CAROLINA ENVIRONMENTAL PROGRAM CAPSTONE PROJECT: A BASELINE STUDY OF THE EFFECTS OF HEMLOCK LOSS IN THE HENRY WRIGHT PRESERVE AND KELSEY TRACT

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INTRODUCTION

Two species of hemlock are found in western North Carolina: the eastern hemlock (*Tsuga canadensis*) and the Carolina hemlock (*T. caroliniana*). These two species dominate the moist cove forests of their ranges because they are slow-growing, long-lived trees that grow well in shade. The eastern hemlock has a broad range, stretching from southern Ontario to Georgia and westward to Minnesota. The Carolina hemlock is endemic to the Blue Ridge region of the southern Appalachian mountains (Little 1980). Unfortunately, both species have declined precipitously in recent years due to an introduced Asian insect, the hemlock woolly adelgid (HWA). This aphid-like insect is responsible for the death of thousands of hemlock trees along the east coast and is proving to be a major threat to hemlock forest ecosystems (McClure et al. 2001).

The hemlock ecosystem provides habitat for many unique plants and animals. Typically, a forest dominated by hemlocks tends to be characterized as moist to very moist. Hemlocks occur in highly acidic coves or cool valleys with good drainage. The trees are typically restricted to north and east facing slopes and often occur in steep valleys where there is significant canopy cover and year-round shade. They often grow along the headwaters of mountain streams, and help to moderate stream temperature by shielding from direct sunlight. This keeps temperatures cool for sensitive endemic fish species (Ross et al. 2003). The ample shade they provide also helps to retain soil moisture, which supplies stable habitat for sensitive terrestrial fauna like salamanders (Brannon et al. 2005). Several avian and mammalian species are associated with the hemlock habitat, including the great horned owl (*Bubo viginianus*), red crossbill (*Loxia curvirostra*), goldfinch (*Carduelis tristis*), pileated woodpecker (*Dryocopus pileatus*), red squirrel (*Tamiasciurus hudsonicus*), and red fox (*Vulpes vulpes*). Hemlocks provide an excellent seed source for such birds and small mammals. Since hemlocks are exceptionally long-lived it allows them to develop a number of cavity sites and a higher level of cavity-dwelling and foraging use by a number of woodpeckers, small mammals, and forest carnivores (Yamasaki et al. 2000). Mature hemlocks are also dominant canopy components in many forests and their loss will result in massive restructuring of the forest canopy in these areas (Orwig et al. 1998).

The hemlock woolly adelgid was introduced to the United States from Asia in 1924. First found in the northeastern U.S., the adelgid has migrated into many forests along the eastern seaboard. White cottony sacs at the base of hemlock needles are indicators of adelgid infestation. The invasive adelgid sucks sap from the base of the needles causing them to drop. In addition, adelgid saliva contains a toxic chemical that prevents new needle growth (McClure et al. 2001). In losing its original needles, the tree also loses its reproductive viability, and as a result, infested trees become permanently defoliated (Orwig et al. 1998). Tree death can occur in as little as four years (McClure et al. 1991). Their loss will likely contribute to significant changes in soil moisture and temperature, stream temperature, nutrient fluxes (i.e. nitrogen), and species assemblages in the canopy and understory (Orwig et al. 1998, Jenkins et al. 1999, Ross et al. 2003).

Currently, there are two standard methods utilized to combat the HWA. Chemical treatments include stem injections, foliar sprays, soil injections, and soil drenching, all using the insecticide Imidacloprid. Once taken up by the hemlock, Imidacloprid kills the adelgids when they feed on its sap (Cox 2001). Perhaps a more environmentally friendly technique is a biological control method that involves releasing an Asian predator insect, the Ladybird beetle (*Sasajiscymnus tsugae*, Coccinellidae). These beetles prey on the adelgid and require adelgid infested trees in order to thrive (Skinner et al. 2003).

Study Area

This study focuses on a western North Carolina cove forest with exceptionally large virgin hemlocks. The cove is located near Highlands, North Carolina, in the Henry Wright Preserve and the adjacent Kelsey Tract (Fig. 1). The Wright Preserve was donated in 1964 to the North Carolina Nature Conservancy by Henry Wright and is currently owned by the nonprofit Highlands-Cashiers Land Trust (HCLT). The Kelsey Tract is a parcel owned by the U.S. Forest Service (USFS). The study area is one of the few remaining sections of the once-extensive "Primeval Forest" of the Highlands Plateau that contained stands of enormous virgin timber and stretched from Highlands, NC to Whiteside Mountain in Cashiers, NC (Zahner 1994). Often sought by locals and tourists as a place of exceptional beauty, the forest remained in a pristine state until the 1940's when the majority was sold to the Champion Lumber Company by the Ravenel family. With the exception of the area that now comprises the Wright Preserve and Kelsey Tract, the 100,000+ acre parcel was heavily logged shortly thereafter and subsequently sold to private investors (Shaffner 2004).

The trees within the Wright Preserve have grown to exceedingly large sizes due in part to the temperate rainforest climate of the Highlands Plateau and partly because the area escaped Champion logging. Today, this remaining piece of the original "Primeval Forest" is overseen by the HCLT, which is responsible for ensuring that it remains undeveloped and uncut. There is limited access to both the Wright Preserve and the Kelsey Tract as they are bordered on all sides by private property. No defined trails go through the property and travel is difficult.

The canopy of the preserve consists primarily of eastern hemlock (*T. canadensis*), sweet birch (*Betula lenta*), red maple (*Acer rubrum*), tulip poplar (*Liriodendron tulipifera*), red oak (*Quercus rubra*), mountain holly (*Ilex Montana*), Frasier magnolia (*Magnolia fraiseri*), and black gum (*Nyssa sylvatica*). Formerly the American chestnut (*Castanea dentata*) was a primary canopy species as well. The Cheoah Hemlock, included in this study as "Big Daddy Hem," is recognized by the Eastern Native Tree Society as a contender for one of the largest hemlocks in the east (Blozan 2006). The understory is dominated by nearly impenetrable stands of rosebay rhododendron

(*Rhododendron maximum*) and also includes mountain laurel (*Kalmia latifolia),* mountain pepperbush (*Clethra acuminata*)**,** and doghobble (*Leucothoe fontanisiana).*

The trees in this forest currently suffer varying degrees of HWA infestation. Soil injections of Imidacloprid and beetle releases were applied to the Cheoah hemlock within the Kelsey Tract in order to slow the rate of infestation and subsequent hemlock damage. Will Blozan, owner of Appalachian Arborists, Inc. and president of the Eastern Native Tree Society (pers. comm.), released 14,000 predator beetles for the USFS in May of 2004. In June 2006 USFS employed Blozan to inject Imidacloprid treatments into the soil at the base of the Cheoah hemlock, at the same site of the beetle release in 2004. However, the success of these treatments is not clear at this time.

