ASSESSMENTS OF BIOLOGICAL CONTROL OF HEMLOCK WOOLLY ADELGID WITH *SASAJISCYMNUS TSUGAE* IN CONNECTICUT AND NEW JERSEY

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ABSTRACT

The health of hemlocks in *S. tsugae* release sites in Connecticut and New Jersey are compared to non-release sites in an attempt to assess the efficacy of introductions of *Sasajiscymnus* (=*Pseudoscymnus*) *tsugae* (Coleoptera: Coccinellidae) for hemlock woolly adelgid control and management and to remediate hemlock decline. Foliage transparency emerged as an important variable for assessing hemlock crown conditions. In Connecticut, mean foliage transparency was significantly better in release than in non-release sites. Significant improvements in foliage transparency of hemlocks were recorded in *S. tsugae* release sites but not in non-release sites from 2003 to 2004 in New Jersey. Foliage transparency and hemlock mortality in Skyland release sites were significantly lower than in comparable non-release sites. Patterns of hemlock health, *S. tsugae* recoveries, and the impact and interaction of abiotic and biotic factors such as drought, winter mortality of adelgids, and concurrent elongate hemlock scale infestations are also discussed.

KEYWORDS

Adelges tsugae, hemlock woolly adelgid, *Sasajiscymnus (Pseudoscymnus) tsugae*, foliage transparency, eastern hemlock, biological control.

INTRODUCTION

While New Jersey is approximately 1.5 times the land area of Connecticut, both states share almost equivalent forest cover and some of the most densely populated areas in the U.S. Forests cover nearly 1.9 million acres in Connecticut, and eastern hemlocks, *Tsuga canadensis* Carriere, are concentrated in Litchfield County, in the northwestern corner of the state (Wharton et al. 2004), where hemlock stands of more than 1000 acres predominate (Hurlock, personal communication). New Jersey has 1.8 million acres of forested land of which 26,000 acres comprise eastern hemlock stands, also located primarily in the northwestern corner of the state in Sussex, Passaic, Warren and Morris counties (Anonymous 2001). Portions of the northwestern corner of Connecticut are also linked geologically to the northwestern corner of New Jersey. Both the New Jersey Highlands and the Housatonic Highlands in Connecticut are part of the Highlands Province, composed of the oldest Precambrian metasedimentary rocks (Stoffer 2003). Climatically, the Highlands and Skylands regions of New Jersey lie within USDA Zone 6a (minimum winter temperatures between –5 to -10°F) and 6b (0 to –5 °F), which is similar to much of central and southern Connecticut. The northwestern and northeastern corners of Connecticut are part of Zone 5b, where minimum winter temperatures range between –10 to –15 °F.

Connecticut and New Jersey also share a common history with some of the first extensive areas of hemlock decline associated with the initial invasion and spread of *Adelges tsugae* Annand, hemlock woolly adelgid (HWA), in the mid to late 1980s (Ward et al. 1992). In New Jersey, the Highlands region has been heavily infested with HWA since the late 1980s while the northernmost high elevation parts of Sussex and Warren counties, known as the Skylands region, has only more recently been heavily infested, as of the late 1990s. In Connecticut, northwestern Litchfield county is also the most recently infested, while much of the rest of the state has experienced adelgid infestations since the late 1980s. The two states have also cooperated closely in biological control implementations involving *Sasajiscymnus* (formerly *Pseudoscymnus*) *tsugae* Sasaji and McClure, originally imported from southern Honshu, Japan, beginning with the shipment of a starter colony of *S. tsugae* from the Connecticut Agricultural Experiment Station in 1997 to the New Jersey Philip Alampi Beneficial Insect Laboratory. Research on *S. tsugae* in Connecticut, funded by the USDA Forest Service, has continued with studies on the biology and behavior of *S. tsugae*, and hemlock health assessments and monitoring of *S. tsugae* release sites. In New Jersey, the Philip Alampi Laboratory has also mass-reared *S. tsugae* for releases and starter colones in other affected states while also maintaining an extensive release program in New Jersey's infested hemlock stands. To date, 298,160 *S. tsugae* have been released in 70 sites in New Jersey from 1998-2004, while 172,020 have been released in 21 sites in Connecticut from 1995-2002. Many of the release sites selected in Connecticut had moderate to high pre-release adelgid populations, as did release sites in New Jersey—in particular, sites in the Highland region. Although the establishment, field reproduction, synchrony of life cycles with *A. tsugae* and overwintering ability of *S. tsugae* has been previously documented in Connecticut (Cheah and McClure 2000 and 2002) and New Jersey (Mayer et al. 2002a), recovery rates have not been consistently high. Thus, much of the ensuing discussion will center on recent comparative assessments of hemlock health in *S. tsugae* release and non-release sites in the two states.

This paper seeks to identify patterns and summarize encouraging results from the release programs in Connecticut and New Jersey after 6-9 years of monitoring and assessments of *S. tsugae* release sites and to highlight important factors influencing the recovery of hemlocks in adelgid-infested stands.

METHODS

CONNECTICUT

In 2003 and 2004, annual summer evaluations of hemlock health in selected release sites were expanded to include a minimum of 10 to 15 trees per site. Trees evaluated were representative of the age classes at each site and comprised mostly intermediate and co-dominant hemlocks.

