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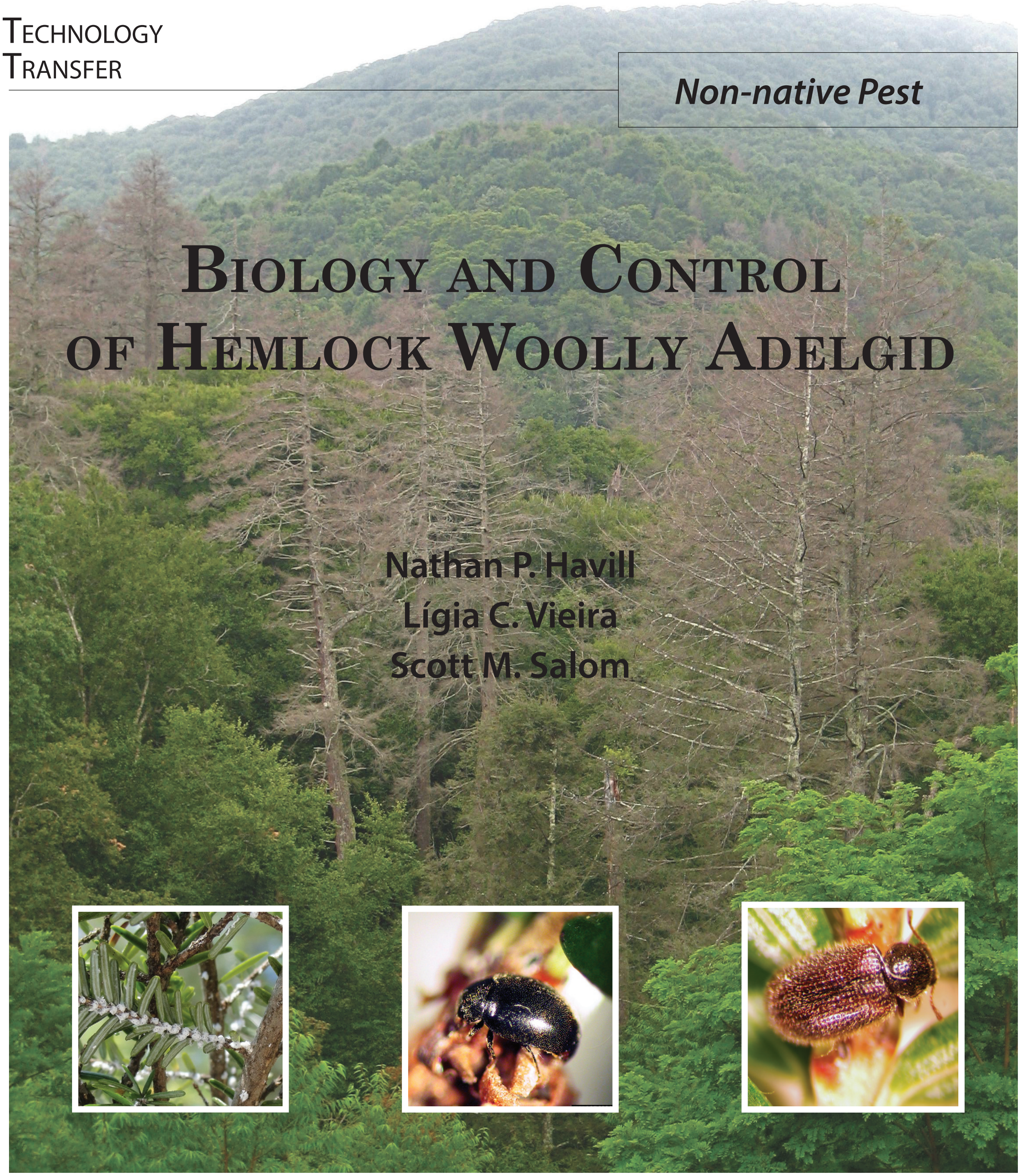

BIOLOGY AND CONTROL OF HEMLOCK WOOLLY ADELGID

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Biological Control

With no specialist natural enemies present in eastern North America, HWA is able to flourish and spread unchecked. Searching for and studying natural enemies in western North America and parts of Asia with native lineages of HWA is considered critical. The primary objective of biological control is to introduce a group of natural enemies considered important in the native habitat and deemed safe for introduction into the eastern United States. Since no known parasitoids are associated with Adelgidae, the classical biological control program for HWA has focused on prey-specific predator species and entomopathogens.

