Proceedings of the 2007 National Silviculture Workshop

# The Role of Silvicultural Thinning in Eastern Forests Threatened by Hemlock Woolly Adelgid (*Adelges tsugae*)

*Mary Ann Fajvan*

## ABSTRACT

In order to increase hemlock survivability in stands threatened by hemlock woolly adelgid (HWA), a new study is developing silvicultural thinning guidelines to reduce stand densities, reallocate resources, and increase hemlock vigor across a range of stand types and structures before HWA invasion. The 7 study areas are all geographically similar in that they regularly experience winter temperatures that can be lethal to hemlock woolly adelgid. The combined effects of climate and silvicultural treatment may serve to moderate adelgid populations and increase hemlock survival. Four Pennsylvania stands received thinnings in 2006 to reduce relative stand density by 30-40%. Half of each stand was not harvested and serve as controls. In New England, four additional sites will be thinned in 2007-08. Pre- and post-harvest sampling includes measurements of stand density and structure, residual "crop" tree stems and crowns; understory vegetation; soil moisture, temperature and nutrients; foliar nutrients; and insect populations.

**Keywords**: hemlock woolly adelgid, silvicultural thinning, stocking, foliar nutrients

This paper was published in: Deal, R.L., tech. ed. 2008. Integrated restoration of forested ecosystems to achieve multiresource benefits: proceedings of the 2007 national silviculture workshop. Gen. Tech. Rep. PNW-GTR-733. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 306 p.

**Mary Ann Fajvan** is a research forester, Northern Research Station, 180 Canfield St., Morgantown, WV 26505

## INTRODUCTION

The hemlock woolly adelgid, (HWA, ***Adelges tsugae*** Annand) is a major threat to the health and sustainability of Eastern North American hemlock species – eastern hemlock (***Tsuga canadensis*** (L.) Carr.) and Carolina hemlock (***Tsuga caroliniana Engelm***.) (Knauer et al. 2002). This introduced insect is currently found in 17 states, covers approximately 50% of eastern hemlock's range (http://www.na.fs.fed.us/fhp/hwa/maps/hwa_2006.pdf), and is causing tree decline and wide-ranging mortality effects. Hemlock mortality associated with HWA establishment can range from almost none to 95% (Bair 2002, Mayer et al. 2002, Orwig and Foster 1998). Mortality can occur quickly and uniformly throughout a stand, especially in the presence of other stressors, or can occur slowly and in patches for more than a decade. The resulting effects on stand dynamics may cause changes in species dominance, age and canopy structures, (Orwig and Foster 1998, Stadler et al. 2006) and hence management direction.

HWA is rapidly spreading to new areas at a rate of 15.6 km/year south of Pennsylvania and 8.13 km/year (or less) in the northern portion of hemlock's range (Evans and Gregoire 2007). Colder winter temperatures are believed to slow spread rates (Evans and Gregoire 2007, Parker et al. 1999). HWA attacks all sizes and ages of hemlock from seedlings to mature canopy trees. Adelgid feeding depletes hemlock's stored nutrient reserves causing a reduction in new shoot production in infested parts of the crown, followed by needle drop, branch tip dieback, foliage thinning, lower branch dieback and mortality in 2 to15+ years (McClure 2001, Mayer et. al 2002, Orwig 2002). Biological and chemical methods to control the pest are costly and impractical for large forest tracts.

The wide range in the rate and extent of eastern hemlock decline and mortality suggest that tree and site variables influence the response of hemlock to HWA infestation. A new study is being implemented to determine if stand structure manipulations can be used ahead of the leading edge of HWA invasion to increase individual host tree and stand resistance. Specifically, silvicultural thinning treatments are being used to remove low vigor trees, which would reallocate site resources to enhance the health of the remaining hemlocks. However, nothing is known about whether such treatments are effective in HWA control. Because thinning also alters forest climate, and soil and foliar nutrient cycles (Van Cleve and Zasada 1979), the attractiveness of thinned stands to HWA feeding must also be evaluated. Therefore, research is needed to determine whether thinning mixed hemlock-hardwood stands to increase the vigor of hemlock trees ahead of the leading edge of HWA will also increase hemlock survivability when HWA attacks a stand. The project involves the collaborative efforts of many individuals from federal and state agencies located in the mid-Atlantic and New England states. Working across organizations and ownerships will develop linkages necessary to translate the research findings quickly and directly to natural resource managers for application.