The purpose of this study was to assess current hemlock health in the Wright Preserve. We measured and mapped precise locations for large old-growth hemlocks in the area and provide a measure of defoliation. In addition, we surveyed the composition and density of canopy species immediately surrounding the largest hemlock trees in order to make predictions about future forest dynamics of the canopy. This study provides a baseline assessment of a current hemlock forest on the brink of rapid change. The Wright Preserve and adjacent areas of the Kelsey Tract present a unique opportunity to initiate a study of canopy dynamics focusing on an old-growth hemlock forest in the early stages of flux.

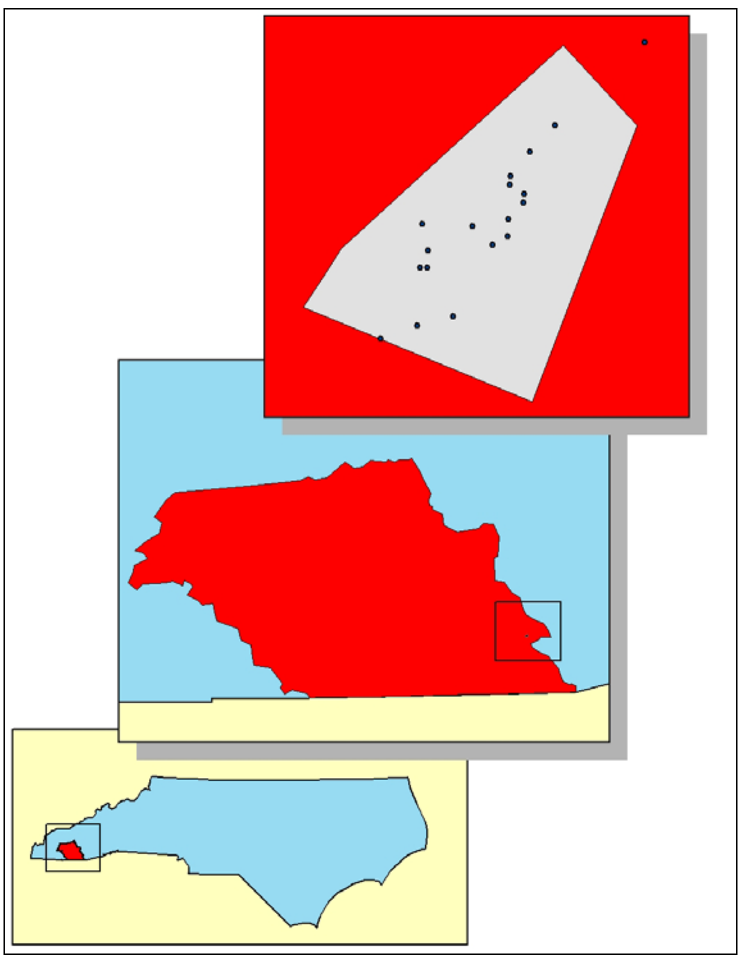


FIG. 1. Map of study area. Dots represent sampled hemlocks in the present study.

MATERIALS AND METHODS

Study Site and Timing

Our study site is located in western North Carolina, in the Blue Ridge region of the southern Appalachian mountains. Our surveys were largely constrained within the boundaries of the Wright Tract, which is bisected by a small creek and bordered by steep ravine on both sides (Fig. 1). The predominant vegetation type in the tract is native, old-growth hemlock forest, which transitions into mixed mesophytic forest on the east and west ridges, respectively. We began our research in early September of 2006, and surveyed throughout the fall, completing sampling in early December of the same year.

Data Collection

A dense understory of rhododendron shrubs made travel through the majority of the Wright Preserve extremely challenging, and establishing straight transects or square vegetation survey plots would have been difficult. We focused our survey on the largest trees, due to the fact that their loss would likely have the largest ecological impact, and the fact that trees of this size have rarely been surveyed in other HWA damage assessments. These large hemlocks served as focal points for our vegetation surveys, and were concentrated along the streambed, which was relatively easy to follow and traverse. Large hemlocks were located by sight and accessed on foot in a manner that caused minimum damage to understory vegetation. After a preliminary evaluation of hemlock sizes in the tract, we determined that trees with a diameter at breast height (DBH) larger than 100 cm represented the largest trees in the area. The DBH of the trees was determined using marked DBH tape or by measuring circumference using transect tape and converting this value to diameter.

In order to assess recruitment potential of other tree species following the predicted loss of hemlocks from the forest canopy, we surveyed all trees and saplings (all size classes) within a 5 m radius of each large hemlock. The species of each tree within this 5 m radius plot, distance from the central hemlock, and DBH were recorded. Shrubs and herbaceous species were not included in our vegetation analysis.

GPS waypoints were taken at each large hemlock location using a Trimble® Model XH global positioning system receiver. Digital cameras were used to make photos of the canopy of the central tree at each of the four cardinal directions. Photographers stood approximately 5 m away from the hemlock's base at each location and positioned the camera lens directly upward to capture as much of the canopy as possible from that angle. These photos were used to create an archived account of current (2006) condition of surveyed trees, and will be available for reference with similar photos taken in subsequent years (Electronic Appendix A).

Finally, we performed a visual assessment to analyze the condition of the large hemlocks, and quantified crown density using a numeric defoliation scale. Crown density surveys have been used in past studies for tree health assessment (Eschtruth et al. 2006). We employed" a modified version of the defoliation scale used by Eschtruth et. al (2006) for our survey in the Wright Preserve. A score of "1" was used to indicate none or very little defoliation (Fig. 2), a score of "3" indicated 50% defoliation (Fig. 3), and a score of “5” indicated complete defoliation (Fig. 4). Three survey team members individually assessed defoliation, and an average of their three numerical scores was taken to assign the final heath assessment score for each tree. Averages were rounded to the nearest whole number for data analysis. Scores from the visual assessments were included in association with the archived canopy photos of the surveyed trees for future reference purposes.

FIG. 2. Example of defoliation score 1 (little or no defoliation; Tree #1).

FIG. 3. Example of defoliation score 3 (50% defoliation; Tree #2).

FIG. 4. Example of defoliation score 5 (complete defoliation, Tree #5).

Data Analysis

We began analysis by designing a simple classification scheme in order to visualize size distributions in the large hemlocks of the Wright Preserve. Size categories were assigned at 5 cm intervals (100.0-105.0 cm, 105.1-110.0 cm, etc. through 145.1-150 cm), and trees were classified according to DBH.

