Patterns of Spread of Hemlock Woolly Adelgid in Carolina Hemlock Populations

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ABSTRACT

Census and mapping of individuals was carried out in four populations of Carolina hemlock to uncover patterns of spread of hemlock woolly adelgid. Spatial cluster analysis was used to distinguish among three patterns of adelgid transmission: random spread, spread in a wavelike pattern, and spread from multiple foci. The finding of clusters in all populations refuted the random spread hypothesis. In the two recently infested populations, trees in all size classes were in good condition, but infestation clusters were evident. In the population with a more advanced infestation but under chemical treatment, tree condition was poorer but infestations were light and seedlings were abundant and in excellent condition. Close monitoring of adelgid infestations and treatment of tree clusters with high densities of adelgids is recommended.

KEYWORDS

Carolina hemlock, cluster analysis, hemlock woolly adelgid, infestation, transmission

INTRODUCTION

Hemlock woolly adelgid (HWA), *Adelges tsugae* Annand, has shown a remarkable ability to extend its range in the eastern United States and to spread within populations of both the wide-ranging Canada hemlock (*Tsuga canadensis* (L.) Carr.) and the southern Appalachian-endemic Carolina hemlock (*T. caroliniana* Engelm.). Over the past two years, HWA infestations have become common in the mountains of east Tennessee and western North Carolina. Demographic studies have documented the spread of HWA at the level of states and counties (Evans and Gregoire 2007; Pontius et al. 20005; Orwig et al. 2002), but there is scant information on the local, fine-scale patterns of infestation. The goal of this study was to determine whether it was possible to discern patterns of pathogen transmission within populations. With limited biological and chemical resources, knowledge of spread patterns could guide potential treatment strategies, which may include whether or not to focus on infested trees or areas adjacent to infestations and whether or not to target particular age classes. We focus on the Carolina hemlock because the limited distribution subjects this species to risk of decimation or perhaps extinction in the wild.

Three alternative but not mutually exclusive patterns of transmission can be envisioned: random spread in which infestations arise and spread with no discernable pattern, spread in a wavelike pattern from a point of introduction, and spread in all directions from multiple foci. For example, the multiple foci alternative may arise as a combination of random dispersals followed by wavelike spread from each new focus.

METHODS

Census and mapping was conducted in four populations of Carolina hemlocks. All populations were located on National Park Service lands associated with either the Blue Ridge Parkway (Linville Falls and Doughton Park) or the Appalachian Trail (Nolichucky and Laurel Fork) (Table 1). The Nolichucky and Doughton Park populations were in the very early stages of HWA infestation; Laurel Fork was more advanced; and the infestation at Linville Falls was advanced, and chemical (imidacloprid) treatments had been conducted.

Table 1. Characteristics of Carolina hemlock populations censused.

Population	Location	Owner	Elev. (ft)	Stage 1	Treatment
Nolichucky	Unicoi Co., TN	AT/USFS	1750	early (fall 2006)	none
Laurel Fork	Carter Co., TN	AT/USFS	2400	mid (2004-5)	none
Linville Falls	Burke Co., NC	BRP/NPS	3350	late (2002-3)	chemical
Doughton Park	Allegheny Co., NC	BRP/NPS	3600	early (2006?)	none

[1]Infestation stage and approximate date of HWA introduction.

In each population, a start point for a line transect was delineated with GIS coordinates. From this point, a line was extended for 100-200 meters, from which all Carolina and Canada hemlocks, including seedlings, were assigned x-y coordinates corresponding to distance on the line and distance perpendicular to the line on either side. Coordinates will allow us to re-census these populations and field-test the mode-of-spread hypothesis derived from the cluster analyses presented here.

For each hemlock, we measured two demographic characters (plant height and diameter at breast-height) and three epidemiologic characters (number of cardinal quadrants showing presence of adelgids [0-4], degree of infestation [absent-low-medium-high], and tree condition [excellent=no impact; good=light and spatially restricted impact; fair=conspicuous loss of foliage; poor=dying tree; dead]). All epidemiologic characters were assessed visually.

