A 10-Year Assessment of Hemlock Decline in the Catskill Mountain Region of New York State Using Hyperspectral Remote Sensing Techniques

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ABSTRACT The hemlock woolly adelgid is a serious pest of Eastern and Carolina hemlock in the eastern United States. Successfully managing the hemlock resource in the region depends on careful monitoring of the spread of this invasive pest and the targeted application of management options such as biological control, chemical, or silvicultural treatments. To inform these management activities and test the applicability of a landscape-scale remote sensing effort to monitor hemlock condition, hyperspectral collections, and concurrent ground-truthing in 2001 and 2012 of hemlock condition were compared with field metrics spanning a 10-yr survey in the Catskills region of New York. Fine twig dieback significantly increased from 9 to 15% and live crown ratio significantly decreased from 67 to 56% in 2001 and 2012, respectively. We found a significant shift from 59% "healthy" hemlock in 2001 to only 16% in 2012. However, this shift from healthy to declining classifications was mostly a shift to decline class 2 "early decline". These results indicate that while there has been significant increase in decline symptoms as measured in both field and remote sensing assessments, a majority of the declining areas identified in the resulting spatial coverages remain in the "early decline" category and widespread mortality has not yet occurred. While this slow decline across the region stands in contrast to many reports of mortality within 10 yr, the results from this work are in line with other long-term monitoring studies and indicate that armed with the spatial information provided here, continued management strategies can be focused on particular areas to help control the further decline of hemlock in the region.

KEY WORDS IPM, biological control, decision support, forest decline, hemlock woolly adelgid

Introduction

The hemlock woolly adelgid, *Adelges tsugae* Annand (Homoptera: Adelgidae), is a serious pest of eastern hemlock, *Tsuga canadensis* (L.) Carriere, and Carolina hemlock, *Tsuga caroliniana* Engelmann, in the eastern United States. This introduced homopteran is easily recognized by the white woolly substance it produces on the young twigs of hemlock. *A. tsugae* was first detected on the east coast in the 1950s (Stoetzel 2002) and continues to spread northward into Maine, New Hampshire, and Vermont, and populations are established as far south as Georgia. *A. tsugae* completes two generations per year and disrupts nutrient storage and transfer in hemlock by inserting a stylet bundle at the base of hemlock needles where it feeds on the xylem parenchyma cells (Young et al. 1995). Once infested by *A. tsugae*, decline and mortality typically occurs within 4 to 10 yr in the northern extent and 3 to 6 yr in the southern extent of its range (McClure 1991, Orwig and Foster 1998). The elongate hemlock scale, *Fiorinia externa* Ferris (Hemiptera: Diaspidae), is another introduced pest of hemlock that was first detected in New York City in 1908 (Sasscer 1912) and has recently expanded to 14 states (Lambdin et al. 2005). Although high densities of *F. externa* can result in branch dieback (McClure 1980), *A. tsugae* is considered a greater overall risk to hemlock mortality (Preisser and Elkington 2008, Miller-Pierce et al. 2010, Radville et al. 2011).

The rate of decline following *A. tsugae* infestations is highly variable, ultimately owing to the patchiness of hemlock in a stand and across the landscape (Orwig and Foster 1998), site characteristics (Pontius et al. 2005a,b), climate (Paradis et al. 2008, Orwig et al. 2012) , and the presence of external stress agents (Stickel 1933, Yorks et al. 1999). Previous work has shown the chemical defense of eastern hemlocks to be more effective at suppressing foliar chewing herbivores [hemlock looper, *Lambdina fiscellaria* (Guenée)], than sucking herbivores like *A. tsugae* and *F. externa* (Lagalante et al. 2007). This is potentially a result of eastern hemlock evolving in the absence of *A. tsugae*, *F. externa*, and other major sucking insects (Havil et al. 2011). Eastern and Carolina hemlock do not appear to recover from chronic infestation, making the detection of early signs and symptoms of these infestations

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imperative to assist land managers in prioritizing decision-making (i.e., silvicultural intervention, biological control, and chemical application).

Individual hemlock trees are often protected from *A. tsugae* through repeated and expensive chemical applications (Ward et al. 2004) that are not practical in hard to access forest systems or across broad landscapes. Silvicultural prescriptions are also an option but are expensive and ultimately not sustainable across an infested landscape (Fajvan and Wood 2008). Several natural enemies of *A. tsugae* have been identified as suitable biological control agents and efforts are being made to develop networks of source pools across the infested range through the Forest Health Technology Enterprise Team biological control program. Understanding natural enemy ecology, hemlock condition, and the spatial distribution of the hemlock resource and its condition across the landscape are necessary to assist forest managers in prioritizing the conservation of eastern and Carolina hemlock through integrated pest management.

To this end, several airborne and spaceborne sensors have been used for landscape-scale assessments including land use classification, ecological modeling, and change detection over space and time (Cohen and Goward 2004). There have been several seminal examples on the development and use of spectral vegetation indices (Rouse et al. 1974, Blaire and Baumgardner 1977) and their application to characterize forest decline because of a host of stress agents (Nelson 1983, Rock et al. 1986, Williams and Nelson 1986, Collins and Woodcock 1994). Specific remote sensing assessments of *A. tsugae* impact on forests range from broadband categorical assessments of hemlock condition (Royle and Lathrop 2002) to field calibrated hyperspectral assessments of early decline symptoms (Bonneau et al. 1999, Pontius et al. 2005a,b).

