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The Hemlock Woolly Adelgid (HWA) newsletter is a service of the USDA Forest Service Northeastern Area in support of the HWA Working Group. This informal newsletter is intended to provide brief updates to those interested in HWA activities, so the editors have condensed the contributions. We encourage readers to contact authors for more detailed information.

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"Mr. Hemlock Woolly Adelgid" Retires

Mark McClure retired in June 2003 after almost 28 years of distinguished service at the Connecticut Agricultural Experiment Station. During those years, he rapidly rose through the ranks and became Chief Scientist at the Valley Laboratory in Windsor. In the late 1980's, Mark began working with HWA. He focused on biology, dispersal, population cycles, effect of fertilizers, insecticide use, and biological control. He discovered *Pseudoscymnus tsugae*, a predatory lady beetle, during a sabbatical stay in Japan, and worked hard to get the beetle evaluated and established in infested States to begin biological control of HWA. Mark received substantial grant support, shared his findings with many individuals and organizations interested in hemlock health, and served on many committees. Mark was active in the Connecticut Tree Protective Association, serving as president in 1991. He received a number of awards and honors for his fine research and service that benefited so many. We will miss him in the battle to keep hemlocks alive and thriving.

BIOLOGICAL CONTROL

Comparison of Numerical Response and Predation Effects of Two Coccinellid Species on Hemlock Woolly Adelgid (Homoptera: Adelgidae)

We compared two coccinellids: *Scymnus ningshanensis* Yu et Yao from China and *Pseudoscymnus tsugae* Sasaji and McClure from Japan. In a laboratory study, we measured the numerical response of each beetle species to a range of prey densities; in field studies we examined the reproductive success and ability of the beetles to reduce populations of HWA. In the laboratory, *S. ningshanensis* showed a positive numerical response as HWA density increased while *P. tsugae* showed a density-independent response. In field cages, the presence of *S. ningshanensis* resulted in negative HWA population growth in contrast to positive growth in both control cages and cages containing *P. tsugae*. Both laboratory and field experiments suggest that *S. ningshanensis* has good potential as a biological control agent for HWA.

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Nontarget Effects of Entomopathogenic Fungi on *Pseudoscymnus tsugae*: Laboratory Evaluation

Entomopathogenic fungi and predatory beetles, particularly *Pseudoscymnus tsugae*, are being developed for biological control of HWA. If both entomopathogenic fungi and predators are deployed in conjunction, it is important that they be mutually compatible. In 2001 we developed a petri dish assay system that provides for both contact and residual exposure of *P. tsugae* to entomopathogenic fungi. During 2002 we completed laboratory testing for nontarget effects against *P. tsugae* of four entomopathogenic fungi being developed to manage HWA. Adult beetles from the Alampi Beneficial Insect Lab were exposed to *Beauveria bassiana* (Bb–726 and GA–082), *Metarhizium anisopliae* (Ma–1080), and *Paecilomyces farinosus* (AT–159). There were no significant differences in survivorship between *P. tsugae* treated with fungi and the controls.

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Exploration in China for Biological Controls of the Hemlock Woolly Adelgid

In October 2002 we went to Ningshan County, Shaanxi Province, China, to collect HWA natural from *Tsuga chinensis*. This location is where *Scymnus ningshanensis* was previously collected. We found 18 species of lady beetles, of which 5 may be new species. The most abundant was a new *Scymnus (Pullus)* species, although it fed poorly on the HWA and aphid prey. We imported 43 specimens nonetheless, which lived several months on HWA infested foliage and honey/wheast, but did not reproduce. This species doesn't seem promising for biological control.

A new *Scymnus (Neopullus)* species similar to *S. ningshanensis* was found and two specimens were imported. These fed well on HWA and laid eggs soon after importation. We found two species of lacewings (*Chrysopa* spp.) to be abundant on the HWA. One species fed well on HWA and preferred it to bean aphids, but once preconditioned to bean aphid, fed readily on it. Although the *Chrysopa* sp. may not have a sufficiently specific host range to allow release here, it was the most significant source of HWA mortality in our late season observations. We also went to Lijiang, Yunnan County, and collected 10 species of lady beetles, including 46 *Scymnus sinuanodulus* and 13 *Scymnus* *yunshanpingensis*. These specimens were imported to add new genetic stock and reestablish the colony, respectively. The *S. sinuanodulus* were found to be parasitized. Although no adults were obtained, it seems similar to a braconid (*Centistes scymni*), reported to attack *Scymnus (Pullus) impexus* in Europe.