DATA ANALYSIS

Demographic characteristics were visualized using size pyramids. The spread hypotheses were evaluated using spatial cluster analysis. Hypothesis testing was possible because each pattern of spread gives rise to a different clustering expectation. Tree locations on the x-y coordinate system were used to conduct spatial cluster analyses using a Poisson model as implemented by SaTScan software (Kulldorff 1997). Monte Carlo replicate randomizations were used to assess significance of the scan statistic. Separate analyses were conducted for each of the four populations and for each of the three epidemiologic characters for a total of 12 analyses.

RESULTS

1. Demographics

The Nolichucky population of Carolina hemlock was relatively small and intermixed with Canada hemlocks. There was a notable absence of seedlings and large trees (>20" DBH) in this population (Figure 1). This size class distribution, if reflective of ages, suggests a recently established population colonized over a short time period. In contrast, there were abundant seedlings at Linville Falls, which led to an age pyramid with an extended base, but Linville Falls also had a relatively high number of large trees. Laurel Fork had a more uniform size pyramid with a relatively small number of seedlings, while Doughton Park had a more classic pyramid-shaped size structure.

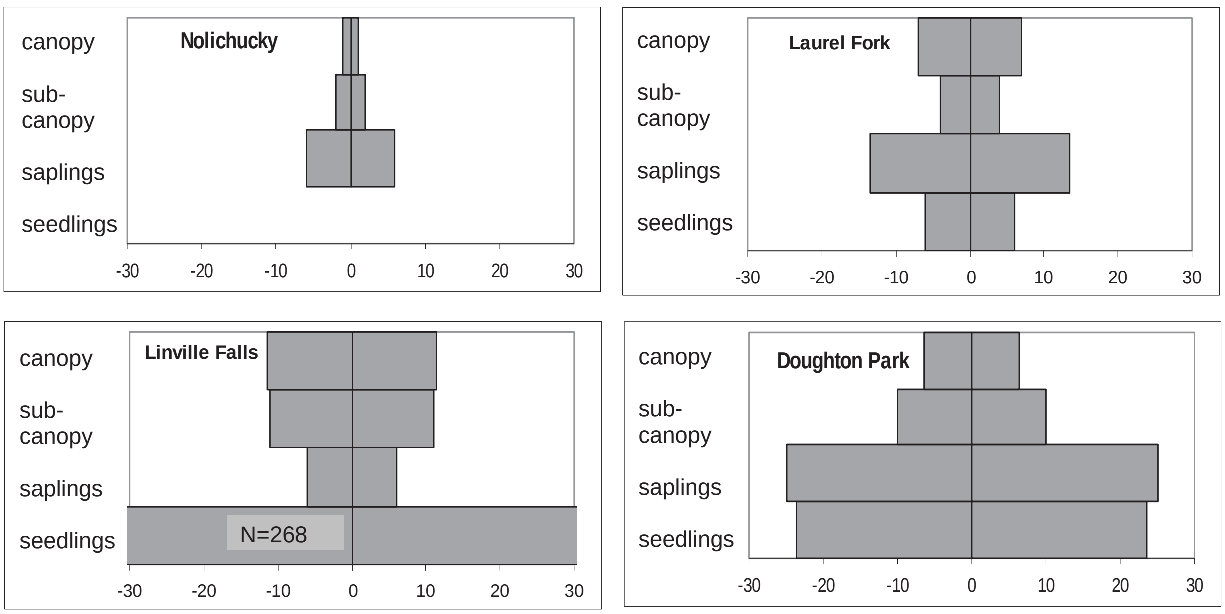


Figure 1. Size pyramids for four Carolina hemlock populations. Size class totals are the combined negative and positive values of the x-axis.

2. Epidemiology

Seedlings were analyzed separately from other height classes because: 1) their numbers would bias results from some populations, and 2) they tended to have different degrees of infestation or their condition was not typical of larger specimens. In all populations, seedlings tended to be in relatively good condition despite infestations in some populations (Figure 2). The notable exception was at Linville Falls, where seedlings were abundant and all were in excellent condition and uninfested.

Regarding non-seedlings, Nolichucky was in a very early stage of infestation, and although adelgid infestation was widespread, virtually all trees were in healthy condition (Figure 2). Similarly, Doughton Park was at an early stage of infestation, with the leading indicators (quadrants infested and degree of infestation) higher than the lagging indicator (tree condition). In contrast, Linville Falls had been infested for several years, and the area we censused was under chemical treatment, with the initial trees treated four years prior and more trees treated in subsequent years. Consequently, few adelgids were observed, but the trees showed extensive signs of impaired health (loss of foliage and dead branches).

