARK SERVICE
Great Smoky Mountains National Park
Gatlinburg, Tennessee 37738

TAKE PRIDE IN AMERICA

IN REPLY REFER TO:
N50

May 3, 1990

Memorandum

To: Division of Visitor Services: See Listing

From: Supervisory Natural Resource Specialist (Vegetation)

Subject: New Forest Pest

As if this park hasn't had enough problems with chestnut blight, balsam woolly adelgid, Dutch elm disease, dogwood anthracnose and butternut canker, another exotic is on the way.--the hemlock woolly adelgid (Adelges tsugae). This insect is in the same genus as the balsam woolly adelgid, which it resembles when young, and is believed native to eastern Asia. It was discovered in the eastern United States 30 years ago, but only recently reached New England and the Appalachians, where its newfound host, the eastern hemlock, is most common. The adelgids mass-attack trees by feeding at the base of the needles, which eventually kills the tree, sometimes in one year.

As far as I can determine, this pest is as close to us as northern West Virginia and Virginia near Peaks of Otter. It was found killing hemlocks at several locations in Shenandoah National Park three months ago.

No doubt people are capable of accidentally transporting this insect at any of its several life stages, but research in Connecticut has shown that the wind, and especially birds, are dispersing the adelgid. It appears very likely to show up at the Smokies eventually, or perhaps it is already here. It may appear first on hemlocks near developed zones such as visitor centers and campgrounds. Please take a close look at the photo on the attached Pest Alert. We would appreciate your circulating it among your employees or posting it on a bulletin board. When in a hemlock area, watch out for this easily noticed pest and collect a sample for us to get verified. Also, if visitors report white woolly masses on hemlocks or dying hemlocks, please get enough details to allow us to relocate the trees in question.

We are still learning about this adelgid, and no one knows the long-term impact of this insect on hemlock stands. It is not out of the question, however, that if this exotic becomes established, much of our hemlock, especially our old growth stands, would be in jeopardy.

An International "Biosphere Reserve" and "World Heritage Site"

Pest Alert

United States
Department of
Agriculture

Forest Service

Northeastern Area
NA-PR-03-94

Hemlock Woolly Adelgid

The hemlock woolly adelgid, *Adelges tsugae*, has been in the United States since 1924. This introduced insect, believed to be a native of Asia, is a serious pest of eastern hemlock and Carolina hemlock. In the eastern United States it is present from the Smoky Mountains, north to the mid-Hudson River Valley and southern New England.

White cottony sacs at the base of the needles are good evidence of a hemlock woolly adelgid infestation. These sacs resemble the tips of cotton swabs. They are present throughout the year, but are most prominent in early spring.

The hemlock woolly adelgid feeds during all seasons with the greatest damage occurring in the spring. It is dispersed by wind, birds and mammals.

By sucking sap from the young twigs, the insect retards or prevents tree growth causing needles to discolor from deep green to grayish green, and to drop prematurely. The loss of new shoots and needles seriously impairs tree health. Defoliation and tree death can occur within several years.

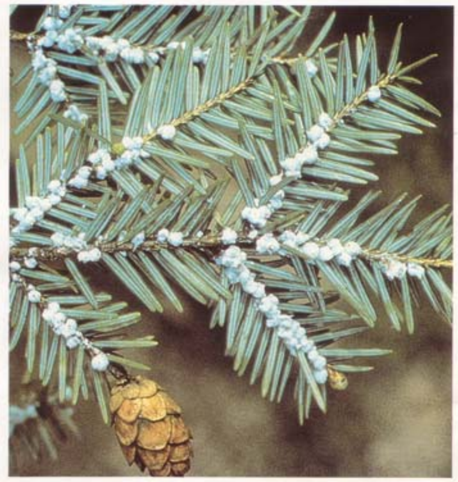

Photo 1. Egg masses produced by overwintering adults.

Photo 3. Hemlock stand heavily damaged by hemlock woolly adelgid.

Photo 2. Discolored foliage and twig dieback caused by feeding nymphs.

For additional information contact your State Forester, State Entomologist, State Extension Specialist, or County Agricultural Agent.

USDA Forest Service
P.O. Box 640
Durham, NH 03824
(603) 868-5719

USDA Forest Service
180 Canfield St., PO Box 4360
Morgantown, WV 26505
(304) 285-1540

Technical Advisor, photo credits:
Mark McClure, Connecticut Agricultural Experiment Station