Formulas from Bower (1997) were used to calculate typical forest composition parameters for each large hemlock plot and for each tree species on a whole. Evaluating dominance relationships within this community affords a sense of its physical structure and interactions among tree species. The first of these composition metrices is relative density, or the prevalence of trees of a particular species relative to prevalence of other species expressed as a percentage. The following formula was used in our calculations:

$$\text{Relative Density for Species X} = \left(\frac{\#\ Individuals\ of\ \ Species\ X}{Total\ \#\ individuals} \right) 100$$

The second composition parameter is basal area (BA), or the total area of the forest floor covered by trees of each species in all plots. It was calculated with the following formula:

$$\text{Basal Area by tree:} \quad BA_{tree\,1} = \pi \left(\frac{dbh}{2} \right)^2$$

$$\text{Basal Area for Species X:} \quad BA_{species\ X} = \sum BA_{tree\,1}, BA_{tree\,2}, BA_{tree\,3}, \ldots$$

$$\text{Total Basal Area:} \quad BA_{Total} = \sum BA_{species\ X}, BA_{species\ Y}, BA_{species\ Z}, \ldots$$

The third parameter, relative dominance, is a metric describing basal area for each species relative to total basal area of all tree species. Relative dominance is calculated using the following formula and is expressed as a percentage:

$$\text{Relative Dominance for Species X} = \left(\frac{BA_{species\ X}}{BA_{Total}} \right) 100$$

Finally, importance value (IV) takes into account relative dominance of a species as well as relative density to give an idea of the overall ecological impact of the species in question in the forest. Species having the highest IV's may have the greatest impact on the community, and may exert greater influence in the forest following the disappearance of hemlocks. IV for each species was calculated with the following formula:

$$\text{IV for Species X} = \text{Relative Density}_{\text{species X}} + \text{Relative Dominance}_{\text{species X}}$$

Data collected on species present in the plots and their DBH were also used in assessing species composition and species diversity in the hemlock cove forest and in projection of future forest composition. The Shannon-Weiner index of species diversity is an index that incorporates both the number of species present (species richness) and their relative abundances (species evenness). This index outputs the probability (H) that the next tree sampled will be of a different species: higher H values indicate higher species diversity, whereas lower H indicates lower diversity (Smith 1996).

$H = -\sum_{i=1}^{s} \left[\mathrm{Re}\,lative\ Density_i\right] \left[\ln\left(\mathrm{Re}\,lative\ Density_i\right)\right]$, where s is the number of species, and i is the species in question.

Analysis with GIS

The map component of the Capstone project was completed using ArcGIS® 9.1, digital mapping software. The X-Y coordinates of the studied hemlocks were acquired using a Trimble® Model XH Global Positioning System (GPS) receiver. The GPS receiver could not detect enough satellites at certain trees to get reliable waypoint data. In these cases, we approximated points using a directional bearing from known points and approximate distances. We downloaded geographic information systems (GIS) data from the Macon County online mapping service website to include a parcel lines layer and a rivers layer within the Wright Preserve (http://63.167.19.7/website/macgis/). The X and Y coordinates were imported into ArcGIS® 9.1 from an excel spreadsheet; the imported coordinates created a point layer on ArcMap™.

Various maps were created in order to visually represent the data we collected in the Wright Preserve, including maps of defoliation, diameter at breast height (DBH), total basal area of canopy species per hemlock, and GIS layers on top of an aerial photo. The defoliation scale was applied to a point layer in ArcMap™ by displaying each tree with a different color (green, light green, yellow, orange, and red) for each value from one to five.

We used a point symbology in ArcMap™ that changed the point's size depending on how the DBH compared to other hemlocks; a small point represented a small DBH and a larger point represented a high DBH. The total basal area of each hemlock was displayed in ArcMap™ using a color scheme that had green representing the lower end of the total basal area scale and red on the higher end of the total basal area scale. A georeferenced aerial photo was added to ArcMap™ as the base layer of our aerial photo map. A point layer with a 5 m buffer for each hemlock was added to the aerial photo map to show the location of each tree and the area of study.

RESULTS

Results provide baseline data for the large hemlocks and the hardwood species immediately surrounding them. Table 1 and Fig. 5 provide further information about hemlock measurements. Fig. 6 shows the locations of sampled hemlocks on an aerial photo.

Hemlock Number	Hemlock Name	DBH (cm)	Defoliation	# of Surrounding Trees	North Coordinate	West Coordinate
1	Big Daddy Hem	149.23	1	5	35.08071	83.1782
2	Fat Albert	142.24	3	1	35.081137	83.177454
3	Lightnin'	130.81	3	2	35.081187	83.177678
4	Tiny Dancer	129.54	2	2	35.082884	83.175869
5	Croaking Hem	129.54	5	2	35.08096	83.177541
6	Beeka	125.86	3	2	35.080708	-83.17819
7	Wishbone	117.77	2	0	35.080188	83.178788
8	Big Bootie Hem	116.84	1	3		
9	Uncle Hemi	116.84	4	3	35.08063	83.177649
10	Sourpuss	116.00	3	0		
11	Earl	113.64	4	1	35.0804	83.178838
12	Hungry Tree	111.73	2	4	35.080153	83.178858
13	Hemi Engine	110.00	1	1		
14	Hemily	109.22	3	0	35.080814	83.177723
15	Baby Hemi	105.41	3	3	35.080502	83.177909
16	Water Log	105.41	3	2	35.081269	83.177674
17	Auntie Hem	101.85	2	2	35.081948	83.177052

TABLE 1. List of hemlocks surveyed. Defoliation (1=least defoliation, 5= most defoliation) and number of surrounding species also listed. GPS waypoints are indicated in decimal degrees. The location of trees with missing GPS data were estimated (Fig. 6).

