The Connecticut Agricultural Experiment Station, New Haven

Biology and Control of Hemlock Woolly Adelgid

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Bulletin 851

December 1987

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In 1985 an important insect pest of eastern hemlock, *Tsuga canadensis* Carriere, was found for the first time in Connecticut on two residential properties in New Haven County. The insect is the hemlock woolly adelgid, *Adelges tsugae* Annand, (Figure 1) so named because for most of its life it is covered with a secreted white woolly substance. The small size of the adelgid and the woolly nature of its egg masses and life stages predispose this insect to dispersal by both wind and migratory birds and mammals. By spring 1986 the adelgid had greatly expanded its distribution in Connecticut (Figure 2). These new infestations along the southwestern coastline, on higher elevations inland, and along the banks of the Housatonic and Connecticut Rivers strongly suggested that Hurricane Gloria in September 1985 blew adelgids across the Sound from Long Island where infestations had existed for several years. More recent isolated infestations of hemlock woolly adelgid in Portland (Middlesex County), Manchester (Hartford County) and Ledyard (New London County) also strongly implicate birds in the natural dispersal of this insect. All three infestations occurred in residential neighborhoods on hemlocks on which bird feeders were being maintained year-round.

Hemlock woolly adelgid was reported in the eastern United States in the late 1960s in southeastern Pennsylvania. It now occurs in at least seven eastern states and the District of Columbia (Figure 2). The origin of this infestation is unknown. However, this same insect has been present for more than half a century in the Pacific Northwest where Annand (1924) first described it from specimens collected on western hemlock, *Tsuga heterophylla* Sargent, in Oregon. Annand (1928) believed that an adelgid collected earlier from western hemlock in Vancouver, BC and identified by Chrystal (1922) as *Chermes funitectus* Dreyfus was also *A. tsugae*, although no direct comparison of specimens was made. Carter (1971) concurs that these species are the same. Takahashi (1937) identified *A. tsugae* from *Tsuga chinensis* Pritzel collected in Formosa and from *Tsuga sieboldii* Carriere collected in Japan. I found *A. tsugae*

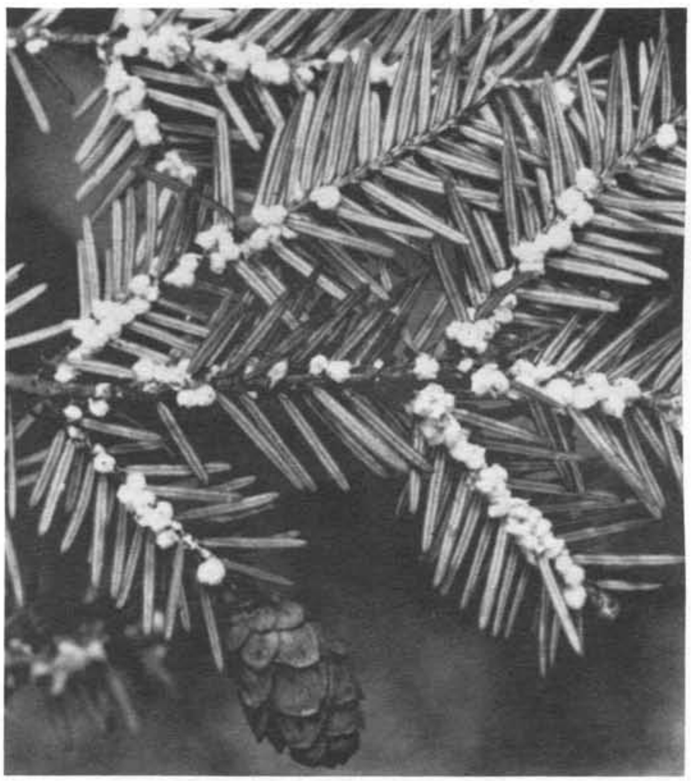

FIGURE 1—Egg masses of hemlock woolly adelgid (*Adelges tsugae*) on hemlock.

