Incorporating Citizen Science into Monitoring Hemlock Following Predator Releases for *Adelges tsugae* (Hemiptera: Adelgidae) Management[1]

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Abstract A photograph-based monitoring system was developed to involve citizen scientists in monitoring sites in western North Carolina and northern Georgia where the predators *Sasajiscymnus tsugae* (Sasaji & McClure) and *Laricobius nigrinus* Fender had been released as part of the U.S. Forest Service's biological control program for *Adelges tsugae* Annand (hemlock woolly adelgid). The study was divided into an initial phase conducted during 2006 and 2007 in Jackson and Macon counties, NC, and Rabun County, GA, and a second phase conducted from 2008 to 2010 in Fannin, Gilmer, Lumpkin, and Union counties, GA. Over the course of the study, 32 volunteers monitored 27 predator release sites and provided 4,356 photographs from which data were obtained. Data from photographs included the number of *A. tsugae* ovisacs present at each sample site and hemlock needle loss on photographed branches. To ensure accuracy in counting *A. tsugae* and assessing hemlock needle loss, personnel from Clemson University's *A. tsugae* insectary evaluated each photograph for data collection. The citizen scientist volunteers participating in this study allowed us to obtain a large amount of quality data from across the wide geographic range of predator release sites. Obtaining that amount of data would not have been possible using only our laboratory personnel. This study shows that including dedicated and properly trained volunteers in large-scale forest surveys was an effective way to dramatically increase the amount of data we could obtain for use in assessing trends in both the numbers of *A. tsugae* present and hemlock needle loss at predator release sites.

Key Words *Adelges tsugae*, citizen science, forest pest monitoring

Adelges tsugae Annand (Hemiptera: Adelgidae), the hemlock woolly adelgid, was unintentionally introduced into eastern Virginia in the early 1950s (Souto et al. 1996) and has subsequently expanded throughout a large portion of the range of eastern hemlock, *Tsuga canadensis* L., and nearly all of the range of Carolina hemlock, *T. caroliniana* Engelm (Evans and Gregoire 2007, Levy et al. 2008) (Fig. 1). In the early 1990s, the U.S. Forest Service began evaluating the potential of several predacious beetle species as biological control agents for use in a forest-scale management program for *A. tsugae* (Knauer et al. 2002, McClure 2001). An *A. tsugae* biological control insectary was established at Clemson University in

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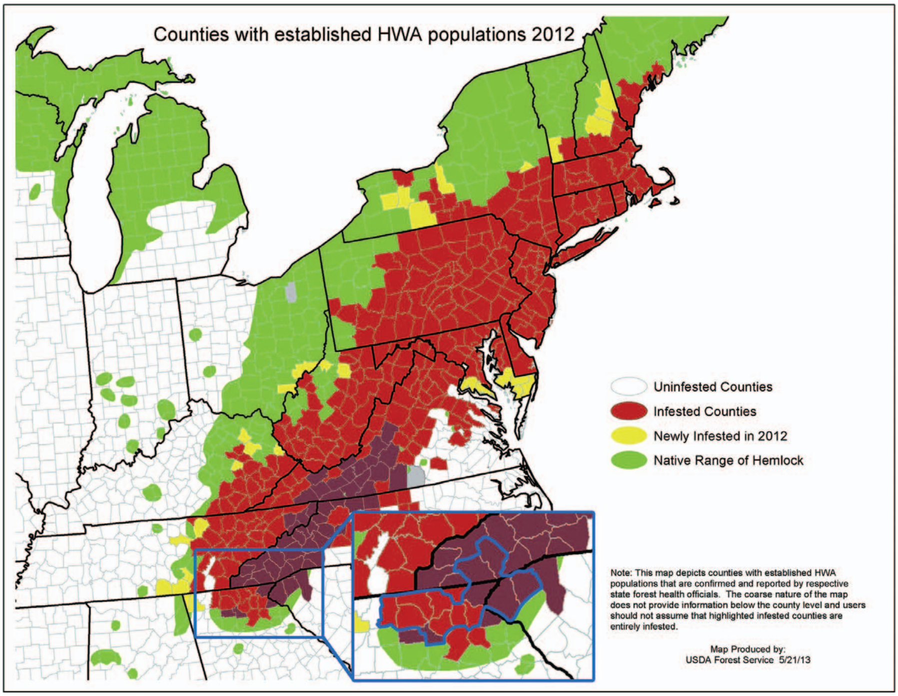

Fig. 1. Reported distribution of *Adelges tsugae* (brown, yellow, purple) as of 2012 superimposed on distribution of eastern and Carolina hemlock in the eastern United States. Original U.S. Forest Service map (source: http://na.fs.fed.us/fhp/hwa/maps/2012.pdf) modified to show distribution of Carolina hemlock (purple and gray) (data from: http://plants.USDA.gov/core/profile?symbol=TSCA2). Counties shaded gray are reported to have Carolina hemlock present but have no reported *A. tsugae* infestation as of 2012. Inset shows counties where the Clemson insectary has released predators for *A. tsugae* biological control.

