

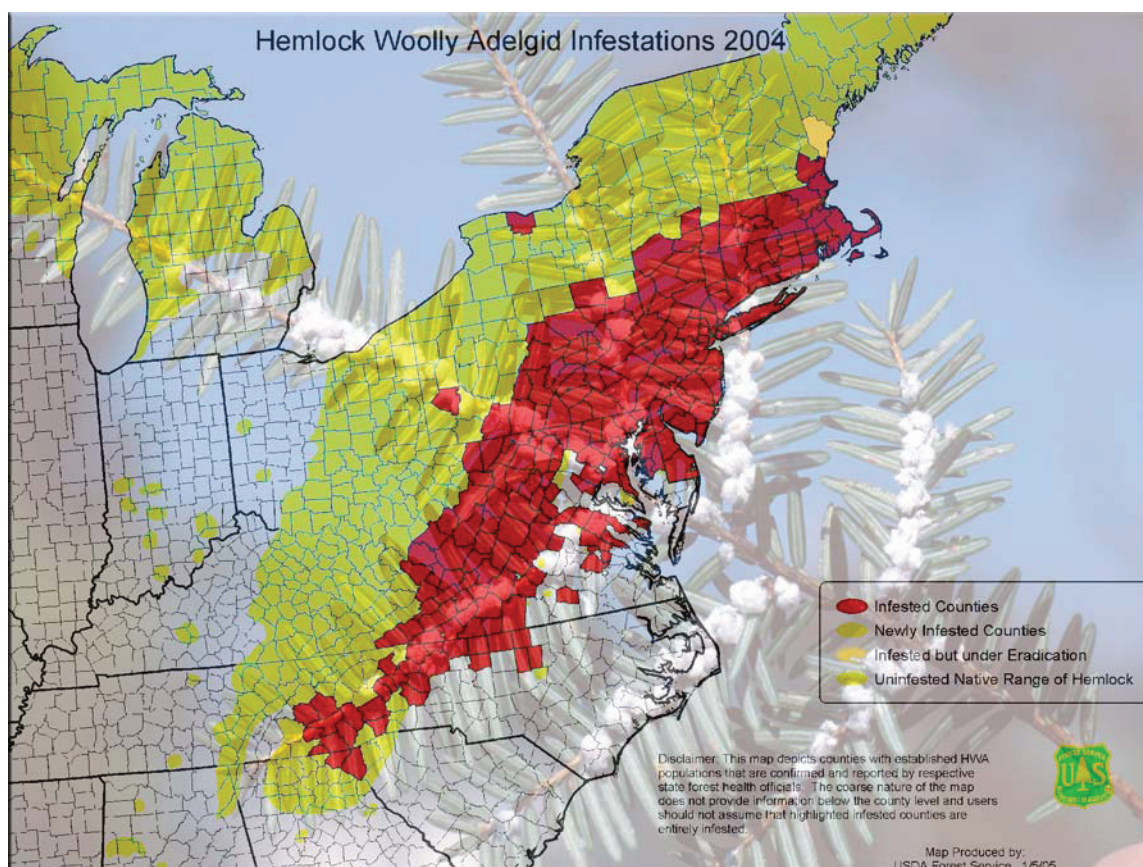
Forest Health Technology Enterprise Team

TECHNOLOGY
TRANSFER

*Hemlock Woolly
Adelgid*

THIRD SYMPOSIUM ON HEMLOCK WOOLLY ADELGID IN THE EASTERN UNITED STATES

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HOST INTERACTIONS OF THE BALSAM WOOLLY ADELGID

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ABSTRACT

The balsam woolly adelgid (BWA), *Adelges piceae* Ratz., has caused immense damage to native and planted fir stands for the past century. This paper highlights the current understanding of the initiation of damage by the insect and the host responses to the insect. Although most native North American firs (*Abies* spp.) are highly susceptible to the adelgid, other firs exhibit a range of resistance and some can tolerate even heavy infestations. Possible mechanisms for resistance are discussed.

INTRODUCTION

The balsam woolly adelgid (BWA), *Adelges piceae* Ratz. (Hemiptera: Adelgidae), an inconspicuous insect that feeds on true firs, has caused considerable damage in North American fir stands for the last century. Native stands of mature Fraser fir (*Abies fraseri* [Pursh] Poir.) in the southern Appalachians have come close to elimination (Dull et al. 1988), and the adelgid has altered the composition of the surviving stands (Jenkins 2003). The balsam fir (*Abies balsamea* [Linn.] Mill.) forests of New England and Canada and the mixed fir forests of the Pacific Northwest have been continually plagued by the insect for almost 100 years and the natural stands of Fraser fir in the Southern Appalachians for over 50 years. Grand fir (*Abies grandis* [Dougl.] Lindl.) is gradually being eliminated from low elevation landscapes in the Pacific Northwest and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) is being removed as a pioneer tree species in the Cascades (Mitchell and Buffam 2001).

Accidentally introduced into Maine and Nova Scotia around the turn of the 20th Century, (Balch 1952), most likely on imported nursery stock of European silver fir (*Abies alba* Mill.), BWA had become established on balsam fir in Maine by 1908 (Kotinsky 1916). The adelgid was first reported on Fraser fir in the Southern Appalachians on Mount Mitchell in 1957 (Speers 1958) and quickly spread throughout the natural range of Fraser fir. On the West Coast, it was first reported on ornamental firs near San Francisco (Annand 1928). In the Pacific Northwest, it was first reported on grand fir in the Willamette Valley of Oregon (Keen 1952). There, the most frequent hosts are Pacific silver fir (*A. amabilis* [Dougl.] Forbes) and subalpine fir at high elevations and grand fir in valleys (Mitchell et al. 1961). The adelgid was reported in British Columbia on Pacific silver fir and on Vancouver Island on grand fir by the late 1950s (Silver 1959).

SUBSPECIES OF THE BWA

Three geographic subspecies of *A. piceae* Ratz. have been identified in North America (Foottit and Mackauer 1983). *Adelges piceae piceae* (Ratzeburg 1844) has been observed in British Columbia, the Pacific Northwest, and in the native Fraser fir range in the Southern Appalachians. This subspecies corresponds morphologically to Pschorn-Walcher and Zwolfer's *forma typica* (1956) and the 'intermediate group' of Foottit and Mackauer (1980). *Adelges piceae canadensis* (Merker and Eichhorn 1956) is found on balsam fir in Quebec and the maritime provinces of Canada, and in the northeastern United States. *Adelges piceae occidentalis*, subsp. nov. has been observed on Pacific silver fir and grand fir in British Columbia and may be the result of a single introduction. The subspecies are based on the morphological differences of first instars and adults between the three subspecies (e.g., body shape, length, dorsal plates, fusion of pleural and mesial plates, shape of pore fields of mesial plates, number and range of wax pores, etc.).