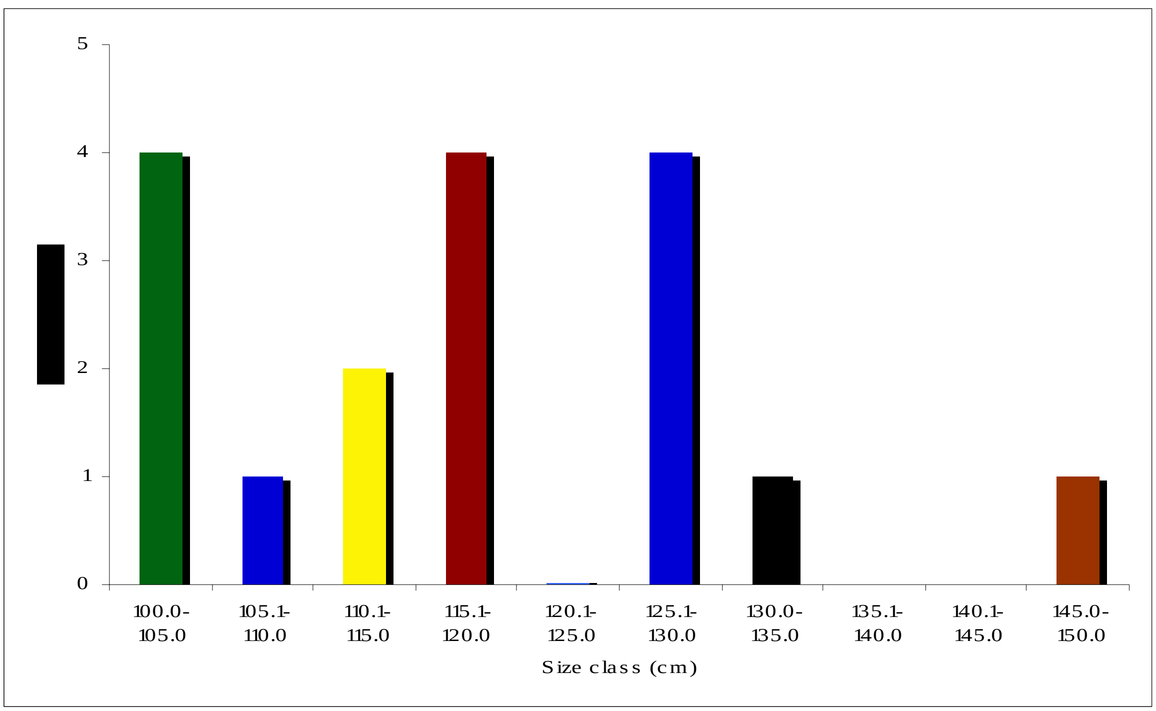


FIG. 5. Hemlocks grouped by size class at intervals of 5 cm DBH.

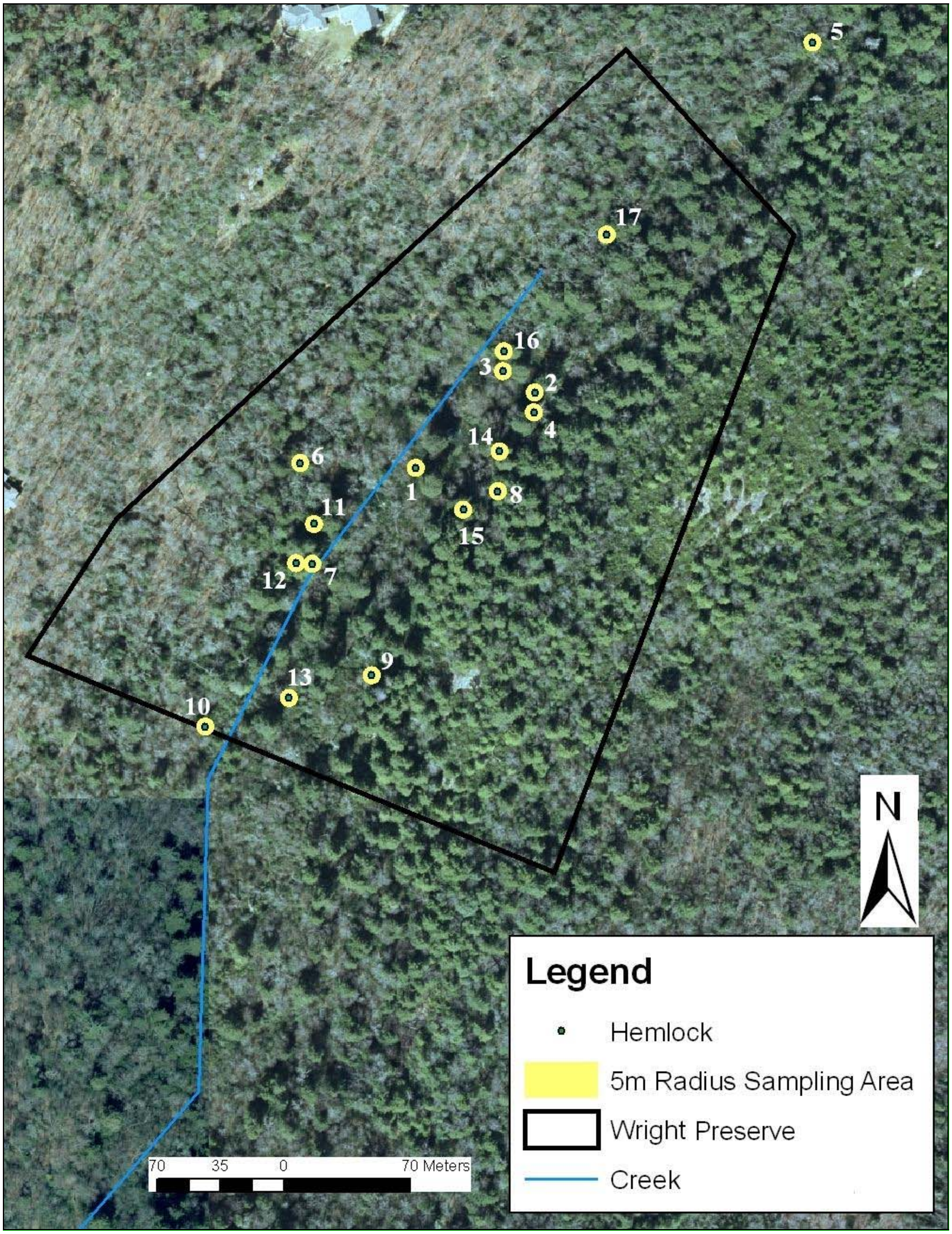
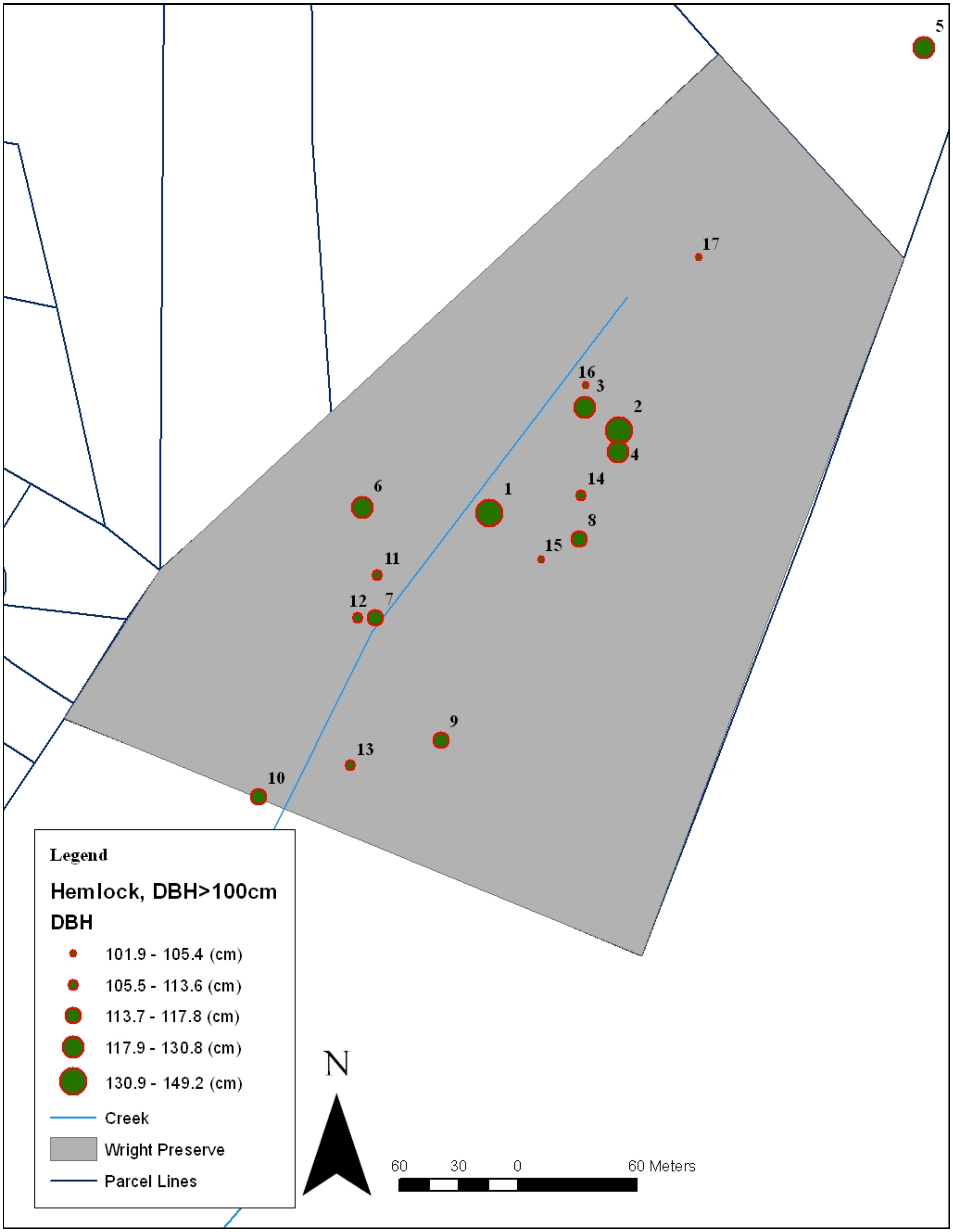