At a few sites, the number of trees rated exceeded this as transects to 200m were also included in site evaluations. In addition, fall 2003- winter 2004 surveys (n = 15 trees/site) was conducted in northwestern Connecticut in 28 hemlock stands by the Connecticut Agricultural Experiment Station plant inspectors. All hemlock health ratings followed the standard Forest Inventory Analysis (formerly Forest Health Monitoring) criteria of live crown ratio, crown density, foliage transparency, percentage crown dieback, and live branches (5% classes). In addition, crown estimates of new shoot production and the overall level of adelgid infestations were estimated with binocular inspection in classes of 0, <10%, 11-50%, 51-75%, and >75% (after Tigner, unpublished). Levels of elongate hemlock scale, *Fiorinia externa* Ferris, infestation were also rated visually as none, very light, light, medium, high or very high. At each *S. tsugae* release site, adelgid-infested hemlock tip samples from healthy branches in the lower crown from a minimum of 10 trees were randomly selected during site visits in late February through April, 2003 and 2004, for estimates of winter mortality of the *A. tsugae* sistens. Counts were made under a dissecting microscope to determine the proportion of live and dead adelgids (minimum of 1,000 adelgids/site) per sample. Soil types for each release and non-release site and corresponding woodland suitability groups, which estimate site quality for forest growth, were determined from county-level soil survey maps for all seven Connecticut counties, compiled by the USDA Soil Conservation Service in cooperation with the Connecticut Agricultural Experiment Station and the Storrs Agricultural Experiment Station from 1966-1983. Woodland suitability groups ranged from 1 to 11: 1 being the best site and 11, the poorest. This ranking was used as a method to account for possible site differences before statistical comparisons.

Sampling for predators at selected release sites continued with lower crown sampling of infested branches using 1 meter^2 beating sheets to catch dislodged debris and insects. Thirty infested hemlock tips per site (18-24”) were also sampled randomly at 1.5-5m intervals from five selected release sites and surroundings that showed patchy and limited resurgence of adelgids in 2004 and inspected under dissecting microscopes for signs of predation.

NEW JERSEY

Crown ratio, foliage transparency ratings and assessments of hemlock mortality were conducted in 2003 and 2004 at 23 selected *S. tsugae* release sites according to the above Forest Inventory Analysis (Forest Health Monitoring) criteria (Mayer et. al 2002a). In 2003 and 2004, hemlock crown ratings performed at 38 matching non-release sites were also conducted for comparisons. These non-release sites consisted of the most proximal non-release hemlock stands that had similar topographical and hemlock characteristics to those of release stands. All sites rated (n = 20 trees/site) were classified by region (Highland or Skyland) to account for differing histories, intensity, and duration of HWA infestation for statistical analyses. Predator sampling of the lower crown was also conducted at release sites as described above. In addition, a bucket truck was used to sample at increasing heights in the crown in one Skyland site in 2001 to investigate distribution of *S. tsugae* four weeks after initial release in comparison to a simultaneous lower crown survey.

STATISTICAL ANALYSES

Statistical analyses on Connecticut and New Jersey data were performed using the Number Cruncher Statistical System 2000 computer program (Hintze 1998). Range estimates for new shoot production, adelgid and scale infestations from Connecticut sites were transformed into ranks for statistical comparisons (0-4 for new shoot production and adelgid levels, and 0-5 for elongate hemlock scale infestations). Data were checked for normality and equal variances, and where appropriate, the Equal Variance T-Test or the Aspin-Welch Unequal Variance T-Test was used. Non-parametric statistical analyses (the Mann-Witney U-Test and the Wilcoxon Signed-Rank paired t-test) were used for comparisons of non-normal distributions of foliar transparency and hemlock mortality. Linear regressions were also performed to investigate relationships between variables.

RESULTS

CONNECTICUT

Eleven release sites were rated for crown health and infestation levels in 2003 and 16 in 2004 (Table 1). Foliar transparency ratings in 2003 and 2004 were not significantly related to woodland suitability groups. Foliar transparencies in 2003 and 2004 were similar ($p > 0.05$) as were levels of new shoot production. In 2003 and 2004, average levels of new growth were between 50 and 75% of the crown in release sites. Foliage transparency in 2004 was significantly correlated to new growth in 2004 (Figure 1a; $r^2 = 0.2783$, $p = 0.0357$). Levels of adelgid in release sites in 2003 were low (<10%) in eight sites, while in three sites, there was patchy resurgence (10-50%). In 2004, 14 sites had <10% levels of HWA while only two sites showed very patchy resurgence. Comparisons of mean HWA levels in release sites in 2003 and 2004 showed no overall increase in 2004 and remained low overall. Both winters of 2003 and 2004 were severe and resulted in heavy mortality of the adelgid in *S. tsugae* release sites. Mean overwintering mortality of HWA in *S. tsugae* release sites in 2003 was 83.1 ± 7.7% and 87.7 ± 10.9% in 2004, which accounted for much of the subsequent depression of adelgid populations in release sites. Release sites were also infested with *F. externa*. In 2004, 31% of sites had high elongate hemlock scale infestations, 56% of sites had light to moderate infestations, and only 12.5% of sites had negligible scale infestations. In 2004, foliage transparency in release sites was slightly correlated to ratings of scale infestations, although the relationship was not significant (Figure 1b; $r^2 = 0.2235$, $p = 0.0644$). There was also no significant relationship between scale infestations and foliage transparency in 2003.

In non-release sites surveyed in fall 2003 and early winter 2004, foliar transparencies in sites that had indications of adelgid infestation were also not related to woodland suitability groups ($p > 0.05$) (Table 2). Seven of the 28 sites surveyed in pristine areas of high elevations and remote locale were identified as having negligible adelgid or scale infestation. Foliar transparencies from 105 trees from these seven sites were used to develop a baseline mean

Table 1. 2003 and 2004 hemlock health assessments in selected *S. tsugae* release sites (1995-2002) in Connecticut. For HWA and new growth levels: 1 = < 10%; 2 = 11-50%; 3= 51-75%; 4 = > 75% for crown infestation. For EHS levels: 0.5 = Very Light, 1 = Light; 2 = Medium; 3 = High; 4 = Very High.

