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Dr. Carole Cheah
Valley Laboratory
The Connecticut Agricultural Experiment Station
153 Cook Hill Road, P. O. Box 248
Windsor, CT 06095

Phone: (860) 683-4980
Fax: (860) 683-4987
Email: Carole.Cheah@ct.gov
Website: www.ct.gov/caes

Hemlock Woolly Adelgid (HWA) and Other Factors Impacting Eastern Hemlock

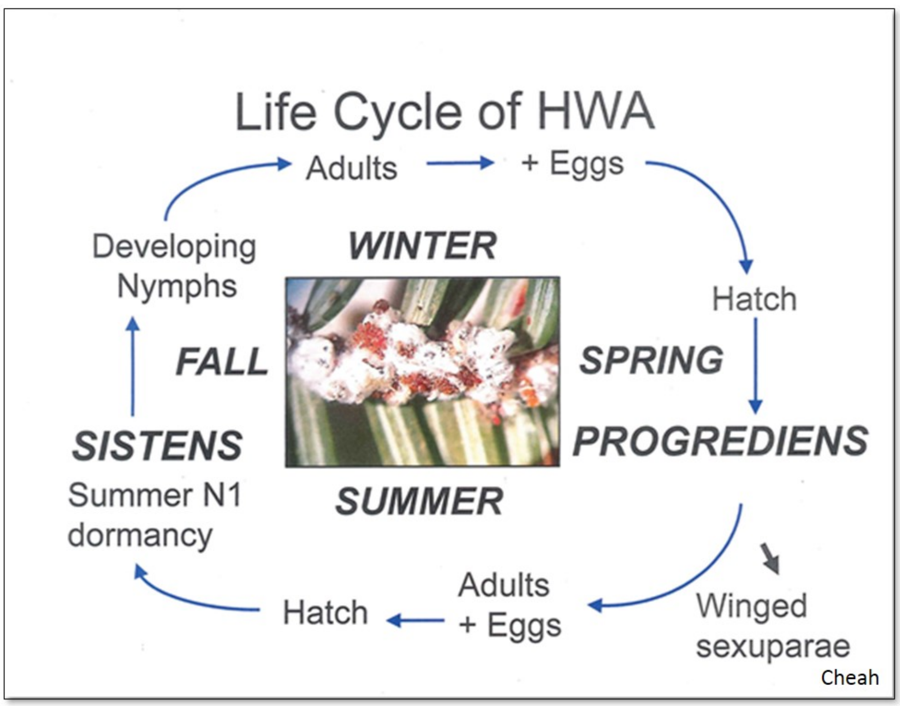
Introduction and Overview

Adelgids are small conifer-feeding insects, related to aphids, belonging to the Suborder Homoptera (1). Hemlock woolly adelgid, *Adelges tsugae* Annand, (HWA), feeds specifically on hemlock species and was first described from samples originally from Oregon by P. N. Annand in California in 1924 (2). In North America, native Eastern hemlock, *Tsuga canadensis* (L.) Carriere and Carolina hemlock, *Tsuga caroliniana* Engelmann are very susceptible to HWA attack (3). Eastern hemlock is the seventh most common tree species in Connecticut and the second most abundant conifer after eastern white pine (4). In the eastern United States, this non-native insect pest was initially reported at a private estate in Richmond, Virginia in the early 1950s (5). The hemlock woolly adelgid in eastern US originated from southern Honshu island, Japan (6) and infestations have since spread widely to attack eastern hemlock and Carolina hemlock in 20 eastern states, from the southern Appalachians in the Carolinas and Georgia, through the Mid-Atlantic States, westwards to Ohio and Michigan and northwards to northern New England (7). Most recently, HWA was found in southern Nova Scotia in Canada in 2017 (8). In Connecticut, HWA was first reported to the Connecticut Agricultural Experiment Station in New Haven in 1985 and by 1997, was found throughout the state, in all 169 Connecticut towns (7). Hemlock tree mortality from HWA attack can occur in a few years (3), often in conjunction with other pests, especially on stressed, drought-prone sites. But infested hemlocks can also survive HWA infestations if regularly controlled, especially in the garden landscape. To date, Connecticut has been dealing with HWA for over 30 years, yet many of the state's forest hemlocks have survived the initial waves of tree mortality to this day.