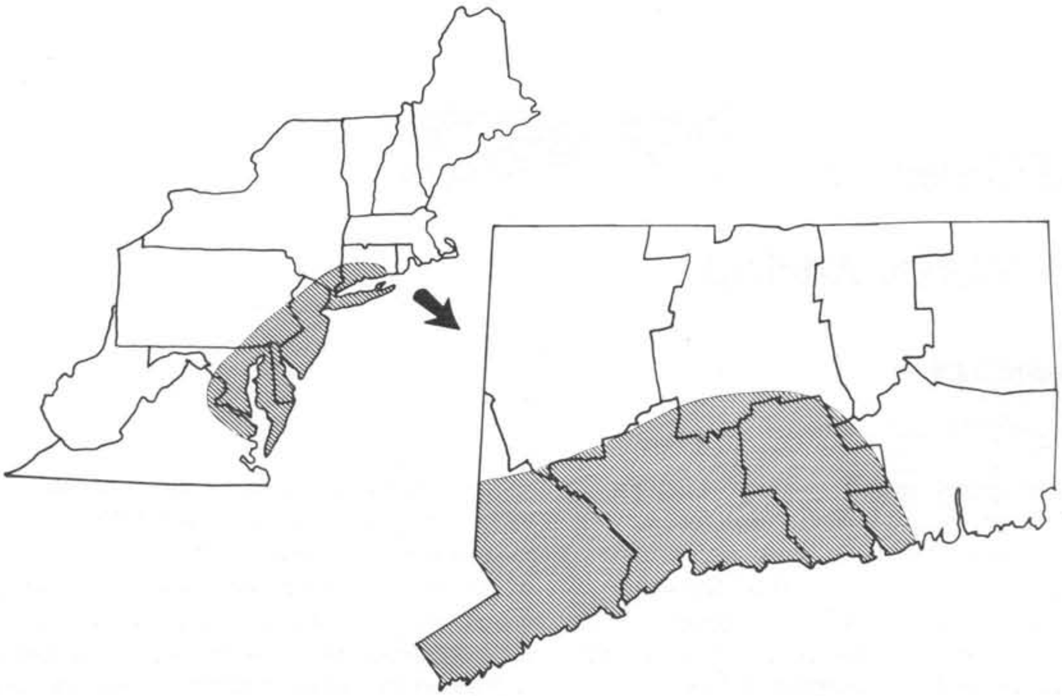

FIGURE 2—Current distribution of hemlock woolly adelgid.

at several locations in Honshu, Japan in 1984 on *T. sieboldii*. I believe that this adelgid may have been introduced accidentally from Asia because its densities were always low and innocuous to hemlock in Japan, which is often characteristic of a native species (McClure 1983).

Unlike in Asia, *A. tsugae* often persists at high injurious densities in the United States. In the Northwest, this insect weakens and sometimes kills ornamental *T. heterophylla*, but it is usually of little consequence in the forest (Keen 1938, Furniss and Carolin 1977). The situation is much different in the Northeast where both ornamental and forest *T. canadensis* have been killed. This small piercing and sucking insect feeds on the young branches and twigs of eastern hemlock, usually near where the needles are attached. Feeding in late winter and early spring retards or prevents the spring flush of new growth and causes existing needles to discolor, desiccate and drop from the branches. Main limbs often die within the first summer, and the entire tree may be dead within one year. The means by which the adelgid kills hemlock is not known, but it is probably the combined result of removing sap and injecting a toxic spittle during feeding.

LIFE CYCLE AND HOST PLANTS

Until recently little was known about the biology and life cycle of *A. tsugae*, despite its presence in the United States for several decades and its importance as a pest of hemlock. This adelgid was thought to have a simple monomorphic life cycle represented by a single wingless parthenogenetic generation that was restricted to hemlock. Host plants other than hemlock as well as winged and sexual life forms of this adelgid were unknown (Annand 1924, 1928). However, my studies in several hemlock forests in Connecticut during 1986 and 1987 revealed a highly complex polymorphic life cycle of *A. tsugae* that involves two annual generations and new life stages, including winged migratory forms (McClure 1987) (Figure 3).

We collected branches weekly or bi-weekly from March through November and monthly from December through February and examined them microscopically to determine the identity and prevalence of life stages of *A. tsugae* and if they were dead or alive. A minimum of 100 adelgids collected each time were mounted on microscope slides and kept as museum specimens.

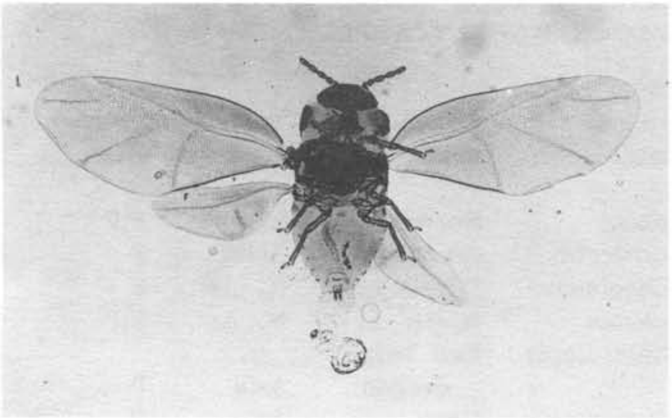

FIGURE 3—Winged adult of hemlock woolly adelgid that migrates to spruce.