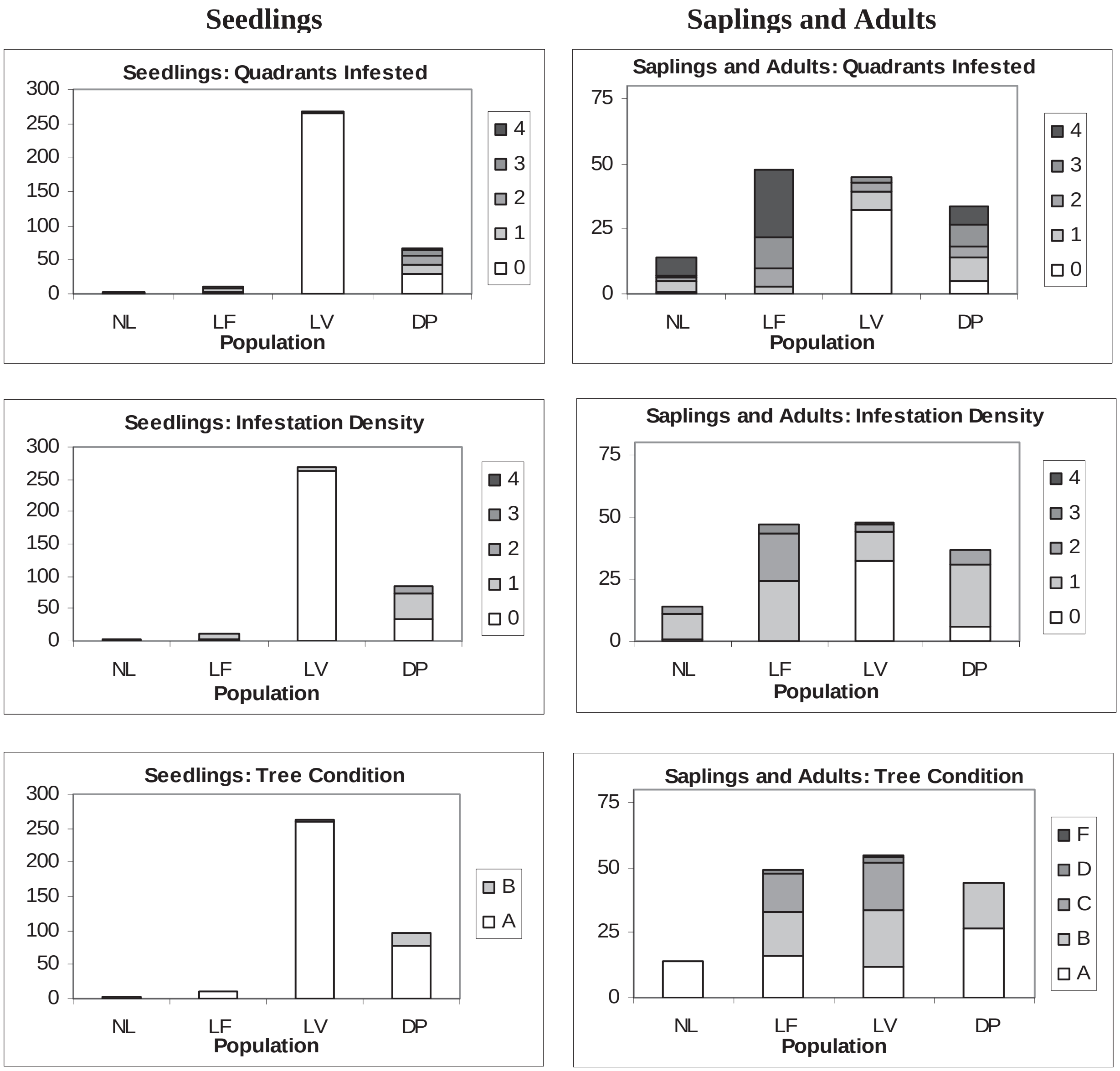


Figure 2. Epidemiologic characteristics of Carolina hemlocks in four populations. For “Infestation” characters, ‘0’ signifies absence and ‘4’ is highest level of infestation. For “Tree Condition”, ‘A’ is excellent and ‘F’ is dead. NL=Nolichucky; LF=Laurel Fork; LV=Linville Falls; DP=Doughton Park.