Life Cycle of HWA on Eastern Hemlock

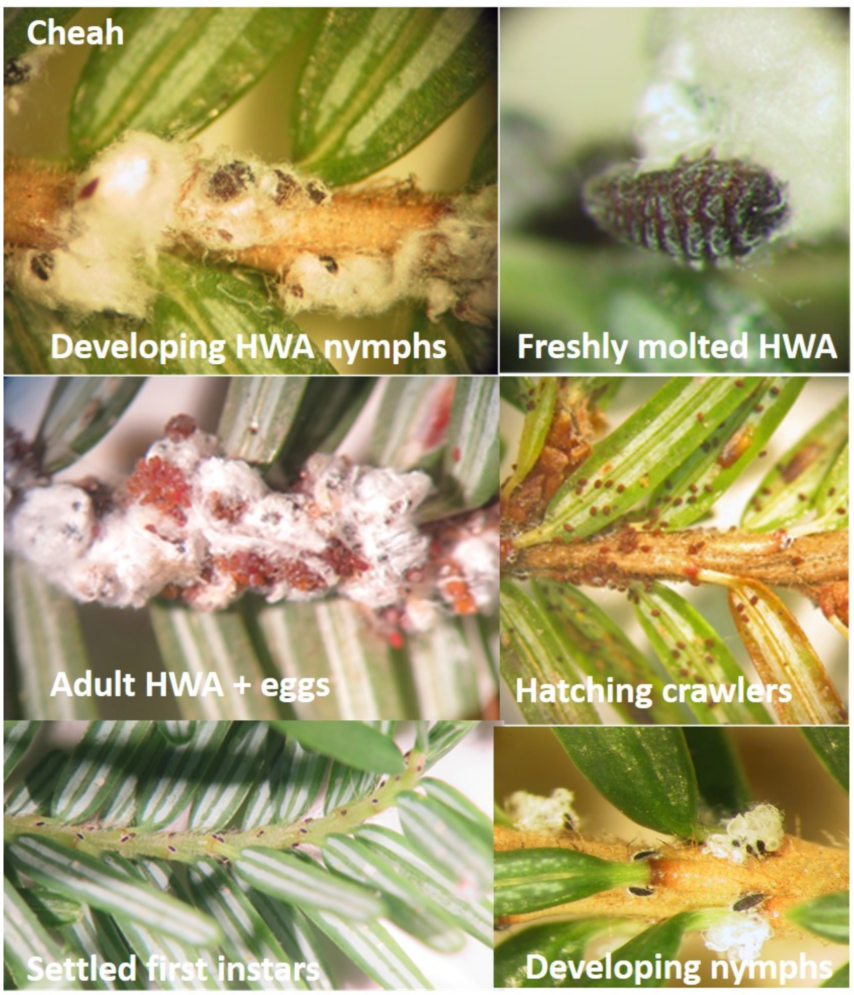
HWA is an unusual parthenogenetic [all female] insect, largely sessile, that has a generation that actually thrives and feeds on hemlocks during the fall and winter when temperatures are mild. The insect feeds on storage parenchyma cells in the stem by insertion of long feeding mouthparts called stylets at the base of hemlock needles and secretes a waxy wool covering for protection (9). A generalized life cycle for HWA on eastern hemlock in the Northeast is shown below (Figure 1), and consists of two generations: the prolonged winter or sistens generation, and the shorter summer or progrediens generation (10).