2003 with production of *Sasajiscymnus tsugae* (Sasaji & McClure) (Coleoptera: Coccinellidae), and made its first predator releases in 2004. A second predator species, *Laricobius nigrinus* Fender (Coleoptera: Derodontidae), was added in 2005, with its first releases made that same year. Initial predator releases from Clemson's insectary were made in Jackson and Macon counties, NC, Oconee and Pickens counties, SC, and Rabun County, GA. Over the past decade the release area has expanded to include Dawson, Fannin, Gilmer, Habersham, Lumpkin, Murray, Stephens, Union, and White counties, GA (Fig. 1).

In the southern Appalachians, infestation of hemlock by *A. tsugae* typically results in a cycle of *A. tsugae* increase–hemlock defoliation–*A. tsugae* decline–new needle production–*A. tsugae* increase–hemlock defoliation–etc. (Elkinton et al. 2011, Mayer et al. 2002, McClure 1991, Paradis 2011). These defoliations lead to a rapid decline of hemlock health, followed by tree mortality in as few as 4 to 5 yr postinfestation. The South Carolina and North Carolina Nature Conservancy Field Offices have listed *A. tsugae* as the greatest threat to the Blue Wall Region of the southern Appalachian forests (Anonymous 2003). Due to the significant impact of *A. tsugae* on the ecology, recreational activities, and aesthetics of these southern Appalachian forests, many local conservation groups have provided assistance in management efforts for this pest (Adams et al. 2002). Assistance has included financial support for predator production or insecticide applications, assistance in predator rearing facilities, participating in predator releases, and assessing hemlock health.

In addition to predator rearing and releases, personnel in Clemson's *A. tsugae* insectary have conducted a variety of studies dealing with *A. tsugae*, *S. tsugae*, and *L. nigrinus* (Burgess 2013; Che 2011; Conway et al. 2005, 2010; Faulkenberry 2004, 2008; Faulkenberry et al. 2009, 2012; Hosey 2005, Klunk 2007; Trninic 2014). Due to the limited number of people working in our laboratory, funding emphasis on predator production and release, and the large geographic area over which predators were being released, it had not been possible for our laboratory to conduct widespread follow-up monitoring of predator release sites. When we discussed our desire to conduct release site assessments with the Jackson-Macon Conservation Alliance, several members volunteered to assist with site monitoring if we could devise a simple monitoring technique and provide them with training on release site assessment.

The study reported here details the development of a relatively simple sampling procedure that placed minimal demand on the volunteers' time, while providing the highest quality possible in the collected data. The project actively involved citizen scientists in assessing both *A. tsugae* numbers and hemlock needle loss at predator release sites in North Carolina and Georgia.

Materials and Methods

Existing protocols designed to evaluate *A. tsugae* infestations provide accurate and consistent data (Costa and Onken 2006, Cowels et al. 2006). However, these protocols can be challenging for citizen scientist volunteers having little or no field research experience. In an effort to simplify data collection, a survey protocol was developed that actively engaged volunteers in a photographic survey of hemlocks at specific monitoring sites where predators had been, or were planned to be, released. The survey consisted of two phases: an initial phase conducted in 2006 and 2007 in the Nantahala National Forest (Jackson and Macon counties, NC) and Chattahoochee National Forest (Rabun County, GA) (Fig. 2), and a second phase conducted in 2008, 2009, and 2010 in the Chattahoochee National Forest (Fannin, Gilmer, Lumpkin, and Union counties, GA) (Fig. 3). At all sites surveyed during the initial phase, *A. tsugae* had been established for 4 to 5 yr prior to the survey, while in the second phase *A. tsugae* was either in its first year of infestation or was expected to be present within a year when the survey began.

Sampling protocol. Each monitoring site consisted of five hemlocks: a central tree with four additional trees located 25 m to 30 m from the central tree in each cardinal direction (Fig. 4). On each tree, one branch approximately 1.0 m to 1.5 m above the ground surface in each cardinal direction was selected as the sample site