The study has two objectives. The first is to determine whether thinning mixed hemlock-hardwood stands to increase the vigor of hemlock trees prior to the arrival of HWA will increase the survivability of hemlock when HWA attacks a stand. Scientific and empirical evidence indicates that while healthy hemlocks are not less susceptible to attack, they do have a better chance of surviving longer than stressed trees (e.g., crowded conditions). Increased survivorship may improve hemlock's chances for recovery (Orwig and Foster 1998), especially if HWA populations crash and/or effective biological controls are developed. To monitor the effects of thinning, it is critical in this study that the approximate time of arrival and subsequent spread of HWA in these stands be carefully monitored. The results from the study will provide management options to forest landowners and land managers faced with pending HWA invasion and potentially prevent pre-emptive harvesting of hemlock, which can contribute to future regeneration failures of this species (Brooks 2004).

A second objective is to monitor ecological changes in forest structure as an HWA infestation progresses in thinned and unthinned stands. Treatments are established in a variety of stand structures located on a range of site conditions in the northern portion of hemlock's range. A number of tree health variables (e.g. mortality, foliage density, foliar nutrients, crown transparency, percent dieback, direct HWA counts, and amount of new crown and stem growth) are used to measure the effects of thinning, and subsequent HWA infestation, on hemlock growth and survival (Colbert et al. 2002, Kimple and Schuster 2002, Scudder et al. 2002). Because both thinning and insect infestation can cause increases in soil N mineralization and nitrification rates, in some of the study areas, soil and foliar sampling are also included.

## BACKGROUND

**Use of Silviculture in Invasive Species Management**

Loss of a tree species due to an introduced pest can initiate ecological change and have potential economic effects (Liebhold et al. 1995). The appropriate silvicultural treatment for managing introduced forest pests requires an understanding of the ecological interactions of both the pest and the host species. Integration of silvicultural techniques at a variety of spatial and temporal scales may be necessary to prevent or mitigate the effects of a pest invasion. Because introduced pests have no natural enemies in native forests, traditional silvicultural approaches designed for managing native pests, such as sanitation or salvage operations (Smith et al. 1997) may need to be modified (Waring and O'Hara 2005).

Hemlock's ecological role in eastern forests far outweighs its economic importance. Hemlock's wood characteristics limit its commercial use to relatively low-grade products (Howard et al. 2000) for which market substitutions are easily made. Conversely, hemlocks occupy an extraordinarily important ecological niche in both pure stands and growing in mixture with hardwoods. The species are very tolerant of shade and typically are found in understory positions as well as in sub-dominant overstory canopy positions. Dense hemlock understories utilize growing space that would be lost to less shade-tolerant species (Kelty 1989), provide winter cover and vertical structure for many wildlife species (DeGraaf et. al 1992), and maintain aquatic habitat integrity by shading streams (Evans 2002). Hemlocks grow slowly even when young and at high densities can survive in supressed conditions for hundreds of years (Godman and Lancaster 1990). Self-thinning is slow and canopy disturbance is typically required for accelerated growth to occur.

The extent to which the presence of other insects, site conditions, and stand structure affect hemlock's susceptibility to HWA or vice-versa is still unclear. Hemlocks growing in areas with adequate, consistent moisture are generally less vulnerable to attack and can survive an HWA infestation better than trees growing on droughty or waterlogged sites (Mayer et al. 2002, Orwig 2002, Sivaramakrishnan and Berlyn 2000, Ward et al. 2004). HWA impacts to stem and branch growth typically progress upward from the lower crown, and reduced growth and possible mortality occur depending on infestation intensity and duration. Hemlocks in dominant and codominant overstory crown class positions had lower mortality during moderate infestations than overtopped and intermediate class trees (Orwig and Foster 1998). However, new evidence suggests that live-crown ratio may have a stronger relationship with vulnerability regardless of crown class (Rentch 2007).

HWA invasions typically follow three phases: arrival, establishment and spread (National Research Council 2002). Combined with local quarantines, preventive silvicultural techniques can be used along the leading edge of a HWA outbreak prior to arrival. Seasonal alterations in management activities (e.g. road closures, harvesting) near HWA infested areas can also be preventive (Waring and O'Hara 2005). Curbing management activities during HWA crawler emergence in both early spring and mid-summer may help curtail spread.

Reduction in stand density through thinning and removal of the most vulnerable individuals of targeted host species can be used alone or in combination with eradication tools, to reduce potential infestation targets and minimize mortality. For example, the goal of thinnings used to lower the density of gypsy moth-preferred host species is to select crop trees with the most vigorous crowns because healthier trees can survive years of defoliation (Gottschalk 1993). The best results from this type of density manipulation occur when the treatments are applied before arrival of the pest.