Figure 4 illustrates the life cycle of hemlock woolly adelgid in Connecticut. Adult females of the overwintering generation deposit eggs into spherical woolly ovisacs of about 50 eggs each for about 16 weeks starting about the middle of February. In the middle of April these eggs begin hatching into crawlers, the mobile first instar nymphs. Individual crawlers, which are only active for one or two days, can be blown by the wind and undoubtedly are important in natural dispersal. During the 4 weeks following hatch, the nymph develops through four instars before becoming an adult. Quite unexpectedly I found two completely different adult life forms matured from the same egg masses laid on hemlock. In addition to the known wingless form (Figure 5), I found a winged migratory form unknown for this species (Figure 3). The development of winged forms is indicative of a life cycle which involves two host species, such as that of *Adelges cooleyi* (Gillette), the Cooley spruce gall aphid, which migrates between spruce and Douglas fir. By definition, spruce (*Picea*) is considered the primary host for all adelgids, while several other genera including *Abies*, *Larix*, *Pinus*, *Pseudotsuga*, and *Tsuga* are considered intermediate hosts, depending upon the adelgid species involved (Annand 1928). Although some adelgids never produce winged forms and never alternate between the primary and intermediate hosts, my discovery of a winged form of *A. tsugae* on hemlock is indicative of a migratory life cycle and, therefore, establishes an important link with spruce.

Adults of the wingless spring generation on hemlock each lay about 25 eggs which hatch from June through mid-July (Figure 4). After settling on the young branches the first instar

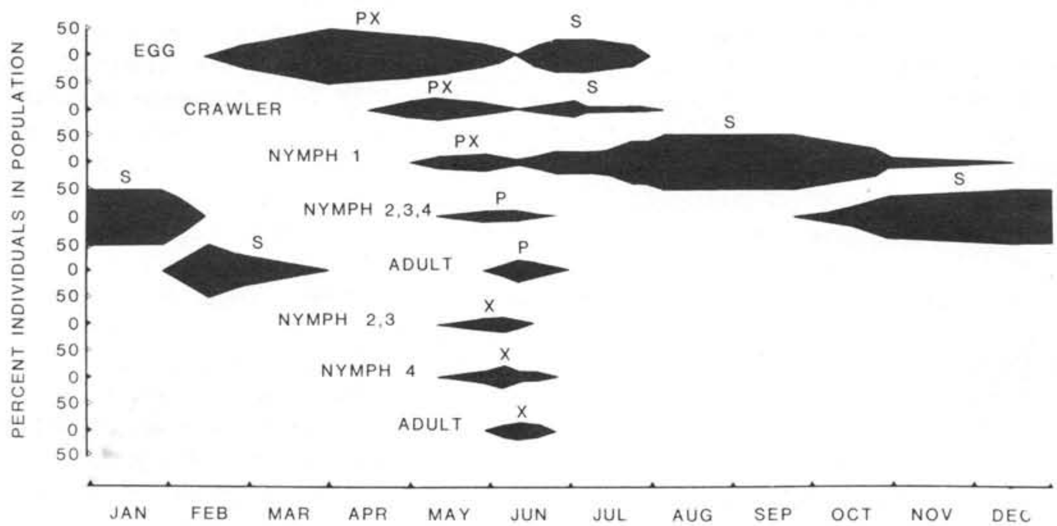

FIGURE 4—Seasonal occurence of *Adelges tsugae* on hemlock. S=wingless overwintering generation; P=wingless forms of spring generation; X=winged migratory forms of spring generation.

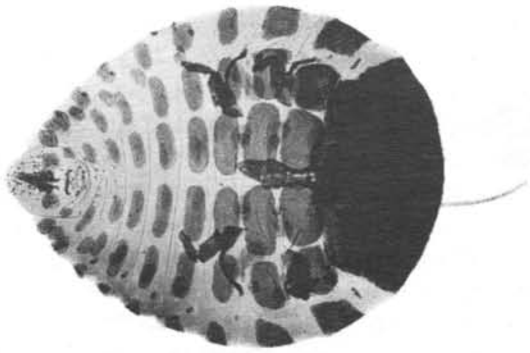

FIGURE 5—Wingless adult female of hemlock woolly adelgid which remains on hemlock.

nymphs become dormant until October when they resume development. Nymphs feed and develop during the warmer periods of late autumn and winter and mature by February, thus completing the two-generation-per-year cycle on hemlock.