3. Cluster Analysis

Significant clusters were observed in all four populations (Table 2). The presence of clusters refutes the random spread hypothesis. There were infestation clusters at Nolichucky (Figure 3-A), Doughton Park (Figure 3-B), and Linville Falls, and there were clusters of trees in declining condition at Laurel Fork (Figure 3-C), Doughton Park and Linville Falls (Figure 3-D). In these figures, each plot is a scaled representation of the locations of trees within a population. The size of the circle is scaled to the size of the tree, but many seedlings may be represented by a single small circle (e.g., the cluster of two small green dots enclosed by a green circle near the bottom of Figure 3-D). For “Quadrants Infested,” the more filled the circle, the more quadrants infested; for "Infestation Density," the higher the red bar from the circle, the denser the infestation, and for "Tree Condition," red indicates poor condition ('F') and green indicates excellent condition ('A'). Significant clusters are enclosed in circles. A red circle indicates a cluster of individuals with either more severe infestation or in poorer condition; a green circle indicates a cluster of individuals with lesser infestation or in better condition.

Table 2. Summary of significant clusters.

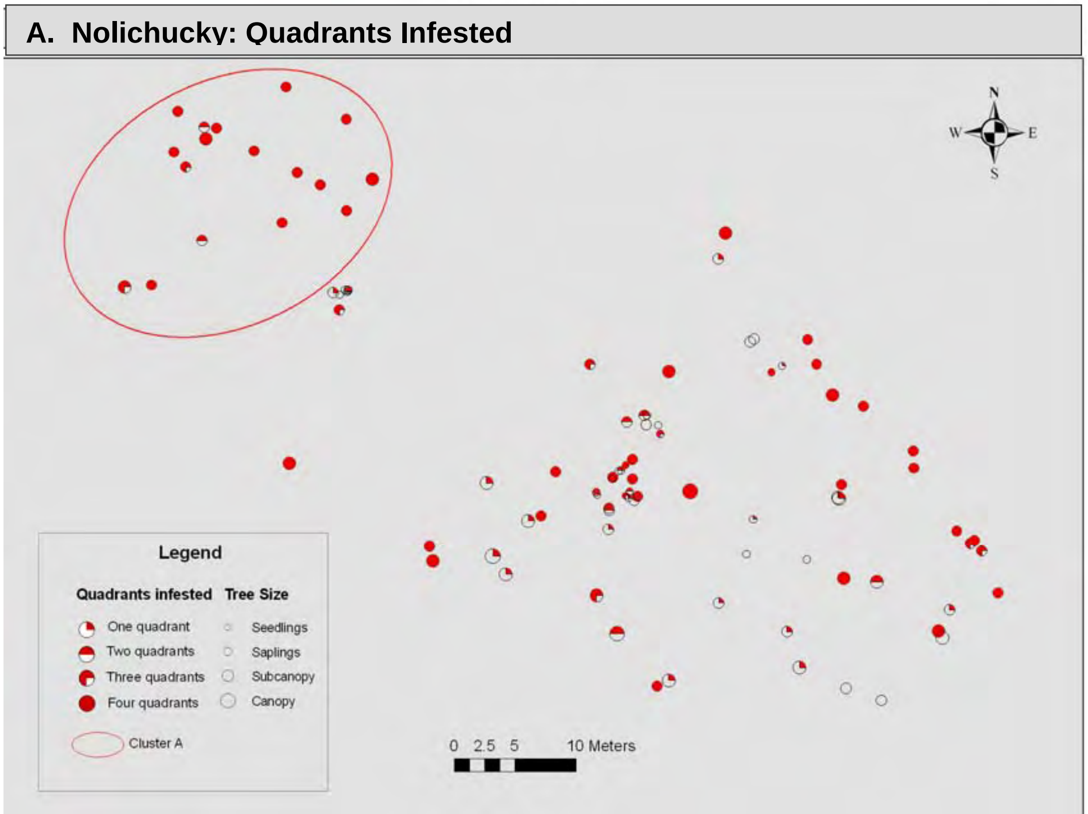
	Significant Clusters					
	Quadrants Infested		Infestation Density		Tree Condition	
	High	Low	High	Low	Poor	Good
A. Untreated Populations						
Nolichucky	1					
Laurel Fork		1		1	1	1
Doughton Park	1	1	1	1	1	
B. Treated Population						
Linville Falls	2		2		4	2