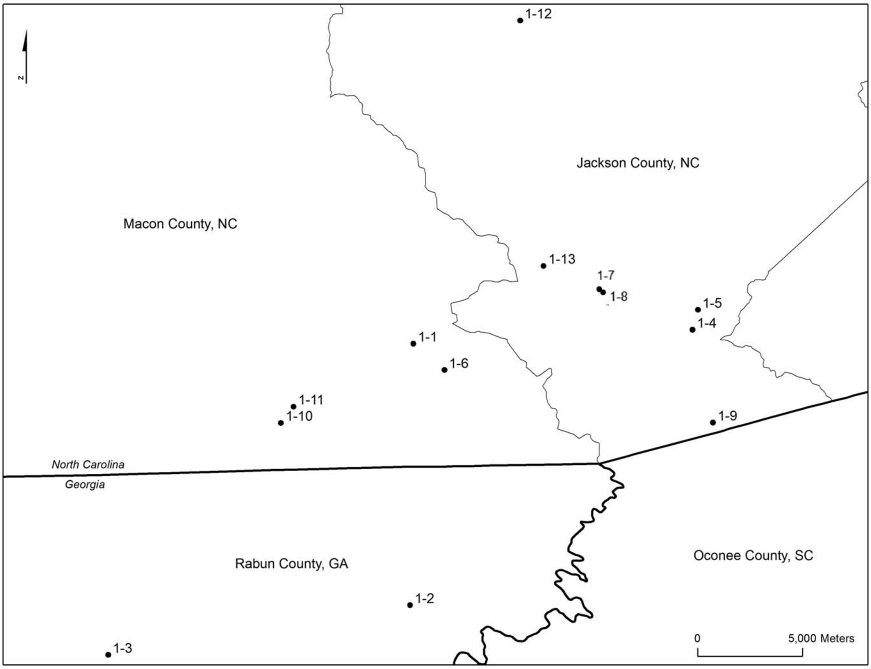

Fig. 2. Monitoring sites from 2006 and 2007 in Jackson and Macon counties, NC, and Rabun County, GA. Site 1-1 was also monitored in 2008. *Sasajiscymnus tsugae* was released at all sites.

to be photographed during the course of the survey (Fig. 4). This resulted in 20 sample sites (5 trees × 4 branches) at each monitoring site. In order to allow identification of specific sample sites in the photographs, a chenille stem marking scheme was developed. The portion of the branch to be photographed was marked using a pair of same-color chenille stem twists spaced 20.5 cm apart. These twists delineated the sampling area within which *A. tsugae* ovisacs would be counted. The distal twist of this pair was located 5 cm to 10 cm from the branch tip, and the color of these twists indicated the cardinal direction of the branch on the tree (Fig. 4). The color of a single twist placed proximally to the innermost twist of the site-identification (ID) pair indicated which of the five trees was being sampled (Fig. 4). The geographic location of the monitoring site was indicated by a site-specific two-color (double chenille stem) twist placed proximally to the tree-ID twist (Fig. 4). Geographic locations, monitoring site color codes, and volunteer names for all sites are presented in Tables 1 and 2. Predator species released at each site are indicated in Figs. 2 and 3.

Volunteers were asked to enable the date function on the camera so that photographs would include a date stamp. If the date function had not been enabled, sample date was determined either from the volunteer's notes or the jpg file creation date. All photographs were taken at the lowest zoom setting on the camera and framed so that the most distal sample site-ID twist and the monitoring site-ID twist

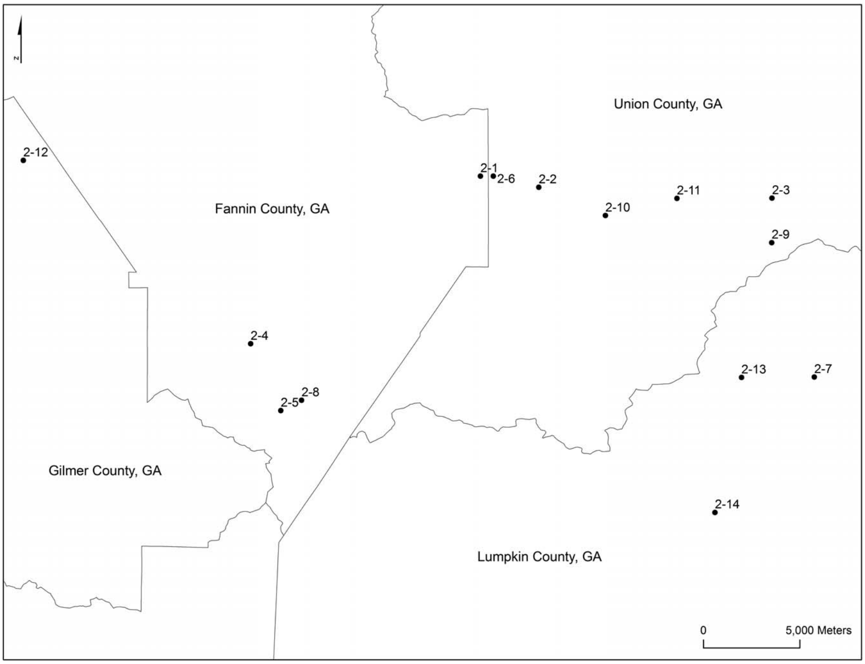

Fig. 3. Monitoring site locations in Fannin, Gilmer, Lumpkin, and Union counties, GA, sampled during 2008, 2009, and 2010. *Sasajiscymnus tsugae* was released at sites 2-1, 2-4, 2-5, 2-7, 2-8, 2-9, 2-10, 2-12 and 2-14, and *Laricobius nigrinus* at sites 2-3, 2-6 and 2-13. No predators were released at sites 2-12 and 2-11.

were just within the edges of the viewfinder. After taking a set of photographs, each volunteer sent them to *A. tsugae* insectary using one of three methods: (1) placing them on a compact disk (CD) and sending by surface mail, (2) sending them as email attachments, or (3) posting them to a file share site such as Google/Picasa, MobileMe, or youSendit.

In the *A. tsugae* insectary, a member of the laboratory group counted *A. tsugae* ovisacs in all photos from each year to provide consistency in counts. Within 6 weeks of receiving photographs, they were examined at 125% to 200% magnification on a computer monitor. All *A. tsugae* ovisacs on both the main branch and all twig branchlets extending from the main branch between the sample site twists were counted. In May 2013, a member of the laboratory group reexamined all photographs and scored needle loss in each photo as: 1, $<$10% needle loss; 2, 10–50% needle loss; 3, 50–90% needle loss; 4, $>$90% needle loss (Fig. 5). For assessing needle loss, photographs were viewed at 100%, with the needle loss rating based on all visible twigs.