Figure 1. Generalized life cycle of hemlock woolly adelgid on eastern hemlock



The winter or **sistens** generation in Connecticut, spanning 8-9 months, generally begins to lay eggs in early spring (March-April). Each egg mass, hidden within the waxy wool of the overwintering female can contain 100-300 eggs by late April. Seasonal timing of egg hatch is temperature-dependent and can be hastened by early warm springs. These eggs generally hatch over an extended period in April and May in the Northeast and develop to produce the second damaging summer **progrediens** generation adult HWA in late May and June. The progrediens HWA is characterized by a much shorter generation time and smaller egg masses. Different adelgid species often alternate between a primary spruce host and a secondary conifer host but to date, no suitable spruce host species for HWA has been recorded in North America (10). A proportion of the progrediens generation form weak wings as sexuparae, a migratory stage which has been presumed to disperse to the primary spruce host. However, these do not survive to reproduce in the US (10). Eggs of the wingless progrediens females generally hatch in late June and early July and the resulting mobile first instar crawlers settle on the newest hemlock growth as the sistens of the next generation but then cease feeding and enter into a summer dormant period (aestivation). During this dormant period which lasts several months until the mid-fall, there is no wool production. This settled first instar stage is highly inconspicuous and easily escapes detection. Both generations of HWA are similar in appearance and there is considerable overlap of the generations in late spring (10).

Figure 2. Stages of HWA damaging to eastern hemlock



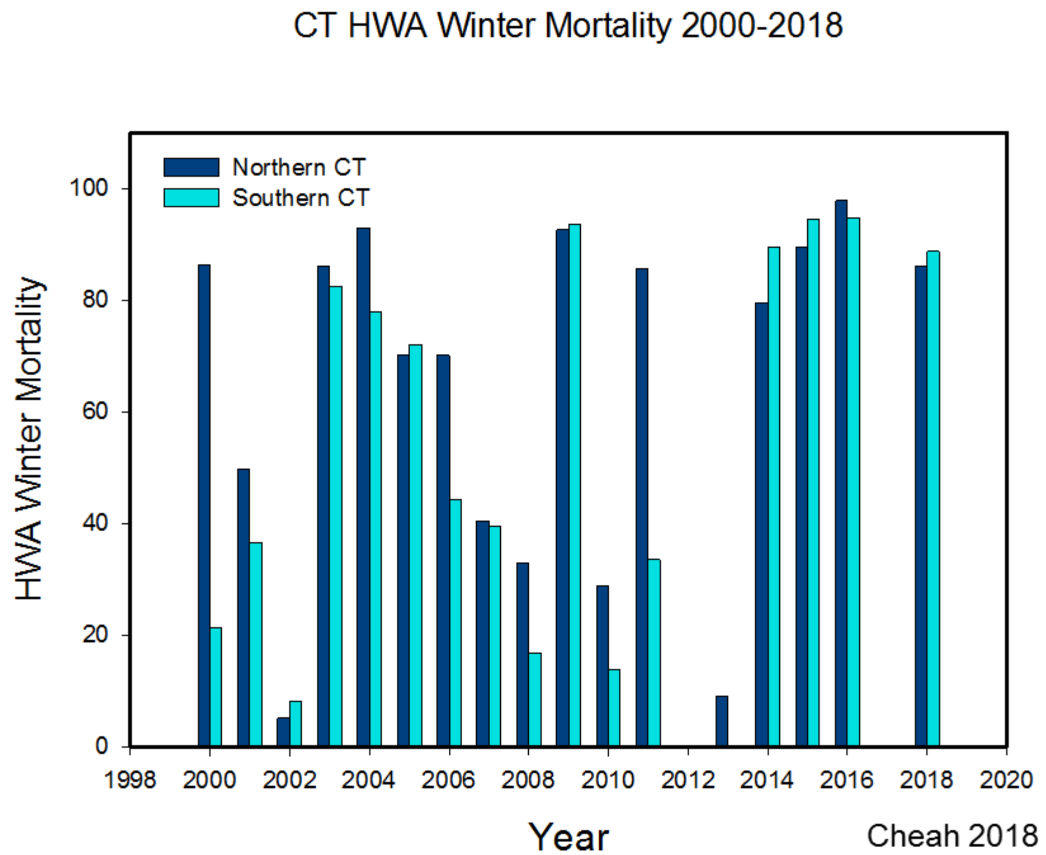
Eggs and mobile first instar crawlers of both generations are spread by wind, birds and other wildlife (11), humans and infested plant material movement from spring through summer. In more northerly latitudes and/or higher elevations, this period for potential dispersal of HWA can be extended due to cooler temperatures which extend the development of adelgid stages.