LIFE HISTORY OF ADELGES PICEAE

In North America, *A. piceae* exhibits an anholocyclic mode of generation on fir and does not migrate to spruce (*Picea*), as it does in its native range. The sistens form is wingless and develops on the stem (lenticels, crevices in bark, or callus tissue), branches, or bases of buds (Crystal 1925, Balch 1952). The number of sistens generations per year depends upon temperature and host condition. There is only one hiemosistens generation per year and as many as three or four aestivosistens generations. The sistens—both hiemosistens and aestivosistens—develop through four stages after emerging from the egg: first instar (crawler, neosistens), second and third instar, and adult. The progrediens form, which never overwinters and rarely enters into any period of diapause, can be wingless (aptera) or winged (alata) and develops on the needles of fir (Crystal 1925, Balch 1952, Varty 1956). The progrediens form, observed only in the subspecies *A. piceae canadensis* in North America (Foottit and MacKauer 1983), arises from the first eggs laid by the hiemosistens, differs morphologically from the sistens, and has a shorter embryonic developmental period than the sistens (Eichhorn 1969).

INITIATION OF DAMAGE TO INDIVIDUAL TREES

Balch (1952) described the process of feeding, a summary of which follows. *Adelges piceae* has piercing-sucking mouthparts (stylets) and feeds on parenchyma tissue within the outer 1.5 mm of bark or on twigs at the base of buds. The stylets are inserted through the phellem (epidermis) into the phelloderm (cortex), probing between cells, until a suitable feeding site can be located. Salivary secretions, which can flow into intercellular spaces, are exuded from the tip of the maxillae to form a sheath that lines the path of the stylets. The neosistens inserts its stylets full length before entering diapause. Feeding occurs through repeated partial withdrawal and reinsertion of the stylets in a new direction. The stylets are withdrawn and completely renewed at each molt, with the new stylets inserted near the original point of entry.

The tracks are branched and affect tissue in a 360° pattern. Aphids feed in a similar pattern and are able to assess feeding sites by intermittently ejecting and sucking back up a watery saliva along with soluble material from the host; this watery saliva is diffused into surrounding tissue and can be transported within the host plant (Miles 1965 and 1999). Because of the close relationship between aphids and adelgids, and the many similarities in feeding patterns and capabilities, it is likely that adelgids also secrete the watery saliva, which is then transported through the tree.

The adelgid's salivary secretions appear to create a chemical imbalance within the tree and disrupt the development of normal tissue. Auxin-like compounds (Balch et al. 1964) and pectinase (Adams and McAllan 1958, Forbes and Mullick 1970) have been found in adelgid saliva. Additionally, the gel-like stylet sheath may often form a barrier around damaged parts of parenchyma cells, preventing the disintegration and rupture of cell vacuoles, which would normally be followed by the production of autotoxic defensive compounds in surrounding cells (Miles 1999). The stylet sheath can also slow down or prevent the production of the phenolics that arise from and promote necrosis by adsorbing and immobilizing the phenolics (Miles 1999).

RESPONSE OF *ABIES* SPECIES TO *ADELGES PICEAE* ATTACK

All *Abies* species are susceptible, in varying degrees, to some species of adelgid throughout the world, and susceptibility to *A. piceae* attack varies widely. Firs native to North America (subalpine fir, balsam fir, and Fraser fir) are highly susceptible. Some western species (grand fir, sacred fir [*Abies religiosa* (H.B.K.) Schlecht. et Cham], and noble fir [*Abies procera* Rehd.]) and firs native to central Europe tolerate infestation (Varty 1956, Mitchell 1966), while some Asian species (Veitch fir [*Abies veitchii* Lindl.] and Momi fir [*Abies firma* Sieb. et Zucc.]) appear to be immune to attack, at least in North America (Hall et al. 1971).

Adelgid infestations follow a general trend. The initial infestation begins with a few large trees, generally with deep fissures, and then spreads to nearby trees. The population peaks and when many trees have been killed or are damaged, the population diminishes. This second period may go on for an indefinite period of time and is characterized by increasing gout and gradual dying of trees. Some trees may nevertheless recover. The first outbreak is generally the most severe (Balch 1952), but the infestations can persist for decades, and many stands are gradually succumbing to the stress (Mitchell and Buffam 2001). Stem attack is generally observed in continental climatic zones and twig attack in maritime zones (Greenbank 1970, Schooley and Bryant 1978). Mass stem infestations can cause tree mortality within two to three years. With a crown infestation, the tree will suffer branch dieback and general deterioration, and it can take as long as 10 to 20 years for mortality to occur (Bryant 1974).

Some species exhibit a 'bottom-up' pattern of infestation, wherein the infestation begins on the lower portion of the stem and works upwards towards the crown over time (e.g., in grand fir [Mitchell 1966] and Fraser fir [Amman and Talerico 1967]). Others exhibit a 'top-down' pattern, with the infestations beginning in the crown and working downward (e.g., in balsam fir [Greenbank 1970]). All ages of fir in plantations are susceptible, particularly with

Fraser fir, while in natural stands, older, mature trees are more susceptible. This begs the question as to whether there is something in younger trees—physical or chemical—that protects them from severe infestations.

Infestations are generally classified as “stem” or “crown” infestations. The damage, both microscopic and macroscopic, is fairly consistent among all susceptible firs. With a crown infestation, gouting is apparent. Growth of wood and bark is stimulated at the point of stylets insertion and both hypertrophy and hyperplasia occur. An enlargement of parenchyma cells (up to six or seven times the size of normal cells), including cell walls and nuclei, occurs and these large cells are continually produced, causing swelling of the twigs and in the bark (Balch 1952). Pock-like swellings are often observed on the bark of young trees (Rudinsky 1956). The number of rays increase (Doerksen and Mitchell 1965), as do the number of parenchyma strands (Smith 1967). Large reductions in carbohydrate reserves of needles and twigs have been observed (Puritch and Talmon-De L’Armee 1971). Increasing numbers of these enlarged parenchyma cells disrupt the phloem channels and interfere with the metabolic pathways in the bark (Bryant 1971). Bud growth often ceases and the twig begins to die back from the ends—a flattened top is often observed in infested trees (Balch 1952, Mitchell 1967). In fact, this loss of apical dominance (observed in stem infestations as well as crown infestations) is often the first symptom looked for in Fraser fir Christmas tree plantations when scouting for *A. piceae* infestation (Sidebottom 2004). In addition to gouting, the number and length of branches and the length of the stem are often reduced in a crown infestation (Balch 1952, Schooley 1974).

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With a stem infestation, although the stylets of the adelgid can be up to 5 mm from the vascular cambium, xylem production is often compromised resulting in abnormal wood called ‘rotholz’ or ‘redwood’. Rotholz is anatomically similar to compression wood in conifers (Balch 1952). These resultant tracheids are circular rather than rectangular (Timell 1986); are short, thick walled, and highly lignified with small lumens (Doerksen and Mitchell 1965); have a reduced number of conducting pits (Puritch and Petty 1971), higher specific gravity, and greater fibril angle (Foulger 1968); and often have encrusted pit membranes such as those found in heartwood (Puritch and Johnson 1971). Traumatic resin ducts may form in the xylem (Saigo 1976). Sapwood permeability in grand fir has been reduced to 5% of that of normal sapwood (Puritch 1971). Ultimately, these changes throw the tree into physiological drought, reducing the flow of water within the tree and compromising photosynthesis, transpiration, and respiration (Puritch 1973). Heavy infestations can result in tree mortality in one to two years (Balch 1952). Adelgid infestation appears to contribute to premature heartwood formation (Puritch 1977). Rotholz production has also been associated with a significant increase in the proportional area of heartwood (Hollingsworth et al. 1991) and higher percentages of latewood (Doerksen and Mitchell 1965, Smith 1967).