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Field Cage Evaluations of Impact of Lady Beetles on the Hemlock Woolly Adelgid

Field cage studies conducted in Pennsylvania focused on the impact of *Scymnus sinuanodulas* and *Pseudoscymnus tsugae* on HWA. In April, the number of ovipositing hemlock woolly adelgids (sistens generation mothers) were counted on the distal 0.3–0.6 m of eastern hemlock branches. A male and female beetle were placed in treatment bags, and bags without lady beetles were used as controls. The branches were collected in early July when the progeny of the sistens—the progrediens—were mature. The number of mature progrediens on all foliage within each bag was counted in the laboratory. These initial and final counts were then used to calculate the changes in HWA abundance. For 2 years, the population decrease in *S. sinuanodulus* bags was significantly lower than in control bags without beetles. Bags with *P. tsugae* were similar to the control, although the net per capita change was lower than the controls.

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Field Evaluation and Rearing of *Lariocobius nigrinus*

Laricobius nigrinus was approved for release in 2000. Small field cage evaluations in 2001–2002 showed that the predator could survive in Virginia under caged conditions during the winter, and feed voraciously and oviposit on HWA. In 2003, adults were caged for 10 days and then moved to another branch, allowing progeny to develop on uncaged branches. HWA progrediens density decreased over 50 percent regardless of the density of predator released, suggesting that low density releases may be effective and economical. From 144 adults available for only half of their ovipositional period, we counted about 12,000 eggs laid on branches. Recovery of the resulting adults will take place in fall 2003.

Our rearing has produced over 20,000 pupae in both 2002 and 2003. One problem yet to be resolved is the early emergence of post-diapausing adults. Adults emerged early last year but without available HWA food, less than 20 percent survived the winter in the lab. Adults emerging in fall 2003 have been delayed by approximately 4 weeks, which is very positive news for rearing. In addition, there are three experiments currently being conducted to identify factors affecting time of emergence.

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Competitive Interactions Among Two Newly Introduced and One Established Predator of the Hemlock Woolly Adelgid

Lab and field studies were initiated in spring 2003 to evaluate competitive interactions among *Laricobius nigrinus*, *Pseudoscymnus tsugae*, and *Harmonia axyridis*. Predator combinations and experimental conditions were selected to emulate the biology and ecology of each species.

2003 Laboratory Studies—In laboratory experiments using petri dish bioassays, adults and larvae of *L. nigrinus* and *P. tsugae* fed on both conspecific eggs and eggs of each another. However, feeding was HWA density dependent, primarily occurring when HWA density was very low or absent. Neither species fed on eggs of *H. axyridis*. Similarly, adults and larvae of *H. axyridis* fed on *L. nigrinus* and *P. tsugae* eggs in a HWA density dependent manner. However, *H. axyridis* preferred conspecific eggs over all other food sources provided, consuming them independent of HWA density. *L. nigrinus* had the highest feeding and reproductive rates at lower temperatures similar to early spring conditions, followed by *H. axyridis* and *P. tsugae*. In contrast, at higher temperature regimes similar to summer conditions, *H. axyridis* had the highest feeding and reproductive rates, followed by *L. nigrinus* and *P. tsugae*, which were similar. In a separate study, survival among all three predators was similar.

2003 Field Studies—Enclosing predators within fabric cages on hemlock branches revealed similar patterns as described above. During the spring sistens generation, all predator species had similar survival rates; however, *L. nigrinus* had much higher feeding and reproductive rates than either *H. axyridis* or *P. tsugae*. The latter two species produced very few eggs and consumed fewer HWA during what proved to be an unseasonably cold spring in Virginia. During the summer progrediens generation, *H. axyridis* and *P. tsugae* both had increased feeding and reproductive rates, which were likely related to the warmer temperatures required by coccinellids for activity and reproduction.

These preliminary lab and field results suggest that the three predator species will be more complementary than competitive, with *L. nigrinus* being more active in early spring on the HWA sistens generation, and *P. tsugae* and *H. axyridis* being more active in late spring and summer on the progredien generation. Although *H. axryridis* is reputed to be a voracious intraguild competitor, in this system it does not appear to be a significant cause of mortality to *L. nigrinus*, possibly due to decreased activity levels in the colder temperatures of early spring when they are both present, or to *P. tsugae*, whose progeny would likely develop after *H. axyridis* disperses to better food sources. *H. axryridis* also appears to regulate its own population through egg predation by conspecifics, allowing them to maintain a stable and persistent presence.

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Foreign Exploration of Natural Enemies

Gabriella Zilahi-Balogh and Tom McAvoy traveled to Sichuan Province, southwest China, in April 2002 to collect HWA predators. Zhang Guoliang and Ding Jianging (Biological Control Research Institute, Chinese Academy of Agricultural Science, Beijing) coordinated the exploration in cooperation with local forestry officials. Two areas in Baoxing and Kangding County were selected based on forest type, elevation, and previous collections of *Laricobius* spp. Using beat-sheet and foliar sampling of Chinese hemlock (*Tsuga chinensis*), *Laricobius sp. n. baoxingensis* Jelínek & Zilahi-Balogh (6 adults) and *Scymnus camptodromus* (39 adults) were collected in Baoxing. In Kangding, *Laricobius sp. n. kangdingensis* Zilahi-Balogh & Jelínek (23 larvae) and *S. camptodromus* (4 larvae) were collected.