When HWA feeding and development resume in the fall, usually in late September-mid October in the Northeast, the first instar sistens swell and molt, and start to produce the characteristic wool in the second instar. Adelgid growth continues throughout the winter into early spring, with increasing production of wool which is most prominent on adults in late March through May, especially on the undersides of hemlock branch tips. This is the best time to monitor and detect active HWA infestations on a hemlock. Eggs are protected by the woolly secretions and populations can quickly explode to infest a tree due to the high fecundity of HWA. HWA prefers to feed on the newest most nutritious growth available, especially on healthy trees. Feeding by the adelgid depletes the tree's storage reserves and results in a decline or cessation in new foliage production, needle drop, twig dieback and thin crowns and even mortality in as little as 4 years (12) (Figure 3).

Figure 3. Hemlock tip dieback resulting from HWA attack

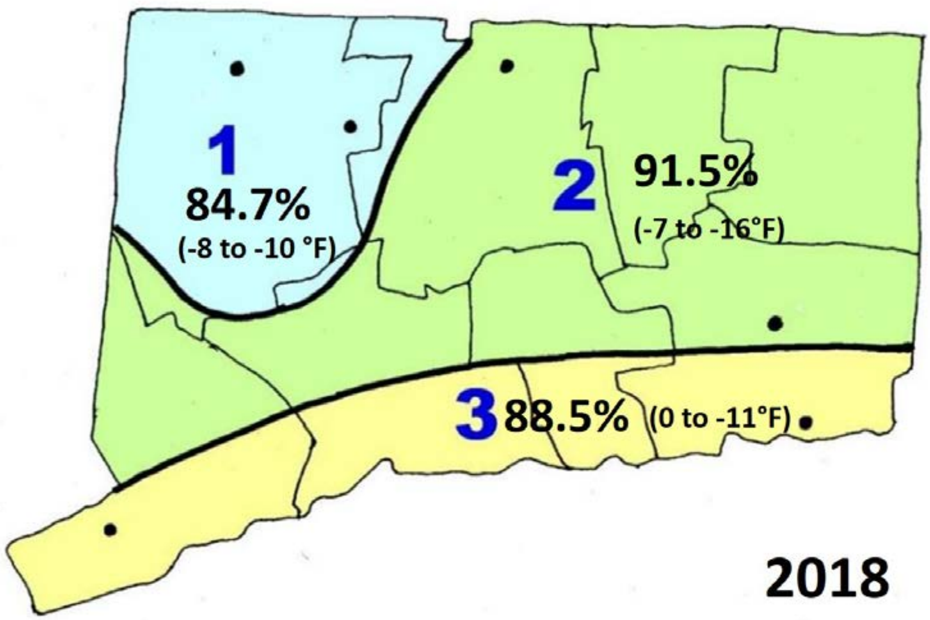
However, in Connecticut, winter populations of HWA can be dramatically reduced by extreme winters (Figure 4) (13): https://www.ct.gov/caes/lib/caes/documents/publications/fact_sheets/plant_pathology_and_ecology/hemlock_woolly_adelgid_winter_mortality__7.12.16.pdf

Figure 4. Patterns of mean percentage winter mortality of hemlock woolly adelgid in northern and southern Connecticut 2000-2018