Volunteer activities. Volunteers interested in monitoring were required to attend a training session during which the project objectives, goals, field protocols, and time requirements were described. *Adelges tsugae* is most visible in winter and

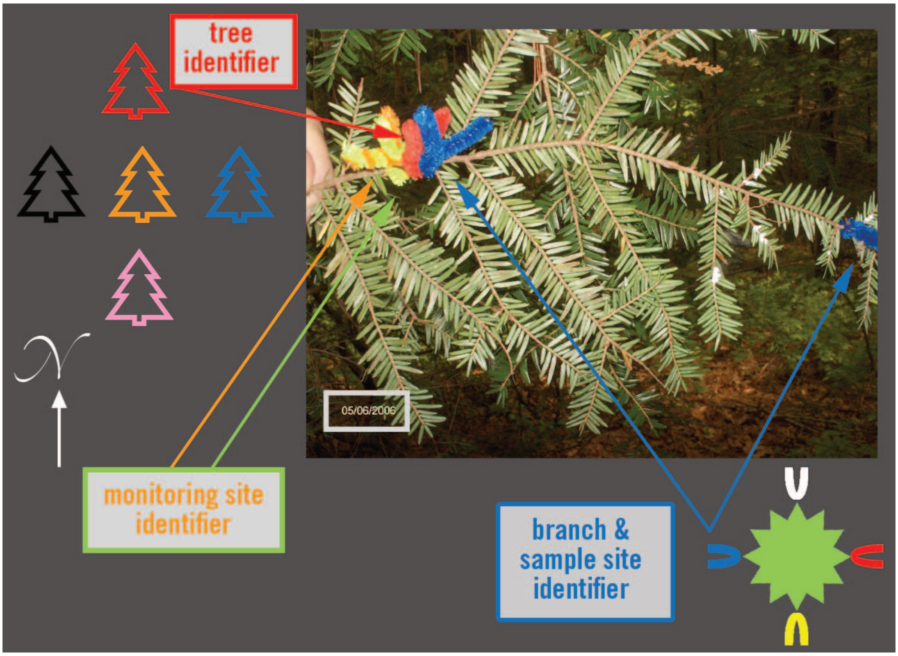

Fig. 4. Sample site marking scheme using chenille stems. Monitoring sites were coded using a two-color twist (shown here in orange and light green). Trees within a monitoring site were color coded as illustrated in the upper left (central = orange, north = red, east = blue, south = pink, west = black). Branches on each tree were color coded as illustrated in the lower right (north = white, east = red, south = yellow, west = blue). Sample date is shown in lower left of photo. This photo, taken on 6 May 2006, shows the west branch of the north tree at the orange and light green monitoring site (Site 1-3 in Fig. 2).

spring when "wool" is present. Volunteers were asked to take photographs monthly through winter and spring, and to do so on approximately the same date each month. However, it was stressed that volunteers had the flexibility to shift sampling dates to avoid hazardous situations caused by inclement weather. They also had the flexibility to shift sampling dates if they had a personal conflict on an intended sampling date.

During the initial phase, volunteers were asked to begin taking photographs in either January or February and continue through June. Based on data gathered during the initial phase, the survey months were shifted to February through July during the second phase. Because of delays in establishing sites in 2008, most volunteers began taking photographs in April. In both phases, volunteers sometimes terminated sampling when most branches being photographed had lost most of their needles. This resulted in variation among end dates among sites during both phases.

Table 1. Site information for initial-phase (2006, 2007) monitoring sites.

Monitoring Site*	Site Color Code	Monitor	GPS °N	GPS °W
1-1**	pink and dark green	P. Brannon	35.05200	83.18810
1-2	yellow and dark green	R. and S. Smith	34.94013	83.18950
1-3	orange and light green	R. and S. Smith	34.91883	83.31867
1-4	purple and orange	R. Daniels	35.05800	83.06867
1-5	purple and yellow	R. Daniels	35.06650	83.06633
1-6	purple and blue	K. Kattel and E. and K. Poole	35.04083	83.17477
1-7	pink and blue	D. and K. Lassiter	35.07533	83.10850
1-8	pink and purple	D. and K. Lassiter	35.07397	83.10682
1-9	purple and white	K. Hawk	35.01833	83.05983
1-10	purple and red	D. Landwher	35.01818	83.24478
1-11	pink and orange	D. Landwher	35.02517	83.23933
1-12	light green and dark green	D. Bates	35.19040	83.14240
1-13	light green and pink	C. Blozan	35.08530	83.13230

* Locations of monitoring sites are shown in Fig. 2.
** Also sampled in 2008, but those data were not included in statistical analyses.

