IMPACT OF THE HEMLOCK WOOLLY ADELGID ON RADIAL GROWTH OF EASTERN HEMLOCK IN PENNSYLVANIA

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Abstract—We evaluated the past 60-70 years of radial growth of old-growth eastern hemlock [*Tsuga canadensis* (L.) Carr] infested with the hemlock woolly adelgid (*Adelges tsugae* Annand) in south-central Pennsylvania. Although undocumented, the initial adelgid infestation may have occurred within the stand in the early 1990s. Increment cores were extracted during May 2003 from lightly infested and severely infested canopy hemlocks. Those hemlocks that were growing more slowly in the decades prior to adelgid infestation ultimately exhibited more severe infestation. This indicates that that slower-growing hemlocks may be inherently more susceptible to the adelgid, or that stressed trees growing on poor sites may be more susceptible. Radial growth of severely infested canopy hemlocks was below normal by the mid-1990s; growth of lightly infested trees began to decline several years later. Severely infested trees exhibited a short-term, spike in growth immediately prior to a precipitous growth decline that eventually lead to mortality.

INTRODUCTION

In eastern North America, the hemlock wooly adelgid (HWA) was introduced into Virginia in the early 1950s (Suoto and others 1996), and has caused mortality of eastern hemlock from New Hampshire to Georgia (Stoetzel 2002). Eastern hemlock has little resistance to this invasive, introduced adelgid, and cannot sprout or refoliate following infestation; hemlocks of all age and size classes may be killed by the adelgid. Presumably, there will be a drastic decrease in eastern hemlock populations and resultant stand composition changes within infested hemlock areas (McClure 1999; Orwig and Foster 1998, 1999).

Severely infested canopy hemlock trees may die within 4 years after the initial infestation by the HWA, or, in contrast, may survive for 10 years after infestation (McClure 1999, Orwig and Foster 1998). In moderately infested stands, suppressed and intermediate canopy trees often experience higher amounts of mortality than dominant and codominant trees, and trees on xeric or stressful sites may exhibit more mortality than trees growing on more mesic sites. Orwig (2002) stated that radial growth of eastern hemlocks declined precipitously in stands heavily infested with the adelgid, but presented only preliminary growth information. Few studies have assessed the effect of the HWA on growth of eastern hemlock, or on the relationship between growth rate and level of infestation. Much remains unknown about the long-term implications of this adelgid on growth of hemlock within forests of eastern North America (Orwig and others 2002, Kizlinski and others 2002). However, dendrochronology (i.e., tree-ring analysis) offers a powerful tool for modeling growth trends and events relating to tree decline and mortality (McClenahen 1995).

The objective of this study was to examine the relationship between infestation by the HWA and radial growth of canopy, old-growth eastern hemlock.

PROCEDURES

Study Area

This study was conducted within the Hemlocks Natural Area (HNA), located within the Ridge and Valley Province of the Susquehanna lowland region in Perry County, PA (40˚15' N, 77˚37' W). The HNA is within the Tuscarora State Forest and encompasses approximately 50 ha of old-growth eastern hemlock in a steep ravine that extends about 2 km in length (Pennsylvania Department of Conservation of Natural Resources, Bureau of Forestry 1998). The area receives approximately 100 cm of annual precipitation,

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has an average annual temperature of 18˚C, and an average temperature of 26˚C from April 1 to August 31 during the growing season. Soils are classified as extremely-stony, sandy-loams that are deep, well drained, and strongly- to extremely-acidic. Stones and rocks 0.5-2 m or more in diameter cover more than 50 percent of the soil surface (U.S. Department of Agriculture, Soil Conservation Service 1986).

By the late 1800s, most old-growth hemlock stands in Pennsylvania had been harvested for their bark that was used for tanning leather; many surviving stands were later cut for lumber. However, the HNA was not logged, and remains one of the few old-growth stands of eastern hemlock in the state. The area has not undergone significant anthropogenic disturbance, and was designated a National Natural Landmark by the National Park Service in 1973. Canopy hemlocks within the stand are several hundred years old; Cook (1982) reported that the oldest hemlock was 448 years old (approximate pith age at 1.4 m in height). Most canopy hemlocks in the stand have a diameter greater than 60 cm dbh; the greatest dbh recorded was 132 cm, and the tallest hemlock was 38 m during the most recent inventory (Pennsylvania Department of Conservation of Natural Resources, Bureau of Forestry 1998).