There were no adelgids noted at Nolichucky in an informal survey in the fall of 2006. When this census was conducted in the spring 2007, Nolichucky had become colonized by HWA but all trees were relatively undamaged, thus accounting for the absence of tree condition clusters. Similarly, the infestation at Doughton Park appears relatively recent, as evidenced by almost all trees in excellent to good condition. However, there are clear areas of infestation foci, and we can expect tree condition to decline if no adelgid control measures are taken.

Linville Falls was unique as a census site because this area has a longer and more serious infestation history and the site censused had been chemically treated for several years. Thus, this site provided the opportunity to observe the combined effects of a long-standing infestation and several years of chemical treatment. There were multiple clusters at Linville Falls. Clusters of trees in poorer condition tended to be larger trees, while the clusters of individuals in excellent condition were mainly seedlings (Figure 3-D). Infestations were relatively light at Linville Falls, and infestation clusters tended to be small in size. Thus, Linville Falls appears to have responded to chemical treatment by a marked reduction in the infestation, but trees and saplings showed the negative effects of infestation, while seedlings were generally adelgid-free and in excellent condition. It is unknown whether the excellent condition of seedlings can be attributed to protection from uptake of residual chemical in the soil (Cowles et al. 2006) or if their condition is a reflection of the benefit of a currently light local infestation of HWA.

Management Implications

Chemical treatment of larger trees led to the unanticipated benefit of a healthy seedling crop, as seen clearly at Linville Falls. This could argue for selective protection of some infested trees to maintain a seed source and to create seedling beds in a protection zone. Protection of seedlings may be particularly important due to the limited time of seed viability in hemlocks (Sullivan and Ellison 2006). Although very preliminary, the finding of infestation clusters suggests treatment should focus on infestation foci and adjacent areas.