The changes that take place in the bark of the fir trees initially create a more favorable environment for adelgid development, and in the early stages of an infestation fecundity is at its peak; as the trees weaken and the population begins to dwindle, fecundity also decreases (Pschorn-Walcher and Zwolfer 1958, Amman 1970).

HOST RESPONSES THAT MAY AID IN RESISTANCE

Some responses to adelgid attack may aid in the resistance or tolerance to infestation. Many conifers have the ability to form a secondary periderm, consisting of necrophylactic tissue, around a wound (Mullick 1975, Hain et al. 1991). This wound healing mechanism can isolate an area of bark occupied by the adelgid and can effectively protect the underlying bark from further attack for years (Balch 1952, Mullick 1971). It has been hypothesized that the formation of the protective secondary periderm may be inhibited or compromised by chemicals secreted by the adelgid's stylets (Mullick 1975, 1977), though subsequent research has both supported (Hay and Eagar 1981) and failed to support (Arthur and Hain 1985) this hypothesis.

Juvabione or juvabione-like compounds may be produced in response to adelgid attack, as has been evidenced in grand fir and Pacific silver fir (Puritch and Nijholt 1974) and Fraser fir (Fowler et al. 2001). Juvabione-like compounds, which were first discovered in 1965—the famous ‘paper factor’ of Slama and Williams (1965) isolated from paper towels produced from balsam fir fiber (most likely adelgid-infested balsam fir)—mimic insect juvenile hormones and have been shown to inhibit or disrupt normal development in a number of insects, including *A. piceae* (Fowler 1999). It is possible that, in mature firs that exhibit some resistance or tolerance to BWA, there is a rapid accumulation of chemicals (monoterpenes and juvabione-like sesquiterpenoids) at the site of attack that may interfere with adelgid development. Younger trees or seedlings may be protected by a naturally high accumulation of juvabione-related compounds.

Some firs, particularly grand fir, produce copious amounts of resin in response to wounds. This may serve as a means of resistance, as grand fir is one of the more resistant species of American firs, with only 20–30% mortality associated with adelgid infestation (Mitchell 1966). Many conifers have evolved resin-based defenses, such as oleoresin—a mixture of terpenoids consisting of a terpentine and rosin fraction—to deter insect pests and their symbiotic fungal pathogens. True firs store only small amounts of primary resin in bark blisters, but respond to wounding by producing oleoresins in nonspecialized, adjacent tissues. But increased resin production may be only a short-term solution to BWA. For example, in *A. grandis*, after two to five years of adelgid feeding, a portion of bark below the surface dies, the bark turns black, and this is accompanied by a heavy resin flow. This discourages further attack, but after a few years, the resin hardens and the bark develops fissures, whereupon the adelgids are able to reinfest the same areas (Mitchell 1966).

OTHER FACTORS THAT MAY AID RESISTANCE

The onset of water stress (physiological drought), one of the chief factors in susceptibility to damage, differs among fir species, and those exhibiting a more rapid onset are more susceptible to intense damage (Varty 1956, Mitchell 1967). It follows that species or individual trees within a species that exhibit high levels of drought resistance would also be more resistant or tolerant of BWA.

Production of thick outer bark, as found in European silver fir, has been associated with resistance to or recovery from adelgid attack (Pschorn-Walcher and Zwolfer 1958, Schooley and Bryant 1978).

The texture of the bark may also be an important factor in resistance or susceptibility. Rough or flaky bark may be more preferable for *A. piceae* for a number of reasons, including the interception of airborne eggs and crawlers, stereotropism (the insect is stimulated to grow or change in response to touch), and more easily accessible nutritive areas (e.g., lenticels and bark crannies) composed of young parenchyma (Varty 1956). In fact, lenticel development has been observed to be 'the best single predictor' for BWA population levels on Fraser fir in the Great Smoky Mountains (Hay and Eagar 1981).

Some provenances of Fraser fir appear to respond to adelgid infestation differently than others. For example, BWA infestation was not discovered on Mount Rogers until 1979, although there was evidence that some trees had been under attack for up to 17 years (Haneman et al. 1981), and high mortality was not observed until the 1990s. Mount Rogers' trees become heavily infested but do not appear to suffer rapid mortality (Hollingsworth and Hain 1991, Nicholas et al. 1992). The fir trees on Mount Rogers have been shown to be genetically different (unique allele frequencies) from other natural populations of Fraser fir (Ross 1988), but these differences have not been correlated with susceptibility to adelgid infestation (Hain et al. 1991). Nonetheless, Mount Rogers trees have been shown to form lower levels of rotholz and higher levels of secondary periderm in response to adelgid attack when compared to trees from Mount Mitchell (Hollingsworth and Hain 1992). It has been suggested that these trees may possess the ability to develop secondary periderm more rapidly than those in other locations—this characteristic may aid in adelgid tolerance (Hay and Eagar 1981). Additionally, the trees on Mount Rogers may be less likely to suffer water stress when infested partly due to environmental factors (deep soil, little wind) (Hollingsworth and Hain 1994).

Within the natural range of Fraser fir, although the majority of mature fir trees have been killed, there are remnant populations that have survived multiple decades of adelgid attack. It remains to be seen as to whether these trees have survived as a result of genetic resistance or whether the environment (most are at the highest elevations) plays a more important role.

Among and within all *Abies* species, even those highly susceptible to BWA, trees have been observed time and again to tolerate and even recover from adelgid attack. It is not an uncommon occurrence for balsam fir to recover from adelgid attack after a few years with a replacement of the original leaders and relatively small stem deformities from gouting (Balch and Carroll 1956, Schooley 1976, Schooley and Bryant 1978). Although Mount Mitchell Fraser firs suffered high mortality during the initial wave of infestation, have been shown to be highly susceptible to adelgid damage (Dull et al. 1988), and individual trees cored at Mount Mitchell showed production of rotholz at some point, the trees were uninfested and otherwise appeared healthy (Hain et al. 1991).

CONTINUING THE RESEARCH

Much of the current research focuses on understanding interactions between adelgid, host tree, and the environment. Putative genetic resistance—even within a highly susceptible species such as Fraser fir—is believed to exist, and studies are underway to begin the process of screening across and within *Abies* species for host resistance to BWA. Bark and wood chemicals associated with resistance are being isolated, and studies into the genetic components of resistance continue. The adelgid itself continues to be studied and a method of artificially rearing the insect is currently being developed. Biological control continues to be an area of interest, particularly in Christmas tree plantations at lower elevations.

Balsam woolly adelgid research is as critical now as ever. The insect is a tremendous problem in Christmas tree plantations and costs growers thousands upon thousands of dollars each year. Native stands of Fraser fir exist only in small island populations at the highest elevations in southern Virginia, western North Carolina and eastern Tennessee. Most mature trees were killed during the initial phase of adelgid infestation, but fortunately, many areas were repopulated with young natural seedlings. These regenerated stands have now reached the age wherein they become more susceptible to adelgid attack. The adelgids have continued to exist at low levels in the native stands, and the question arises as to whether the regenerated firs are more resistant to the adelgid than their predecessors. Adelgid populations should be evaluated to determine whether they are increasing, and the compounding effects of air pollution on the physiology of both tree and adelgid should be further assessed.