The Catskill Park consists of ~283,280 ha, of which 41% is classified as forest preserve, and 5% is owned by New York City to protect four of the city's water supply reservoirs. Hemlock tends to prefer moist site conditions such as northern slopes, stream, and wetland and lake borders. In addition to its role in maintaining soil and water quality, the growth of hemlock near streams and lakes has also created an aesthetic value that is difficult to quantify (Moore et al. 2011) and further supports the all-around importance of hemlock in the Catskills region. *A. tsugae* was first detected in the Hudson River Valley of New York State in the 1980s and has since spread throughout the Catskill Mountain Region and across the Catskill Park. Two of the four counties (Sullivan and Ulster) that house the Catskill Park were listed as "infested" by *A. tsugae* in 1997 based on annual state survey data. Greene County was added in 1999 and Delaware County added in 2002 based on state survey data. The spread of *A. tsugae* has progressed north to south and from the eastern coast inland to the west. *A. tsugae* distribution maps from 1997 to 2012 can be found at the following address: http://na.fs.fed.us/fhp/hwa/maps/distribution.shtm.

Despite the relative success of these landscape-scale remote sensing efforts, most hemlock change detection assessments remain limited to ongoing field monitoring. Most recently, range-wide Forest Inventory and Analysis data were used to examine gross changes in hemlock abundance and mortality (Trotter et al. 2013). They found that while the median percent of live hemlock had declined over the 20-yr study period, total live hemlock basal area had increased. Such conflicting reports highlight the need for broad monitoring programs to fully understand both the temporal trends and spatial patterns in hemlock decline.

To address this need, we examined hemlock health across the Catskill Park region, NY, between 2001 and 2012 by comparing field and remote sensing-based monitoring efforts. Our multi-scale approach included: 1) an extensive field monitoring plot network to examine hemlock decline symptoms and *A. tsugae* densities across a range of infestation histories, and 2) a landscape-scale hyperspectral remote sensing assessment of hemlock condition over the same time period. While the field metrics provide a level of accuracy and detail not possible with remote sensing assessments, the larger extent and scope of the imagery provides a more comprehensive assessment of hemlock across the region and a tool to examine spatial patterns in hemlock decline rates. Ultimately our goal was to provide land managers with a spatial tool that can be used for widespread change detection assessments of the hemlock resource across the region and to inform hemlock management efforts including optimization of biological control release sites.

Materials and Methods

Site Description. This study was conducted in the ~283,280 ha Catskill State Park within the Catskill Mountains of New York State and is home to the watersheds that provide a large majority of New York City's drinking water. The ~71,430 ha area of interest (AOI) for this study spread across Delaware, Sullivan, and Ulster Counties and was selected based on a wide range of hemlock density and *A. tsugae* infestation histories identified from previous field monitoring data and remote sensing imagery obtained in 2001 (Fig. 1).

Field Plots. In total, 23 ground plots (20 original plots from the 2001project and 3 new plots located to replace original plots where access was limited) were measured within the AOI 2 wk prior to the 2012 remote sensing image acquisition. Plot center posts were relocated using Global Positioning System coordinates and verified by tagged trees on all original plots. The distance and azimuth to each tree from plot center was used to generate a stem map for image calibration and accuracy assessment. Plot measurements in 2012 duplicated the methods used in 2001 with the addition of chlorophyll fluorescence and digital canopy transparency measurements. Stand composition and structure measurements were based on a variable radius, basal area factor 10 prism sample and included species composition, diameter at breast height (DBH), basal area, canopy position, and general condition (dead or alive) for all trees. Additional forest health metrics were collected for five canopy dominant hemlocks at each plot, including percent fine twig dieback (dieback), live