Year	# Trees	# Sites	Woodland Suitability Group	Means				
				Foliar Transparency	HWA on Crown	New Growth	EHS	Cumulative % Hemlock Mortality
2003	202	11	1-9	33.4 ± 9.5	1.3 ± 0.4	3.1 ± 0.7	1.7 ± 1.1	-
2004	300	16	1-11	37.5 ± 9.3	1.1 ± 0.4	3.3 ± 0.6	2.4 ± 1.3	7.6 ± 13.1

Table 2. Hemlock health assessments in non-release sites in northwestern Connecticut in fall 2003 and early winter 2004. For HWA and new shoot production levels: 1 = < 10%; 2 = 11-50%; 3= 51-75%; 4 = > 75% for crown infestation. For EHS levels: 0.5 = Very Light; 1= Light; 2 = Medium; 3 = High; 4 = Very High.

Non-release Sites	# Trees	# Sites	Woodland Suitability Group	Means			
				Foliar Transparency	HWA on Crown	New Growth	EHS
HWA + EHS	315	21	5-11	47.9 ± 5.2	1.0 ± 0.5	3.7 ± 0.4	2.1 ± 1.5
Negligible HWA/EHS	105	7	2-9	37.0 ± 7.1	0.01 ± 0.04	3.8 ± 0.4	0.1 ± 0.2

foliar transparency that was reflective of healthy, relatively uninfested forest hemlocks growing under normal environmental and climatic conditions in northern Connecticut. Both summer and fall ratings for foliar transparency are still valid for comparisons as both measured the amount of 2003 foliage on the crown, which included the new growth for that same growing season in a non-drought year.

Foliar transparency ratings from all sites were not influenced by woodland suitability groups and allowed direct statistical comparisons of 2003 foliar transparencies of release and non-release sites. Mean foliar transparency in release sites (34.4%) was lower than in non-release sites (47.9%) (Mann Witney U Test; Z = -3.7901, p = 0.000082). Foliar transparency in release sites compared very favorably (p > 0.05) with the baseline foliar transparency (37.8%), while foliar transparencies of infested non-release sites were higher than in baseline sites (Equal Variance t-test; t = 4.0013, p = 0.00023). Healthy 2003 new shoot production in release sites (50-75%) was slightly lower as compared to non-release sites (>75%) (Mann Witney U-Test; Z = -2.8992, p = 0.00187), but still reflected recovery. Adelgid levels were not directly comparable as ratings were for different generations of HWA. Hemlock mortality assessments were conducted in 2004 at 16 sites. Mean cumulative hemlock mortality was 7.6 ± 13.1% (3-40%) recorded at six sites (37% of sites), all of which had hemlock borer activity (Table 1). This mortality represented trees that had initially died in 2000 and 2001. However, even in sites with hemlock mortality, hemlocks that survived often showed good recovery and healthy refoliation.