In addition to eastern hemlock, the HNA contains a cohort of old-growth hardwoods including yellow birch (*Betula alleghaniensis* Britton), sweet birch (*B. lenta* L.), northern red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), chestnut oak (*Q. prinus* L.), black gum (*Nyssa sylvatica* Marsh), yellow-poplar (*Liriodendron tulipifera* L.), cucumbertree (*Magnolia acuminata* L.), and basswood (*Tilia americana* L.). However, eastern hemlock is the dominant tree species in the HNA, representing 80 percent of the old-growth total basal area (Pennsylvania Department of Conservation of Natural Resources, Bureau of Forestry, unpublished census data). Understory vegetation is very sparse beneath the dense hemlock canopy, with pockets of regeneration occurring mainly within canopy gaps. The understory flora is comprised mainly of birch seedlings, woodfern (*Dryopteris* spp.), and mountain winterberry (*Ilex montana* Torr. and Gray), along with a very few hemlock seedlings. The invasive tree-of-heaven [*Ailanthus altissima* (Mill.) Swingle] seedlings are beginning to colonize canopy gaps.

The natural area has not been actively managed since its inception, in order to allow undisturbed processes of tree mortality, decay, and succession to take place (Pennsylvania Department of Conservation of Natural Resources, Bureau of Forestry 1998). This was a rather simple task until infestation by the adelgid. The date of initial infestation in the HNA is unknown, but local accounts state that visual effects of the adelgid were apparent on the hemlocks by the mid-1990s. As of 2002, the old-growth canopy hemlocks in the natural area were experiencing initial mortality caused by the HWA.

Data Collection and Analysis

During May 2003, increment cores were taken from 20 lightly infested and 20 severely infested, codominant, canopy, old-growth, hemlock trees. Lightly infested trees were those that retained mainly green needles and experienced <25 percent defoliation. Severely infested hemlocks retained very few green needles and experienced >50 percent defoliation; crowns of severely infested trees often had a distinct grayish cast. Most canopy hemlocks in the stand were likely infested at time of sampling.

Two cores were extracted from each tree at dbh, 180˚apart, and parallel with the slope contour. Since Cook (1982), had already cored the hemlocks to the pith in this same stand, we extracted shorter cores containing only the past 60–70 years of growth. Increment cores were air-dried, glued in grooved wooden mounts, sanded with progressively finer grits of sand paper, and buffed with lamb's wool to enhance ring boundaries. Cores were visually cross-dated (Stokes and Smiley 1996) to ensure that each ring was assigned to the correct year, and to help with detection of missing, partial, or false rings. Annual ring widths were measured to the nearest 0.001 mm with a Velmex (East Bloomfield, NY) tree ring-measuring device. Data were organized using the program MeasureJ2X (Voor Tech Consulting, Holderness, NH), and initially evaluated using the quality control program COFECHA (Grissino-Mayer 2001; Holmes 1983, 1985). Cores that did not meet quality control standards were re-measured and data re-evaluated using COFECHA. Growth data from cores that still did not meet standards were not used in further analyses.

Mean annual growth patterns (ca. 1930-2002) of lightly infested trees (36 individual cores from 19 trees) were graphed against the mean growth data from severely infested trees (31 individual cores from 17 trees). A dimensionless ratio was constructed as: (mean annual growth of severely infested trees) ÷ (mean annual growth of lightly infested trees) (Davis and Frontz 2003). This ratio allowed a direct comparison of the difference in growth rates of severely vs. lightly infested trees. Since sampled hemlocks were all codominants, and of approximately the same dbh, conversion of raw ring widths to basal area increment (BAI) (Phipps and Field 1988) was deemed not necessary. In addition, we were interested in growth trends, not absolute growth values.

RESULTS

Local reports indicated that the initial adelgid infestation of hemlock in the HNA probably occurred in the early 1990s. Our results reveal anomalous growth patterns beginning approximately with the 1993 growing season, which supports these observations.

Examination of growth patterns prior to infestation revealed that slower growing hemlocks ultimately became more severely infested by the HWA (in 2003), as compared to trees exhibiting better growth (fig. 1). In addition, the slower growing trees generally did not respond as much to favorable environmental growing conditions as compared to the faster growing trees. This is especially noticeable during periods for favorable growth, such as in 1943 and 1973.