FIG. 6. Aerial photograph of the Henry Wright Preserve showing all of the hemlocks sampled and the 5 m-radius sampling area around them.


5
17
16
3
2
4
6
1
14
8
15
11
12
7
9
13
10
Legend
Hemlock, DBH>100cm
DBH
101.9 - 105.4 (cm)
105.5 - 113.6 (cm)
113.7 - 117.8 (cm)
117.9 - 130.8 (cm)
130.9 - 149.2 (cm)
Creek
Wright Preserve
Parcel Lines
N
60 30 0 60 Meters
FIG. 7. DBH map.

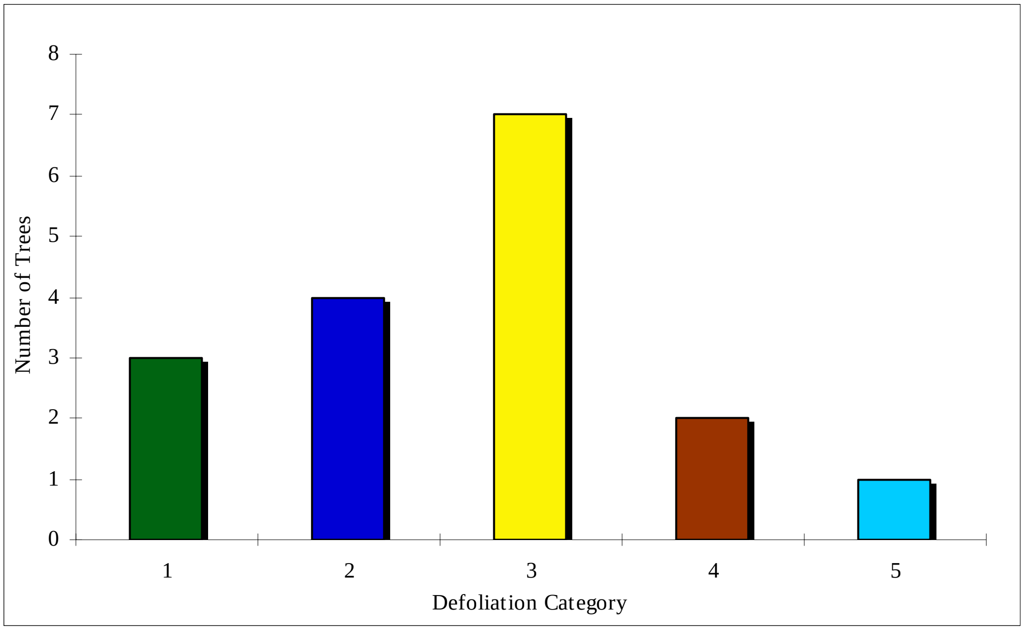


FIG. 8. The defoliation of surveyed hemlocks, represented graphically from no defoliation (1) to completely defoliated (5).

Fig. 7 shows the sizes of sampled hemlocks in terms of diameter (cm) at breast height (DBH), and Figs. 8 and 9 show their defoliation.