Specific chemical characteristics of the foliage may affect a tree's resistance to HWA or may act as a physiological defense strategy (Clancy et. al 2004). Healthy hemlock forests typically have slow decomposition and N-cycling rates because of their low foliar N content and cool microclimate. Trees infested with HWA were found to have significantly higher needle concentrations of N, Ca, K, Mn, Al, lignin and cellulose compared to those not infested (Pontius et al. 2002); although, total soil nutrient content did not change in infested stands. HWA feeding and needle mortality effects nutrient cycling in the canopy, the chemical composition of the litter, and hence nutrient availability in biogeochemical cycles (Stadler et al. 2006). In HWA-infested forests, nitrogen mineralization and nitrification rates are higher than uninfested forests (Jenkins et al., 1999, Yorks et al. 2000). Yet, there is a decline in nitrogen fluxes over time as infestation increases and needle biomass decreases (Stadler et al. 2006).

Thinning also effects biogeochemical cycles because of increases in light, soil temperature, soil moisture, and litter and root system decomposition, at least until canopy closure (Van Cleve and Zasada 1976). Thinning hemlock stands will probably cause temporary increases in soil nitrification rates, which may or may not cause increases in foliar N and other elements. Depending on individual site conditions for a given stand, microbial soil populations can increase enough to tie up nitrogen so that foliar amounts remain unchanged (Van Cleve and Zasada 1976).

After arrival, the next invasion phase occurs when the pest begins the process of establishing a permanent population. Early in the establishment phase when pest populations are typically low, biological and chemical eradication tools can be successful for removal of all or most individuals, especially if treatments are repeated. There are several insecticides used for controlling HWA (McClure 1991b) but these are only effective as individual tree applications, restricting their use in treating entire stands.

Once an established population begins to rapidly increase, silvicultural efforts should focus on containment of the pest. HWA has been spreading through the Eastern United States for over 50 years (Cheah et al. 2004). Spread rates were initially slow but have increased substantially in the last decade (Ward et. al 2004). In the spread phase, silvicultural efforts target reducing host damage/mortality and slowing the spread.

**Detection and assessment of HWA**

Understanding HWA's complex reproduction cycle is important for monitoring population spread and for planning silvicultural activities. HWA produces abundant progeny in two parthenogenetic (all-female) wingless generations per year. The winter generation develops over 9-10 months (early summer to mid-spring of the following year) and the spring generation occurs from spring to early summer of the same year. These generations overlap in middle to late spring and life cycle timing is influenced by local climate. The winter generation lays up to 300 eggs per female in late winter/very early spring (McClure et al. 2001). The eggs hatch in April and May and mobile brownish-red nymphs ("crawlers") crawl along the branches but can only be dispersed between trees by wind, animals and humans. Crawlers settle on twigs and insert their stylets into the base of hemlock needles and obtain nutrients from xylem ray tissue (Young et al. 1995). They remain at the same feeding site for 4 nymphal stages and develop into adults in early June. These spring generation adults lay eggs between mid-June to July, but the number of eggs produced is only 20-75 per adult (McClure 1989). Eggs hatch in early July, enter a summer dormancy period and begin feeding around October. The prolonged winter feeding of this generation allows it to tap into a tree's stored food reserves in the absence of any potential predators.

Several studies examined the spatial distribution and dispersion patterns of HWA throughout the forest (McClure 1990, Gray et al. 1998, Kimple and Schuster 2002). Other studies on egg, crawler and adult distributions (McClure 1990, 1991a, Evans 2004) suggest that HWA is evenly distributed throughout the vertical layers of forest and tree canopies. More recently, however, entire stem and branch dissections reveal that in trees with high HWA populations a larger percentage of nymphs are found in the lower crown while in trees with low HWA populations a larger percentage of nymphs are found in the upper crown (Evans and Gregoire 2007). These findings suggest that early detection of HWA invasion would be more difficult because the population would at first be more numerous in the inaccessible upper crown. Costa (2005) developed a sampling plan for the detection of HWA but it is based on sampling only lower branches within reach. A modified version of his sampling system, as well as visual observation with binoculars will serve as the foundation for the detection surveys in this study. Impact survey assessments similar to those used by Colbert et al. (2002) will be used to measure the effects of HWA on hemlock tree health variables.