Recent research at the Station has shown that HWA from more interior regions are more cold tolerant than coastal populations (7). A predictive model was developed, based on the absolute minimum daily winter temperature occurring between December and February (7) and is helpful in determining expected HWA winter mortality and the subsequent need for chemical or other control treatments of HWA for Connecticut homeowners in the relevant climate divisions. In the past 20 years, extremely high HWA mortality has been documented recorded during severe Connecticut winters (13). Exceedingly high HWA winter mortality in 2014, 2015, 2106, and 2018, due to weak polar vortex events which allowed extreme arctic air outbreaks into the lower latitudes, have resulted in the lowest levels of HWA in Connecticut since the peak in the 1990s. Maps showing the highest HWA winter mortalities in Connecticut from 2000-2016 in the different climatic divisions of Connecticut from 2000 – 2016 are referenced in Cheah (2016) (13) The winter of 2018 was also severe and extreme temperatures in early January after a warm December killed a high percentage of HWA and sudden wind chills resulted in extreme winter desiccation and injury to exposed hemlocks. Figure 5 shows the 2018 mean HWA winter mortality in the northwest (Division1), central (Division 2) and coastal (Division 3) regions of Connecticut, with lowest minimum daily temperatures recorded at official weather stations.

Figure 5. Mean 2018 winter mortality of HWA in the 3 climatic divisions of Connecticut



Other Serious Hemlock Pests and Stressors

Hemlocks can also suffer severe decline from another serious non-native pest, elongate hemlock scale, *Fiorinia externa* Ferris (EHS), which occurs as the major hemlock pest or in combination with HWA (Figure 6). Elongate hemlock scale is an armored scale which feeds on the needles of hemlocks, firs, spruce and other conifer species (14) and it preceded HWA in infesting hemlocks in Connecticut. Elongate hemlock scale initially spread from New York into Fairfield County, CT in the 1970s (15). By the mid-1980s, EHS had infested a greater part of south west Connecticut (14). This scale is native to Japan (16). Scale infestations on hemlocks can be controlled in the garden landscape by regular timely horticultural oil applications (17) and in the forest, the native twice-stabbed ladybeetle, *Chilocorus stigma* Say, can sometimes be seen feeding on higher density infestations of EHS and other scales on hemlock. However, natural enemies of EHS, including an exotic parasitoid of EHS in Japan, *Encarsia* (formerly *Aspidiotiphagus*) *citrinus* Craw appear unable to control the increasing spread of this pest in the Northeast (18).

Figure 6. Elongate hemlock scale as the primary pest or concurrent with hemlock woolly adelgid on eastern hemlock

Concurrent HWA and EHS infestations have occurred in the past in many hemlock stands in parts of Connecticut and have, together, caused heavy damage to the trees. In recent years, EHS has spread to very damaging levels in western Connecticut while HWA infestations have greatly decreased due to winter kill. Scale populations have increased steadily and have now spread east of the Connecticut River. This scale is less susceptible than HWA to winter temperature extremes (Cheah unpub. data) and EHS, not HWA, is responsible for recent hemlock decline, especially in northwest Connecticut (Cheah personal observations). Decline in hemlock health due to EHS is indicated by increasing chlorosis of hemlock needles, resulting in yellowish-green foliage. When trees are heavily infested with EHS, widespread loss of old and new needles and a reduction in new shoot production on infested branches all result in reduced, grayish thin crowns (Figure 7).

Figure 7. Thinning hemlock crowns in Connecticut damaged by heavy EHS infestations

Drought also has significant devastating impacts on moisture-loving hemlocks, especially in poor growing sites. Records from the Northeast Regional Climate Center indicate that Connecticut experienced the worst prolonged severe to extreme drought periods in 1966-1968, followed by 2001-2002 and 2016-2017. During such extended extreme drought periods, stressed, weakened hemlocks are also targeted by the native hemlock borer, *Phaenops* or *Melanophila fulvoguttatta* Harris, a buprestid beetle, which in large numbers, often overwhelm and eventually kill the trees (19). Woodpeckers strip the bark of infested trees to feed on the larvae exposing the reddish inner bark riddled with larval tunnels (Figure 8). Recent extreme drought conditions in Connecticut in 2016-2017 precipitated hemlock borer outbreaks, especially on rocky ridges with heavy infestations of EHS.

Figure 8. Hemlock borer attack following severe drought

However, later ample rains in 2017 and 2018, together with significant statewide reductions of HWA by successive severe winters have enabled the excellent recovery of formerly stressed hemlocks in many sites throughout Connecticut (Cheah personal observations).