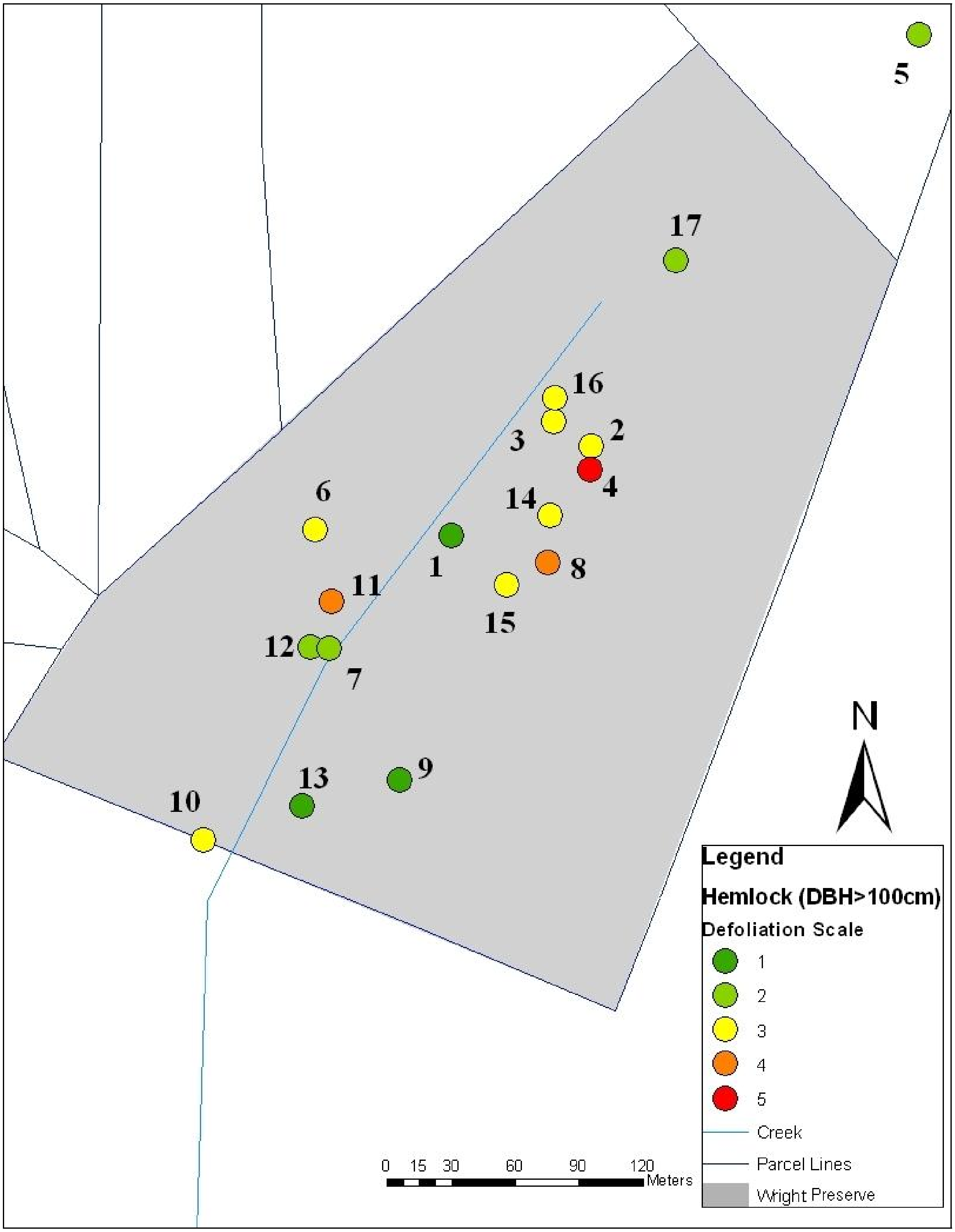


FIG. 9. Defoliation map of surveyed hemlocks, represented graphically from no defoliation (1) to completely defoliated (5).

Further data provide information about tree species in the surveyed plots around the mapped hemlocks. Table 2 details the species present and summary statistics about them. Figs. 10 and 11 represent basal area. Fig. 12 shows species diversity from which we calculated the Shannon-Wiener Index value of 1.79.

Species	# of trees	Basal area	Relative Dominance	Importance Value	Relative Density
Betula lenta	13	7991.26	372.98	882.98	0.5
Tsuga canadensis	6	26657.24	571.65	996.65	0.23
Ilex montana	4	144.68	100.64	250.64	0.15
Magnolia fraseri	3	318.72	112.73	262.73	0.12
Quercus rubra	1	93.69	16.18	36.18	0.04
Nyssa sylvatica	1	433.55	74.87	94.87	0.04
Liriondendron tulipifera	1	7894.88	50.96	75.96	0.04
TOTAL	26	43534.03			

TABLE 2. Data and metrics for species surrounding the surveyed hemlocks

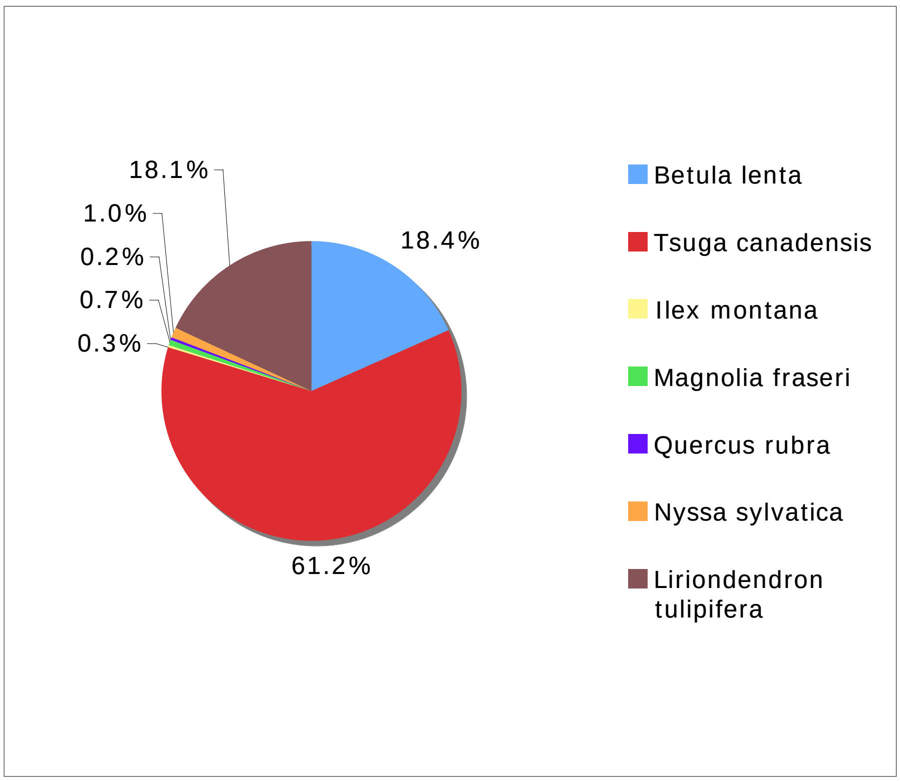


FIG. 10. Total basal area of the species within the survey plots.