Researchers continue to delve into the interactions between the balsam woolly adelgid and its host species, advancing the understanding of both insect and host genetics and physiology. The hope remains that host resistance mechanisms can be identified and that, between the inherent resistance in some trees and the breeding or nurturing of resistance in others, the balsam woolly adelgid can be better tolerated in plantations and natural stands and that Fraser fir will remain an important component in the high elevation ecosystems of the Southern Appalachians.

REFERENCES

- Adams, J.B. and J.W. McAllan. 1958. Pectinase in certain insects. *Canadian Journal of Zoology* 36: 305-308.
- Amman, G.D. and R.L. Talerico. 1967. Symptoms of infestation by the balsam woolly aphid displayed by Fraser fir and bracted balsam fir. USDA Forest Service Research Note SE-85. 4 p.
- Amman, G.D. 1970. Phenomena of *Adelges piceae* populations (Homoptera: Phylloxeridae) in North Carolina. *Annals of the Entomological Society of America* 63(6):1727-1734.
- Annand, P.W. 1928. A Contribution Toward a Monograph of the Adelgidae (Phylloxeridae) of North America. Stanford University Press, Palo Alto, California. 146 p.
- Arthur, F.H. and F.P. Hain. 1985. Effects of selected chemicals on non-suberized impervious tissue (NIT) formation in Fraser fir. *Journal of Entomological Science* 20(3):305-311.

- Balch, R.E. 1952. Studies of the balsam woolly aphid, *Adelges piceae* (Ratz.) and its effect on balsam fir, *Abies balsamea* (L.) Mill. Canadian Department of Agriculture Publication 867. 76 p.
- Balch, R.E. and W.J. Carroll. 1956. The balsam woolly aphid. Canadian Department of Agriculture, Forest Biology Division, Publication 977. 7 p.
- Balch, R.E., J. Clarke, and J.M. Bonga. 1964. Hormonal action in products of tumors and compression wood (in *Abies balsamea*) by an aphid (*Adelges piceae*). *Nature* 202:721-722.
- Bryant, D.G. 1974. A review of the taxonomy, biology and importance of the adelgid pests of true firs. Canadian Forest Service, Newfoundland Forest Research Centre, Information Report N-X-111. 50 p.
- Bryant, D.G. 1971. Balsam woolly aphid *Adelges piceae* (Homoptera: Phylloxeridae) seasonal and spatial development in crowns of balsam fir, *Abies balsamea*. *Canadian Entomologist* 103:1411-1420.
- Crystal. 1925. The genus *Dreyfusia* in Britain and its relation to the Silver fir. Phil. Trans. London Roy. Soc., Ser. B., CCXIV:29-61.
- Doerksen, A.H. and R.G. Mitchell. 1965. Effects of the balsam woolly aphid upon wood anatomy of some western true firs. *Forest Science* 11:181-188.
- Dull, C.W., J.D. Ward, H.D. Brown, G.W. Bryan, W.H. Clerke, and R.J. Uhler. 1988. Evaluation of spruce and fir mortality in the Southern Appalachian mountains. USDA Forest Service Southern Region Protection Report R8-PR 13.
- Eichhorn, O. 1969. Problems of the determination of morphs in the genus *Dreyfusia* C.B. (Homoptera: Adelgidae), p. 437-446. In Proceedings of the 148th Annual Meeting of the Suisse Society of Natural Sciences in Einsiedeln (Sept. 27-29, 1969).
- Footitt, R.G. and Mackauer, M. 1983. Subspecies of the balsam woolly aphid, *Adelges piceae* (Homoptera: Adelgidae), in North America. *Ann. Entomol. Soc. Am.* 7:299-304.
- Footitt, R.G. and M. Mackauer. 1980. Morphometric variation between populations of the balsam woolly aphid, *Adelges piceae* (Ratzeburg) (Homoptera: Adelgidae), in North America. *Can. J. Zool.* 58:1494-1503.
- Forbes, A.R. and D.B. Mullick. 1970. The stylets of the balsam woolly aphid, *Adelges piceae* (Homoptera: Adelgidae). *The Canadian Entomologist* 102:1074-1082.
- Foulger, A.N. 1968. Effect of aphid infestation on properties of grand fir. *Forest Products Journal* 18(1): 43-47.
- Fowler, G. 1999. The Potential of Juvabione as a Host Resistance Mechanism against the Balsam Woolly Adelgid (*Adelges piceae* [Ratzeburg]). Ph.D. Dissertation, North Carolina State University Department of Entomology. 118 p.
- Fowler, G., J. Zhang, F.P. Hain, and J.F. Manville. 2001. The distribution pattern of two juvenile hormone related compounds in Fraser fir and the induced response to a balsam woolly adelgid infestation. *Canadian Journal of Forest Research* 31(10):1701-1707.

- Greenbank, D.O. 1970. Climate and the ecology of the balsam woolly aphid. *The Canadian Entomologist* 102:546-578.
- Hain, F.P., R.G. Hollingsworth, F.H. Arthur, F. Sanchez, and R.K. Ross. 1991. Adelgid host interactions with special reference to the balsam woolly adelgid in North America. *In* Forest Insect Guilds: Patterns of Interaction with Host Trees, ed. Y.N. Baranchikov, W.J. Mattson, F.P. Hain, and T.L. Payne. U.S. Dept. Agric. For. Serv. Gen. Tech. Rep. NE-153: 271-287.
- Hall, J., P. Singh, and H.O. Schooley. 1971. Survival and growth of some exotic firs in Newfoundland. *For. Chron.* 47:279-291.
- Haneman, D.M., H.L. Lambert, and D.D. Johnston. 1981. Detection and evaluation of the balsam woolly aphid infestations on Mount Rogers, Virginia, 1980. Forest Insect and Disease Management (US Forest Service, Southeast), Report #81-1-12.
- Hay, R.L. and C. Eagar. 1981. Stem morphology and physiology of Fraser fir in relation to balsam woolly aphid attack preference. Final Contract Report for Regional Chief Scientist, Southeast Regional Office, National Park Service. 60 p.
- Hollingsworth, R.G. and F.P. Hain. 1991. Balsam woolly adelgid (Homoptera: Adelgidae) and spruce-fir decline in the Southern Appalachians: assessing pest relevance in a damaged ecosystem. *Florida Entomologist* 74(2):179-187.
- Hollingsworth, R.G. and F.P. Hain. 1992. Balsam woolly adelgid (Homoptera: Adelgidae) effects on wood and bark structure of Fraser fir and silver fir. *Environ. Entomol.* 21(5):1103-1109.
- Hollingsworth, R.G. and F.P. Hain. 1994. Effect of drought stress and infestation by the balsam woolly adelgid (Homoptera: Adelgidae) on abnormal wood production in Fraser fir. *Can. J. For. Res.* 24:2295-2297.
- Hollingsworth, R.G., U. Blum, and F.P. Hain. 1991. The effect of adelgid-altered wood on sapwood conductance of Fraser fir Christmas trees. IAWA (Int. Assoc. Wood Anat.) Bull. New Ser. 12: 235-239.
- Jenkins, M.A. 2003. Impact of the balsam woolly adelgid (*Adelges piceae* Ratz.) on an *Abies fraseri* (Pursh) Poir. dominated stand near the summit of Mount LeConte, Tennessee. *Castanea* 68(2): 109-118.
- Keen, F.P. 1952. Insect enemies of western forests. USDA Misc. Pub. 273 (revised). Washington, D.C. 280 p.
- Kotinsky, J. 1916. The European fir trunk louse, *Chermes (Dreyfusia) piceae* Ratz. *Proc. Entomol. Soc. Wash.* 18: 14-16.
- Merker, E. and O. Eichhorn. 1956. (Grouping in the genus *Adelges*.) *Die Naturwissenschaften* 43: 453-454. (In German.)
- Miles, P.W. 1965. Studies on the salivary physiology of plant-bugs: the saliva of aphids. *Journal of Insect Physiology* 11:1261-1268.
- Miles, P.W. 1999. Aphid saliva. *Biol. Review* 74:41-85. Cambridge Philosophical Society.