Over 90 percent of the *L. sp. n. kangdingensis* completed larval development on HWA from eastern hemlock in the quarantine facility at Virginia Tech. Approximately 70 percent of the individuals that migrated to the soil for pupation emerged as adults after 4 months in aestivation at 15 °C, 12:12 (L:D) photoperiod. Adults became active in mid-September and started laying eggs in November 2002. Mean lifetime fecundity (± SD) at 5–15 °C, 12:12 (L:D) was 196.4 ± 53.4 eggs per female (range 134–299) (n = 8). Currently there are approximately 80 F1 adults and 10 F2 larvae. Holly Gatton is investigating the biology of *L. sp. n. kangdingensis* and will be conducting host-specificity studies in spring 2004.

A second survey was done at Baoxing in October 2002 by Zhang Guoliang. No *Laricobius* spp. were found; however, 66 hemipteran (Anthocoridae) nymphs (*Tetraphleps sp. n. yulongensis*) were collected on hemlock foliage. Thirteen adults were reared from these nymphs exclusively on HWA, although only 1 was a female.

Surveys for HWA predators have also been contracted and conducted in Nepal by Vasant Kumar Thapa, Tribhuvan University. The first documentation of HWA in Nepal was made; however, no potential HWA predators have been collected.

Continued collaboration and collections will continue in Nepal and China. Dr. Scott Salom and Tom McAvoy are planning a trip to Taiwan in early 2004.

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STATUS IN STATES AND ON FEDERAL LANDS

Connecticut

In collaboration with Kathleen Shields (Northeastern Research Station), we assessed 2003 HWA winter mortality in March and April, including *Pseudoscymnus tsugae* release sites previously sampled in 2000 and 2001. Throughout the Northeast, winter temperatures were below normal with heavy snowfall. HWA mortality was high (84.9 ± 10.1%) in 23 Connecticut sites. HWA mortality was slightly lower in the southern coastal region than in the northwest and central regions. HWA mortality in other eastern States was also generally high, except in North Carolina.

Connecticut experienced extremely wet and cool conditions in spring and summer 2003. Hemlock health assessments conducted in *P. tsugae* release sites indicated low HWA populations, with hemlock recovery and abundant new growth in southern sites. Northern sites experienced slightly higher adelgid levels, especially on the lower crown (protected by snow cover), while new growth was variable. Overall thinning of hemlock crowns was observed, possibly arising from the severe drought of 2002 and increased elongate hemlock scale infestations. Approximately 162,000 adult *P. tsugae* have been released in 20 sites in Connecticut from 1995 to 2002 and another 10,000 at the Mashantucket Pequot Nation near Ledyard.

An ongoing collaboration with Charlene Donahue (Maine Forest Service) is investigating the potential of *P. tsugae* for biological control of balsam woolly adelgid (*Adelges piceae*) and establishing the beetle on alternate adelgid species at the northern fringes of HWA expansion. *P. tsugae* has survived, overwintered, oviposited, and reproduced successfully on balsam woolly adelgid in field cages on balsam and Fraser firs in Maine and Connecticut in 2001–2002 and in Connecticut in 2003. Live *P. tsugae* adults were recovered in cages at Great Mountain Forest, Norfolk, Connecticut, in March 2003, where minimum 2003 winter temperatures reached -21°C (-7 °F). This represents the lowest field temperature at which survival of *P. tsugae* has been recorded. Pine bark adelgid (*Pineus strobi*) has also proved acceptable to *P. tsugae* for oviposition and development in the laboratory.

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Maine

Maine continues to find HWA infestations in planted nursery stock shipped from other States. Since 1999, over 142 planted hemlocks on 42 sites have been removed. In 2003 HWA was found in landscape plantings at two sites in Kennebunkport and South Portland. Both were detected by residents after seeing media releases and pest alerts. Although the infested plants had been in the ground for at least 5 years, HWA was not found on nearby hemlocks. The Maine Forest Service will monitor these sites—as well as all infested sites—for 5 years before declaring the eradication successful. Eradication at the South Portland site was filmed by Maine PBS as part of a *Quest* program to be aired in early 2004.

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Maryland

HWA has been present in Maryland for about 20 years but only recently began to affect hemlock health. Hemlock forests are not common in Maryland except for the mountainous areas of Garrett County. HWA was first detected in Garrett County in 2001, not far from important and picturesque hemlock stands like those at Swallow Falls State Park.

In response, the Maryland Department of Agriculture and the Maryland Department of Natural Resources jointly formed the Maryland HWA Task Force. This task force brings together expertise and interest in hemlock ecology and health, and includes the Department of Agriculture's Forest Pest Management Section; the Department of Natural Resources' Forest Service, Parks Service, Wildlife Service, Fisheries Service, and Natural Heritage Program; the USDA Forest Service; and the National Park Service.