Fungal Pathogens

Twenty fungal genera and 79 entomopathogenic fungus isolates were found in association with HWA in the eastern United States and southern China. Of all the isolates, no putative specialists were found. A combination of generalist fungi that included two strains of *Beauveria bassiana* Balasamo, one of *Lecanicillium lecanii* Zimmermann, and one of *Metarhizium anisopliae* Metchnikoff, demonstrated high efficacy against HWA. A commercially available *Lecanicillium lecanii* formulated with a whey carrier has been tested in small-scale forest trials and has been shown to be effective, especially against early instar HWA before they produce wool. This augmentative approach is still in the early developmental stages.

Predators

The first efforts toward the application of biological control of HWA in eastern North America started in 1992. Of the predators first collected from Japan, the most promising at the time, *Sasajiscymnus tsugae* (Sasaji and McClure) (Coleoptera: Cocinellidae) was imported, evaluated, mass reared, and cleared for release (Figure 15). Field releases started in 1995 in Connecticut and more than two million *S. tsugae* have been released throughout the introduced range of HWA. Post-release evaluations indicated successful overwintering, reproduction, and dispersal of *S. tsugae*, but establishment of the predator and impact on HWA populations has been inconsistent. In the South where establishment has been closely monitored, the predator population takes 5 to 7 years to reach a detectable level at

Fig 15. Sasajiscymnus tsugae adult (left) and late instar larva (right) (Photos: Carole Cheah, Bugwood.com.)

only some of the locations where releases were made. Large-scale rearing of this insect for release is being phased out, yet monitoring its presence and impacts will continue.

Additional foreign explorations for natural enemies were carried out from 1995 until 1997 in Yunnan, Sichuan, and Shannxi provinces in China. Three previously unknown lady beetles (Coleoptera: Coccinellidae), *Scymnus camptodromus* Yu et Liu, *Scymnus sinuanodulus* Yu et Yao, and *Scymnus ningshanensis* Yu et Yao, were found to be the most abundant predators in different locations. The predators were imported, evaluated in quarantine, and cleared for release. However, due to difficulties in mass rearing, releases of *S. ningshanensis* and *S. sinuanodulus* were delayed until 2004, and *S. camptodromus* was not released. There were no recoveries of the first two species following their limited releases, and work continues on rearing of *S. camptodromus*.

Laricobius beetles in the family Derodontidae are specialist predators of adelgids. In 1997, a predator native to western North America, *Laricobius nigrinus* Fender, was found to consistently feed only on HWA in the lab, and its life cycle was shown to be synchronous with HWA (Figure 16). Oviposition and subsequent larval development coincides with oviposition by the HWA sistens adults. Females oviposit within HWA ovisacs from January to March. After hatching, larvae go through four instars

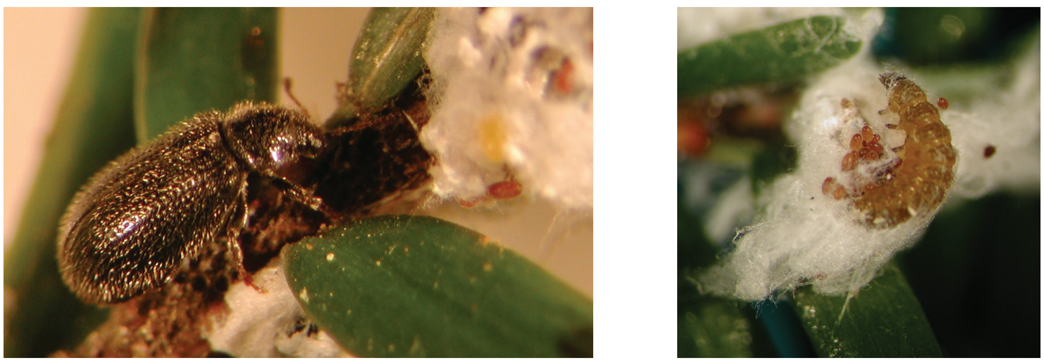

Fig 16. *Laricobius nigrinus* adult and its yellow egg (left) and late instar larva with HWA eggs (right) (Photos: Rob Flowers, Virginia Tech).

and mature larvae drop to the soil to pupate within two weeks. Eclosed adults remain in the soil in a state of aestival diapause that coincides with diapausing first instar sistentes. Adults resume activity in the fall coinciding with resumption of development by HWA.

Following host-range testing studies in quarantine, the predator was cleared for release in 2000. Rearing procedures were developed and releases began in 2003. To date, more than 200,000 beetles have been released at over 200 sites. Evaluations after release showed that establishment is positively correlated with minimum winter temperature and with the number of beetles released. Beetles initially disperse slowly up the release tree and then away from the release tree at a rate of close to 40 m/yr. Some anecdotal evidence suggests this could be greater at times.