- Mitchell, R.G., N.E. Johnson and J.A. Rudinsky. 1961. Seasonal history of the balsam woolly aphid (*Adelges piceae*) in the Pacific Northwest. *Can. Ent.* 93:794-798.
- Mitchell, R.G. 1966. Infestation characteristics of the balsam woolly aphid in the Pacific Northwest. U.S. Dept. Agric. Serv. Res. Pap. PNW-35. 18 p.
- Mitchell, R.G. 1967. Translocation of dye in grand and subalpine firs infested by the balsam woolly adelgid. USDA Forest Service Research Note PNW-46. 17 p.
- Mitchell, R.G. and P.E. Buffam. 2001. Patterns of long-term balsam woolly adelgid infestations and effects in Oregon and Washington. *Western Journal of Applied Forestry* 16(3):121-126.
- Mullick, D.B. 1971. Natural pigment differences distinguish first and sequent periderms of conifers through a cryofixation and chemical techniques. *Canadian Journal of Botany* 49:1703-1711.
- Mullick, D.B. 1975. A new tissue essential to necrophylactic periderm formation in the bark of four conifers. *Canadian Journal of Botany* 53(21):2443-2457.
- Mullick, D.B. 1977. The non-specific nature of defense in bark and wood during wounding, insect and pathogen attack, pp. 395-441. *In* Recent Advances in Phytochemistry, Vol. 11, ed. F.A. Loewus and V.C. Runeckles. New York: Plenum Publishing.
- Nicholas, N.S., S.M. Zedaker, and C. Eagar. 1992. A comparison of overstory community structure in 3 Southern Appalachian spruce-fir forests. *Bulletin of the Torrey Botanical Club* 119(3):316-332.
- Pschorn-Walcher, H. and H. Zwölfer. 1956. The predator complex of the white-fir woolly aphids. (*Dreyfusia*: Adelgidae). *Zeitschrift fur Angewandte Entomologie* 39:63-75.
- Pschorn-Walcher, H. and H. Zwölfer. 1958. Preliminary investigations on the *Adelges* populations (Hemiptera: Adelgidae) living on the trunk of the silver fir. *Zeitschrift fur Angewandte Entomologie* 42:241-277. (In German.)
- Puritch, G.S. 1971. Water permeability of the wood of grand fir (*Abies grandis* [Doug.] Lindl.) in relation to infestation by the balsam woolly aphid *Adelges piceae* (Ratz.). *J. Exptl. Bot.* 22:936-45.
- Puritch, G.S. 1973. Effect of water stress on photosynthesis, respiration and transpiration of four *Abies* species. *Can. J. For. Res.* 3:293-298.
- Puritch, G.S. 1977. Distribution and phenolic composition of sapwood and heartwood in *Abies grandis* and the effects of the balsam woolly aphid. *Canadian Journal of Forest Research* 7(1):54-62.
- Puritch, G.S. and R.P.C. Johnson. 1971. Effects of infestation by the balsam woolly aphid, *Adelges piceae* (Ratz.) on the ultrastructure of bordered-pit membranes of grand fir, *Abies grandis* (Doug.) Lindl. *J. Exp. Bot.* 22:953-958.
- Puritch, G.S. and W.W. Nijholt. 1974. Occurrence of juvabione-related compounds in grand fir and Pacific silver fir infested by balsam woolly aphid. *Can. J. Bot.* 52:585-587.

- Puritch, G.S. and J.A. Petty. 1971. Effect of balsam woolly aphid, *Adelges piceae* (Ratz.), infestation on the xylem of *Abies grandis* (Doug.) Lindl. *J. Exp. Bot.* 22:946-952.
- Puritch, G.S. and M. Talmon-De L'Arme. 1971. Effect of balsam woolly aphid, *Adelges piceae*, infestation on the food reserves of grand fir, *Abies grandis*. *Can. J. Bot.* 49:1219-1223.
- Ross, R.J. 1988. Patterns of Allelic Variation in Natural Populations of *Abies fraseri* (Pursh.) Poir. Ph.D. Thesis, North Carolina State University, Raleigh, North Carolina. 119 p.
- Rudinsky, J.A. 1956. Notes on the balsam woolly aphid. Presented by Pacific Northwest Forest and Range Experiment Station at annual meeting of Northwest Forest Pest Action Council, 10/29/56 in Portland, Oregon. Weyerhaeuser Timber Company. 12 p.
- Saigo, R.H. 1976. Anatomical changes in the secondary phloem of grand fir (*Abies grandis*) induced by the balsam woolly adelgid (*Adelges piceae*). *Canadian Journal of Botany* 54:1903-1910.
- Schooley, H.O. 1974. Balsam woolly aphid damage to the crowns of balsam fir trees. Can. For. Serv. Nfld. Inf. Rep. N-X-121. 27 p.
- Schooley, H.O. 1976. Recovery of young balsam fir trees damaged by balsam woolly aphid. *For. Chron.* 52:143-4.
- Schooley, H.O. and D.G. Bryant. 1978. The balsam woolly aphid in Newfoundland. Canada Forest Service, Newfoundland Forest Research Centre, Inf. Rep. N-X-160. 72 p.
- Sidebottom, J. 2004. Christmas Tree Notes: Balsam Woolly Adelgid. North Carolina Cooperative Extension Service CTN-020. 4 p.
- Silver, G.T. 1959. The balsam woolly aphid, *Adelges piceae* (Ratz.) in British Columbia. Bi-Mon. Progress Report, Can. Dept. Forest. 15(1):3.
- Slama, K. and C.M. Williams. 1965. Juvenile hormone activity for the bug *Pyrrhocoris apterus*. *Proc. Natl. Acad. Sci. USA* 54:411-414.
- Smith, F.H. 1967. Effects of balsam woolly aphid (*Adelges piceae*) infestation on cambial activity in *Abies grandis*. *American Journal of Botany* 54:1215-23.
- Speers, C.F. 1958. The balsam woolly aphid in the Southeast. *Journal of Forestry* 56:515-516.
- Timell, T.E. 1986. Compression Wood in Gymnosperms. Volume 3. Ecology of compression wood formation, silviculture and compression wood, mechanism of compression wood action, compression wood in the lumber and pulp and paper industries, compression wood induced by the balsam woolly aphid, opposite wood. Springer-Verlag. p. 1339-2150.
- Varty, I.W. 1956. *Adelges* insects of silver firs. For. Comm., Edinburgh, Bull. 26. 75 p.