During each training session, we traveled to the monitoring site and demonstrated how to: (1) select the five hemlock trees making up a monitoring site, (2) place the chenille twists on the branches, and (3) take a set of photographs for the site. Each monitoring team was provided an HP Photosmart M22 camera (Hewlett-Packard Co., Palo Alto, CA), compass (Outdoor Products, Los Angeles, CA), carrying case (InGEAR Corp., Buffalo Grove, IL), tree and branch color-code information card, and notebook. Because several volunteers in the initial phase had been actively involved in releasing predators and were familiar with predator release locations, those who felt comfortable establishing a monitoring site on their own were allowed to do so. J. Culin met individually with any volunteers who requested assistance in locating and establishing their monitoring site.

Sampling. In the initial phase, members of the Jackson-Macon Conservation Alliance volunteered to use this protocol at 13 predator release sites located in Jackson and Macon counties, NC, and Rabun County, GA (Table 1; Fig. 2) where *A. tsugae* had been established for approximately 4 to 5 yr. This phase was conducted during 2006 and 2007, with one volunteer (Site 1-1) providing data in 2008. Predators had been released at these sites in either 2004 or 2005 under the release protocol being used at that time. Under that protocol, predators were released in areas: (1) having numerous hemlock trees, (2) where an *A. tsugae* infestation had been present for at least 1 yr, and (3) where *A. tsugae* was present

Table 2. Site information for second-phase (2008, 2009, 2010) monitoring sites.

Monitoring Site*	Site Color Code	Monitor	GPS °N	GPS °W	HCA**
2-1	yellow and red	A. Leventhal and D. Thompson	34.77016	84.09674	79
2-2	yellow and light blue	J. Carter and K. Boff	34.76501	84.06947	75
2-3	orange and white	H. and L. Markel	34.75990	83.96060	71
2-4	orange and brown	D. Stelts	34.69202	84.20398	88
2-5	pink and black	D. Hicks	34.66084	84.18991	88
2-6	brown and green	J. Carter and K. Boff	34.77016	84.09070	79
2-7	orange and blue	C. Osicka	34.67650	83.94086	72
2-8	black and purple	S. Smith	34.66562	84.18024	88
2-9	black and blue	J. Stansell	34.73917	83.96078	71
2-10	black and red	S. Breunig, S. Miller, and P. Davis	34.75182	84.03838	74
2-11	blue and white	R. and D. Roberts	34.75981	84.00500	74
2-12	black and white	S. Creek and C. Lambrecht	34.77756	84.31013	86
2-13	brown and white	F. Hilyer	34.67628	83.97484	29
2-14	orange and red	F. Hilyer	34.61334	83.98724	115

* Locations of monitoring sites are shown in Fig. 3.
** HCA = Georgia Hemlock Conservation Area designations.

at high densities. Under this protocol, predators were released on a single hemlock located in the approximate center of a hemlock stand. The release tree served as the central tree at monitoring sites.

The second phase of the study was conducted during 2008, 2009, and 2010 with volunteers from the Atlanta Audubon Society or Lumpkin Coalition monitoring 14 sites in Fannin, Gilmer, Lumpkin, and Union counties, GA (Table 2; Fig. 3). Monitoring sites were selected by James Wentworth (Central Zone Biologist, U.S. Forest Service). By 2008, the predator release strategy had changed so that predators were being released in areas: (1) having a relatively high density of hemlock, and (2) where *A. tsugae* infestations were in the initial year of infestation and present at low densities, or were expected to be found at the site within a year. At the majority of these sites, the initial *A. tsugae* infestation, predator releases, and photographic sampling all occurred during the same year. In addition, the release strategy had changed so that predators were released at lower numbers on multiple trees within a hemlock stand. Because there was no single predator release tree,

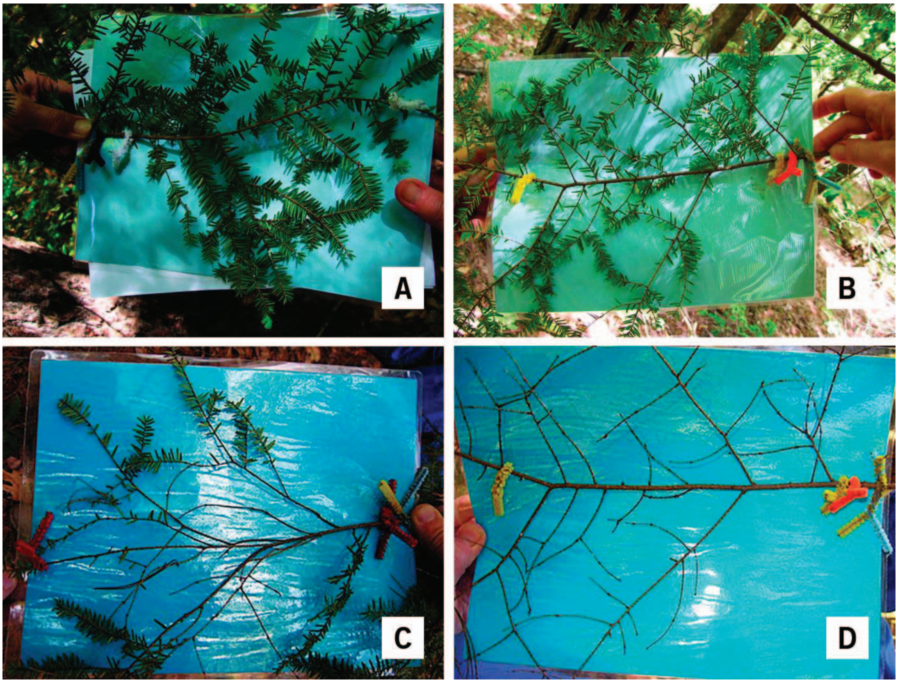

Fig. 5. Examples of needle loss ratings: (A) 1 (<10% needle loss), (B) 2 (10–50% needle loss), (C) 3 (50–90% needle loss), (D) 4 (>90% needle loss).

monitoring site trees were selected to be roughly in the center of the area where predators had been released.