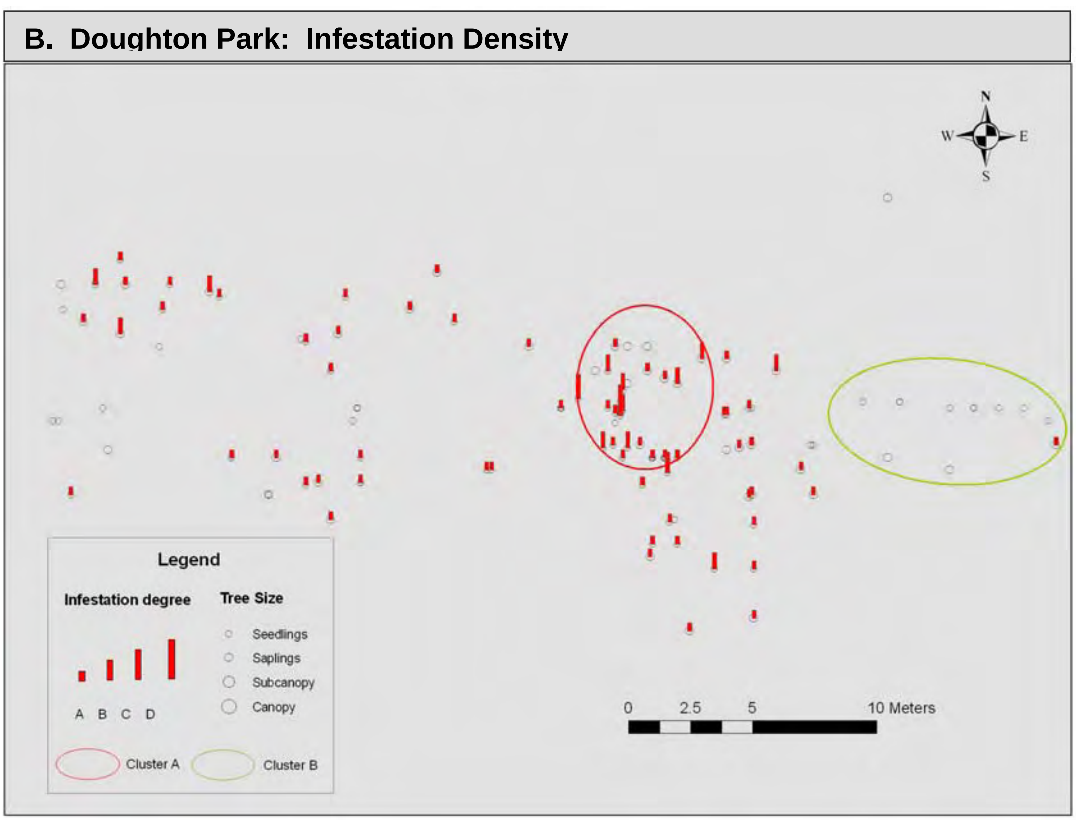
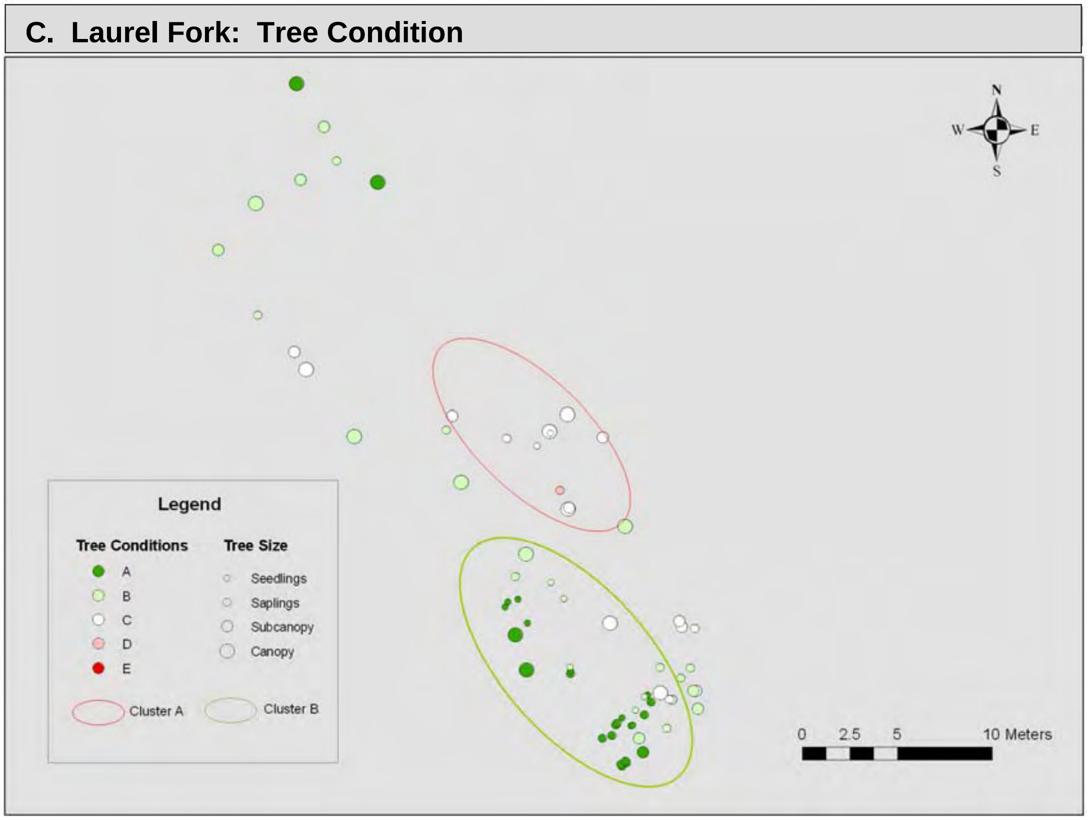


Figure 3, A-B. Spatial clusters in four Carolina hemlock populations. (See description in text.)