THE THREAT TO SPRUCE

As indicated, the development of winged migratory adults of *A. tsugae* in June implicates spruce in the life cycle of this adelgid. If hemlock woolly adelgid could survive and reproduce on spruce, its ability to attack hemlock would be enhanced because some individuals that develop on spruce could migrate back to hemlock. During 1986 and 1987 I conducted studies at two sites in southern Connecticut and in the laboratory to determine the potential of *A. tsugae* to survive and reproduce on species of native and exotic spruce. One site located in Essex (Middlesex County) was a mature forest composed mostly of hemlocks. Although the infestation was less than 2 years old, hemlocks were heavily infested with the adelgid and showing injury. Prior to the production of winged adults, 15 trees representing eight species of *Picea* were obtained from forests and nurseries in Connecticut (Table 1) and in May planted randomly in the understory of the Essex forest. These trees, which ranged in height from 1 to 2 m, were watered and checked for adelgids weekly until mid-August. During peak abundance of winged adults in June, infested branches from the hemlock overstory were placed at the base of each tree to ensure that the winged adults had the opportunity to colonize each spruce. In July and in August branches were sampled from each tree and examined microscopically to determine if winged *A. tsugae* had colonized the trees and if offspring were being produced.

TABLE 1—SPRUCE SPECIES ON WHICH HEMLOCK WOOLLY ADELGID DID NOT SURVIVE.

Picea species	Common name	Native continent	Study site*
P. abies	Norway	Europe	F,P
P. asperata	Dragon	Asia	P
P. engelmannii	Engelmann	N. Am.	F
P. glauca	White	N. Am.	F,P
P. heterolepis	Red twig dragon	Asia	P
P. jezoensis	Yezo	Asia	F
P. mariana	Black	N. Am.	F
P. orientalis	Oriental	Asia	P
P. polita	Tigertail	Asia	L
P. pungens	Colorado	N. Am.	F,P
P. rubens	Red	N. Am.	F
P. sitchensis	Sitka	N. Am.	F

*F=Essex hemlock forest; L=Laboratory, P=Montgomery Pinetum

Concurrent studies were being conducted at the Montgomery Pinetum, Greenwich (Fairfield County), which is a 125-acre park where more than 80 species and varieties of conifers from around the world are growing among native hardwoods and evergreens. Eastern hemlock abounds in the surrounding forest and occurs throughout the park where it is by far the dominant conifer. These hemlocks were heavily infested with *A. tsugae* and, like in Essex, the adelgid population was producing both wingless and winged adults in June. In July, when winged adults were no longer active, branches were sampled from each of 14 spruce trees which were growing within 20 m of infested hemlocks; the foliage on some trees was actually touching infested hemlock branches. These spruce represented six different species of *Picea*, including three species not included in the Essex

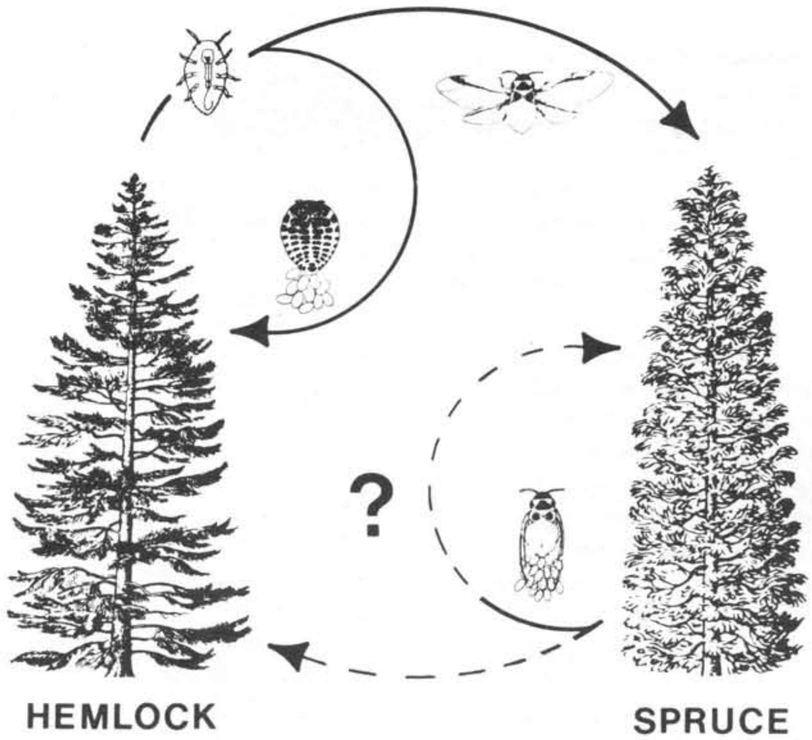

FIGURE 6—Polymorphic life cycle of *Adelges tsugae* alternating between hemlock and spruce.