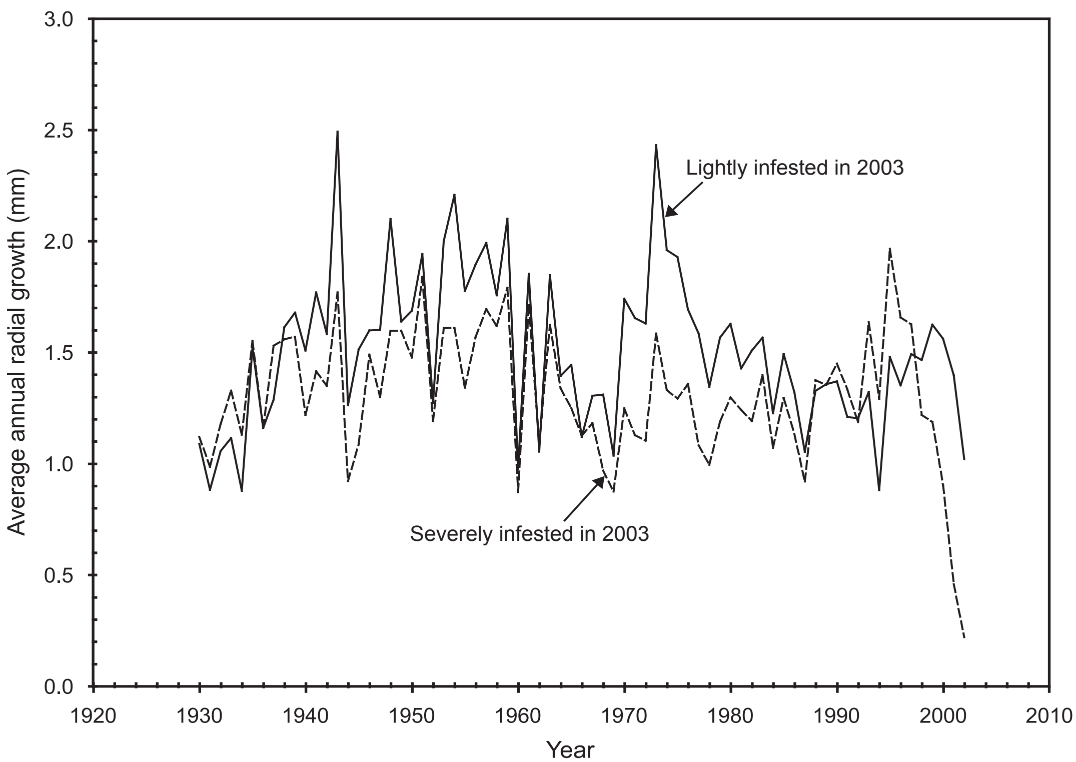

Figure 1—Average annual radial growth (mm) of old-growth eastern hemlock trees within the Hemlocks Natural Area in southcentral Pennsylvania. The solid line indicates growth patterns of trees that were lightly infested (n = 36 cores from 19 trees) at time of sampling in May 2003. Dashed line represents growth patterns of trees that were severely infested (n = 31 cores from 17 trees) at time of sampling.

The calculated ratio (fig. 2), although not illustrating the high frequency variation in annual growth, illustrates even more clearly that trees that became severely infested were growing much slower (ratio < 1.0) during most of the pre-infestation period, as compared to trees that became lightly infested. However, this pattern was not as evident during the early to mid-1930s and 1990s.

Growth patterns of the lightly infested and severely infested trees began to diverge in the early 1990s (figs. 1 and 2). From 1993-1997, growth was greater in the severely infested trees, for the first time since the early 1930s. The calculated ratio illustrates this most dramatically. The ratio noticeably displays the magnitude of the growth decline of the severely infested trees. At the end of the study (May 2003), 7 of the 17 severely infested hemlocks were dead.

DISCUSSION

During the pre-infestation period of 1930-1992, the slower growing hemlocks ultimately became more severely infested by the HWA than did the faster growing trees. The slow growing trees may be located on poor, dry micro-sites within a stand. This may cause increased stress to this shallow-rooted and drought-sensitive species, resulting in less growth before the infestation, as well as more rapid decline following infestation. Orwig and others (2002) reported that hemlock stands on xeric aspects succumb rapidly to infestation, supporting this supposition.