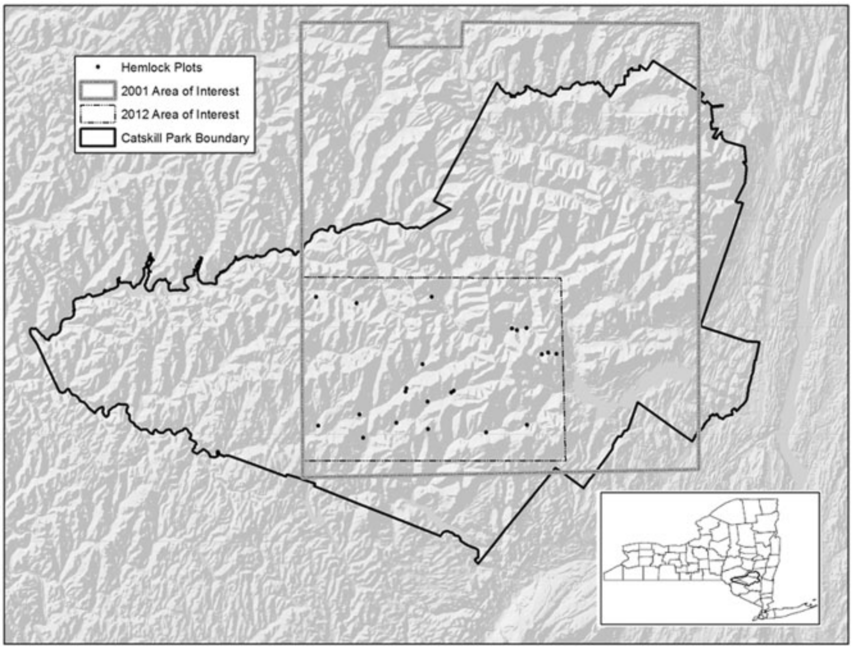

Fig. 1. The 2001 and 2012 image acquisition footprints within the Catskill Park, NY, along with the hemlock plots used in the change detection exercise.

crown ratio (LCR), percent new growth (new growth), presence and abundance of *A. tsugae* and *F. externa*, and percent canopy transparency. Ocular estimates of stress-related fine twig dieback were made by at least two independent observers to 5% classes based on the percent of the total live canopy area occupied by upper and outer branches missing foliage, but only where fine twigs remain (U.S. Department of Agriculture [USDA] 1997).

Canopy transparency is a metric used to evaluate increased sunlight through the crown as needles desiccate and drop. In 2001, canopy transparency was quantified using a spherical densitometer at four locations under each tree (Pontius et al. 2005a,b). For the 2012 assessment, canopy transparency was measured with digital photographs taken vertically through the canopy at four locations for each sample tree. The camera lens was focused to include only the canopy of the sample tree. Automatic camera settings were used to optimize photographs for interpretation. All digital images were taken from a consistent height with no understory obstructing the field of view. Digital images (JPG files) were processed using an open-source program called cell profiler (Lamprecht et al. 2007) (http://www.cellprofiler.org/). A custom "pipeline" was created to convert color photos to binary light-dark images using a transparency threshold. The output black and white images were then used to calculate percent transparency for each photograph.

As hemlocks experience severe and prolonged stress exposure, death of entire branches results in canopy reductions not characteristic of shade tolerant species. This more severe stress symptom was characterized by LCR measurements. By measuring the ratio of the total tree height to the height at the live crown base using a Nikon Forestry Pro laser hypsometer (Nikon Vision Co., Tokyo, Japan), LCR approximates the total proportion of the main stem that is photosynthetically active (USDA 1997).

We created a summary condition or stress index value for each tree from percent new growth, transparency, LCR, *A. tsugae* infestation, and dieback by normalizing each variable based on a probability distribution score (Z-score) developed from an extensive hemlock database (Pontius and Hallett 2014). Standardized Z-scores were then inverted if necessary so that they all scale from healthy (negative Z-score) to stressed (positive Z-score), and then averaged to capture overall condition in one continuous value. Paired *t*-tests were then applied to compare tree-level changes in field metrics from 2001 to 2012 for the summary Z-score along with each of the individual stress metrics (Fig. 2).

Hyperspectral Imagery Change Detection. Imagery from NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) were obtained for the ~283,280 ha Catskill Park region and surrounding area on 20 July 2001. The AVIRIS sensor was flown on an ER-2 aircraft and measured upwelling radiance in 224 contiguous channels between 400 and 2,400 nm with a 10-nm spectral resolution and 18-m spatial resolution. The 2001 imagery was processed as part of a hemlock health study conducted by Pontius et al. (2005a). Preprocessing included an atmospheric correction using Atmospheric Correction Now software (ACORN 4.0 Analytical Imaging and Geophysics LLC, ImSpec 2002), brightness gradient correction using a modified CSIRO destreak algorithm (Datt et al. 2003) and geocorrection to a U.S. Geological Survey 1-m resolution

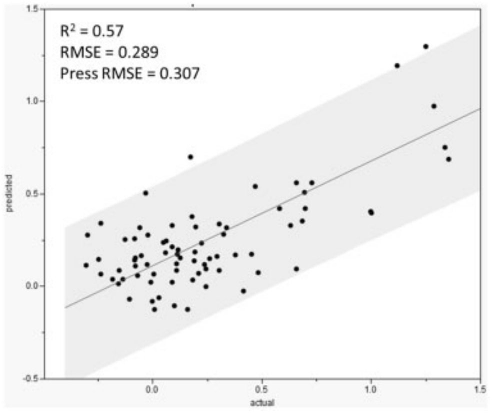

Fig. 2. The 2012 hemlock condition calibration showing summary Z-score and confidence interval.

digital orthoquad using a polynomial degree 2 warping method (ENVI 4.0 software, Research Systems Inc.).