The first job is to prioritize hemlock stands across the State in order to direct survey and management resources. Management options will be developed for each stand based on its recreational, forestry, wildlife, heritage, and fisheries values. A management and restoration project has already begun at Cunningham Falls State Park in Frederick County. This high-use recreation area has been infested since 1990, but hemlock health only began to decline within the past few years. HWA combined with recent drought and elongate hemlock scale are responsible. The task force has identified management strategies for the park that include (1) the removal of hazard trees in developed visitor use areas; (2) insecticide treatments for hemlocks within view of trails and visitor use areas; and (3) plans for restoration plantings.

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New Hampshire

Through natural spread, hemlock woolly adelgid has now been found on native hemlock in four of the southernmost counties in New Hampshire. The largest population of HWA remains at the original detection site in Portsmouth (Rockingham County). Our focus has been to eliminate the spotty pop-up populations of HWA that have occurred in the areas outside of Rockingham County. We do this by cutting and burning infested hemlock or using pesticides. In June 2003 we released 5,000 *Psuedoscymnus* beetles, bringing the total of beetles released in the State to 7,500.

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New Jersey

In 2003, 17,500 *Pseudoscymnus tsugae* were released at 5 sites, bringing the total released in New Jersey since 1998 to 271,260 at 61 sites. All areas where hemlock is still somewhat healthy have now received beetle releases. Because of low HWA population levels resulting from little new growth on trees, the 2001–2002 drought, and the recent cold winter, only one *P. tsugae* larva was recovered this season at a 2003 release site. No adults were recovered, but we expect to recover more adults and larvae when HWA rebounds in the future. In 1 of the 11 permanent study plots that have been monitored since 1988, the last tree died. Tree mortality has increased in the southern plots where HWA has been present the longest. Hemlock mortality is over 90% in about half the plots. Tree health has remained stable in northern sites, but there is some tree mortality attributed to drought and secondary pests such as the hemlock borer and elongate hemlock scale.

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Oregon

Despite its 80-year presence, HWA is uncommon and not damaging to hemlock forests in the Pacific Northwest. However, HWA reports are increasing in Oregon, primarily from distant locations in the western half of the State. Three western hemlock seed orchards in the Willamette Valley recently developed HWA populations. At one site, HWA was abundant enough to cause branch dieback on a few trees and was treated. Where it occurs in western Oregon, HWA usually infests pole-size or larger trees that are open-grown on sites with a history of disturbance.

In 2003 Maggie Byrkit, a graduate student under Dr. Darrell Ross at Oregon State University, began looking at insect predators associated with HWA populations. This is the first time funds have been available in Oregon to identify possible interactions that may explain why HWA is not a significant pest in native hemlock stands.

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West Virginia

The West Virginia Department of Agriculture made 4 *Pseudoscymnus tsugae* releases in 2003, bringing the total number of release sites up to 16, distributed over 11 counties. HWA was discovered in Webster County for the first time in 2003; 20 of the State's 55 counties are now infested.

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Delaware Water Gap National Recreation Area

HWA was first detected in the Delaware Water Gap National Recreation Area in Pennsylvania and New Jersey in 1989. By 1999 it was present in nearly all areas surveyed. A total of 81 permanent plots (10 hemlock trees/plot) were established in 1993 among 7 sites with differing physiographic conditions. Tree health and HWA trends are monitored annually using the USDA Forest Service's Forest Health Monitoring "Visual Crown Rating" method and other standardized protocols.

Between 1993 and 2002 the percentage of trees rated "healthy" declined dramatically (92% to 28%), while dieback (2% to 24%) and foliage transparency (15% to 37%) increased. In contrast, crown ratio (ratio of live crown to total tree height) and crown density (amount of light blocked by foliage, stem, and branches) changed little during this period. In 2002, 15% of the plot trees were dead.

By 2002, all plots had been infested for at least 3 years; many had been infested for more than 5 years. Crown changes became noticeable within 3 years of infestation; however, crown conditions did not decline progressively each year, and many trees actually showed improvement for a year or two before declining further. We are now evaluating the 2003 data from the Delaware Water Gap National Recreation Area and other plots in Pennsylvania, Maryland, and West Virginia.

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Great Smoky Mountains National Park

HWA was discovered in the southwest part of the park in April 2002. By fall 2003 most areas in the park were at least lightly infested. Only the initially infested areas are showing crown thinning, and no mortality has been recorded yet. Great Smoky Mountains National Park has nearly 5,000 acres of hemlock-dominated forests, including 700 acres of old growth hemlock (the oldest individuals reach 500 years old). Management activities include insecticide treatments and release of *Pseudoscymnus tsugae*. In 2003 the University of Tennessee (Department of Entomology and Plant Pathology) began a multi-year agreement with the park to produce *P. tsugae* for release here and in other nearby infested National Park Service units.