**Management Guidelines for Hemlock-Hardwood Stands Threatened by HWA**

Current management guidelines target stands with an identified HWA infestation and anticipated hemlock decline and mortality within several years. Management options include harvesting stands before notable decline, salvage harvesting, felling trees without removal, protecting individual trees using biological controls or insecticides, and taking no action (Ward et. al 2004). Stands are prioritized for type and intensity of management activities based on economic, ecological, esthetic criteria and site characteristics. Regardless of management objective, stands are selected for treatment with the goal of maintaining their health and vigor until effective biological controls are developed.

There are few thinning studies in hemlock-hardwood stands that focus on reducing stand density to favor hemlock growth. Hemlock height and diameter growth after crown release is related to how dense the preharvest stand was and a tree's canopy status (overstory vs. understory) (Merrill and Hawley 1924, Marshall 1927). Trees growing in dense stands showed 60% greater growth after thinning (from above and below) than stands that were understocked. Stands with higher hemlock stocking exclude more rapidly growing shade intolerant competitors and growth is concentrated on the main stem instead of branches (Tubbs 1977). Hemlocks previously growing in suppressed canopy positions tend to have better stem form and faster growth after release than open-grown associates of similar size. Age appears to be a minor factor in tree growth response; older trees typically grow better than younger ones unless a tree has been suppressed for so many decades (>60 years) that it has lost too much crown area to increase growth (Marshall 1927). Generally, hemlock can be thought of as a species that shows a growth response to environmental change based on its size (e.g. smaller trees grow faster than larger trees) and not its age. Evidence from thinned hemlock stands indicates that hemlock can continue favorable volume increases through at least age 200 (Ward and Smith 2000). Current management guidelines recommend that thinning operations should remove at least 6 to 7 $m^2$/ha of basal area; however, if stands are very dense (> 46 $m^2$/ha), basal area removal should not exceed more than 1/3 of the total in any given operation (Lancaster 1985).

In this study, thinnings are designed to reduce stand densities in fully-stocked and overstocked hemlock-hardwood stands and hemlock-hardwood-white pine (*Pinus strobus* L.) stands. When a stand is at full-stocking it contains the maximum sustainable amount of foliage given fixed site resources. Fixed site resources are those resources that cannot be manipulated silviculturally (Vose and Allen 1988). Thinnings reallocate fixed resources among fewer stems increasing the amount of light, water and nutrients per tree. Foliar quantity is affected because of modifications to the branch size – foliage weight relationship and the number and (or) size of branches within the crown (Gillespie et al. 1994). Healthier hemlocks can tolerate high densities of HWA better than can trees of low vigor (McClure 1995, Sivaramakrishnan and Berlyn 2000) and hence may survive or persist longer during an infestation. However, because thinning affects foliar nutrient content, measuring the changes in foliar nutrients in thinned and unthinned stands prior to and during HWA infestation, may indicate whether silvicultural manipulations make hemlocks more or less attractive to HWA attack.

In this study, the silvicultural approach to HWA management is modeled after the gypsy moth management guidelines developed by Gottschalk (1993) from research conducted since the early 1980s. Currently, all standard silvicultural thinning guidelines for hemlock-hardwood stands are based on data from stands in New England and the Lake States (Lancaster 1985, Tubbs 1977), and none of them addresses mitigating the impacts of HWA. Because the study sites are located in areas either on the leading edge of the invasion or up to 10 years away from invasion, pre-arrival stand conditions can be measured, silvicultural treatments applied, and ecosystem responses after arrival and establishment can be monitored.

## METHODS

**Site Selection**

Study sites, on federal and nonfederal land, are being used in the study. Selection criteria include stand size, soil/site limitations to harvest, and stand structure (density, species composition, hemlock component). Stands need to be at least 24 ha and have a minimum of 7 m2/ha of hemlock basal area distributed uniformly throughout the stand. As of May 2007, four stands received treatments on the Allegheny National Forest in northwestern Pennsylvania. An additional Pennsylvania stand, managed by the Pennsylvania Game Commission, is currently being marked for thinning. All those areas were initially overstocked with total basal areas averaging around 46 m2/ha. Three study areas in New England will be thinned in summer/fall 2007. Two stands are on Massachusetts state forest land and the other stand is located at the U.S. Department of the Air Force, New Boston Air Force Station in New Hampshire.