In 2012, SpecTIR was contracted to fly the ProSpecTIR-VS (visible or short-wave infrared) sensor on a fixed wing aircraft over an ~84,500 ha subset of the original AVIRIS coverage within the Catskill Park, NY, between 11 and 25 July 2012. The ProSpecTIR-VS is a dual sensor instrument covering the visible infrared wavelengths from 400 to 1,000 nm (2.9-nm bandwidth) and the short-wave infrared (SWIR) wavelengths from 1,000–2,500 nm (8.5-nm bandwidth), resulting in 360 contiguous channels, with a 5 m spatial resolution. SpecTIR delivered a level 1 product, which included radiometrically calibrated, atmospheric (ATCOR-4f Version 5.0.0, 2009), and geometric corrected reflectance for 30 flight lines oriented north/south. Poor weather resulted in image collects over a 2-wk window, with a wide range of image acquisition times. To account for this variability in illumination geometry and intensity, we applied a brightness correction using an additive, polynomial level 1 cross-track illumination correction in ENVI (version 5.0 ITT Visual Information Solutions, Boulder, CO) on images masked to include only forested pixels. To further normalize reflectance across various aspects and slopes, we conducted a topographic correction on all image bands using a shaded relief based on a 10-m digital elevation model (ArcGIS Version 10.0 ESRI) as:

$$Rn = Rr \times \frac{\cos Z}{\cos I}$$

Where R_n = normalized reflectance
R_r = calibrated reflectance
Z = sun zenith angle
I = solar incidence angle.

While the methodology for developing hemlock condition predictive equations was the same for both 2001 and 2012 imagery, each was calibrated independently based on field data concurrent with image collection. Any differences in sensor configuration, illumination, or atmospheric condition were effectively normalized for direct comparison of hemlock condition between the two imagery sets. This calibration process included spectral extraction for pixels covering 13 plots for the 18-m resolution 2001 imagery and 100 trees for the 5-m resolution 2012 imagery. A suite of narrow-band vegetation indices (VIs; Table 1) were then calculated from extracted spectra for each observation to characterize biophysical canopy characteristics. We then used a stepwise linear regression model to identify the optimal combination of VIs to predict hemlock condition while minimizing autocorrelation and overfitting (Pontius et al. 2005b). Full, double-cross validation was used to assess predictive accuracy (Kozak and Kozak, 2003).

The final predictive equation for the 2001 imagery was detailed in Pontius et al. (2005b) as decline = $-16.82 + (R683 \times 0.02) = (WBI \times 15.40)$. For the higher resolution 2012 imagery, a five-term equation was selected to predict hemlock condition ($R^2 = 0.566$, RMSE = 0.289, using only live trees unobscured by cloud cover (77 calibration sites; Table 2). Error estimates were similar for both the 2001 (RMSE = 0.23) and 2012 calibration (RMSE = 0.289) and sufficiently smaller than average predicted change in condition between the two imagery collection years (decline increase = 0.36). This indicated that condition assessments were comparable in spite of differences in sensor resolution and sensitive enough to detect changes in hemlock condition across the region. The low variance inflation factor (VIF < 4 for all variables) indicates negligible autocorrelation among predictor variables, while the PRESS RMSE (0.307) indicates that calibration should be robust when applied to independent pixels. Model variables included the photochemical reflectance index (PRI), a measure of xanthophyll activity; the Water band index (WBI), a measure of canopy water content; normalized pigment chlorophyll index (NPCI), a measure of chlorophyll content; the simple ratio (SR), a general measure of overall canopy greenness; and the structure insensitive pigment index (SIPI), a measure of photosynthetic pigments. The final calibration equation was applied to the 2012 hyperspectral image on a pixel-by-pixel basis for all pixels identified to have greater than 45% hemlock basal area (Pontius et al. 2005a,b; Fig. 3) using ENVIs band math as:

$$\text{Predicted Decline} = -53.52 - (10.66 * ((r531 - r570)/(r531 + r570))) + (4.12 * (r970/r900)) - (4.21 * ((r680 - r430)/(r680 + r430))) + (0.18 * (r800/r550)) + (47.49 * ((r803 - r445)/(r800 - r680)))$$

The distribution of decline values obtained from 2001 and 2012 image histograms were used to compare how overall hemlock condition had changed between the 2001 and 2012 images across the full study area. By reclassifying each pixel into a categorical value (Table 3) using the range of typical Z-scores for five vigor classes (Millers et al. 1991) that were also measured on our study trees, we were able to translate Z-scores into terms more useful to land managers and to more clearly visualize where pixels were stable, improving, or declining over the 11-yr period. The final