The severely infested hemlocks experienced a sharp increase in growth in 1993, and for the first time since the late 1930s, experienced greater growth rates than did lightly infested hemlocks. Although the reasons for the rapid growth spike are unknown, the increase may be due to growth release due to mortality of adjacent, competing, severely infested trees. In addition, infestation by insects may temporarily stimulate growth of some tree species (Alfaro and Shepherd 1991). Also, increased soil

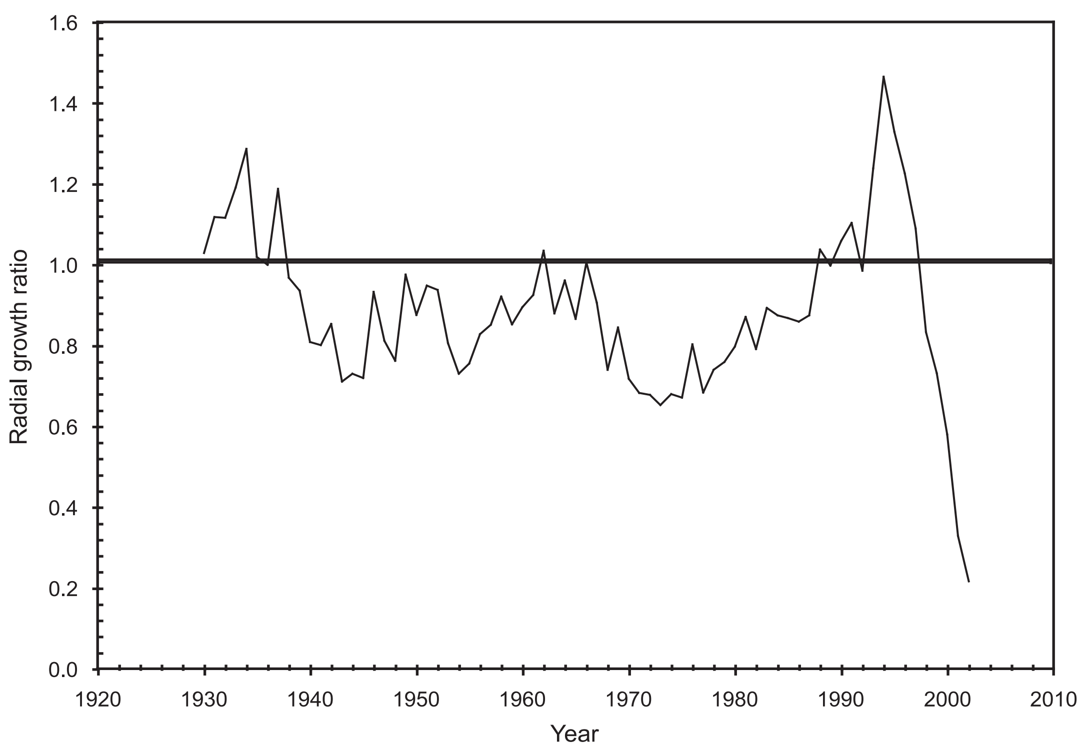

Figure 2—Ratio of average annual radial growth (severely infested:lightly infested) of old-growth eastern hemlock trees within the Hemlocks Natural Area in southcentral Pennsylvania. The horizontal line at 1.0 represents approximately equal growth between trees that were lightly infested (n = 36 cores from 19 trees) vs. trees that were severely infested (n = 31 cores from 17 trees) at time of sampling in May 2003.

nitrogen levels, possibly related to nitrogen in needle-fall from adjacent dying trees (Jenkins and others 1999), may stimulate growth. This growth spike in 1993 further suggests that the adelgid infestation in HNA was well established in 1992, and that the initial infestation likely occurred earlier, before visual symptoms were apparent in the hemlock crowns.

Although faster growing hemlocks became less infested by 2003, radial growth decline was evident within this population beginning around 2000. Duration of infestation ultimately controls the intensity of decline and mortality (Orwig and others 2002), suggesting that these trees will likely continue to decline in following years and succumb to the HWA. Severely infested trees were dying by the end of our study. It took approximately 10 years for mortality to begin in this stand. However, at the current rate of hemlock mortality, most old-growth trees in the HNA may be dead in a few years. This is important, as most old-growth forests on public land in Pennsylvania contain eastern hemlock is a major component of the overstory (www.dcnr.state.pa.us/wrcf/keynotes/summer99/growth.htm). Although small in area, these old-growth hemlock stands are important as watersheds, recreation areas, and various public-use activities. Perhaps more importantly, they serve as a benchmark describing real old-growth conditions. We may have to use such datasets and descriptions in the future, to re-create new stands that will serve as "old-growth" stands for future generations.

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