Due to the difficulty in rearing *L. nigrinus*, only 500 beetles were available for each release in forested settings. As rearing has improved and beetles can now be collected and redistributed from already established sites, the numbers being released have increased to range from 750 – 2,000 beetles per site.

Laricobius nigrinus collected from coastal sites in the West (coastal strain) appear to establish better in warmer climates (plant hardiness zones 6a and higher). *Laricobius nigrinus* from Idaho and Montana (interior strain) that are better adapted to colder temperatures are being reared and are beginning to be released in the more northern range of introduced HWA.

A native eastern North American *Laricobius* species (*Laricobius rubidus* Le Conte) has also been found on HWA infested hemlock. This predator feeds mainly on native pine bark adelgid, *Pineus strobi* Hartig. It prefers this prey when given a choice, but is able to feed and develop on HWA. It is also active from fall through mid-spring and there is a considerable overlap of feeding by both beetle species. *Laricobius nigrinus* and *L. rubidus* have been found to interbreed at sites where *L. nigrinus* was released in the eastern United States. Research indicates that at these sites, *L. nigrinus* and *L. rubidus* are hybridizing at a steady rate (ca. 10 - 15%) and *L. nigrinus* over time may reduce the proportion of *L. rubidus* on hemlock, but not on white pine at sites where both tree species are present.

Because the strain of HWA that was introduced to eastern North America is from southern Japan, an additional effort was made to look for natural enemies in this location. A new species, *Laricobius osakensis* Montgomery and Shiyake, was discovered in 2005 and imported to quarantine to study its biology and host-range (Figure 17). The insect was also studied in its native habitat. *Laricobius osakensis* has host preferences similar to *L. nigrinus*, greater fecundity, and a higher predation rate then *L. nigrinus*. Lab studies showed that it cannot hybridize with the North American *Laricobius* species. In its native habitat, it is shown to be the key natural enemy on sistentes, being consistently present in association with HWA, and having a synchronous life cycle with HWA. Its population fluctuations were correlated with those of the HWA sistens population, and it was shown to reduce populations of HWA on *T. seiboldii*. Permission to remove *L. osakensis* from quarantine was received in 2010 and the first open releases began in 2012. Continued efforts toward large-scale operational releases and monitoring of this predator are underway.

Fig 17. *Laricobius osakensis* adult female with typical reddish brown coloration (upper left), adult male with typical dark coloration (upper right), and larva (bottom center) (Photos: Ligia C. Viera, Virginia Tech).

Additional predators from western North America that could target the progrediens generation include *Scymnus coniferarum* (Crotch) (Coleoptera: Coccinelidae), found in association with HWA in Washington, and silver flies (*Leucopis* spp.: Diptera: Chamaemyiidae) whose larvae and adults were found to be positively correlated to HWA densities in Oregon and Washington. Work is ongoing to determine their viability as biological control agents.

Toward Integrated Pest Management of HWA

Researchers working in open-grown hemlock plantations have noticed that trees growing under full sunlight do not appear to support dense populations of HWA. Trees in the shade and under forest canopies, or a tree's lower branches shaded by upper branches, tend to be colonized more readily by HWA. At this time we do not know if HWA survival is impacted by direct radiation and increased temperature or by physical differences in trees growing in direct sun versus those growing in shade. It has also been found that infested trees survive longer if they have higher live crown ratios, even those in the understory. The most vulnerable trees seem to be those that have small crowns relative to their stem and are therefore not producing enough carbohydrates to support growth under stress from HWA. It is therefore useful to consider that under certain conditions, trees may be less susceptible to HWA colonization and impact. For example, further investigations can test whether thinning stands to expose hemlock trees to more sunlight can be used to reduce HWA infestations and subsequent impacts on hemlock health. Note, that in dense hemlock stands, abrupt thinning could cause damage to shade needles, so it may be necessary to thin incrementally over several treatments.

It has recently been proposed that the integration of chemical and biological control on an area-wide scale may help save some hemlocks that otherwise would not survive in the long-term by any one control method used alone. The concept currently being tested involves the chemical treatment of a subset of mature infested hemlock while releasing predators on understory trees. The chemical treatment could provide short-term protection for the larger trees and allow the predator populations to build up in the understory. Once the larger trees lose their chemical protection, an established predator population might be more capable of controlling a building HWA population than a predator population still on the process of becoming established. These kinds of integrated approaches should continue to be evaluated while new management tools are developed for HWA control.