A METHODOLOGICAL APPROACH TO ELUCIDATE THE EFFECT OF BALSAM WOOLLY ADELGID INFESTATION ON THE STRUCTURE OF WOOD AND BARK

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Traditional analytical methods used in wood chemistry require a significant amount of time and labor to obtain comprehensive information. Better understanding of the mechanisms of pest-host interaction requires new methodological developments to elucidate changes in the chemical structures in components of various parts of the tree (wood, bark, foliage) triggered by infestation. This paper reports development of a rapid and informative approach to elucidate the structures of lignin and polyphenolics with nuclear magnetic resonance (NMR) spectroscopy and its application to track the effect of balsam woolly adelgid (BWA) infestation on the chemical composition of Fraser fir wood and bark. Components of wood and bark have been characterized by wet chemistry methods, correlation 2D NMR techniques (HMQC, HMBC, TOCSY), and quantitative ^{13}C and ^1H NMR.

In response to infestation, Fraser fir produces reddish wood (*rotholz*) with a high density and low conductivity that is eventually responsible for the tree death. The *rotholz* wood has a ~15% higher amount of lignin and much higher amount of galactans than that of uninfested trees. *Rotholz* lignin has higher amounts of p-hydroxyphenyl (H) units and aliphatic OH groups and lower amount of interunit linkages, implying that it is less crosslinked. The degree of condensation of the *rotholz* lignin is not higher than that of normal wood.

Chemical analysis of inner and outer bark samples from infested *A. fraseri*, uninfested *A. fraseri*, and resistant *A. veitchii* showed a tendency toward lower amounts of lipophilic extractives and higher amounts of low molecular mass phenols and polyphenols in the bark of the infested trees as compared to the bark of the uninfested trees. An NMR approach developed for comparative analysis of ethanol- and water-soluble fractions allows for the characterization of the phenolic compounds without tedious chromatographic separation. These fractions consist predominantly of flavanoids and condensed tannins with small amounts of phenylpropanoids and lignans. The bark polyphenolics of the infested trees contain much higher amounts of p-hydroxyphenyl moieties and lower amount of guaiacyl (G) aromatic moieties than that of uninfested Fraser fir. The amount of H-moieties in bark polyphenolics of the resistant Veitch fir is also high, but this does not result in a decrease in the G-unit content, in contrast to infested Fraser fir.

USING MITOCHONDRIAL DNA TO DETERMINE THE NATIVE RANGE OF THE HEMLOCK WOOLLY ADELGID

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ABSTRACT

The history of the introduction and spread of the hemlock woolly adelgid (HWA), *Adelges tsugae* (Hemiptera: Adelgidae), is well known for eastern North America where it is causing serious decline of eastern and Carolina hemlocks. However, while it is assumed that these insects were introduced from somewhere in Asia, we do not know their precise geographic origin. Adelgids can also be found on other hemlock species in western North America and east Asia, but these trees are not significantly damaged, suggesting the existence of different varieties of HWA.

The purpose of this study is to use molecular methods to clarify the relationship among hemlock adelgids worldwide, and therefore determine the geographic origin of the introduction to eastern North America. Three mitochondrial genes (COII, ND1, and cytB), providing a total of over 1,500 base pairs of DNA, were sequenced for adelgid samples collected from hemlock in multiple locations in eastern and western North America, China, and Japan to identify their differences.

Phylogenetic analyses indicate that the source of *A. tsugae* in eastern North America was a population of adelgids living on *Tsuga seiboldii* that occurs in the south and at lower elevations in Japan. Adelgids collected in China appear to represent a separate lineage, as do adelgids collected from the other Japanese hemlock species, *T. diversifolia*. It is unclear whether adelgids collected on *T. heterophylla* in western North America represent a native population, or were introduced from an un-sampled population in Japan.

These results indicate that molecular methods can be used to successfully pinpoint the origin of introduced insect pests. In addition, these results can be used to facilitate quarantine efforts by helping to prevent the introduction of other non-native adelgid genotypes, and can help direct resistance breeding and biological control programs.

KEYWORDS

Mitochondrial DNA, phylogeny, native range.

SILVICULTURAL OPTIONS FOR MANAGING HEMLOCK FORESTS THREATENED BY HEMLOCK WOOLLY ADELGID

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ABSTRACT

The introduced hemlock woolly adelgid (HWA), *Adelges tsugae*, continues to migrate north into New England, causing widespread hemlock decline and mortality, and an increase in hemlock removal. This outbreak has led to management dilemmas about pre-salvage and salvage logging in hemlock stands: should they be cut down or not? Regardless of the decision made, there is a critical need to review the available options and clearly determine the appropriate goals first, especially if HWA has not reached your forest yet. Although there are various chemical and biological control options for HWA that are effective in ornamental situations, they are not practical or effective at larger scales of stands to landscapes. This paper describes silvicultural options available to help landowners manage their hemlock forests infested with or threatened by HWA.

KEYWORDS

Silviculture, salvage logging, forest management, hemlock forests.

HWA INFORMATION

HWA is widely distributed throughout the eastern United States and moves from 10 to 20 miles per year, transported primarily by wind, birds, and humans. In New England, adelgid movement has been primarily in a northeasterly direction. Tree health and the timing and severity of HWA impacts are influenced by several site and forest factors, including elevation, latitude, topographic position (ridgetop, side slope, hollow, wetland, riparian area etc.), and structure. For example, research has shown that hemlock trees are just as likely to be infested with HWA whether they occur in a hemlock-dominated system or in mixtures with hardwoods or other conifer species (Orwig et al. 2002). It appears that no sites are immune from HWA damage once the insects are firmly established, although hemlock trees growing on ridgetops, on exposed drier sites, or infested with any other secondary pests like scale insects often succumb more quickly to HWA infestation (Bonneau et al. 1999, McClure et al. 2000, Orwig et al. 2002). In addition, extreme cold winter temperatures (below – 5°F or – 20°C) can cause severe HWA population reductions that may temporarily slow the spread and impact of HWA across the landscape (Parker et al. 1998, 1999, Skinner et al. 2003).

SILVICULTURAL OPTIONS

We often desire to manage forests in a way that is most “natural”; however, the current HWA outbreak is novel and many would argue not natural. Harvesting options and related costs differ depending on the unique structure of hemlock in a particular forest and whether the management goal is aesthetics, wildlife habitat, water quality protection, public safety, future successional dynamics, timber revenue, or a combination of these goals. Pre-emptive cutting of uninfested forests is not recommended unless maximizing timber revenue is the main objective, because many questions exist regarding the future dynamics of hemlock and HWA, and cutting could remove potentially resistant hemlock genes. Once a decision has been made to cut hemlock, Best Management Practices (BMPs) should be used to protect forest soils and water quality (Kittredge and Parker 1989, Ward et al. 2004; see also below) during harvesting operations.