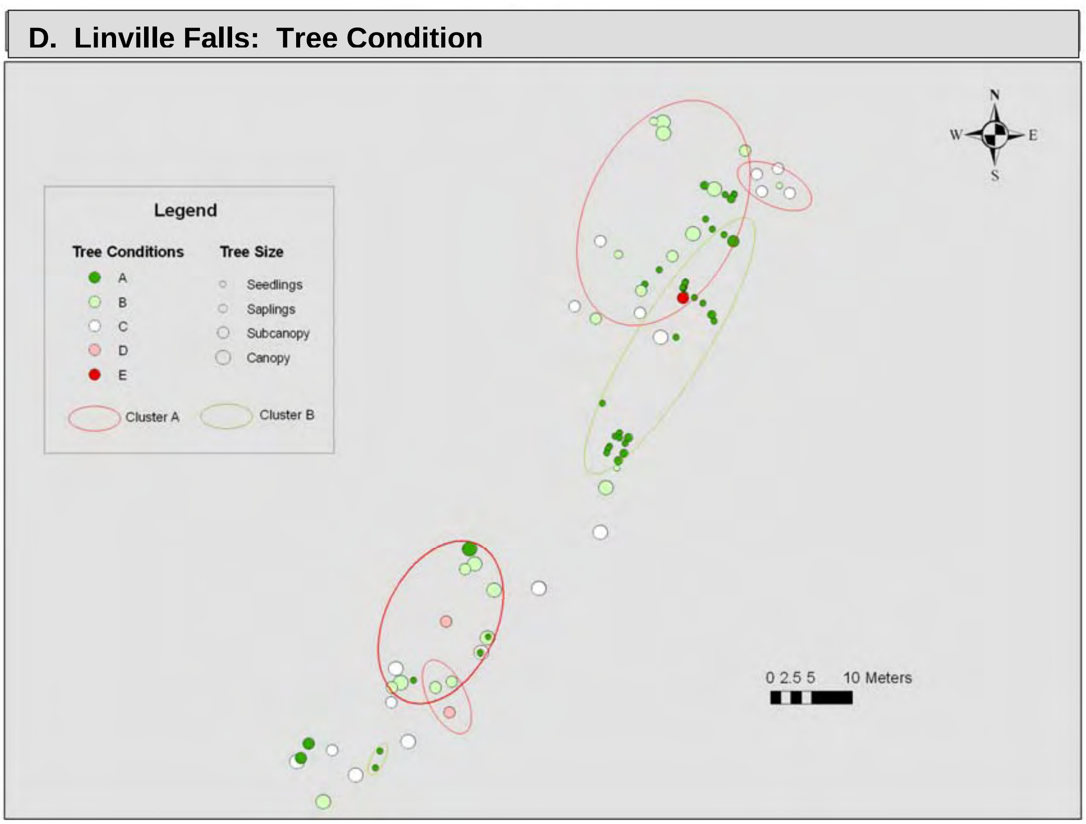


Figure 3, C-D. Spatial clusters in four Carolina hemlock populations. (See description in text.)

Unanswered Questions

Our first-year results provide baseline data on infestation patterns within Carolina hemlock populations. Subsequent surveys are needed to uncover patterns of spread over time and to address the following questions:

- Are clusters of high infestation simply expanding from one year to the next?
- Does infestation in untreated populations progress from high infestation to poor tree condition?
- Are seedlings, small trees, and larger trees equally vulnerable to HWA colonization?
- Does transmission of HWA follow human trails to expand infestations?
- Do clusters of low-infestation and good-condition trees persist over succeeding years?

SUMMARY

Cluster analysis was successful in identifying population sectors of high and low infestation and trees in poorer and better health. The clusters that indicate negative impacts of adelgid attack (more quadrants infested, higher infestation density, and trees in poorer condition) clearly reflect regions within populations where the adelgids have established. An unexpected outcome is that, with the exception of one small area within Linville Falls, there were no locations with significant clusters for all three negative impact indicators. This is probably a reflection of our choice of two populations in very early stages of infestation (Nolichucky and Doughton Park) where tree health is still relatively good. In contrast, at Linville Falls, the combination of a longer infestation and chemical treatment has resulted in the mix of larger trees in poorer condition, but subsequent clearing of the infestation by chemical treatment accounts for the generally light infestation. Many trees were adelgid-free, including a seedling population that is large and in excellent condition.

ACKNOWLEDGMENTS

We thank the National Park Service Appalachian Highlands Learning Center at Purchase Knob, for funding, and the Cherokee and Pisgah National Forests for permission to conduct work on federal lands.

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