**Treatment**

Prior to timber marking, six, 4-ha treatment blocks are established in each stand. Three of the treatment blocks are then randomly selected to be marked for a thinning to reduce relative stand density 30-40 percent. Because stand structures are typically spatially variable throughout the treatment areas, a combination of low and crown thinning (Smith et al. 1997) is sometimes used to remove hardwood trees overtopping hemlocks with good stem form and live crown ratios > 30%, and to reduce density in hemlock clumps. Hemlocks with <30% live crowns are less likely to respond to the treatment (Smith et al. 1997). Otherwise the treatment is primarily a crown thinning to reduce density among competing hemlocks. Both commercial and noncommercial harvests are sometimes necessary. The other three treatment blocks in each area are not thinned and serve as reference stands for sampling vegetation dynamics pre- and post-HWA invasion.

Trees are marked for thinning according to guidelines developed specific to each stand's characteristics based on recent inventory data summaries. After marking, ten, 0.04 ha circular vegetation sample plots are located in each treatment block according to a systematic random procedure wherein each block is roughly divided into ten, 0.4 ha sections and one sample plot randomly located within each section. In the blocks designated for thinning, a residual hemlock tree that was targeted for canopy release (e.g. has 3-4 surrounding stems marked for removal), serves as the plot center. This center tree is referred to as the "subject" tree. Similar selection criteria are used to identify 10 hemlocks to serve as subject trees in the untreated blocks. In addition to the subject trees, each spring 120 randomly selected hemlock "HWA monitoring" trees at each site (20 trees/block) will be examined for presence of HWA according to a procedure described by Costa (2005) as modified by Turcotte (described in Fajvan et al. 2005).

**Vegetation Sampling**

Plot-level vegetation measurements of overstory and understory are conducted prior to thinning and repeated the first growing season after thinning (Fajvan et al. 2005). Plots are revisited at 1, 3, 5, 7 and 9 years post harvest to re-measure the vegetation. Future sampling will be determined by timing of HWA invasion.

Measurements collected on the subject trees include: stem diameter, total height and height to base of live crown, and crown width. Crown health variables (foliage density, transparency, percent dieback) and branch tip assessments of new growth, are measured according to criteria outlined in Colbert et al (2002). On the Pennsylvania sites, soil and foliar sampling for nutrient elemental content were conducted prior to harvest and continue annually for 5 years starting the first growing season after harvest (Piatek 2006).

## DISCUSSION

Because the timing, extent, and duration of HWA invasion will differ for individual study areas, each 60 + acre stand is considered an experimental unit, with 3 replicated treatment blocks each of thinned and control. Valuable information about the effects of thinning on hemlock growth, vigor, and vulnerability to HWA will be gained by monitoring the subject trees. The value of having pretreatment and pre-HWA vegetation sampling plots will also serve to monitor changes in vegetation structure cause by HWA-induced mortality. In addition, in stands with foliar and soil elemental chemistry monitoring, data will be collected on the effects of thinning on biogeochemical cycles in hemlock-hardwood mixtures. The relationship of foliar nutrients and hemlock's attractiveness and palatability to HWA can be determined as well as the interaction of thinning and HWA infestation on elemental chemistry.

This new study faces many challenges in its implementation and subsequent monitoring. Study areas are geographically distant requiring the coordination of different field personnel to sample vegetation and monitor HWA at each location. HWA is difficult to detect during early stand invasion because initial infestations are typically in upper crown locations, so sites need to be carefully monitored.

At the northern range of HWA spread, cold winters are believed to cause slower spread rates and help explain the longer survival of infested hemlocks (Paradis et al. 2007). The study areas are all located in this northern spread range and it is hoped that the combination of silvicultural thinning to improve hemlock vigor, combined with colder temperatures, will increase survival rates. Entomologists believe that a complex of introduced predatory insects and diseases will be needed to maintain HWA below lethal levels (Ward 2004). Forest managers in the hemlock region need to test various treatments in order to maintain a hemlock component in stands while biological controls are tested and released in the field. Silvicultural thinning is one technique that can be tested in an attempt to avoid the loss of an ecologically important tree species found across most of the eastern United States.

## ACKNOWLEDGEMENTS

This project is a partnership among the U.S. Department of Agriculture, Forest Service Northern Research Station, Northeastern Area State & Private Forestry, Forest Health Protection and the Allegheny National Forest. Other collaborators include: Dr. Kathryn Piatek, West Virginia University; State of Massachusetts Department of Conservation and Recreation, U.S. Department of the Air Force, New Boston Air Force Station, NH, and Pennsylvania Game Commission.

## LITERATURE CITED

**Bair, M.W. 2002**. Eastern hemlock (*Tsuga canadensis*) mortality in Shenandoah National Park. Proceedings: Hemlock Woolly Adelgid in the Eastern United States Symposium. Feb. 5-7, 2002, East Brunswick, NJ, USDA For. Serv./State Univ. of N. J. Rutgers, Onken, B., R. Reardon, and J. Lashomb (eds.), pp. 61-66.