For infested hemlock-dominated forests, silvicultural options include:

Do nothing: Infested hemlock trees will die gradually over 4- 12 years depending on site characteristics, and the amount of light reaching the ground will gradually increase. Hemlock mortality will typically result in hardwood establishment, primarily black birch (*Betula lenta*) (Orwig and Foster 1998, Orwig et al. 2002). In Massachusetts and northern New England, white pine (*Pinus strobus*), yellow birch (*Betula alleghaniensis*), oak (*Quercus*), and maple (*Acer*) species may also replace hemlock. In addition, herbaceous plants like ferns and sedges (*Carex* spp.) may establish with the death of hemlock (Orwig 2002). Branches, treetops, and boles will fall over a period of 8 to 15+ years, with little or no scarification (soil disturbance). The dead standing and downed wood will provide valuable wildlife habitat for a variety of bird, mammal, and invertebrate species (Brooks 2001, Tingley et al. 2002). In public areas, doing nothing may require fencing to limit access to hazard trees along trails, roads, and vistas.

Light selection cut/shelterwood cut: This option removes 20 to 50% of the tree basal area, including the dying and heavily damaged hemlock trees throughout the stand or in 0.5- to 1-acre openings. Since more light enters the stand through this treatment than the *Do nothing* option, raspberry (*Rubus* spp.), black birch, and white pine will be stimulated (Kizlinksi et al. 2002), and they can be enriched with plantings (see below). Skid roads and landings used in this treatment can be used for subsequent cuts and/or salvage.

High intensity cutting: This option involves removing more than 50% of the tree basal area and is used if the stand is heavily damaged and/or recovering timber value is the main goal. High light reaches the forest floor, often leading to regeneration of black birch and several weedy species, including raspberry, pokeweed (*Phytolacca Americana*), hay-scented fern (*Dennstaedtia punctilobula*), and—sometimes—invasive species (Kizlinksi et al. 2002, Orwig and Kizlinksi 2002). Heavy cutting may also lead to more abundant slash and damage or mortality of residual trees. In many cases, more valuable hardwood species are also removed to increase the value of the timber sale (Brooks 2004), leading to hardwood sprouts from the stumps. The decision to remove species other than hemlock needs to be carefully considered prior to cutting activity. If cutting is done without any regeneration present on steep slopes or near streams, it may pose risks of erosion and nutrient export to streams until newly established vegetation takes up nutrients and impedes overland flows.

For hemlock-hardwood or hemlock-conifer mixes (with or without planting) silvicultural options include:

Do nothing: As with hemlock dominated forests, infested hemlock trees will gradually die over 4 to 12 years, and the stand will convert to a hardwood dominated stand or a mix of hardwoods and white pine. The dead standing and downed wood will provide valuable wildlife habitat for a variety of bird, mammal, and invertebrate species. Often no understory changes will occur if hemlock is a minor component of stand.

Cut hemlock in groups or throughout stand: This option will speed up the conversion to hardwood stands or will facilitate white pine and hemlock regeneration, especially if the stand is not infested or only lightly infested.

If cutting infested hemlock for timber revenue or removing hazard trees is the objective, cutting should begin by the time hemlocks have lost 50 to 75% of foliage, since it is unlikely that they will recover with continued HWA infestation, and they become more hazardous to cut if severely damaged or dead.

PLANTING OPTIONS

Tree planting is not necessary, since trees and other vegetation will reproduce abundantly on their own in the brighter environment caused by hemlock mortality. There are no species that can adequately replace hemlock. However, many species have been planted on sites that have lost or will lose their hemlocks due to HWA or logging (Ward et al. 2004). If conifer trees are desirable, consider planting native species like white pine, red pine (*Pinus resinosa*), or white or red spruce (*Picea glauca* and *Picea rubens*). The exotic Norway spruce (*Picea abies*) has been planted because of its full crown of dark green foliage. If promoting desirable hardwoods is the goal, then various oak species could be planted. If planting in areas of high deer densities (i.e., greater than 20-25/mile²), seedling shelters and/or fencing may be required to allow the young trees to become established. When planting in logged areas, be aware that black birch and raspberry species will directly compete with any species planted, so planting should immediately follow logging.

HWA/HEMLOCK BEST MANAGEMENT PRACTICES (BMPS)

To reduce the chance that logging activities will spread HWA, consider:

Time of year — HWA has two generations per year and has mobile crawler stages in both late spring and early summer from March through June (McClure 1989). Examine the foliage and logs for the presence of HWA during this time as the pest may be transported on machinery that is moved from site to site, including personal vehicles. If possible, harvest in fall and winter to reduce the risk of transporting the pest and minimize soil disturbance.

Machinery — If harvesting during the months of March through June, power wash logging equipment to remove HWA.

State Quarantines — Vermont, New Hampshire, and Maine currently have quarantines that prevent transportation of hemlock seedlings, nursery stock, logs, lumber, bark, and chips into their

states except to pre-approved locations or under specific conditions. Contact individual State Forest Health specialists listed below for details.

Location — Know where your logging is with respect to HWA. Has HWA been identified in the town where logging is taking place? Is it nearby? To find out the current distribution of HWA in your state contact the forest health specialists listed at the end of this paper.

SUMMARY

In conclusion, a variety of silvicultural alternatives are available for forest landowners with hemlock threatened by HWA. The options range from doing nothing to directly influencing vegetation succession with a variety of cutting methods and supplemental plantings, depending on landowner objectives, overall hemlock health, and stand conditions. All options and associated costs should be considered carefully when planning the appropriate management strategies to effectively meet the desired goals.

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REFERENCES

- Bonneau, L.R., K.S. Shields, and D.L. Civco. 1999. Using satellite images to classify and analyze the health of hemlock forests infested by the hemlock woolly adelgid. *Biological Invasions* 1:255-267.
- Brooks, R.T. 2001. Effects of the removal of overstory hemlock from hemlock-dominated forests on eastern redback salamanders. *Forest Ecology and Management* 149:197-204.
- Brooks, R. T. 2004. Early regeneration following the presalvage cutting of hemlock from hemlock-dominated stands. *Northern Journal of Applied Forestry* 21:12-18.
- Kittredge, D.B. and M.L. Parker. 1989. Massachusetts Best Management Practices: Timber Harvesting Water Quality Handbook. Cooperative Extension, University of Massachusetts and Massachusetts Department of Environmental Management. 46p.