Control and Management of HWA

Regular inspections of foliage on the outermost growth of hemlocks is prudent for detection of initial infestations of HWA in the garden landscape. When HWA infestations are minimal, infested branch tips can be easily pruned out and removed from the vicinity of the hemlocks. The adelgids will subsequently die from desiccation and optimal times to remove HWA infestations are in the fall when the woolly masses are more visible and before egg masses are formed in late winter through early summer. Annual applications of spray treatments are recommended when HWA is prevalent in the area. Thorough coverage with 2% horticultural oil or insecticidal soap sprays can be used on accessible trees or hedges in the garden landscape to effectively manage and kill HWA (3) but is costly and impractical for large scale control in the forest. Systemic and foliar chemical control with neonicotinoids have been widely utilized in some other states for control of HWA but in Connecticut, this is now restricted to licensed use (CT Public Act No. 16-17 An Act Concerning Pollinator Health: https://www.cga.ct.gov/2016/ACT/pa/2016PA-00017-R00SB-00231-PA.htm

With mounting environmental concerns for honeybees, other pollinators and wildlife, biological control remains the safest strategy for managing HWA resurgence in the natural landscape. Several predator species have also been introduced in other parts of the HWA range but are largely still under evaluation or not available to homeowners, except for one species researched by the CAES (see below).

Biological Control of HWA in Connecticut

In Connecticut, biological control of HWA has focused exclusively on mass releases of the tiny Japanese coccinellid, *Sasajiscymnus* [formerly *Pseudoscymnus*] *tsugae*, discovered and described by Japanese and CAES scientists (20). This tiny black ladybeetle, about 2mm in length, was the first non-native HWA predator species imported into the US from southern Honshu island, Japan. A federal permit was issued after an environmental assessment and the first release of this species was in Connecticut in 1995. Thus, Connecticut has had the longest history and implementation of biological control of HWA in the USA. *Sasajiscymnus tsugae* is the first predator species introduced in the U.S. for biological control of HWA. It was first released in a town park in Windsor, Connecticut, and since then, several million have since been released throughout the eastern USA on federal, state and private lands (21). It is the only HWA predator that is being reared commercially, for over 10 years and is available to the public from Tree-Savers, a company from Pennsylvania (http://tree-savers.com/).

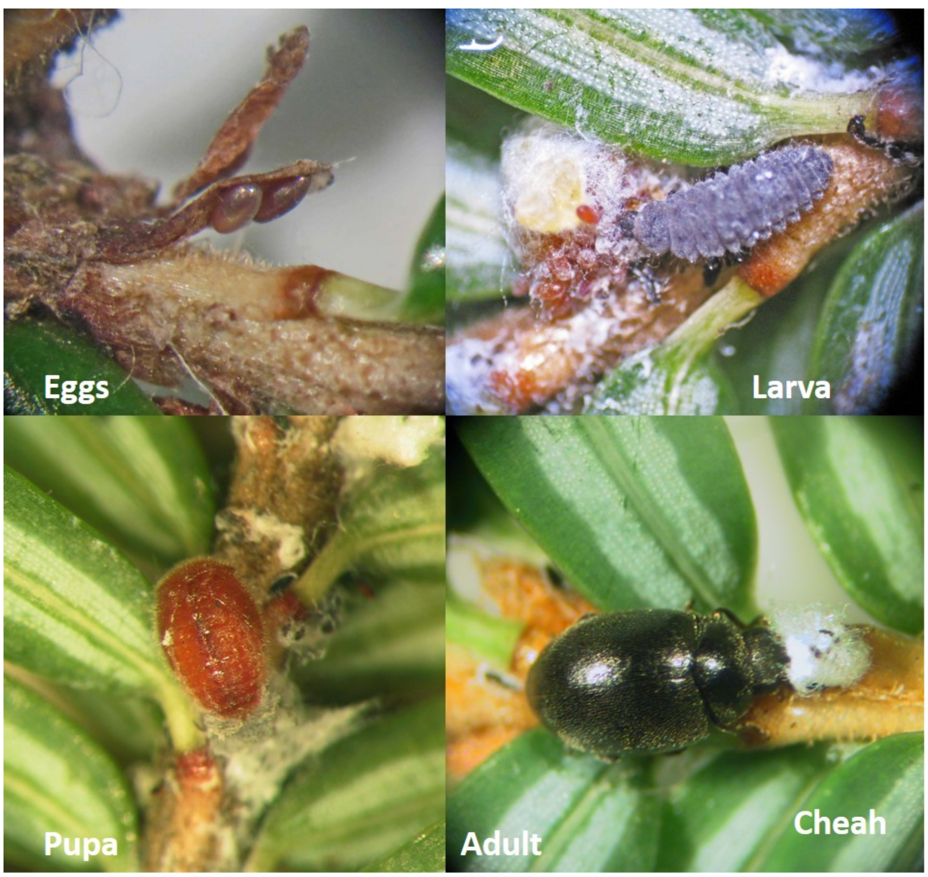
Sasajiscymnus (formerly *Pseudoscymnus*) *tsugae* (Coleoptera: Coccinellidae: Scymninae)