Table 1. Broad- and narrow-band VI considered to predict canopy characteristics

Vegetation index	Formula	Reference
Simple ratio (SR)	R_{550}/R_{800}	(Rouse et al. 1974)
Chlorophyll fluorescence (CF)	FD_{690}/FD_{735}	(Buschmann and Nagel 1993)
Curvature index (CUR)	$(R_{675} \times R_{690})/R_{683}^2$	(Zarco-Tejada et al. 2002)
(CSc)	R_{605}/R_{760}	(Carter 1994)
(CSd)	R_{710}/R_{760}	(Carter 1994)
(CSe)	R_{695}/R_{760}	(Carter 1994)
(CSe2)	R_{694}/R_{420}	(Carter 1994)
(Datt)	$R_{672} \times (R_{550} \times R_{708})$	(Datt 1998)
(Dattc)	FD_{754}/FD_{704}	(Datt 1999)
Derivative chlorophyll index (DCI)	FD_{705}/FD_{723}	(Zarco-Tejada et al. 2002)
Difference vegetation index (DVI)	$R_{800} - R_{680}$	(Tucker 1979)
(EZ)	$\Sigma\ FD_{625}:FD_{795}$	(Elvidge and Chen 1995)
Fluoresence index (Flo)	FD_{690}/FD_{735}	(Mohammed et al. 1995)
(FP)	$\Sigma\ FD_{680}:FD_{780}$	(Filella and Penuelas 1994)
Greenness index (GI)	R_{554}/R_{677}	(Smith et al. 1995)
(Gitc)	$1/R_{700}$	(Gitelson and Merzlak 1994)
(GM)	R_{750}/R_{550}	(Gitelson and Merzlak 1994)
(GMb)	R_{750}/R_{700}	(Gitelson and Merzlak 1994)
(Mac)	$(R_{780} - R_{710})/(R_{780} - R_{680})$	(Maccioni et al. 2001)
Modified chlorophyll absorption ratio index (MCARI1)	$1.2[2.5(R_{800} - R_{670}) - 1.3\ (R_{800} - R_{550})$	(Daughtry et al. 2000)
Modified chlorophyll absorption ratio index (MCARI2)	$1.5\ [2.5(R_{800} - R_{670}) - 1.3(R_{800} - R_{550})\ /$ $\sqrt{(2R_{800}+1)^2 - (6R_{800} - 5\sqrt{R_{670}}) - 0.5}$	(Haboudane et al. 2004)
(McM)	R_{700}/R_{760}	(McMurtrey et al. 1994)
Chlrophyll index (mND705)	$(R_{750} - R_{705})/(R_{750} + R_{705} + 2R_{445})$	(Sims and Gamon 2002)
Modified simple ratio (MSR)	$(R_{800}\ /\ R_{678} - 1)/\sqrt{(R_{800}\ /\ R_{760} + 1)}$	(Sims and Gamon 2002)
Modified simple ratio (MSR705)	$R_{750} - R_{705}/R_{705} - R_{445}$	(Sims and Gamon 2002)
Modified triangular vegetation index (MTVI)	$1.2[1.2(R_{800} - R_{550}) - 2.5(R_{670} - R_{550})]$	(Haboudane et al. 2004)
Modified triangular vegetation index (MTVI2)	$1.5[1.2(R_{800} - R_{550}) - 2.5(R_{670} - R_{550})]\ /$ $\sqrt{(2R_{800}+1)^2 - (6R_{800} - 5\sqrt{R_{670}}) - 0.5}$	(Haboudane et al. 2004)
(NDI)	$R_{750} - R_{705}/R_{750} + R_{705}$	(Gitelson and Merzlak 1994)
Normalized difference vegetation index (NDVI)	$(R_{800} - R_{670})/(R_{800} + R_{670})$	(Rouse et al. 1974)
Normalized pigment chlorophyll index (NPCI)	$R_{680} - R_{430}/R_{680} + R_{430}$	(Peñuelas et al. 1994)
Normalized pheophytinization index (NPQI)	$R_{415} - R_{435}/\ R_{415} + R_{435}$	(Barnes et al. 1992)
Optimized soil-adjusted vegetation index (OSAVI)	$R_{800} - R_{680}/R_{800} + R_{680} + 0.16$	(Rondeaux et al. 1996)
Photochemical reflectance index (PRI)	$R_{531} - R_{570}\ /\ R_{531} + R_{570}$	(Gamon et al. 1992)
PSNDb	$R_{800} - R_{635}\ /\ R_{800} + R_{635}$	(Blackburn 1998)
Pigment specific simple ratio (PSSRa)	$R_{600}\ /\ R_{680}$	(Blackburn 1998)
Pigment specific simple ratio (PSSRb)	$R_{800}\ /\ R_{635}$	(Blackburn 1998)
Renormalized difference vegetation index (RDVI)	$\sqrt{(NDVI*DVI)}$	(Roujean and Breon 1995)
Red edge inflection point (REIP)	λFD max	(Rock et al. 1986)
Ratio vegetation index (RVI)	R_{800}/R_{680}	(Royle and Lathrop 2002)
Structure insensitive pigment index (SIPI)	$R_{803} - R_{445}\ /\ R_{800} - R_{680}$	(Peñuelas et al. 1995)
Simple ratio pigment index (SRPI)	$R_{430}\ /\ R_{680}$	(Peñuelas et al. 1993)
Triangular vegetation index (TVI)	$0.5[120(R_{750} - R_{550}) - 200(R_{670} - R_{550})]$	(Broge and Leblanc 2001)
(Voga)	$R_{740}\ /\ R_{720}$	(Vogelmann et al. 1993)
(Vogb)	$FD_{715}\ /\ FD_{705}$	(Vogelmann et al. 1993)
Water band index (WBI)	$R_{970}\ /\ R_{900}$	(Peñuelas et al. 1997)

R, percent leaf reflectance spectra; FD, first derivative of leaf reflectance spectra.

change detection products were then used to generate management recommendations including biological control prioritization maps based on isolating stands that were likely to have been recently infested (change from a class of 1: healthy to a class of 2: early or 3: moderate decline), and in relatively easy to access locations (<200 m of existing roads). Priority was also placed on stands within 150 m of surface waters based on the potential impact of hemlock mortality on surface water quality.