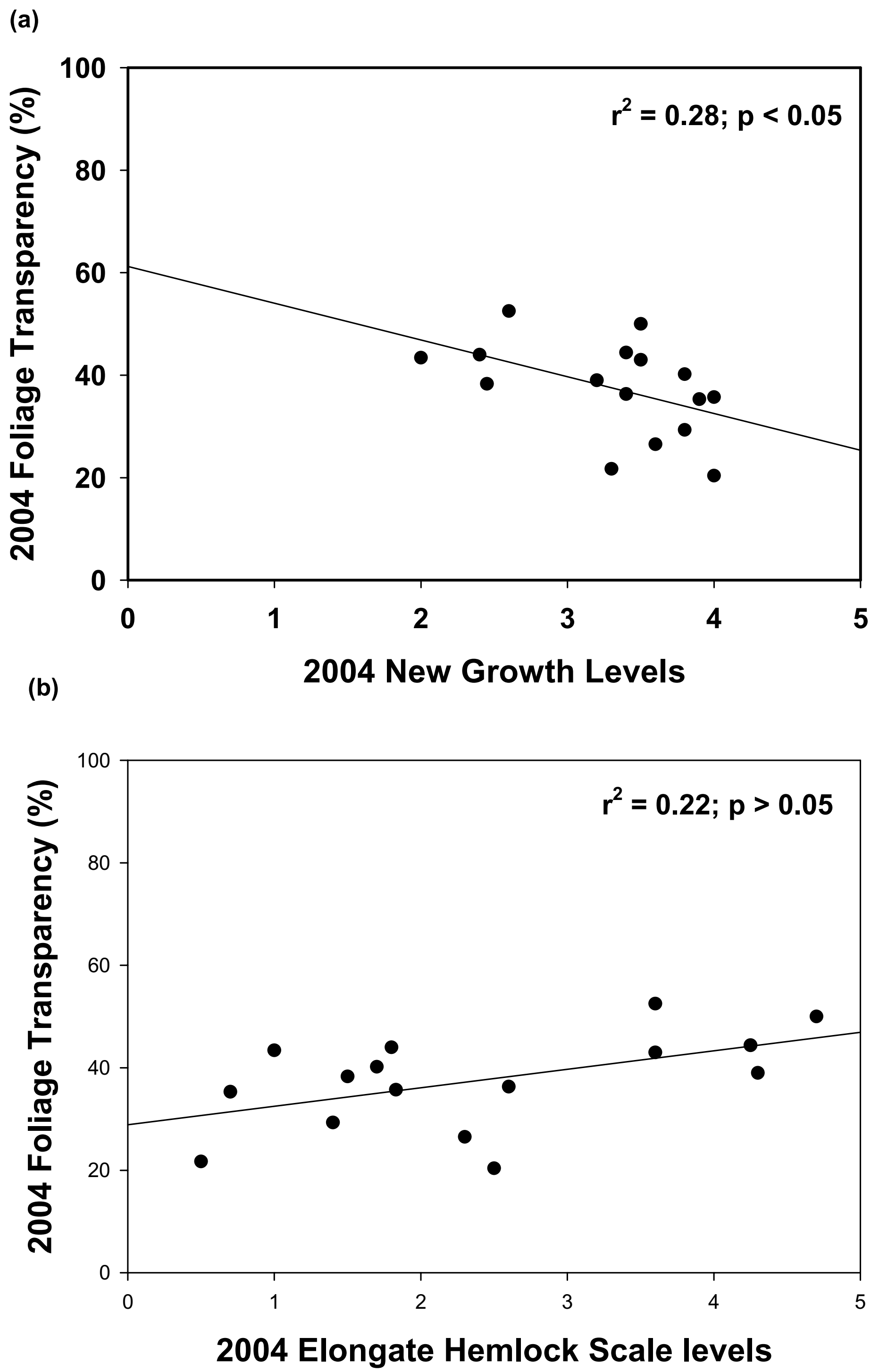


Figure 1. The relationships between foliage transparency and (a) new growth (b) elongate hemlock scale levels in 2004 at Connecticut *S. tsugae* release sites.

In four selected sites where *S. tsugae* had been recovered in previous years, trends in foliage transparency, HWA, and new growth levels on the crown through 2004 are shown in Figures 2(a)- (c). In these sites, mean HWA levels have not risen beyond 50% of the crown over the site. In combination with severe winter mortality in 2003 and 2004, adelgid levels at release sites have remained very low, at less than 10% on the crown. Foliage transparencies have also improved through 2004 from the higher transparencies observed in 2002. Crown levels of new growth have also surged in 2004 at all sites, even in northern sites such as Burr Pond State Park, which had shown severe defoliation and decline just the year before.

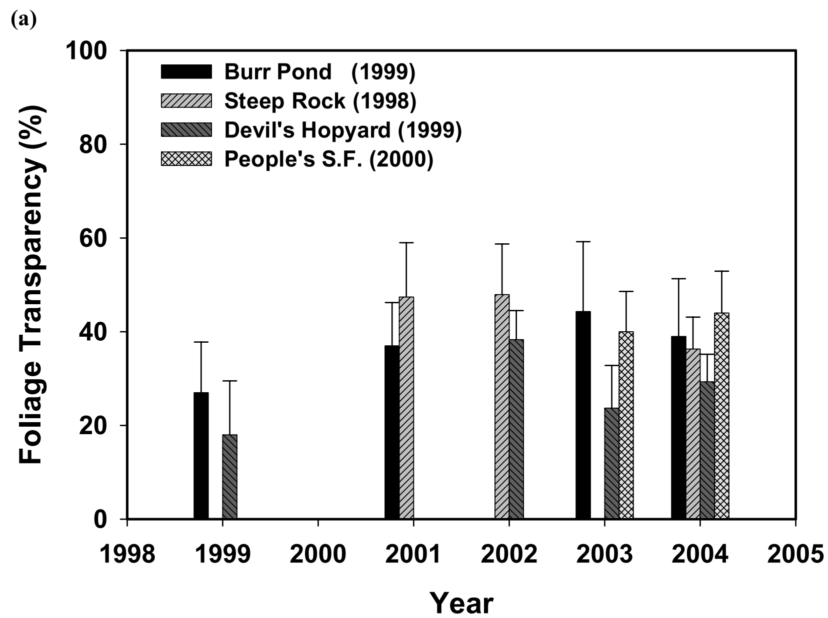
Predator surveys were conducted at a few sites where there was very patchy and light resurgence of adelgids by dislodging insects from lower crown branches into a collecting sheet and by branch tip sample collection for examination under a dissecting microscope. Ground surveys in late June and July at five sites did not recover any *S. tsugae* stages. However, examination of adelgid-infested foliage samples revealed one pre-pupating *S. tsugae* larva, in a web of dead needles, recovered in early June 2004. Dispersal had occurred from the top of the knoll approximately 700-1000m from the original 1999 release area in northeastern Connecticut. This was the first recovery at this site since recoveries of adults and larvae of *S. tsugae* in 2000. To date, recoveries of *S. tsugae* adults and larvae have been made in 13 Connecticut sites (65% of release sites) ranging from 1-6 years after the initial release.