Biology and Synchrony with HWA

This tiny ladybeetle only measures 2mm in length but it is a specialized, long-lived adelgid feeder which highly prefers HWA but will also feed on other adelgid pests such as balsam woolly adelgid, pine bark adelgid and eastern spruce gall adelgid. Both larva and adult stages (Figures 9 & 10) feed voraciously on all stages of HWA, including the dormant HWA first settled instars in the heat of summer. In Connecticut, two field generations are possible and adults have overwintered in Connecticut. Adults are highly mobile and fly readily to disperse. Female *S. tsugae* beetles are highly fecund and can produce, on average, 280 eggs in a lifetime. The life cycle of this species is highly synchronized to that of its prey, HWA, and it has a long season of predation and impact from mid-spring to late fall (22, 24, 25, 26).

Figure 9. Adult *Sasajiscymnus tsugae* feeding on hemlock woolly adelgid eggs

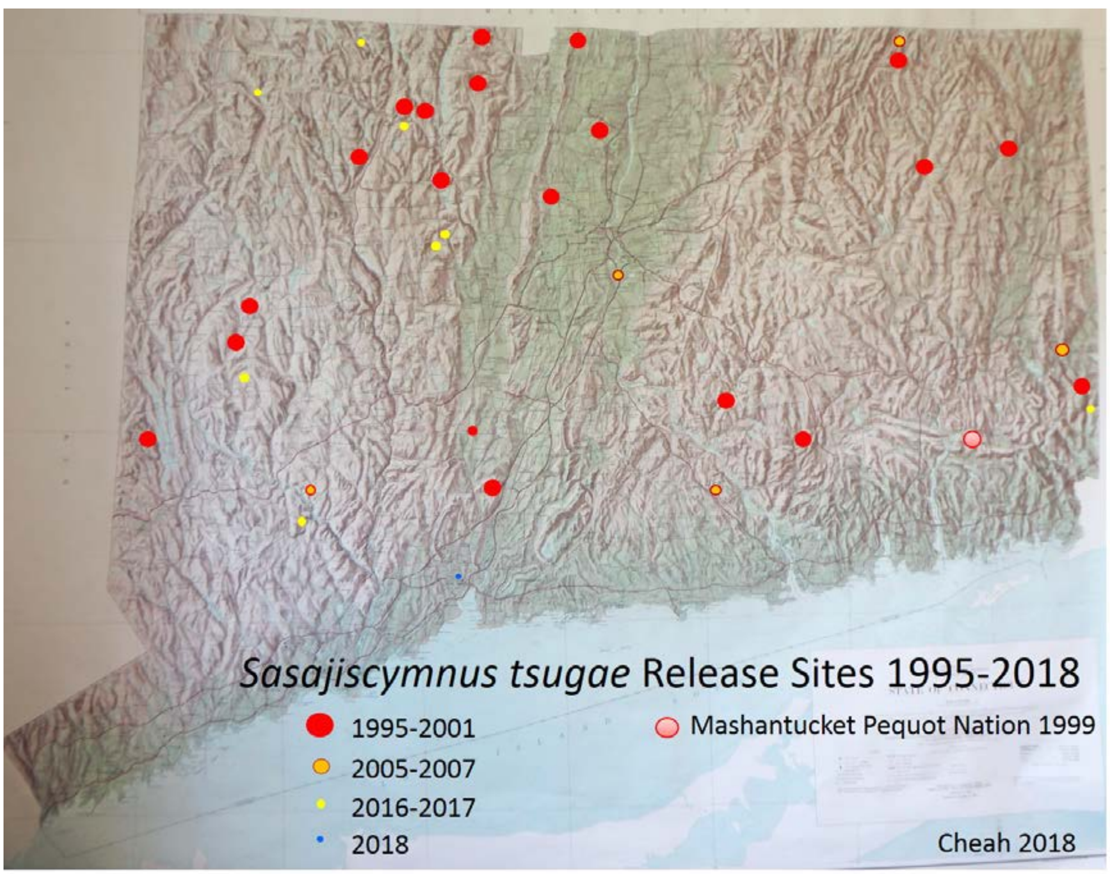
Figure 10. Stages of *Sasajiscymnus tsugae*, ladybeetle predator of HWA