Results

Field Plots. All field plots were dominated by hemlock, with varying components of hardwoods primarily represented by red maple, *Acer rubrum* L., and birch species. The pioneer species black birch, *Betula lenta* L., and striped maple, *Acer pensylvanicum* L.,

Table 2. Summary of regression analysis and the accepted prediction model for hemlock decline in the Catskills

Analysis of variance

Source	df	Sum of squares	Mean square	*F*
Regression	5	7.789929	1.55799	18.5749
Residual	71	5.955197	0.08388	
Total	76	13.745126		

Independent variables (listed in order entered)	ß	SE ß	Partial *F*
Intercept	−53.52356	6.727	–
PRI	−10.65646	3.592	1.923*
WBI	4.118115	0.964	1.860*
NPCI	−4.209405	1.004	3.360*
SR	0.1813546	0.041	1.797*
SIPI	47.492703	6.569	3.355*

*Significant at the $\alpha = 0.05$ level.

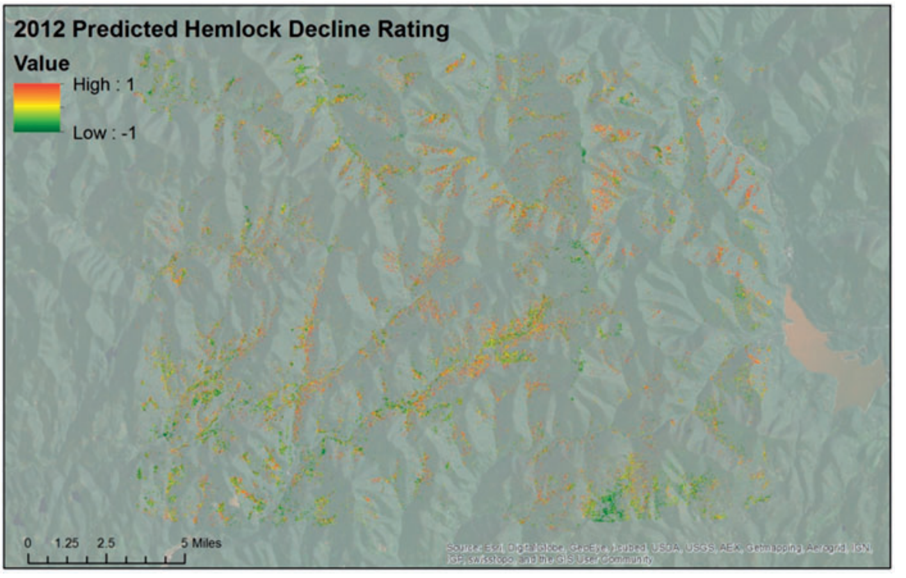

Fig. 3. The 2012 hemlock decline predictive equation applied to all hemlock-dominated pixels.

Table 3. Reclassification of the continuous, predicted hemlock Z-score

Decline class	Z-score range	Description
1	−3.0–0.0	Healthy
2	0.0–0.5	Typical condition
3	0.5–1.0	Early decline
4	1.0–1.5	Moderate decline
5	1.5–3.0	Severe decline

dominated plots where noticeable hemlock mortality was observed. Hemlock density ranged from 50% basal area to 100% basal area across the field plots with an average of 75% (Table 4). Hemlock DBH ranged from 5 to 94 cm with a mean of 29-cm DBH. In the 2001 survey, less than 1 percent of hemlocks were dead. By 2012, the average percent dead hemlock surpassed 8% across the region. However, the percent hemlock basal area on each plot remained relatively constant owing to continued growth of living hemlock from 2001 to 2012.

Dependent *t*-tests comparing tree-level field measurements from 2001 and 2012 (Table 4) found that fine twig dieback significantly increased ($P = 0.03$) from a mean of 9% in 2001 to 15% in 2012. LCR significantly decreased ($P < 0.006$) from a mean of 67% in 2001 to 56% in 2012. Canopy transparency increased significantly ($P < 0.0001$) from 15% in 2001 to 24% in 2012. There were no significant changes in percent new growth. Similarly, while percent *A. tsugae* infestation increased from 36 to 39% between 2001 and 2012, this was not a significant change based on our field sample size. However, 7 of the 23 plots that did not have *A. tsugae* in 2001 were infested in 2012. This indicates that while overall *A. tsugae* density was not significantly higher in 2012 on average, it had spread to new stands in low levels. Because *A. tsugae* density and hemlock new growth are known to fluctuate from year-to-year based on *A. tsugae* population dynamics and the subsequent decline and recovery cycle that typically follows infestation (McClure 1991), it is not surprising that while the overall condition of hemlock has declined, the more direct metric of *A. tsugae* population densities has not changed significantly. Despite this apparent stability of short-term *A. tsugae* and stress symptoms, the longer-term, chronic impact of *A. tsugae* across the region is clearly evident in the other stress metrics. *F. externa* presence was not recorded in 2001 but was observed on 13 of the 23 plots in 2012.