study (Table 1). Again, branches were examined microscopically to determine if *A. tsugae* had become established.

Experiments were also conducted in the laboratory to determine whether progeny of winged adults could survive and mature on hemlock and an exotic spruce, *P. polita*. Winged adults were placed on branches within nylon mesh cages to prevent them from escaping. After 2 weeks cages were removed and branches were examined for progeny.

Winged adults colonized and laid eggs on the caged *P. polita* in the laboratory and on all 11 spruce species growing in the understory of the Essex forest and at the Montgomery Pinetum. However, all nymphs which hatched and settled on these spruces died within a few days. None developed beyond the first instar. Because these nymphs had settled and begun to feed, it is certain that none of the 12 spruce species are suitable hosts for *A. tsugae*.

Occasional winged adults were seen on forest hemlocks after the migration period; but all died without producing eggs. Because the same die off occurred on caged hemlocks in the laboratory, it does not appear that winged adults contribute to population growth or to spread of *A. tsugae* from hemlock to hemlock.

Our present understanding of the complex life cycle of *A. tsugae* involving both hemlock and spruce is illustrated in Figure 6. We now know this adelgid completes two wingless generations each year on hemlock, which helps explain how it builds injurious population densities so rapidly. We also know that about half of the offspring produced by the overwintering generation develop wings and migrate from hemlock in pursuit of an unknown spruce. Fortunately none of these winged adults produced offspring that are able to survive on the most common spruce species in our area. However, as *A. tsugae* continues to spread it may encounter a spruce species on which it can survive. Meanwhile, because the adelgid does not require spruce to survive, we are left with the difficult task of saving our hemlocks from this destructive pest.

CONTROL OF HEMLOCK WOOLLY ADELGID

An experiment was conducted during 1987 in Gillette Castle State Park located in East Haddam (Middlesex County) and Hadlyme (New London County) Connecticut to determine the effectiveness of chemical pesticide sprays for controlling hemlock woolly adelgid on eastern hemlock. In March when studies were initiated, trees were heavily infested and injured, indicated by discolored foliage and dead branches. Trees were sprayed with seven different chemicals on four dates; April 14 when adelgids were adults and eggs, May 13 when eggs and nymphs of various ages were present, July 16 when all adelgids were aestivating first instar nymphs and October 20 when nymphs had resumed development. All treatments were applied with a SOLO Jetpak 425 Knapsack Sprayer in sufficient volume to drench the foliage and branches completely, but not excessively. Treatments were applied to each of five forest hemlocks that ranged in height from 3 to 7 m. Four branches were sampled from each of the five sprayed trees and five unsprayed trees 2-3 weeks after treatments. Branches were examined microscopically and the first 100 adelgjds encountered on each branch were recorded as dead or alive. Therefore, a total of 2,000 adelgids was examined for each treatment. Sprayed trees were examined periodically for evidence of phytotoxicity during the 9-month study period.

Although the seven chemical pesticides tested are registered for use on hemlock and available without restriction, they differ both in their mode of action and in their degree of toxicity. Among the more toxic compounds tested were diazinon, dimethoate, ethion, fluvalinate, and malathion. These are the more typical petrochemical insecticides which poison their victims either on contact or by ingestion. Two less toxic compounds tested were insecticidal oil and insecticidal soap. Both pesticides are manufactured specifically to control small, sessile insects such as adelgids, aphids and scales, and both kill by suffocation rather than by direct poisoning. When diluted with water and applied as a spray, the oil or soap covers its victim with a film which impedes its ability to exchange air.

TABLE 2—EFFECTIVENESS OF PESTICIDES FOR CONTROLLING HEMLOCK WOOLLY ADELGID. NUMBERS ARE MEANS (± S.D.).