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Survey and Monitoring

Developing a Hemlock Woolly Adelgid Sampling Plan

We chose hemlock stands across the Connecticut River Valley and the Quabbin Reservoir region of Massachusetts in spring and summer 2003. The presence or absence of ovisacs or their remains on 100 trees in 17 sites were made at tree level, 2 lower branches per tree, and 5 twigs per branch. Our findings suggest that the most reliable method for sampling involves examining two lower branches per randomly selected tree for the presence or absence of ovisacs. The minimum detection threshold based on a 75% probability of detecting 1 or more infested trees within a 100-tree sample is slightly lower than a 2% infestation rate. There was no significant difference between observed and predicted infestation levels. Based on optimum sampling size analysis, a minimum of 25 and a maximum of 150 samples are needed to characterize HWA populations down to 10% trees infested. Greater precision, needed for research, would increase the number of samples needed.

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A Binomial Sampling Method for the Hemlock Woolly Adelgid

Previous efforts to create a binomial sampling procedure for estimating HWA population density showed promise. Its flaw was the inability to harmonize the relationship between the proportion of twigs infested and the number of HWA with a predetermined threshold, from one site to the next. In a renewed effort, we sampled only trees that hadn't yet declined in health and only sistens. In 2002, using a stratified random sample design, 320 eastern hemlock branches were collected from 80 trees in southwestern Virginia to relate HWA density to the proportion of shoots infested with at least one HWA sisten ($P_{T=1}$). Statistical analysis identified crown areas to sample for representative estimates of density and $P_{T=1}$, and determine if the relationship between HWA density and $P_{T=1}$ was similar among plots. We estimated whole tree HWA density and $P_{T=1}$ by collecting 1-meter-long branches from the lower or middle third of the live crown and sampling the medial or basal third of each branch. The density to $P_{T=1}$ relationship was consistent among plots, explaining 96% of observations 95% of the time.

In 2003 the project expanded to include additional plots in southwestern Virginia (3), northwestern North Carolina (3), and south-central Pennsylvania (6); 720 branches were collected from 180 trees. If the data across the geographic scale tested remains consistent, we could deliver an operational sampling procedure for population estimation of sistens by spring 2004.

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GIS-Based Assessment of Susceptibility and Vulnerability of Hemlock to Hemlock Woolly Adelgid

To help Vermont prepare for HWA, existing spatially explicit data layers were gathered and new layers representing factors known to influence susceptibility to infestation and survival of infested hemlock stands were developed. Remotely sensed data sources were also used to locate potential host material. These data were consolidated into a coregistered database.

Using this data as well as research findings, a predictive model of susceptibility of stands to HWA infestation and their potential vulnerability was developed. To make the translation from research to application feasible, a collaborative approach was used with researchers during the model-building process. This approach yielded a pest risk assessment system based on the current understanding of HWA but with the flexibility to adapt to new research findings and new spatially explicit data layers as they become available in the future.

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Developing Methods to Estimate the Benefits of Protecting Hemlock Trees on Private, Residential Landscapes

A Web-based survey will ask homeowners to describe their landscapes, the presence of hemlock and HWA, and what control actions they have chosen to minimize hemlock damage. The survey will also include questions about the sources of information that helped households learn about HWA and its management in order to guide managers in their public awareness efforts. The survey's design and implementation will also help guide future research in estimating the benefits of protecting hemlocks on private landscapes. Please contact me if you would like to participate!

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CHEMICAL CONTROL

Effect of Imidacloprid Application Technique on Hemlock Woolly Adelgid Mortality and Insecticide Concentration in Sap

An imidacloprid efficacy study is in progress at several forest sites in Connecticut. The treatments consist of three types of soil application, three types of trunk injection, and an untreated check. Moderately infested, vigorously growing trees were chosen at least 50 m apart to avoid root overlap and treatment contamination. Insecticides were applied October 1–29, 2002, and May 28–June 6, 2003. Kioritz®-injected imidacloprid at a rate of 1 g of active ingredient (a.i.) per inch d.b.h. was applied to the soil as two treatments: either close to the base of the trunk or dispersed within the dripline. Bayer Advanced

Garden™ Tree & Shrub Insect Control Concentrate (68 mL of product per inch d.b.h., equivalent to 1 g a.i./d.b.h., as above) was diluted in 3.8 L of water and drenched outwards from the trunk of the tree to a distance of 45 cm. Trunk injection applications were made with Mauget's Imicide®, the Wedgle® system using Pointer® (with the new 12% a.i. formulation), and the Arborjet™ system following each manufacturer's recommended method.