The comprehensive Z-score stress index incorporating all field measured stress symptoms reveal a significant increase in overall hemlock decline ($P < 0.0001$) across plots from 2001 (mean Z-score = −0.002) to 2012 (mean Z-score = 0.405). Comprehensive Z-scores are designed to make inferences from the sample of data collected (our plots) to the larger population (the Catskills region; Fig. 4). The change in Z-score from 2001 to 2012 suggests that the overall condition of hemlock in the Catskills went from average health (50th percentile) to decline more severe than witnessed in 77% of the larger hemlock population.

Hyperspectral Imagery Change Detection. We randomly selected 1,000 points with minimum predicted hemlock basal area of 45% from the 2001 and 2012 decline condition images (Fig. 3) and recorded the predicted Z-score. The 45% cut-off was selected to maximize the amount of hemlock within a given pixel. A Wilcoxon matched-pairs signed rank test showed a significant ($P < 0.0001$) increase in decline symptoms between the 2001 and 2012 imagery (Table 4). Similar to the field decline summary value, this represents a shift in hemlock in the Catskills region transitioning from slightly above average condition to more severe decline across the region. The average remote sensing

Table 4. Descriptive data for all field and remote sensing hemlock condition metrics

Field metric	2001		2012		P-value
	Mean	Std	Mean	Std	
% Hemlock	75.19%	(12%)	75.86%	(17%)	0.81
Dead Hemlock	**0.38%**	**(0.5%)**	**8.88%**	**(16%)**	**0.042***
Z-score	**−0.002**	**(0.517)**	**0.405**	**(0.515)**	**<0.0001**
Z-score (predicted)	**−0.128**	**(0.754)**	**0.227**	**(0.251)**	**<0.0001**
% new growth	62%	(23%)	61%	(14%)	0.40*
Transparency	**15%**	**(5%)**	**24%**	**(7%)**	**<0.0001**
LCR	**67%**	**(10%)**	**56%**	**(8%)**	**0.006***
HWA infestation	36%	(40%)	39%	(36%)	0.16*
Dieback	**9%**	**(9%)**	**15%**	**(19%)**	**0.03***

* Indicates the use of Wilcoxon signed rank S for non-normal data.
Bold indicates significant differences between 2001 and 2012 ($P \leq 0.05$).

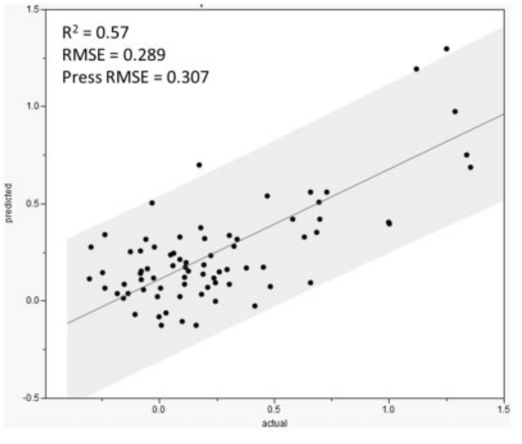

Fig. 4. Cumulative frequency distribution of Z-scores for 336 hemlock plots measured across the northeastern United States between 2001 and 2012.

predicted hemlock decline increased 0.36 Z-score units (from a mean Z-score of −0.128 in 2001 to 0.22 in 2012).

We conducted comparative change detection between the 2001 decline condition image and the 2012 decline condition image (Fig. 5) to assess broader changes across the identified landscape. Converting Z-scores to a class variable similar to coarse assessments used in the field (Table 3), we found that in 2001, 59% of hemlocks in the study area were considered to be in healthy condition (Table 5). That proportion dropped to 16% by 2012. Twenty-eight percent of hemlock dominated pixels remained in stable condition between 2001 and 2012, while 51% shifted from healthy to declining condition classes. Approximately 20% of the pixels improved in average condition class, likely a result of ingrowth and regeneration of non-hemlock species following hemlock mortality.

To isolate newly infested locations, all pixels shifting from decline class “1” (healthy) to decline classes “2” or “3” (early decline) were then added to a Geographic Information System (GIS) (ESRI 2009) model that also included roads, campgrounds, and slope. Early decline pixels were then prioritized by occurrence within 200 m of roads, campgrounds, rivers, streams, and water bodies. Eight potential biological control release sites were then identified across the AOI (Fig. 6).

Discussion

Both field and remote sensing assessments show a significant increase in hemlock decline in the Catskills region. In 2001, 59% of hemlock stands were classified as “healthy.” This number dropped to 16% in 2012, suggesting overall hemlock health is in decline in the Catskills region. The concurrent spread and increase in *A. tsugae* infestation is likely the primary driver of this decline. It is difficult to speculate what role *F. externa* has played because of the absence of data collection in 2001. However, this shift from healthy to declining classifications was mostly a shift to decline class 2 (early decline), which means a large majority of previously uninfested hemlock are now showing signs of infestation. The 21% of hemlock stands classified as “stable” are likely stands that *A. tsugae* have not yet reached or populations were not discernable. The remaining 28% of hemlock stands that reported “improved” conditions are likely a result of ingrowth of other species as hemlock mortality resulted in canopy openings that are now being replaced with new species. This was verified by the high densities of black birch and striped maple observed in the understory of plots with accelerated hemlock mortality. Significant changes in the overall decline summary values were driven by significant increase in fine twig dieback and canopy transparency and decreased LCR over the 10-yr period (Table 4). Foliar transparency and crown dieback have been used to predict hemlock mortality at 1, 3, and 5 yr post-measurement with high accuracy (Eschtruth et al. 2013). Eschtruth et al. (2013) recommend insecticide intervention when foliar transparency is greater than 35% and crown dieback is greater than 30%. Across our field sites, mean canopy transparency was 24% while dieback averaged 15%. Our findings are well within the limits set by Eschtruth, indicating that mitigation for hemlock across the region is still possible and currently being pursued by state agencies and regional partnerships. However, some field sites included in this survey exceeded 90% dieback and 65% canopy transparency, indicating that some locations have declined too much to warrant effective treatment intervention.