Data analyses. Two aspects of volunteer activities were examined. First, we determined the number of missed sample dates between the first sample date at a given site and the last sample date for that site. Second, the number of usable (clearly focused) photographs in relation to the total number of photographs taken during the survey was determined.

Data obtained from the photographs were analyzed to determine the effects of year and needle loss on mean *A. tsugae* ovisac numbers. The experimental design was similar to a split plot design, so a mixed linear model was developed with terms for the fixed effects (year, needle loss, year × needle loss), and the random effects (site, tree [nested within site], and branch (nested within tree × site]). To account for the different stages of the *A. tsugae* infestation during the initial and second phases of the study, the model was run separately for each phase so that any phase effect could be removed. ANOVA was used to determine if the model terms for year, needle loss, and year × needle loss were significantly different from 0. If terms were significant, Tukey's range test was used to compare means and determine the nature of the model terms. Although there was some evidence of a nonnormal distribution of residuals (specifically log-normal), adjusting for the log-normal distribution yielded similar results to the original analysis. Therefore, the results based on original counts are reported. All analyses were performed using SAS/

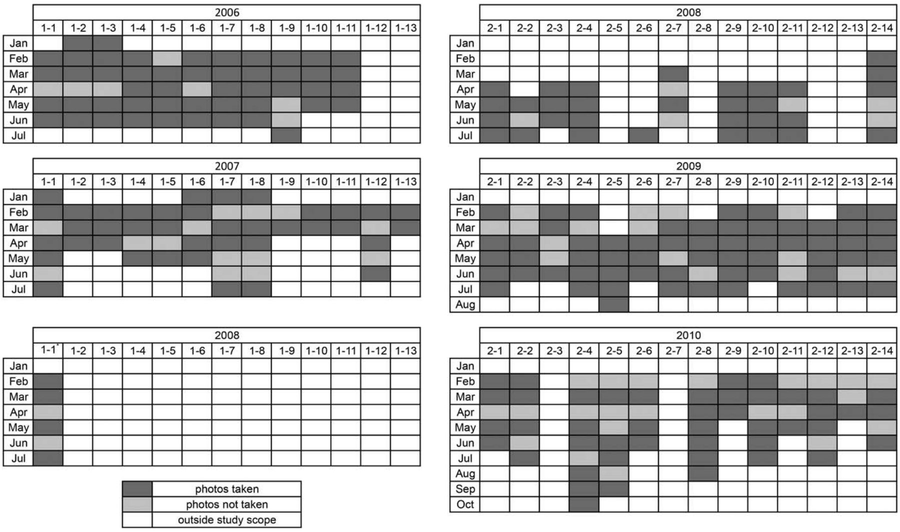

Fig. 6. Sampling periods for each monitoring site. Initial phase on left; second phase on right. Site-specific sampling periods are bounded by the earliest month shaded dark gray to the latest month in dark gray for each phase. Months within those bounds when photographs were not taken are shaded light gray and indicate missed sampling dates. *Data from site 1-1 in 2008 are shown here but were not incorporated in statistical analyses as it was the only initial-phase site sampled in 2008.

STAT 9.3 (SAS Institute 2011). Additionally, a mixed model was also developed to determine the effects of year on needle loss. The model contained year as the only nonrandom factor with a nested design similar to that described above (site nested in tree nested in branch). This model was also analyzed separately for each phase of the study. All data are presented as LSmean ± SE.

Results and Discussion

Volunteer activity. Thirty-two volunteers participated in this project, 13 in the initial phase and 19 in the second phase (Tables 1, 2). Sampling periods are shown in Fig. 6. Months when photographs were taken are indicated in dark gray, and months when they were not taken during the sampling period are indicated in light gray. Within each phase, the total sampling period varied by site and is indicated by the earliest to the latest months marked in dark gray (Fig. 6). During the course of this study, there were 300 potential sampling dates with photographs being taken on 233 of them (Fig. 6). We feel that having obtained data from 77.7% of the possible sample dates indicates the high level of commitment that the volunteers had in gathering data for use in assessment of *A. tsugae*.