Cold winter temperatures resulted in HWA mortality of 85%–95% in surrounding untreated trees; therefore, mortality was not evaluated for the overwintering generation but delayed until July 7–15, 2003, when progrediens had developed. The soil applications, especially the fall applications using the Kioritz injector, gave the greatest mortality. All the trunk injection methods were ineffective. Mortality will be evaluated again in October 2003 and spring 2004.

Anticipating the effect of winter mortality on evaluation of the treatments, we used an immunological method to measure imidacloprid residues (EnviroLogix test kit). Single branches of ~45 cm in length were cut from fall-treated trees on May 2–6, 2003, and all study trees on July 7–15 and August 20–27, 2003. Sap was extracted at the field site using a pressure chamber and ~200 psi nitrogen. Volumes of 250–700 µL were obtained for each sample with 100 µL required for the imidacloprid determination. The ELISA assay of sap indicated that soil-based application of imidacloprid resulted in good mobilization and persistence in branches. With the Mauget system injections, a relatively short-lived peak of imidacloprid was found in the branch sap. Residues from the other two trunk injections were not detectable. Detected concentrations for all treatments were low (< 20 ppb).

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Hemlock Woolly Adelgid Management Using Ima-Jet in the Arborjet Microinjection System

The Arborjet™ injection device is an air-over-hydraulic system designed as a closed system to deliver products from a 500 mL reservoir directly into a tree's transport tissues while its dosage metering device measures the amount of product applied. Since trees vary anatomically, different species vary in their response to take up injected products. This rate is positively correlated with the size of the xylem, or transport, elements. Canadian hemlock is particularly resistant because its transport tissues are formed exclusively of tracheids, which are typically 10 to 20 times smaller in diameter than the vessels found in hardwoods. At the same time, conifers typically have a whorled tissue arrangement so saps ascends/descends uniformly into the canopy. These anatomical features led us to modify microinjection for hemlock and decrease the number of injection sites from d.b.h./2 to d.b.h./4, resulting in half the number of injection sites per tree. We also switched to a 3/8-inch diameter Arborplug™ rather than the standard 9/32-inch diameter but maintained the same drill depth of 5/8 inch into the sapwood (i.e., not including bark).

Arborjet's proprietary formula of 5% imidacloprid (Ima-jet) was used in the spring 2003 injection program. A total of 500 HWA-infested hemlocks were treated at a rate of 2 mL/caliper inch. An additional 50 hemlocks were injected at a rate of 4 mL/caliper inch. HWA mortality in injected trees was 85% compared to 36% in control trees, and 75% in trees injected the previous year. The success of the spring 2003 injection program will be evaluated in November 2003. Tree health is monitored using a rating system that includes canopy health (dieback and signs of phytotoxicity) and injection sites (evaluated for wound response). We want to refine application rates to extend the injection cycle from once annually to once every two or three years.

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HEMLOCK RESISTANCE

Measurement of Volatile Semiochemicals in *Tsuga* Species

For 2 years our studies have attempted to link the volatile semiochemicals of different species of hemlock to the biological response of the HWA. We developed a sampling method to determine the volatile chemical composition from single needles of seven *Tsuga* species using headspace solid-phase microextraction/gas chromatography/mass spectrometry (SPME/GC/MS). The method identified 51 semiochemicals (terpenoids) in 7 of the world's 9 species of hemlock. Principal component analysis (PCA) was applied to the volatile chemical signatures for each species to find similarities and differences that relate to HWA behavior. Two components accounted for 90% of the variance among the seven species and were interpreted as a "species" component and a "resistance/susceptibility" component. Three intraspecies groupings were evident. The eastern North American hemlock species (*T. canadensis* and *T. caroliniana*) were chemically similar and are very susceptible to HWA. The hemlocks from western North America, Japan, and China (*T. chinesnsis, T. diversifolia, T. heterophylla,* and *T. sieboldii*) comprised a second group and are much more resistant to HWA. *T. mertensiana* was grouped alone and is far removed from the other species, adding to other morphological evidence that this species should be segregated from the other *Tsuga* groups. Furthermore, PCA revealed 13 volatile terpenoids are highly correlated to HWA resistance/susceptibility.

Our current research focuses on how terpenoids change when foliage matures and the link to the settling preference of HWA crawlers. Crawlers prefer foliage of a specific maturity that may reflect changes in structure, nutrients, or secondary chemicals such as terpenoids. We plan to assess the HWA response to terpenoids strongly correlated to HWA resistance/susceptibility. This information may help develop hemlock varieties resistant to HWA or use the terpenoids themselves or analogs as natural insecticides.