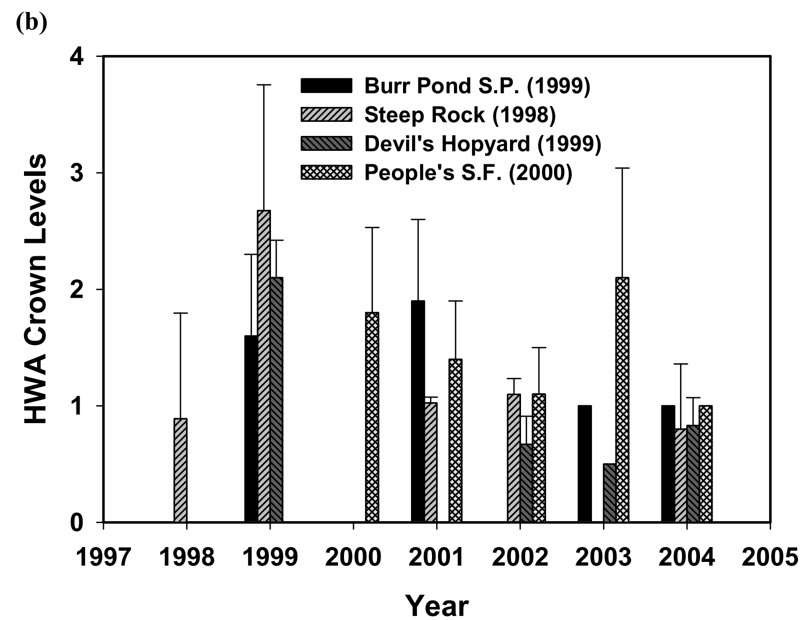
NEW JERSEY

In New Jersey, foliar transparencies and hemlock mortality in release sites were compared by region (Table 3). Mean 2003 foliar transparency in Highland release sites (n = 11; 76%) was higher than in Skyland sites (n = 12; 65.8%) (Equal Variance T-Test; t = 2.5877; p = 0.00859). Hemlock mortality in Highland sites in 2003 was also higher than in Skyland sites (Mann-Witney U-Test; Z = -2.6434, p = 0.00410). In 2004, this trend was repeated with higher mean foliar transparency in Highland as compared to Skyland sites (Mann Witney U-Test; t = 3.2643, p = 0.00055). However, within regions, Highland sites showed significant improvements in foliar transparency from 2003 to 2004 (Paired t-test; t = 3.6829, p = 0.00253), as did Skyland sites (Paired t-test; t = 6.3358, p = 0.00003).

Non-release sites were also compared by region (Table 3). Mean 2003 foliar transparency in Highland sites was higher than in Skyland sites (Equal variance t-test; t = 2.5877, p = 0.00859). In 2004, foliar transparency was also higher in Highland than in Skyland non-release sites (Mann Witney U- Test; Z = 3.2643, p = 0.00055). There were no differences in hemlock mortality between Highland and Skyland non-release sites (Mann Witney U-Test; Z = -1.4902, p = 0.1361). Within regions, foliar transparency in Highland sites did not differ from 2003 to 2004 (Equal Variance T-test; t = 1.1751, p = 0.12256). Foliar transparency in Skyland sites also showed no differences from 2003 to 2004 (Equal Variance T-test; t = 0.5395, p = 0.59433).

Comparisons were made of foliar transparencies and hemlock mortality between *S. tsugae* release and non-release sites by region. Mean 2003 foliar transparency in release sites in the Highland region was similar to that in non-release sites (Equal Variance T-test; t = 0.4913, p = 0.62617). Mean 2003 foliar transparencies also showed no differences between Skyland release and non-release sites (Equal Variance T- Test; t = -0.2692, p = 0.79071). In 2004, foliar





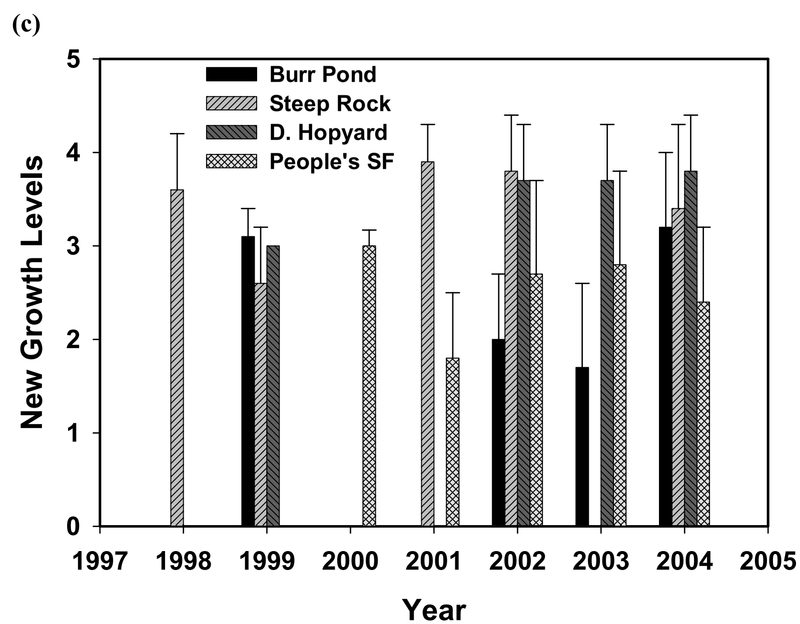


Figure 2. Trends in (a) foliage transparency (b) hemlock woolly adegid crown levels (c) new growth crown levels at selected Connecticut sites where *S. tsugae* had been previously recovered. Year of *S. tsugae* release is shown in parentheses.

Table 3. Foliar transparencies and hemlock mortality in 2003 and 2004 from selected New Jersey *S. tsugae* release sites (R) 1998-2002 and non-release sites (NR) in Highland (H) and Skyland (S) regions.