Over the course of the study, volunteers took 4,509 photographs, 1,637 during the initial phase and 2,872 during the second phase (Fig. 7). Of these, 153 (3.5%)

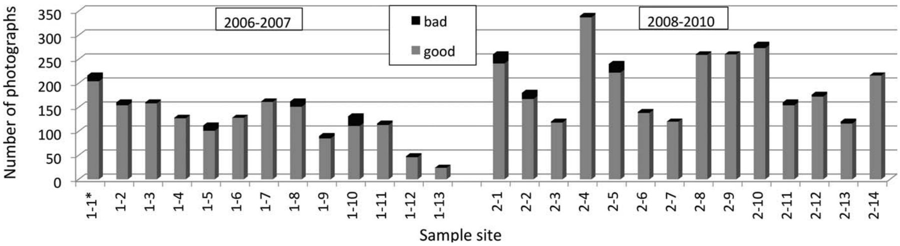

Fig. 7. Number of photographs taken at each monitoring site during the study. Photographs in which *Adelges tsugae* ovisacs could be counted are indicated in gray, while those that could not be analyzed are indicated in black. *Data from site 1-1 in 2008 are included here but were not included in statistical analyses as it was the only initial-phase site sampled in 2008.

could not be used, resulting in 4,356 photographs from which data were obtained. Issues causing photographs to be unusable were: (1) out of focus, (2) did not include the distal site-delineation twist in the photograph, or (3) did not have enough contrast between the branch and the background to allow *A. tsugae* ovisacs to be counted. The effort provided by the volunteers in this study provided a significant amount of data from which we were able to assess both *A. tsugae* numbers and hemlock needle loss at these 27 predator release sites.

Hemlock health. Twig quality, based on needle loss, declined significantly during each phase of the study (Fig. 8). In the initial phase, twig quality declined from 2.12 ± 0.09 in 2006 to 2.40 ± 0.09 in 2007 ($F = 169.92$; df = 1, 1,271; $P <$ 0.0001). There also was a significant decline across the three years of the second phase from 1.54 ± 0.12 in 2008 to 2.05 ± 0.12 in 2009 to 2.49 ± 0.12 in 2010 ($F =$

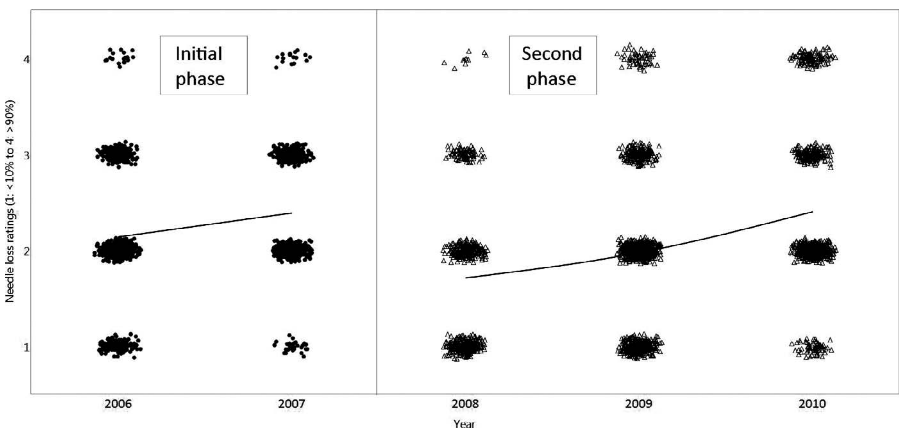

Fig. 8. Needle loss ratings (1 = <10% to 4 = >90%) for initial- (2006, 2007) and second- (2008, 2009, 2010) phase monitoring sites.

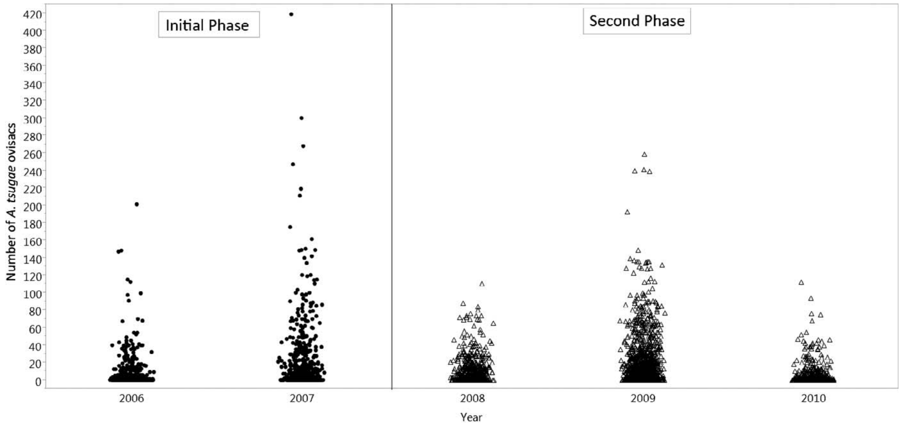

Fig. 9. Number of *Adelges tsugae* ovisacs counted from photographs taken during initial (2006, 2007) and second (2008, 2009, 2010) phases of this study.

638.68; df = 1, 2,519; $P < 0.0001$). Although comparisons of needle loss between initial- and second-phase sites are not statistically valid, the cyclical nature of *A. tsugae* defoliation (Elkinton et al. 2011, Mayer et al. 2002, McClure 1991, Paradis 2011) can be seen in the similarity of needle loss values after 4 to 5 yr of infestation (2006 and 2007) with those during 1 or 2 yr of infestation (2008 and 2010), respectively (Fig. 8). Following initial infestation, *A. tsugae* feeding results in significant needle loss, which is followed by a decline in *A. tsugae* numbers. Release from herbivore pressure results in a flush of new needles, which is followed in turn by another increase in *A. tsugae* numbers. This infestation-and-defoliation cycle occurs several times before a tree's energy stores are depleted to the point at which new needles are no longer produced (Elkinton et al. 2011, Mayer et al. 2002, McClure 1991, Paradis 2011).