**Brooks, R.T. 2004**. Early regeneration following the presalvage cutting of hemlock from hemlock-dominated stands. Northern Journal of Applied Forestry 21(1): 12-18.

**Cheah, C. M.E. Montgomery, S. Salom, B.L. Parker, S. Costa and M. Skinner. 2004**. Biological Control of hemlock woolly adelgid. Technical Coordinators – R. Reardon and B. Onken. Forest Health Technology Enterprise Team – Technology Transfer: Biological Control. FHTET-2004-04.

**Clancy, K.M., Z. Chen, and T.E. Kolb. 2004**. Foliar nutrients and induced susceptibility: genetic mechanisms of Douglas-fir resistance to western spruce budworm defoliation. Can. J. For. Res. 34: 939-949.

**Colbert, J., M. Seese, and B. Onken, 2002**. Hemlock woolly adelgid impact assessment survey. Proceedings: Hemlock Woolly Adelgid in the Eastern United States Symposium. Feb. 5-7, 2002, East Brunswick, NJ, USDA For. Serv./State Univ. of N. J. Rutgers, Onken, B., R. Reardon, and J. Lashomb (eds.), pp. 323-328.

**Costa, S.D. 2005**. Sampling for detection and monitoring of hemlock woolly adelgid within hemlock stands. Proceedings of the 3rd Symposium on Hemlock Woolly Adelgid in the Eastern United States, Asheville, NC. USDA Forest Service FHTET-2005-01. 384 p.

**DeGraaf, R.M., Yamasaki, M., Leak, W.B. and J.W. Lanier. 1992**. New England wildlife: Management of forested habitats. USDA Forest Service, Gen. Tech. Rep. NE-144. 271 p.

**Evans, A.M. 2007**. The tree crown distribution of hemlock woolly adlegid, *Adelges tsugae* (Hem., *Adelgidae*) from randomized branch sampling. J. Appl. Entomol. 131(1): 26-33.

**Evans, A.M. 2004**. Initial results in measuring hemlock woolly adelgid populations in trees and forests. Forestry Across Borders, 84th Winter Meeting, New England Society of American Foresters, Quebec City, Canada, Mar. 23-26, 2004. USDA For. Serv. NE-314. Ward, J.A. and M.J. Twery (eds.). pp. 3-5.

**Evans, R.A. 2002**. An ecosystem unraveling? In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America; 2002 February 5-7; East Brunswick, NJ. N.J. Agricultural Experiment Station, Rutgers University. pp. 9-12.

**Evans, A.M. and T.G. Gregoire. 2007**. A geographically variable model of hemlock woolly adelgid spread. Biological Invasions (In Press).

**Fajvan, M.A., Gottschalk, K.W., Turcotte, R. and A. Hille. 2005**. Integration of silvicultural strategies for hemlock management in eastern forests threatened by Hemlock Woolly Adelgid (*Adelges tsugae*). Study Plan. On file at: USDA Forest Service, Northern Research Station, 180 Canfield St. Morgantown, WV. 17 p.

**Gillespie, A.R., Allen, H.Lee, and J.M. Vose. 1994**. Amount and vertical distribution of foliage of young loblolly pine trees as affected by canopy position and silvicultural treatment. Can. J. For. Res. 24: 1337-1344.

**Godman, R.M. and K. Lancaster. 1990**. *Tsuga canadensis* (L.) Carr. Eastern Hemlock *Pinaceae*. Pine Family. In: Burns, R.M. and B.H. Honkala (eds.), Silvics of North America, Vol. 1, Conifers. USDA, Forest Service, Agricultural Handbook 654. Washington, D.C.

**Gottschalk, K.W. 1993**. Silvicultural guidelines for forest stands threatened by the gypsy moth. Gen. Tech. Rep. NE-171. USDA Forest Service, Northeastern Forest Experiment Station. 49 p.

**Gray, D.R., Evans, R.A. and S.M. Salom. 1998**. Hemlock woolly adelgid dispersion and the failure of binomial sampling to estimate population density. Environmental Entomology 27(3):564-571.

**Howard, T, Sendak, P and C. Codrescu. 2000**. Eastern hemlock: A market perspective. In: K.A. McManus, K.S. Shields and D.R. Souto eds. Proc. Symposium on sustainable management of hemlock ecosystems in eastern North America. pp. 161-166.