- Kizlinski, 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.
- 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., C.A.S.-J. Cheah, and T.C. Tigner. 2000. Is *Pseudoscyrnus tsugae* the solution to the hemlock woolly adelgid problem?: an early perspective, pp. 89-96. In *Proceedings: symposium on sustainable management of hemlock ecosystems in eastern North America*, ed. by K.A. McManus, K.S. Shields, and D.R. Souto. USDA Gen. Tech. Rep. 267. Newtown Square, Pennsylvania.
- Orwig, D.A. 2002. Stand dynamics associated with chronic hemlock woolly adelgid infestations in southern New England, pp. 36-46. In *Proceedings: Hemlock Woolly Adelgid in the Eastern United States Symposium*, ed. R.C. Reardon, B.P. Onken, and J. Lashomb. New Jersey Agricultural Experiment Station Publication, New Brunswick, New Jersey.
- 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* 125:59-72.
- Orwig, D.A. and M.L. Kizlinski. 2002. Vegetation response following hemlock woolly adelgid infestation, hemlock decline, and hemlock salvage logging, pp. 106-117. In *Proceedings: Hemlock Woolly Adelgid in the Eastern United States Symposium*, ed. R.C. Reardon, B.P. Onken, and J. Lashomb. New Jersey Agricultural Experiment Station Publication, New Brunswick, New Jersey.
- Orwig, D.A., D.R. Foster, and D.L. Mause. 2002. Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. *Journal of Biogeography* 29: 1475-1487.
- Parker, B.L., M. Skinner, S. Gouli, T. Ahikaga, and H.B. Teillon. 1998. Survival of hemlock woolly adelgid (Homoptera: Adelgidae) at low temperatures. *Forest Science* 44:414-420.
- Parker, B.L., M. Skinner, S. Gouli, T. Ahikaga, and H.B. Teillon. 1999. Low lethal temperature for hemlock woolly adelgid (Homoptera: Adelgidae). *Environmental Entomology* 28:1085-1091.
- 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.
- Tingley, M.W., D.A. Orwig, G. Motzkin, D.R. Foster, and R. Field. 2002. Avian response to removal of a forest dominant: consequences of hemlock woolly adelgid infestations. *Journal of Biogeography* 29:1505-1516.

Ward, J.A., C.A.S.-J. Cheah, M.E. Montgomery, B.P. Onken, and R.S. Cowles. 2004. Eastern hemlock forests: guidelines to minimize the impacts of hemlock woolly adelgid. U.S. Department of Agriculture Forest Service, NA-TP-03-04, Morgantown, West Virginia.

STATE FOREST HEALTH COOPERATORS

CONNECTICUT : Connecticut Agricultural Experiment Station, P.O. Box 1106, 123 Huntington Street, New Haven, CT 06504-1106

MAINE: Maine Department of Conservation, Maine Forest Service, 22 State House Station, Augusta, ME 04333-0022

MASSACHUSETTS: Massachusetts Department of Conservation and Recreation, Division of Forests and Parks, Region 4 Headquarters, P.O. Box 484, Amherst, Massachusetts 01004-0484

NEW HAMPSHIRE: NH Dept. of Resources and Economic Development, Division of Forests and Lands, P.O. Box 1856, 172 Pembroke Rd., Concord, NH 03302-1856

NEW YORK: New York Dept. of Environmental Conservation, Division of Lands and Forests, 625 Broadway, Albany, NY 12233-4253

RHODE ISLAND: Rhode Island Dept. of Environmental Management, Division of Forest Environment, 1037 Hartford Pike, North Scituate, RI 02857-1030

VERMONT: Forest Resource Protection, VT Dept. of Forests, Parks and Recreation, 103 S. Main Street, 10 South, Waterbury, VT 05671-0602

For more information on HWA and various control methods, see: <http://www.fs.fed.us/na/morgantown/fhp/hwa/hwasite.html>.

For information about hemlock timber value, see: <http://forest.fnr.umass.edu/stumpage.html>.

THE MARYLAND HEMLOCK WOOLLY ADELGID MANAGEMENT PLAN

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Hemlocks are a limited resource in Maryland. Although they are relatively common ornamental trees in the Baltimore-Washington urban area, most natural stands of hemlock are found only in the northern and western parts of the state. Hemlocks are normally restricted to riparian areas, and it is estimated that they occur on approximately 50,000 acres in Maryland. Several stands in Garrett and other western counties are valued for their ecological uniqueness and recreational opportunities.

Hemlock woolly adelgids (HWA), *Adelges tsugae*, have been in Maryland since at least the mid-1980s. The first infestations in the state were found in the suburban ornamental hemlocks in the Baltimore-Washington area, and natural stands in the area became infested by 1990. The infestation steadily moved westward and native stands in Frederick and Washington Counties became infested in the early to mid-1990s. Infested hemlocks in Allegany County were found in 1999, and the first infested hemlock in Garrett County (the most western Maryland county) was found in December, 2001.

In areas where HWA has been recorded for 10-15 years, it has resulted in mostly light mortality, but significant hemlock decline. Areas that experienced drought in the late 1990s or have significant infestations of elongate hemlock scale have had the most decline and mortality.

During the past 15 years the Maryland departments of Agriculture and Natural Resources have been involved in various HWA management activities. Statewide delimiting surveys were conducted in the early 1990s, impact plots were established, there have been several releases of biocontrol organisms, and several trees were injected with an insecticide.

Some high use recreation areas, such as Cunningham Falls State Park, have experienced hemlock mortality and decline. In 2003, a team was assembled to initiate a hemlock management and restoration plan for the Park. More than 50 trees in the Park were injected with imidacloprid, and approximately 50 hazard trees were felled.

In 2003, the Hemlock Woolly Adelgid Task Force was assembled to develop a more unified approach to statewide HWA management. The Task Force included members from the Maryland Department of Agriculture-Forest Pest Management (MDA), Maryland Department of Natural Resources, Maryland Forest Service, Wildlife and Heritage Program, Fisheries, State Parks, USDA Forest Service, and U.S. National Parks Service. After several meetings, the Task Force developed a Maryland Hemlock Woolly Adelgid Management Plan to slow the damage and minimize the impacts of HWA. The objectives of the Plan are to identify HWA infested stands, prioritize stands of highest resource value, and recommend actions in the highest priority stands. Additionally, the Plan is to serve as request for environmental review from the Department of Natural Resources to expedite approval of treatment options.

The first step in the Management Plan is to identify the resource. The experience and knowledge of MDA and other professionals was used to inventory the known hemlock stands throughout the state. MDA staff ground-checked many of the hemlock stands to estimate the hemlock component and describe its health. The Task Force then met to prioritize the hemlock stand treatment based on the recreation, fisheries, wildlife, heritage, and forestry value of each stand. In addition, each stand was assessed for hemlock health and HWA infestation levels. A priority rank was then assigned to each of 150 stands across Maryland. Each stand was digitized into a GIS, and information on rank, hemlock health, HWA levels was added to a database.

By the fall of 2004, the Management Plan was approved by a Department of Natural Resources Management Team. The top ranking 75 stands were then surveyed by MDA staff to assess HWA levels and assess the need for treatment. Two treatment options were selected for stands during the fall of 2004. Part of Rocky Gap State Park was chosen as a site for *Laricobius* beetle release. This part of the Park is inaccessible for other treatment types and is in a designated Wildlands Area. During the fall and early winter of 2004, approximately 150 trees in 15 stands were treated with imidacloprid. These trees were injected using the ArborJet Tree IV system using the IMAJet formulation.

In 2005, additional treatments are scheduled for the high priority sites. Tree injections, soil treatments, and biocontrol releases are treatment options being considered for these sites.