Year	Region	Type	# Trees	# Sites	Mean Foliar Transparency	# Sites	Mean % Hemlock Mortality
2003	H	R	220	11	76.0 ± 10.9	19	25.3 ± 26.1
	S	R	240	12	65.8 ± 7.7	21	6.1 ± 11.9
2003	H	NR	540	27	74.1 ± 11.1	26	27.9 ± 24.0
	S	NR	180	9	66.9 ± 10.6	8	16.7 ± 19.7
2004	H	R	220	11	67.7 ± 12.2	-	-
	S	R	240	12	55.5 ± 8.0	-	-
2004	H	NR	580	29	70.8 ± 1.0	-	-
	S	NR	360	18	64.4 ± 12.6	-	-

transparencies in Highland release sites did not differ from that in non-release sites (Equal Variance T-Test; t = -0.8017, p = 0.42771). However, in Skyland sites, mean foliar transparency was significantly lower in release sites than in non-release sites (Mann Witney U-Test; Z = -1.9689, p = 0.02448). Similarly, hemlock mortality was lower in Skyland release sites than in non-release sites in 2003 (Mann Witney U-Test; Z = -3.1763, p = 0.000746), while mortality in Highland sites did not differ between release and non-release sites (Mann Witney U-Test; t = -0.8818, p = 0.37787). Eighty-four percent of Highland sites assessed had hemlock mortality while mortality was observed in only 24% of Skyland sites. In contrast, 2003 hemlock mortality was recorded in 96.3% on non-release Highland sites and 66.7% of non-release Skyland sites surveyed. Hemlock borer activity was recorded in sites with hemlock mortality.

An adult *S. tsugae* was recovered in a 1998 Skyland site in 2004 where previous recoveries had also been made in 1999, 2000 and 2002. This site was also one that had heavy adelgid densities in 2003. In the 2001 site sampled with a bucket truck four weeks after a single release of 2500 adults on the lower branches, no *S. tsugae* were recovered from the lower crown (≤3m) during a simultaneous ground survey. In contrast, adults were readily recovered at heights of 5-12m in the canopy of the release and adjacent tree (Figure 3). From 1998 to 2004, *S. tsugae* adults and larvae have been recovered in 20 New Jersey release sites (29% of the release sites), the majority by ground surveys.

DISCUSSION

Connecticut has witnessed the overall recovery of hemlocks on a statewide scale in 2004 in both release and non-release sites. The hemlock recovery in *S. tsugae* release sites, which represented some of the heaviest adelgid-infested stands in Connecticut from 1996-2001, has even surpassed that in non-release sites surveyed in 2003 in the northwestern corner of the

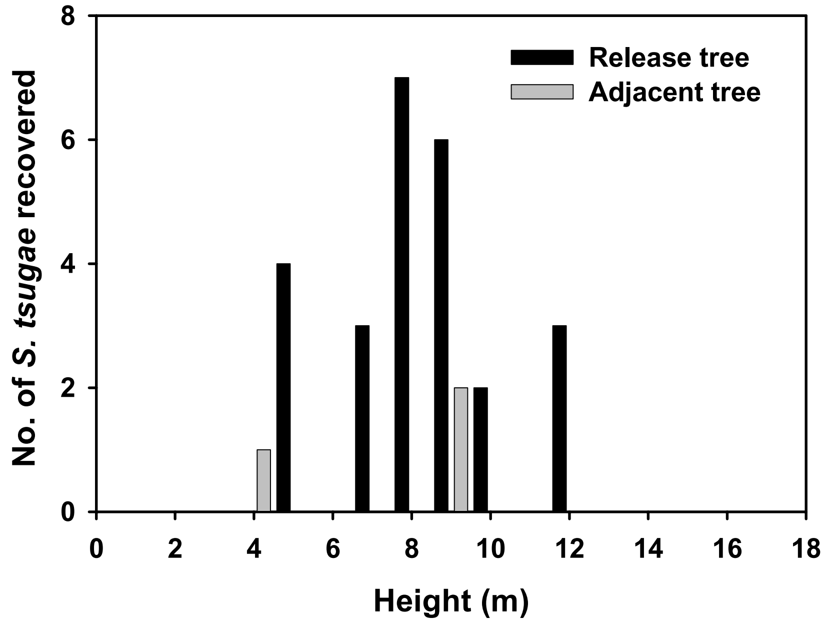


Figure 3. *Sasajiscymnus tsugae* recoveries in New Jersey by bucket truck sampling at different canopy heights on release and adjacent trees four weeks after release in 2001.

state. This region, which is home to some of the most extensive and dense (>50%) hemlock stands in the state, was also moderately infested with adelgid prior to 2003. In addition, approximately 50% of these release sites have also been moderately to heavily infested with elongate hemlock scale for several years, which has also compromised the hemlock crown through its direct feeding impact on the needles. The foliage transparency criterion proved to be most informative for depicting trends in hemlock health over time, as it measures the fullness of the crown in terms of the amount of skylight visible through the foliated portion of the crown. A high rating for foliage transparency indicates defoliation and a thin crown and thus, poor tree health. Transparency ratings of 30% or less are considered the norm for most tree species (Anonymous 2002). Ratings conducted under the Forest Health Monitoring Program from 1996-1999 at 18 Connecticut plots indicated that 4.5% of eastern hemlocks assessed had the highest transparency rating category of 51-100% with 54% showing significant damage and 4.5% with high dieback ratings of 21-50% (Anonymous 2002).

Foliage transparencies in 2004 were significantly lower in release sites as a whole as compared to the non-release sites and previously thin hemlock crowns in release sites have recovered to fullness levels observed in uninfested hemlock stands at high elevations in isolated locations. This recovery comes on the heels of the effects of an extreme drought in 2002 (Table 4) and significant droughts in 1999 and 1998, which were followed by cool, abnormally moist growing seasons in 2000, 2003 and 2004 (data from the Northeast Regional Climate Center). These environmental conditions have facilitated remarkable hemlock refoliation across all woodland suitability sites assessed, even in the poorest sites such as in Washington, Connecticut's Steep Rock Preserve, proving that adelgid-damaged hemlock stands can recover under the right conditions. Woodland suitability groups did not influence hemlock recovery in 2003 and 2004 but this is not unexpected as moisture was not limiting in 2003 and 2004 and pest levels had been reduced. Moisture capacity of different forest soil types in

Table 4. Periods of two months or more of severe and extreme droughts in northern New Jersey and Connecticut (data from the Northeast Regional Climate Center).