**Jenkins, J.C., Aber, J.D., and Canham, C.D. 1999**. Hemlock wooly adelgid impacts on community structure and N cycling rates in eastern hemlock forests. Can. J. For. Res. 29: 630-645.

**Kelty, M.J. 1989**. Productivity of New England hemlock/hardwood stands as affected by species composition and canopy structure. Forest Ecology and Management 28:237-257.

**Kimple, A. and W. Schuster. 2002**. Spatial pattern of HWA damage and impacts on tree physiology and water use in the black rock forest, Southern New York. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America; 2002. February 5-7; East Brunswick, NJ. N.J. Agricultural Experiment Station, Rutgers University.

**Knauer, K., J. Linnane, K. Sheilds, and R. Bridges. 2002**. An initiative for management of hemlock woolly adelgid. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America; 2002 February 5-7; East Brunswick, NJ. N.J. Agricultural Experiment Station, Rutgers University. pp. 9-12.

**Lancaster, K.F. 1985**. Managing eastern hemlock a preliminary guide. USDA Forest Service NA-FR-30, 5p.

**Lambdin, P.L. and J.F. Grant. 2004**. Final report: A checklist of the insect fauna associated with eastern hemlock, *Tsuga canadensis* (L.), in the Great Smoky Mountains National Park. Department of Entomology and Plant Pathology, The University of Tennessee, Knoxville, TN. Unpub. Report. 17 p.

**Liebhold, A.M., MacDonald, W.L., Bergdahl, D., and V.C. Mastro. 1995**. Invasion by introduced forest pests: A threat to forest ecosystems. For. Sci. Monograph 30: 41-49.

**Marshall, R. 1927**. The growth of hemlock before and after release from suppression. Harvard Forest Bulletin #11. 43 p.

**Mayer, M., R. Chianese, T. Scudder, J. White, K. Vongpaseuth, and R. Ward. 2002**. Thirteen years of monitoring hemlock woolly adelgid in New Jersey forests. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid in Eastern North America; 2002 February 5-7; East Brunswick, NJ. N.J. Agricultural Experiment Station, Rutgers University, pp. 50-60

**McClure, M.S. 1989**. Evidence of a polymorphic life cycle in the hemlock woolly adelgid. *Adelges tsugae* (*Homoptera: Adelgidae*). Annals of the Entomological Society of America 82:50-54.

**McClure, M.S. 1990**. Role of wind, birds, deer and humans in the dispersal of hemlock woolly adelgid (*Homoptera: Adelgidae*). Environ. Entomol. 19(1): 36-43.

**McClure, M.S. 1991a**. Density-dependent feedback and population cycles in *Adelges tsugae* (*Homoptera: Adelgidae*) on *Tsuga canadensis*. Environ. Entomol. 20(1): 258-264.

**McClure, M.S. 1991b**. Pesticides will protect ornamentals from hemlock woolly adelgid. Frontiers of Plant Science 44 (1):2-3.

**McClure, M.S. 1995**. Managing hemlock woolly adelgid in ornamental landscapes. Connecticut Agricultural Experiment Station Bulletin 925. 7p.

**McClure, M.S. 2001**. Biological control of hemlock woolly adelgid in the eastern United States. FHTET 2000-08. Morgantown, WV: USDA Forest Service. Forest Health Technology Enterprise Team; 10 p.

**McClure, M.S., Salom, S.M., and K.S. Shields. 2001**. Hemlock woolly adelgid. FHTET-2001-03. Morgantown, WV: USDA Forest Service. Forest Health Technology Enterprise Team; 14 p.

**McWilliams, W.H. and T.L. Schmidt. 2000**. Composition, structure and sustainability of hemlock ecosystems in eastern North America. In: K.A. McManus, K.S. Shields and D.R. Souto eds. Proc. Symposium on sustainable management of hemlock ecosystems in eastern North America; 1999 June 22-24; Durham, NH. GTR-NE-267. Newtown Square, PA; USDA Forest Service, Northeastern Research Station, pp. 5-10.

**Merrill, P.M. and R.C. Hawley. 1924**. Place of Hemlock in Silviculture. Yale School of Forestry and Environmental Studies Bulletin #12. New Haven, CT.

**National Research Council. 2002**. Predicting invasions of nonindigenous plants and plant pests. National Academy Press, Washington, D.C.

**Orwig, D.A. 2002**. Stand dynamics associated with chronic hemlock woolly adelgid infestation in southern New England. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid in Eastern North America; 2002 February 5-7; East Brunswick, NJ. N.J. Agricultural Experiment Station, Rutgers University. pp. 36-46.