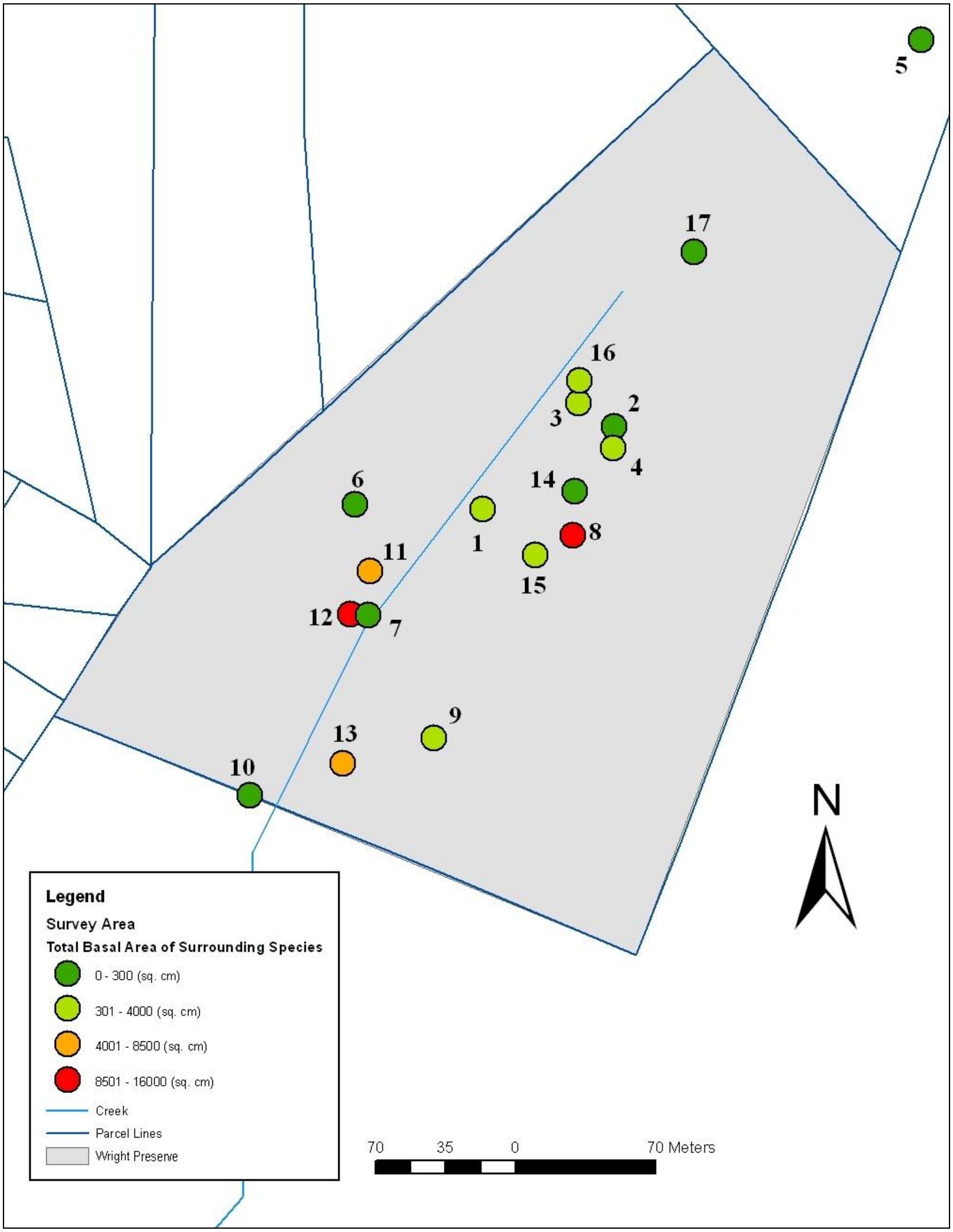


FIG. 11. Total basal area of surrounding species of each hemlock surveyed within 5 m.

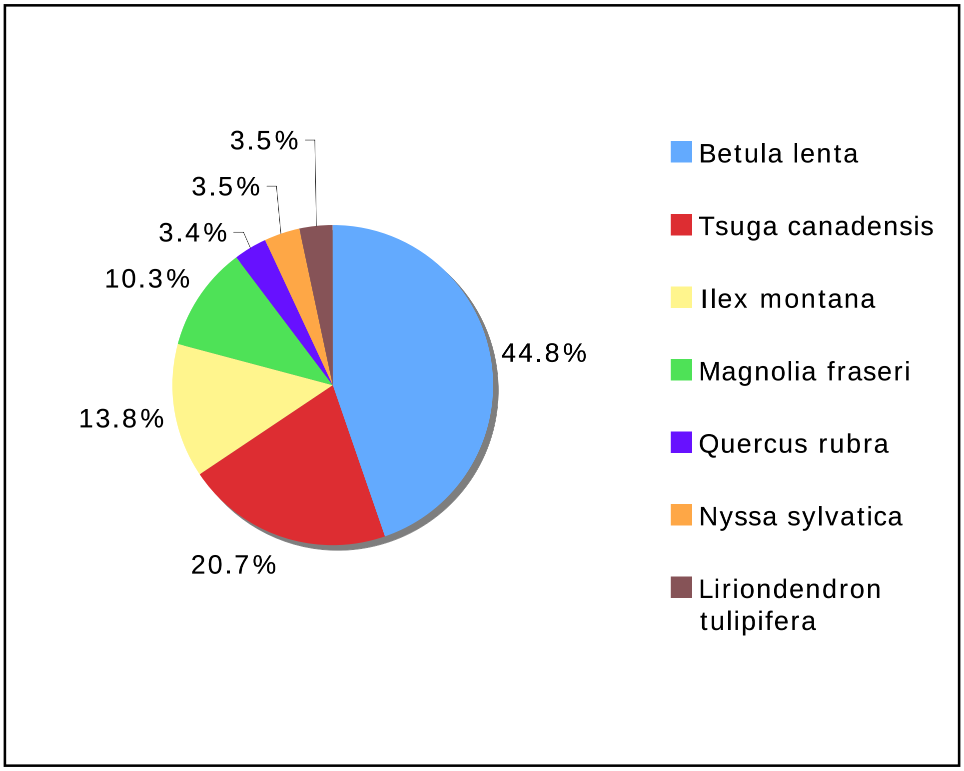


FIG. 12. Relative density of the species within the survey plots

DISCUSSION

Aspects of the data provide baseline information on the health of the large trees in the Wright Preserve. The observed defoliation levels indicate that there are varying degrees of hemlock decline, with most trees in mid-stages of deterioration. We anticipate that as the adelgid invasion proceeds, trees will continue to lose canopy cover, thus allowing more light to reach the understory and the forest floor. Continued defoliation and eventual loss of hemlocks will inevitably change the forest ecosystem.

As observed in Fig. 10, *Tsuga canadensis*, *Betula lenta*, and *Liriodendron tulipifera* have the most basal area within surveyed plots. *B. lenta* is the most frequent species in the sampled area (Fig. 12); however, *T. canadensis* and *L. tulipifera* significantly contribute to overall basal area as trees sampled are older with significant DBH.