State	Climate Division	Severe/ Extreme Drought Period	Duration (in months)
NJ	Northern	7/1999 - 8/1999	2
	Northern	12/2001- 5/2002	6
CT	Northwest	1/2002 - 4/2002	4
	Central	2/2002 - 4/2002	3
	Coastal	7/1999 - 8/1999	2
	Coastal	1/2002 - 4/2002	4

Connecticut is probably much more of a factor affecting tree health and growth in drought years (Lunt 1948).

Although severe winter mortality in 2003 and 2004 statewide has significantly depressed adelgid populations in subsequent seasons, the continued trend in low adelgid levels is remarkable for its lack of resurgence. Figure 4 shows the dramatic fluctuations in average winter temperatures in Connecticut, New Jersey, and the Northeast region as a whole from 1990 to 2004. While severe winters in 1994 and 1996 (ranked 15 and 39, respectively, since 1896; Northeast Regional Climate Center) were followed by the explosive expansion of HWA in Connecticut, this expected resurgence of HWA has not occurred (ranked 26 and 41 respectively). Significantly, adelgid resurgence also did not occur to any marked extent in 2002 in release sites (Figure 2b) following the warmest winter on record (Northeast Regional Climate Center) where there was negligible winter mortality of HWA. Although there had also been a severe winter drought in 2002, healthy new growth, favorable to adelgid colonization, was also at high levels in monitored trees (Figure 2c) in 2002, so poor hemlock health was not a limiting factor for recolonization by *A. tsugae*.

Could the low levels of HWA be partially attributable to the establishment and impact of *S. tsugae*, acting in concert with other native natural enemies as part of a complex? Figure 5 shows the recoveries of *S. tsugae* in (a) Connecticut and (b) New Jersey in the years following the initial release. Recoveries of *S. tsugae* adults and larvae were readily recorded in the first two years after release using ground surveys. Although recoveries of *S. tsugae* from lower crown sampling have diminished in time, the New Jersey bucket truck study has showed quite conclusively that shortly after release, beetles display a tendency to move upward into the crown and well out of reach of current sampling procedures. Similar results were obtained in another bucket truck survey in Connecticut in June 2001. No *S. tsugae* were detected in a lower crown ground survey a week before but larvae and an adult were recovered at 12- 20m in the hemlock canopy in the year following release (Cheah and McClure 2002). The winters of 2003 and 2004 have also been severe in northwestern New Jersey. One Skyland release site recorded 89% mortality in 2004 (Shields and Cheah unpub.) resulting in very low adelgid levels in subsequent seasons. Concurrently, it is not unexpected that *S. tsugae* and other predators have been hard to find in recent years. Dieback of lower hemlock crown

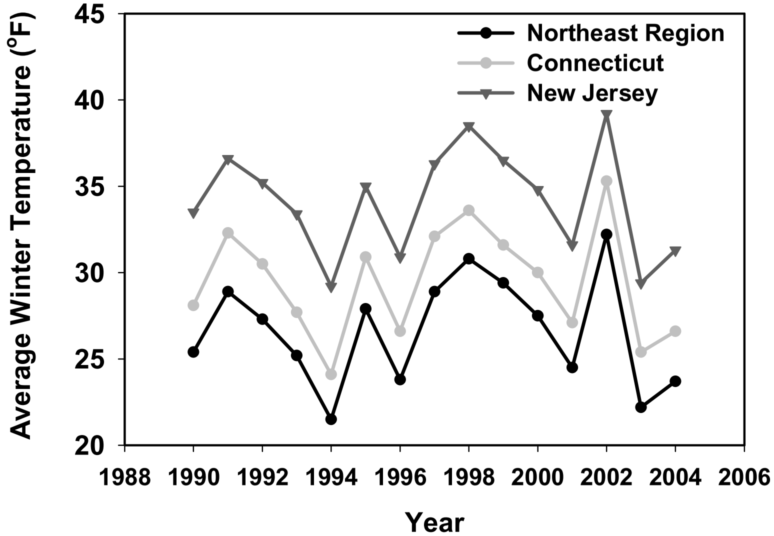
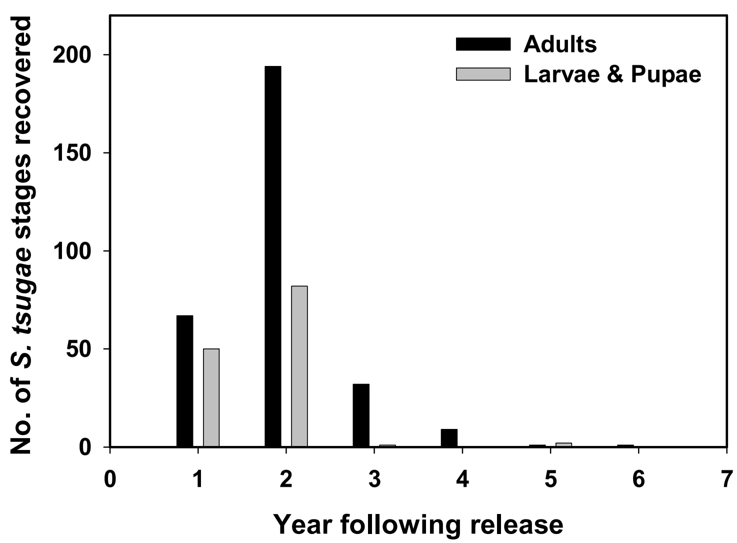


Figure 4. Average winter temperatures in Connecticut, New Jersey and the Northeast region from 1990-2004. Data from the Northeast Regional Climate Center at Cornell University.