Rearing and Releases of *S. tsugae* in Connecticut

From 1995-2007, >176,000 adult *S. tsugae* were reared at the Kenneth White Insectary, Valley Laboratory in Windsor and released at 26 sites on state lands, town and private forests (21). The majority of forest sites received several thousand (2,000-10,000) mated adult *S. tsugae*. More recently, this biological control program with *S. tsugae* was revived in 2017 through the generous donation and cooperation of the sole commercial producer of *S. tsugae*, Tree-Savers of Greentown, PA. Two thousand beetles were released at 7 new forest sites in June 2017 in small groups of 100-300 to control small pockets of resurgent HWA in new areas of Connecticut. As of 2018, a total of 178,442 *S. tsugae* have been released at 35 sites throughout Connecticut since 1995: 22 on state lands, 5 in town/city parks, 7 on private forests/land trusts and 1 on tribal land at the Mashantucket Pequot Tribal Reservation (Figure 11). Research at the Connecticut Agricultural Experiment Station, supported by the USDA Forest Service from 1994-2009, has documented the life history, biology, mass rearing potential, establishment and suitability as a biological control agent. Assessments in older Connecticut release sites from 1995-2001 showed that *S. tsugae* had reproduced and overwintered successfully in many locations with subsequent hemlock tree recovery, after favorable environmental conditions, attesting to the resilience of eastern hemlocks (22, 23, 27, 28, 29, 30, 31).

Figure 11. Connecticut release sites for *Sasajiscymnus tsugae* for biological control of hemlock woolly adelgid 1995-2018



The large, colorful and exotic Halloween ladybeetle, *Harmonia axyridis* Pallas occasionally feeds on HWA but its preferred prey are aphids (Figure 12).

Figure 12. *Harmonia axyridis* adult and larva feeding on hemlock woolly adelgid

Hemlock trees at selected Connecticut *S. tsugae* release sites have been assessed annually for HWA winter mortality, crown conditions, pests and general health for many years since the initial releases in the 1990s. Currently, an integrated assessment of the state of Connecticut's hemlocks and the efficacy of these biocontrol implementations of *S. tsugae* in Connecticut at older sites is underway, funded by the USDA National Institute of Food and Agriculture. Field release sites are being revisited and reassessed 12-20 years after release.

Tremendous hemlock recovery was recorded in 2005 and has continued at many *S. tsugae* release sites in Connecticut, to a greater degree than in non-release hemlock sites (22, 27). Similar impressive hemlock recovery and refoliation throughout the state, after the extreme drought of 2015-2017 is currently being documented, following above normal precipitation in 2017 and 2018. Long term studies at the CAES are showing that eastern hemlocks can be very resilient, contrary to conventional predictions (Figure 13).

Figure 13. Eastern hemlock recovery in northwestern Connecticut 2018

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