Date/Stages Pesticide	Active ingr. (oz./100 gal.)	Mortality%*
April 14; Adult, egg		
Insecticidal Oil	245	95.6±2.3a
None		13.5±4.4b
May 13; Egg, nymph		
Diazinon	25	99.1±4.7a
Dimethoate	8	32.6±8.3b
Fluvalinate	1.25	99.2±0.8a
None		8.0±1.3c
July 16; Dormant nymph		
Diazinon	25	99.8±0.1a
Fluvalinate	1.25	100.0±0.0a
Insecticidal Soap	250	100.0±0.0a
Malathion	16	99.9±0.1a
Insecticidal Oil	122	100.0±0.0a
Insecticidal Oil	122	
with 2% Ethion	0.9	100.0±0.0a
None		11.8±6.7b
Oct. 20; Nymph		
Diazinon	25	99.8±0.1a
Fluvalinate	1.25	99.8±0.1a
Insecticidal Soap	250	100.0±0.0a
Insecticidal Oil	245	100.0±0.0a
None		17.8±9.3b

* Means for each date followed by the same letter are not significantly different (DMRT; $P>0.05$).

Results of the treatments are given in Table 2. Excellent control of hemlock woolly adelgid was obtained during every spray period using nearly every pesticide. In addition, none of the treatments caused obvious phytotoxicity. The only treatment that was ineffective was dimethoate applied in May to control eggs and nymphs. Inexplicably, this compound killed only one-third of the adelgids (Table 2). By contrast, all 8,000 adelgids examined on branches that had been sprayed with oil or soap in July and October were killed by these compounds. This is remarkable considering the large number of adelgids involved and their often tight packing on the branches, which can preclude adequate coverage of individuals with pesticide. The somewhat lower mortality (95%) following an oil treatment in April (Table 2) can undoubtedly be attributed to less than thorough coverage of adelgids with the pesticide spray. The few survivors of that oil spray in April were found amidst the protective, woolly egg masses that were prevalent at that time.

Clearly, hemlock woolly adelgid can be controlled throughout the growing season using any one of the several registered pesticides listed. However, critical to the success of each of these pesticides is that infested branches be drenched completely. The importance of thorough coverage became readily apparent from the results of an effort by the State of Connecticut to control *A. tsugae* on forest hemlocks at Gillette Castle State Park in September 1987. Hemlocks in the immediate vicinity of the castle, in the picnic and parking areas and along the roads were sprayed with insecticidal oil at the summer rate (1 part oil to 100 parts water) by a commercial arborist using a John Deere hydraulic sprayer at 700-800 psi pressure. Excellent control was obtained on individual hemlocks that were accessible to the spray equipment on all sides and on the road-facing portions of trees along the roads. However, on hemlocks which were amongst other forest trees and on the forest-facing side of trees along the roads where complete coverage with pesticide was not achieved, adelgids survived and thrived.

Obviously, hemlocks in forested areas of Connecticut are in the greatest danger from *A. tsugae*. It is here, where chemical control is impractical if not impossible to obtain, that the salvation of eastern hemlock may well depend upon a natural enemy, be it a disease, a parasitoid or a predator, to regulate adelgid numbers. With this in mind we have been identifying natural enemies of hemlock woolly adelgid and monitoring their impact on adelgid populations from year to year in several Connecticut forests. We have found that several native predators including midges (Cecidomyiidae), flower flies (Syrphidae) and lacewings (Chrysopidae) attack *A. tsugae* from time to time, but their numbers are too few to be of any significance in reducing adelgid density.

We will continue to study populations of these natural enemies and continue our search for others in hopes that we can someday save our hemlock forests from the hemlock woolly adelgid. Fortunately until then chemical pesticides provide a means for controlling *A. tsugae* on hemlocks that can be drenched thoroughly.

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ACKNOWLEDGMENT

I thank T. Childs and D. Russ of Great Mountain Forest, Norfolk and W. Kogut of Kogut's Nursery, Meriden for the spruce trees; and the Connecticut Nature Conservancy, Gillette Castle State Park and the Montgomery Pinetum for allowing me to conduct studies on their properties; and B. Beebe for technical assistance.

The Connecticut Agricultural Experiment Station, founded in 1875, is the first experiment station in America. It is chartered by the General Assembly to make scientific inquiries and experiments regarding plants and their pests, insects, soil and water, and to perform analyses for State agencies. The laboratories of the Station are in New Haven and Windsor; its Lockwood Farm is in Hamden. Single copies of bulletins are available free upon request to Publications; Box 1106; New Haven, Connecticut 06504. ISSN 0097-0905