(a)



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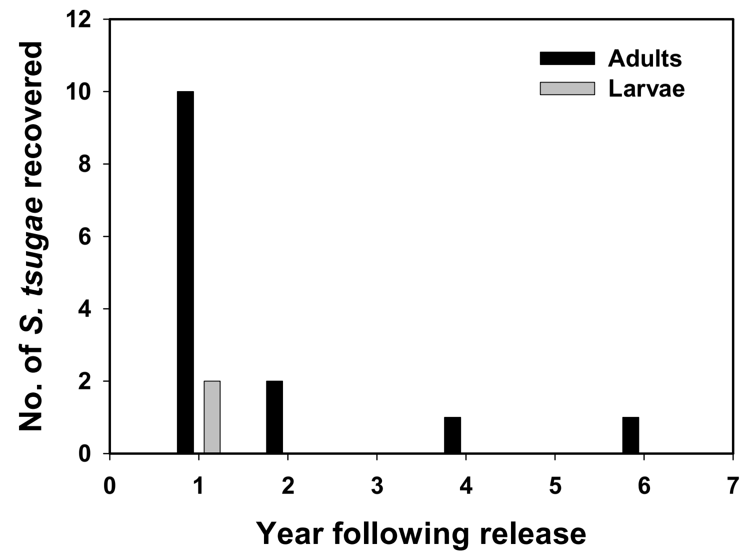

Figure 5. *Sasajiscymnus tsugae* field recoveries following the year of release in (a) Connecticut 1996-2004 and (b) New Jersey 1999-2004.

branches in New Jersey sites has also restricted the ability to sample for predators. Adelgid population rebound should result in better recoveries of *S. tsugae*. However, more efficient and better methods of sampling for *S. tsugae* higher up in the crown need to be developed for monitoring their establishment and impact. The role of *S. tsugae* in biological control of HWA cannot be discounted simply on the basis of the lack of recovery data for the factors outlined above. Since foliage transparency primarily measures the upper foliated crown, it is reasonable to hypothesize that this healthier portion of the hemlock crown may also house predators such as *S. tsugae.*

Previous assessments of HWA damage to hemlock stands in New Jersey have shown that foliage transparency was directly related to the density of adelgid infestation, and that transparencies of >60% have marked a threshold where tree mortality increased significantly (Mayer et al. 2002b). However, adelgid-damaged hemlock stands in New Jersey *S. tsugae* release sites in both Highland and Skyland regions are showing signs of reversing this trend with initial recovery from 2003 – 2004. This improvement in foliage transparency is most evident in the Skyland sites. Skyland release sites have had a more recent history of adelgid population explosion and the initiation of recovery in these sites has occurred at a greater rate than in Highland sites. The Highland region has been heavily infested with HWA and elongate hemlock scale since the late 1980s, a decade more than the Skyland region and has suffered extensive decline from 1984 to 1994 (Royle and Lathrop 2002). In contrast, non-release sites in both regions have not shown improvements in foliage transparencies from 2003 to 2004. Most significantly, comparisons between release and comparable non-release stands in Skyland sites indicated that hemlock recovery, in terms of foliage transparency improvement, was very significantly higher in release sites in 2004. This trend has not yet been detected in Highland sites where foliage transparencies remained similar in release and non-release sites in 2003 and 2004. Hemlock mortality in Skyland release sites was also significantly lower than in non-release sites. Releases of *S. tsugae* appear to be correlated to the reduction of hemlock mortality, at least in the healthier Skyland sites. All release and non-release sites in New Jersey have also been infested with elongate hemlock scale since the late 1980s or earlier. In addition, this northern region suffered extreme drought lasting two months in the summer of 1999 and six months extending into the spring of 2002 (Table 5), and these additional stressors on hemlock, of greater magnitude in New Jersey than in Connecticut, have probably contributed to the greater loss of foliage and hemlock decline in affected stands. As a result, recovery is expected to progress at a slower rate. However, the data appears to indicate that establishment of *S. tsugae* in Highland and Skyland release sites in New Jersey, together with favorable environmental conditions, has helped improve declining hemlock crowns, a trend that has not been paralleled in surveyed non-release sites.

SUMMARY and CONCLUSIONS

Connecticut's eastern hemlock stands, which have been under siege in the last two decades from hemlock woolly adelgid, other pests and drought episodes, have shown recent trends in remarkable recovery from a period of decline and damage in the mid-late 1990s. This trend is also correlated with the release of the introduced *S. tsugae* for biological control of hemlock woolly adelgid. This improvement in hemlock health at *S. tsugae* release sites has also occurred at a greater rate than in non-release stands. The ability of affected hemlocks to recover and reverse the trend in defoliation and mortality in just a few years with the intervention of more favorable environmental conditions for hemlock growth is testimony to the species' resilience. In New Jersey, this pattern of recovery has been a little slower to emerge but recent evaluations indicate it is on the right course. The key questions that remain concerning the effectiveness of the introduced biological control agent, *S. tsugae*, is not whether we can detect the beetles numerically with current inadequate procedures, but whether adelgid populations will continue to remain depressed at the current low levels, when winters are not limiting, and whether hemlock decline can be reversed and mortality halted. A prudent strategy might be to augment and reintroduce *S. tsugae* into hemlock stands that show any resurgence of the adelgid, especially after severe winters, as overwintering mortality of *S. tsugae* has not been assessed to date.

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