In terms of species density, *B. lenta* is again the most prevalent species, followed by *T. canadensis* and *Ilex Montana*; in contrast, there was only a single *L. tulipifera* specimen (Fig. 12). A Shannon-Wiener index calculation in the Wright Preserve yielded a score of 1.790. For perspective, lowland mesoamerican rain forests can have Shannon-Wiener index values over four (Bongers et al. 1988). This illustrates that the study forest is not only low in diversity but also has skewed composition proportions toward *B. lenta* (i.e. future forest growth favors *B. lenta*). In addition, these measurements are helpful for predicting how the forest will change with further hemlock decline.

A 1979 study by Barden showed increases in *Betula* spp., *Liriodendron tulipifera*, and *Magnolia fraseri* in hemlock treefall gaps in southern Appalachian forests. This is consistent with our results that indicate that *B. lenta* is already a prevalent species in the study area. Other studies note the likelihood of an increase in *B. lenta* in damaged hemlock stands due to its large seed production and superior dispersal abilities, in addition to its preference for relatively high light conditions (Barden 1979, Orwig and Foster 1998, Kizlinski et al. 2002). As the quantity of large trees in the Wright Preserve continues to decline, it is likely that *B. lenta* presence will increase.

Although we did not quantify the species composition of the understory, significant amounts of *Rhododendron maximum* dominated the study plots. The loss of hemlocks may allow for further growth of *R. maximum*, as it is a robust, tolerant species. Further, it may be reasonable to suspect that these dense thickets will interfere with the recruitment of canopy species, including *B. lenta*. A 2000 study by Beckage et al. indicates that while reduced canopy cover allows for increased seedling densities, *R. maximum* prevents growth of tree seedlings by creating a low-light microenvironment at the forest floor, i.e. the shrub acts as canopy cover that blocks light from reaching developing plants.

The present study provides a basis for several future studies about changing forest structure due to hemlock loss. In light of the impacts of *R. maximum* on other forests with canopy gaps, quantification of understory cover within plots may be informative regarding future forest constitution. Additionally, future studies should collect data on soil content, including moisture and acidity, which are important determining factors in forest vegetation composition that may change with hemlock loss. Further study at this site could also include the use of remote sensing to estimate percent canopy cover. Continued assessment will provide further data on the rate of canopy loss. Finally, continued monitoring of vegetation surrounding chosen hemlocks and an increase in studied individuals will further strengthen available data about the changing forest.

This study provides a baseline for continues monitoring of forest flux in response to hemlock decline. With continued monitoring and data collection in this area, we will gain better knowledge of the hemlock's role in old growth forest ecosystems and how secondary succession occurs when a dominant canopy species is lost.

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Literature Cited

Barden, L. S. 1979. Tree replacement in small canopy gaps of a *Tsuga canadensis* forest in the Southern Appalachians, Tennessee. Oecologica **44**:141-142.

Blozan, W. "The Cheoah Hemlock." May 2006. 13 Dec. 2006 <http://www.nativetreesociety.org/index.html>.

Beckage, B., J. S. Clark, B. D. Clinton, and B. L. Haines. 2000. A long term study of tree seedling recruitment in southern Appalachian forest: the affects of canopy gaps and shrub understories. Canadian Journal of Forest Research **30**:1617-1631.

Bongers, F., J. Popma, J. Meave del Castillo, and J. Carabias. 1988. Structure and floristic composition of the lowland rain forest of Los Tuxtlas, Mexico. Plant Ecology **74**:55-80.

Bower, J. E., J. H. Zar, and C. von Ende. 1997. Field and Laboratory Methods for General Ecology. McGraw-Hill, New York, USA.

Brannon, M. P., and S. R. Rogers. 2005. Effects of canopy thinning by hemlock woolly adelgids on the local abundance of terrestrial salamanders. Journal of the North Carolina Academy of Science **121**:151-156.

Cox, C. 2001. Imidacloprid: Insecticide factsheet. Journal of Pesticide Reform **21**:15-21.

Eschtruth, A. K., N. L. Cleavitt, J. J. Battles, R. A. Evans, and T. J. Fahey. 2006. Vegetation dynamics in declining eastern hemlock stands: 9 years of forest response to hemlock woolly adelgid infestation. NRC Canada **36**: 1435-1450.

Jenkins, J. C., J. D. Aber, and C. D. Canham. 1999. Hemlock woolly adelgid impacts on community structure and N cycling rates in eastern hemlock forests. Canadian Journal of Forest Research **29**:630-654.

Kizlinksi, M. L., D. A. Orwig, R. C. Cobb, and D. R. Foster. 2002. Direct and indirect ecosystem consequences of an invasive pest on forests dominated by eastern hemlock. Journal of Biogeography **29**:1489-1503.

Little, E. L. 1980. National Audubon Society Field Guide to North American Trees: Eastern Region. Chanticleer Press, Inc.: New York, NY.

McClure, M. S., S. Salom, and K. S. Shields. 2001. Hemlock wooly adelgid. Forest Health Technology Enterprise Team. U.S. Forest Service Publication FHTET-2001-03. Morgantown, WV. p 14.

Orwig, D. A. and D. R. Foster. 1998. Forest response to the introduced hemlock woolly adelgid in southern New England, USA. Journal of the Torrey Botanical Society **125**:60-73.

Ross, R., R. M. Bennett, C. D. Snyder, J. A. Young, D. R. Smith, and D. P. Lemarie. 2003. Influence of eastern hemlock (*Tsuga canadensis* L.) on fish community structure and function in headwater streams of the Delaware River basin. Ecology of Freshwater Fish **12**:60-65.

Shaffner, R. P. 2004. Heart of the Blue Ridge: Highlands, North Carolina. Faraway Publishing, Highlands, North Carolina.

Skinner, M., B. L. Parker, S. Gouli, and T. Ashikaga. 2003. Regional responses of hemlock woolly adelgid (Homoptera: Adelgidae) to low temperatures. Environmental Entomology **32**: 523-528.

Smith, R. L. 1996. Ecology and Field Biology. HarperCollins, New York, USA.

Yamasaki, M., R. M. DeGraaf, and J. W. Lanier. 2000. Wildlife habitat associations in eastern hemlock-birds, smaller mammals, and forest carnivores. In: McManus, K. A.; Shielfd, K. S.; Souto, D. R., eds. Proceedings: Symposium on sustainable management of hemlock ecosystems in eastern North America; 1999 June 22-24; Durham, NH. Gen. Tech. Rep. NE-267. Newtown square, PA: U. S. Department of Agriculture, Forest Service, Northeastern Research Station: 135-143.

Zahner, R. 1994. The Mountain at the End of the Trail: A History of Whiteside Mountain. Highlands, NC, USA (private publisher).