***Adelges tsugae* trends.** The cyclical nature of an *A. tsugae* infestation was indicated during both phases in this study (Fig. 9). In the initial phase, in which the *A. tsugae* infestation was well established, numbers were extremely low in 2006 (0.27 ± 3.36), then increased significantly in 2007 (10.45 ± 3.54) ($F = 13.76$; df = 1, 1,265; $P < 0.0001$). This corresponded to an increase in needle loss from 2006 to 2007 (Fig. 8). During the second phase of the study, in which the *A. tsugae* infestation was just beginning, there was a moderate number of ovisacs in 2008 (7.09 ± 2.38), which increased significantly in 2009 (14.16 ± 1.76), then declined significantly (1.85 ± 1.79) in 2010 ($F = 56.97$; df = 1, 2,508; $P < 0.0001$). These changes occurred in conjunction with needle loss increases across all three years (Fig. 8).

We also examined the relationship between *A. tsugae* numbers and needle loss ratings (Fig. 10). In the initial phase in which the infestation was well established prior to sampling, we observed that there were significantly lower *A. tsugae* numbers on the highest level of defoliation (>90% defoliation, 0.00 ± 5.49)

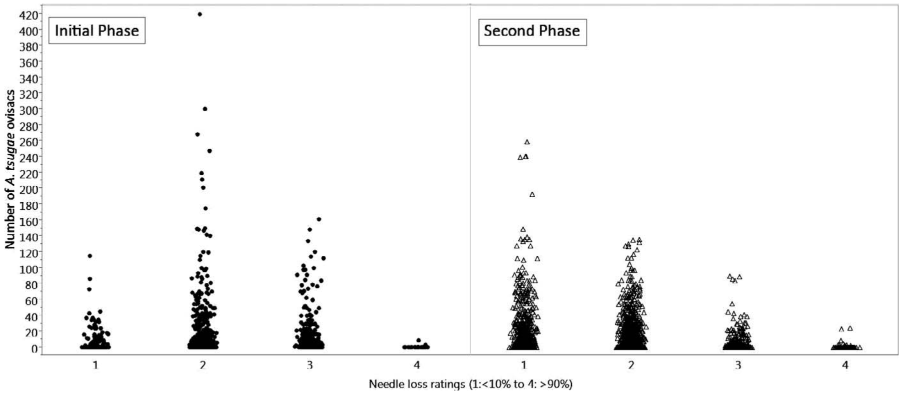

Fig. 10. Relationship of *Adelges tsugae* ovisac numbers to needle loss ratings during the initial and second phases of this study.

compared to the other three defoliation levels (50–90% defoliation, 8.79 ± 3.17; 10–50% defoliation, 12.35 ± 3.00; <10% defoliation, 7.68 ± 4.12), which were not significantly different from each other ($F = 6.43$; df = 3, 1,265; $P = 0.0003$).

In the second phase, in which the *A. tsugae* infestation was beginning, there were no significant differences between the two lowest levels of defoliation (<10% defoliation, 11.01 ± 1.90; 10–50% defoliation, 10.88 ± 1.67), while the two higher defoliation levels were significantly different from both the two lower levels and each other (50–90% defoliation, 7.45 ± 1.98; >90% defoliation, 1.46 ± 2.98) ($F = 5.40$; df = 3, 2,508; $P = 0.0011$).

This project has shown that properly trained citizen scientist volunteers were able to gather useful data over the course of multiple years from predator release sites throughout the hemlock forests of western North Carolina and northern Georgia. The data they provided allowed assessment of both hemlock needle loss and *A. tsugae* numbers during this survey.

Acknowledgments

We thank the members of the Jackson-Macon Conservation Alliance, Atlanta Audubon Society, and Lumpkin Coalition who participated in this study. Without their efforts we could not have gathered these data. James Wentworth (Central Zone Biologist, U.S. Forest Service) provided valuable assistance in selecting monitoring sites for the second phase. We thank LayLa Burgess for assisting in volunteer training sessions, Brittany Russ and Michael Simmons for counting *A. tsugae* ovisacs in the photographs, Suzette Sharpe for rating needle loss in the photographs, and Walker Massey and Chris Semerjian for producing the final figures. Reviews of this manuscript by LayLa Burgess, Mike Vickers, and two anonymous reviewers are greatly appreciated. This project was funded by the National Forest Foundation, 2005 Centennial Year Challenge Program (5CY-08-05) with matching funds provided by the Jackson-Macon Conservation Alliance and Chattooga Conservancy. Additional support was provided by Clemson University's College of Agriculture, Forestry, and Life Sciences, and the Clemson University Experiment Station.

This manuscript is dedicated to the memory of David Bates, former chair of the Jackson-Macon Conservation Alliance, who believed that biological control of *A. tsugae* was the correct approach to save the hemlocks he loved.

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