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IMPACTS

Landscape-Level Analyses of Hemlock Woolly Adelgid Outbreaks in Massachusetts

We mapped all hemlock stands (> 3 ha) prior to HWA infestation in a 4,000 km^2 transect through Massachusetts. We are interested in characterizing the temporal and spatial damage patterns. Over 5,000 stands with > 10% hemlock have been mapped, representing 86,000 ha, or 21% of the study area. We have sampled 80 stands during the summers of 2002 and 2003, and collected information on forest structure and composition, crown vigor, site characteristics, potential replacement species, presence of HWA, and the extent and spatial patterns of canopy damage. Overstory *Tsuga canadensis* importance ranged from 24% to 92%, and total stand densities varied from 225 to 2,025 ha^{-1}. Many stands were found on northern and western aspects on slopes of 20%–30%. HWA was found in close proximity (a few kilometers) to Vermont, suggesting it is continuing to move and may already be in Vermont and New Hampshire. Almost 50% of sampled stands had HWA, although overstory hemlock mortality is still very low. Our GIS will analyze landscape-level, biological, edaphic, and historical factors that control hemlock damage patterns.

HWA vs. Logging—Both hemlock decline and logging profoundly change the structure, composition, and ecosystem functions in forests at different spatial and temporal scales. Hemlock harvesting imposed more abrupt micro-environmental changes and rapidly reduced vegetative cover, while chronic HWA infestation led to gradually thinning canopies. Both disturbances led to forests dominated by black birch, although logging resulted in greater amounts of shade-intolerant regeneration, higher soil pH and nitrification rates, and reduced forest floor mass. Preemptive cutting of undamaged forests may lead to greater nitrogen losses than those associated with HWA infestation or logging of deteriorated hemlock forests, due to reduced vegetative uptake. Silvicultural methods that allow for vegetation establishment prior to harvesting will likely lessen the ecological impacts of hemlock removal. A newly funded National Science Foundation project will examine the vegetation and ecosystem consequences of hemlock removal by logging. Results will be incorporated into outreach efforts to a range of user groups.

Stand Dynamics—We have monitored eight Connecticut stands for 6 years to evaluate hemlock mortality and subsequent community reorganization. Since 1995, overstory and understory mortality has risen 5 to 15% per year to overall values of 50% to 99%. There has been no sign of tree recovery, and the health and vigor of remaining trees deteriorated in all infested stands. Results suggest that trees on some sites can remain alive for over 10 years following initial infestation and remain standing for 6 to 8 years following mortality. Seedling densities increased in damaged stands and seedlings quickly reached heights of 3 to 7 m. The few hemlock seedlings found contained HWA infestation. Shrub cover remained low following infestation while herbaceous cover, consisting primarily of hay-scented fern, has gradually increased over time. Tree-ring analysis of hardwood and declining hemlock trees, coupled with age-structure analysis of newly established birch saplings, helped determine when initial HWA impact occurred in stands of unknown infestation date.

Ecosystem Analyses of Hemlock Woolly Adelgid Outbreaks in Southern New England—In 1998 we began examining the magnitude and duration of nitrogen (N) cycling dynamics at eight sites with varying HWA abundance in southern New England. During the first 5 years, thinning canopies resulted in increased light, soil temperature, and mineral soil moisture, and decreased forest floor moisture content. Heavily infested sites continue to have larger extractable NH_4-N and NO_3 – N pools, and significantly higher net nitrification rates than healthy hemlock forests. In addition, resin bags captured more NH_4-N and NO_3 – N in infested stands. In 2001 we added two stands with heavy hemlock mortality and a dense black birch understory. For 4 years we have looked at how hemlock decline affects decomposition rates. Our three key drivers of decomposition are (1) changes in foliar quality; (2) changes in microclimate; and (3) replacement by black birch. Foliar percent carbon and lignin were not affected, but foliar percent nitrogen was higher in infested stands. Higher initial foliar nitrogen increased the rate of nitrogen immobilization in decomposing foliage, leading to the increased nitrogen availability. Microclimatic changes led to more rapid subsurface decomposition and initially slower decomposition on the forest floor in infested vs. uninfested forests. We are continuing a 2-year comparative litter decomposition study of hemlock, black birch, and a mixture of the two to examine long-term dynamics as these substrates break down.

The Impact of Hemlock Woolly Adelgid on Throughfall Chemistry and Microorganism Abundance—In 2002 we began to examine trophic interactions between HWA and epiphytic bacteria on the spatial and temporal variability in flows of energy and matter through the canopy at three sites. Uninfested hemlock had a decline in canopy biomass from the tree's center to its periphery. In contrast, infested trees had less biomass in the canopy and produced less new foliage. Needle litter was positively correlated with the estimated canopy biomass on uninfested trees but not infested trees. Infested trees had higher foliar nitrogen content, while foliar carbon content was not affected by HWA or foliar age. Foliar nitrogen content was highest in young foliage where HWA was found in the highest density. Bacteria, yeasts, and filamentous fungi thrived on medium and heavily infested trees compared to uninfested trees. Throughfall chemistry was strongly affected by HWA infestation, as higher concentrations of different nitrogenous compounds, carbon, and different ions were leaching from infested canopies to the forest floor.