**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 (1): 60-73.

**Paradis, A., Elkinton, J., Hayhoe, K., and J. Buonaccorsi. 2007**. Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (*Adelges tsugae*) in eastern North America. Mitigation and Adaptation Strategies for Global Change (In Press).

**Parker, B.L., Skinner, M., Gouli, S., Ashikaga, T., and H.B. Teillon. 1999**. Low lethal temperatures for hemlock woolly adelgid (*Homoptera: Adelgidae*). Environmental Entomology 28: 1085-1091.

**Pontius, J., Hallett, R. and M.Martin. 2002**. Examining the role of foliar chemistry in hemlock woolly adelgid infestation and hemlock decline. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid in Eastern North America; 2002 February 5-7; East Brunswick, NJ. NJ Agricultural Experiment Station, Rutgers University.

**Piatek, K. 2006**. Changes in soil and foliar nutrient status of eastern hemlock – A cause or consequences of HWA attack? Study Plan. On file at: USDA Forest Service, Northern Research Station, 180 Canfield St. Morgantown, WV. 8 p.

**Rentch J. 2007**. Dendrochronological analyses for determination of host plant resistance to hemlock woolly adelgid: a logistic model. 33. p. Unpublished report. On file with: Forest Service, U.S. Department of Agriculture, Northern Research Station, 180 Canfield St., Morgantown, WV 26505.

**SAS Institute Inc. 2004**. SAS/STAT 9.1 User's Guide. Cary, NC: SAS Institute Inc.

**Scudder, T., M. Mayer and R. Chianese. 2002**. The effect of the Hemlock woolly adelgid, *Adelges tsugae* (*Homoptera: Adelgidae*) in the natural hemlock stands in New Jersey. Annual Report. Division of Plant Industry, Phillip Alampi Beneficail Insect Laboratory, Trenton, NJ. 8 p.

**Sivaramakrishnan, S and G.P. Berlyn. 2000**. The role of site conditions in survival of hemlocks infested with the hemlock woolly adelgid: Amelioration through the use of organic biostimulants. In: K.A. McManus, K.S. Shields and D.R. Souto eds. Proc. Symposium on sustainable management of hemlock ecosystems in eastern North America. pp. 201-204.

**Smith, D.M., Larson, B.C., Kelty, M.J. and P.M.S. Ashton. 1997**. The practice of silviculture: Applied forest ecology. Wiley, New York. 537 p.

**Stadler, B., Muller, T and D. Orwig. 2006**. The ecology of energy and nutrient fluxes in hemlock forests invaded by hemlock woolly adelgid. Ecology 87(7): 1792-1804.

**Tubbs, C.H. 1977**. Manager's handbook for northern hardwoods in the North Central States. USDA For. Serv. Gen. Tech. Rep. NC-39. 29 p.

**Vose, J.M. and H.L. Allen. 1988**. Leaf area, stemwood growth and nutrient relationships in loblolly pine. For. Sci. 34:547-563.

**Ward, J.S., Montgomery, M.E., Cheah, C.A.S.-J., Onken, B.P. and R.S. Cowles. 2004**. Eastern hemlock forests: Guidelines to minimize the impacts of hemlock woolly adelgid. USDA Forest Service, Northeastern Area State and Private Forestry, NA-TP-03-04, Morgantown, WV. 27 p.

**Ward, J.S. and D.M. Smith. 2000**. Dynamics of Connecticut hemlock stands. In: K.A. McManus, K.S. Shields and D.R. Souto eds. Proc. Symposium on sustainable management of hemlock ecosystems in eastern North America. pp. 50-54.

**Waring, K.M., and K.L. O'Hara. 2005**. Silvicultural strategies in forest ecosystems affected by introduced pests. Forest Ecology and Management 209: 27-41.

**Yorks, T. E., Jenkins, J.C., Leopold, D.J., Raynal, D.J. and Orwig, D.A. 2000**. Influences of eastern hemlock mortality on nutrient cycling. In: K.A. McManus, K.S. Shields and D.R. Souto eds. Proc. Symposium on sustainable management of hemlock ecosystems in eastern North America; 1999 June 22-24; Durham, NH. GTR-NE-267. Newtown Square, PA; USDA Forest Service, Northeastern Research Station, pp. 126-133.

**Young, R.F., Shields, K.S. and G.P. Berlyn. 1995**. Hemlock woolly adelgid (*Homoptera: Adelgidae*): Stylet bundle insertion and feeding sites. Ann. Entomol. Soc. America. 88(6):827-835.