Appendix B: Preliminary Infestation Data

Site Number	Start UTM E	Start UTM N	End UTM E	End UTM N
1	228504	3938331	229335	3938520
2	229335	3938520		
3	242430	3943093	241540	3945220
4	242041	3945444		
5	266417	3950389	264759	3951300
6	264756	3951364		
7	264758	3951440		
8	264759	3951300	264463	3951359
9	264464	3951462		
10	265925	3946574		
11	258968	3950148		
12	310445	3941668		
13	265879	3947256	264631	3947348
14	264631	3947393		
15	264631	3947348	263865	3947892
16	263899	3947699		
17	263875	3947518		
18	254332	3949910		
19	253155	3945920	251338	3943982
20	254552	3945450		
21	254318	3944825		
22	253794	3944695		
23	263895	3947892	263743	3947862
24	263685	3948689		
25	263759	3948689		
26	243106	3937325		
27	261213	3942659		
28	259816	3947858		
29	269968	3944303		
30	248365	3945932	248009	3945976
31	246599	3945732		
32	246841	3944338	246963	3945118
33	238712	3928434	242589	3930302
34	242589	3930302		
35	277493	3950896		
36	249850	3940422		
37	248709	3943607	248606	3942928
38	267318	3942293		
39	258731	3943342		

40	234238	3944523		
41	251478	3940613		
42	290490	3937614		
43	290838	3932250		
44	282639	3941818		
45	289322	3942269		
46	235677	3935644		
47	239526	3928988		
48	261227	3943005		
49	288484	3954774		
50	279590	3927988		
51	279527	3930445		
52	283201	3952027		
53	283201	3952027	284612	3948300
54	307553	3942137		
55	235916	3942734		
56	235361	3943700		
57	235311	3943840		
58	240766	3941946		
59	240173	3941737		
60	249409	3941612		
61	265294	3949692		
62	266860	3948261		
63	266090	3947544		
64	300660	3958589		
65	284799	3931554		
66	244794	3943793		
67	242285	3938623		
68	242367	3938185		
69	271316	3949299		
70	277943	3950689	278436	3950593
71	269929	3927412		
72	272798	3953452	272575	3952950
73	272575	3952950	272557	3952887
74	272557	3952887	272496	3952297
75	272496	3952297	272603	3952057
76	286783	3953440		
77	288226	3953461		
78	288525	3953373		
79	249965	3927808		
80	249790	3927886		
81	249706	3927804		

82	249862	3927748		
83	308802	3959189	307896	3959221
84	255055	3945953		
85	257095	3946435		
86	277137	3951233	275071	3954931
87	294585	3958992	300192	3959134
88	290548	3932953		
89	291732	3932205		
90	289264	3942255		
91	285962	3940752	285771	3941503
92	285458	3956233		
93	308475	3957537		
94	245046	3927238		
95	241953	3939789	242017	3938936
96	251340	3943606		
97	251237	3943888		
98	251071	3944086	251018	3944213
99	251103	3944500		
100	251048	3944502		
101	251069	3944696	251044	3944896
102	251178	3945012		
103	251115	3945081		
104	251158	3945282		
105	251371	3945405		
106	251161	3945493		
107	251796	3946600		
108	252013	3946819		
109	252275	3946844		
110	269730	3926643	269422	3926896
111	235803	3942727	234820	3939545
112	297691	3940987	299840	3943582
113	273643	3951881	272828	3953344
114	288210	3938295		

Appendix C: Field Collected Data

Site Num	Start UTM E	Start UTM N	End UTM E	End UTM N
1	310611	3943718	310429	3943651
2	310090	3943361		
3	310093	3943150	310072	3943051
4	309695	3942325		
5	309706	3941912		
6	310145	3941976	310889	3941985
7	311039	3942089	311132	3942081
8	311373	3942162		
9	311525	3942255		
10	311572	3942267	311555	3942409
11	311469	3942673		
12	311308	3942907		
13	311265	3943092		
14	311182	3943213	311217	3943369
15	311255	3943458		
16	311409	3943698		
17	290345	3937205		
18	290260	3937270		
19	290017	3937592		
20	289921	3937790		
21	289696	3938453		
22	289603	3938536		
23	288940	3939634		
24	289249	3939578	289386	3939798
25	289551	3939715		
26	289818	3939704		
27	290583	3939291	290693	3939144
28	290685	3938834		
29	266551	3950527	266656	3950525
30	266758	3950500	266829	3950522
31	266951	3950460		
32	267125	3950341		
33	267809	3950059		
34	268822	3949130		
35	269762	3948783		
36	269901	3948781		
37	269991	3948802	270184	3948837
38	270371	3949053	270493	3949199
39	270541	3949221	270787	3949415
40	270943	3949400	271353	3949486
41	276357	3946339		
42	276321	3946155		
43	249159	3943566		

44	249435	3943272	251464	3941289
45	251876	3940743	252174	3940937
46	252193	3940965		
47	252213	3941261		
48	252295	3941614	252208	3941734
49	252564	3942378		
50	251682	3942949	251316	3943861
51	276088	3951011		
52	276459	3952983	276581	3952929
53	276711	3952772	276806	3952847
54	241509	3942366	241285	3942427
55	241210	3942544	241055	3942810
56	240940	3942886		
57	240817	3943123		
58	240707	3943290	240521	3943436
59	240472	3943438	239205	3944309
60	239227	3944487		
61	239162	3944480		