Avian Response to the Selective Removal of a Forest Dominant: Consequences of the Hemlock Woolly Adelgid—The impact of dramatic structural and compositional changes in hemlock forests on wildlife, particularly avifauna, is unknown. Breeding season bird surveys were conducted once in 2000 at 32 points and twice during 2001 at 40 points in 12 hemlock stands in central Connecticut. In addition, overstory and understory vegetation was sampled at the 40 points in 2001. Stands were selected representing three levels of hemlock mortality: low (0%–10%), medium (11%–60%), and high (> 60%). A total of 637 individual birds of 49 species were recorded during the 2 years. Overstory hemlock mortality was highly correlated with avian community composition. Abundance of eastern wood-pewee (*Contopus virens*), brown-headed cowbird (*Molothrus ater*), tufted titmouse (*Baeolophus bicolor*), white-breasted nuthatch (*Sitta carolinensis*), red-eyed vireo (*Vireo olivaceus*), hooded warbler (*Wilsonia citrina*), and several woodpecker species was highest at points with > 60% mortality. Black-throated green warbler (*Dendroica virens*), Acadian flycatcher (*Empidonax virescens*), blackburnian warbler (*Dendroica fusca*), and hermit thrush (*Catharus guttatus*) were strongly associated with intact hemlock stands that exhibit little or no mortality from HWA. In general, high mortality stands had higher species diversity than undamaged hemlock forests. Black-throated green warbler, blackburnian warbler, and Acadian flycatcher are very strongly associated with hemlock forests in southern New England and are particularly sensitive to hemlock removal. The hooded warbler, a species of regional concern, may benefit from a dense seedling layer associated with high hemlock mortality.

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Local to Regional Scale Above- and Belowground Effects of Hemlock Woolly Adelgid

We examined the effects of eastern hemlock defoliation and distribution on ectomycorrhizal fungal community composition from local to regional scales in infested forests. This research follows up on studies that evaluated how eastern hemlock dominance regulates the HWA impacts on forests. Our research focused on changes in tree species diversity, aboveground net primary production, and nitrogen cycling in hemlock-dominated, hemlock-hardwood, and hardwood-dominated stands in the Hudson Highlands of New York.

A long-term goal is to understand the abiotic and biotic factors regulating local to regional scale patterns in the distribution of mycorrhizal fungal species. Morphological and molecular techniques are used to quantify fungal diversity in hemlock-dominated and oak-dominated stands spanning three watersheds of Black Rock Forest. Defoliation is associated with reduced ectomycorrhizal fungal species richness and diversity on individual host trees due to diversion of carbohydrates produced by the host. As individual trees and stands die from HWA infestation, eastern hemlock are replaced by hardwood species. As a result, spatial patterns in ectomycorrhizal fungal communities from within-tree to regional scales are likely to reflect heterogeneity in host community composition and hemlock decline. Studies like this one are crucial to examine the relationship between species diversity and ecosystem functions such as carbon partitioning and sequestration. We will use our data to develop a model for HWA effects on belowground carbon storage.

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Rehabilitation Guidelines for Hemlock Stands Damaged by the Hemlock Woolly Adelgid

We are finishing the first draft of a handbook, *Rehabilitation Guidelines for Hemlock Stands Damaged by Hemlock Woolly Adelgid*. It will highlight current understanding of rehabilitating hemlock stands that have been, or will be, damaged by HWA. The handbook is based on a successful program that familiarizes land managers and researchers with key concepts in planning for and dealing with hemlock mortality. Local forest management decisions have a profound impact on community and regional habitat diversity. Increased awareness of current research should foster increased acceptance of HWA management activities by the public and local officials.

The handbook has five sections:

Section 1. Importance of eastern hemlock

Section 2. Planning—Addresses salvage cutting priorities and standards to meet objectives and allocate limited resources.

Section 3. Managing HWA—Examines advantages, disadvantages, and costs associated with alternative methods of minimizing mortality of hemlock trees.

Section 4. Managing salvage operations—Discusses best management practices to minimize impact on adjacent wetlands and riparian zones.

Section 5. Replacing an evergreen component—Covers regeneration techniques for conifers including esthetic and ecological attributes of selected species.

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Effects on Soil Water Chemistry and Vegetation from Simulating HWA Impacts

We monitored soil water chemistry and vegetation for almost 1 year before and 4 years after treatment in two healthy hemlock stands and two stands subjected to a girdling treatment. Maximum mean annual weighted ion concentrations and fluxes were observed 2–3 years after girdling and were comparable to values reported for clear cutting effects on nutrient cycling. Yellow birch seedling changes and percent cover of several herbaceous species (hay-scented fern, evergreen woodfern, wood sorrel, and New York fern) also increased in response to hemlock mortality.

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PESTICIDE PRECAUTIONARY STATEMENT

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