The presence of *F. externa* was not recorded or observed during the 2001 field work. However, the 2012 survey detected *F. externa* in 27% of the samples collected. Unlike *A. tsugae*, studies indicate that *F. externa* has no immediate impact on plant growth or foliar chemistry in the early stages of infestation (Miller-Pierce et al. 2010) but does have demonstrated long-term impacts. Despite the low-level impact of *F. externa*, the cumulative effects of this insect and *A. tsugae* likely adds to long-term stress on eastern hemlock in the Catskills region and should therefore

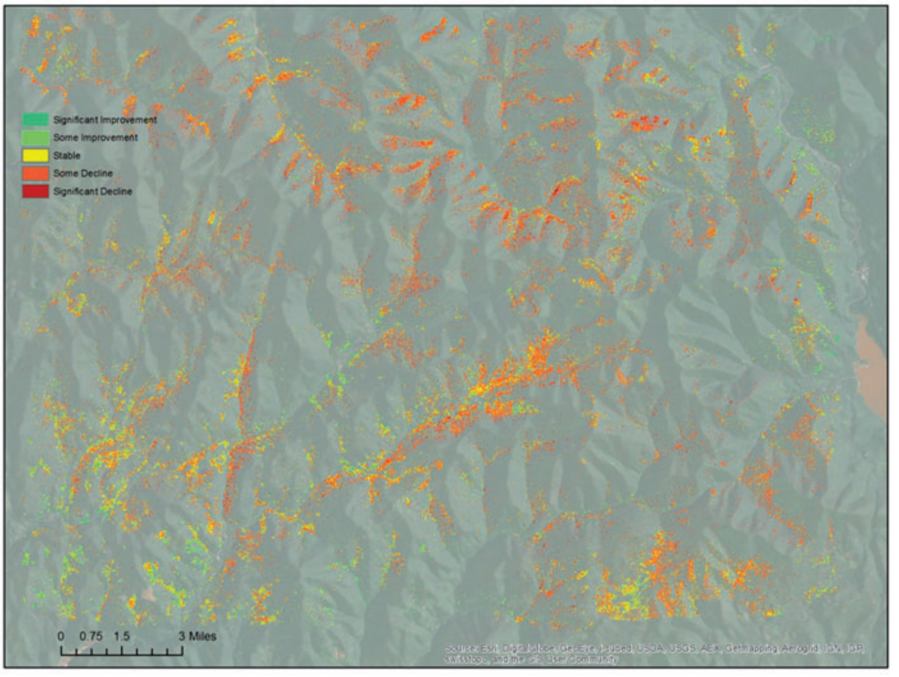

Fig. 5. Change detection coverage differentiating stands with demonstrated stability, improvement, or decline in condition over the 10-yr study.

Table 5. Pixel percentages falling into healthy (class 1) to severely declining (class 5)

	2012 class						
2001 class		**1**	**2**	**3**	**4**	**5**	**2001 Totals**
	1	9%	44%	5%	0%	0%	58%
	2	4%	18%	2%	0%	0%	24%
	3	2%	9%	1%	0%	0%	12%
	4	1%	3%	0%	0%	0%	4%
	5	0%	1%	0%	0%	0%	1%
	2012 Totals	16%	75%	8%	0%	0%	

also be considered as a serious potential threat to maintaining these forests.

The majority of decline in 2001 was concentrated in the southeastern region of the Catskills. The areas of "severe decline" within this region showed signs of recovery in 2012, suggesting ingrowth and regeneration of non-hemlock species. Priority areas for predator release have been identified and are centered in high-density areas of decline class 1 and 2 (early decline) from the updated 2012 hemlock condition coverage. These conditions should allow released predators optimal conditions for establishment and propagation with the long-term goal while still allowing opportunities for hemlock health improvement. Predator insectaries are an evolving concept that have been identified as effective systems for field-based biological control propagation and establishment (Stoyer and Kok 1986, DeBach and Rosen 1991, Kok and Salom 2002) with more specific examples in forested systems (Starý 1976), including *A. tsugae*-specific predators (Mausel et al. 2008).

While biological control of *A. tsugae* has potential as a management tool, success is dependent on deployment of predators in locations where *A. tsugae* densities are sufficient to support their populations, but where hemlock are not yet so severely impacted by *A. tsugae* that they are unable to recover (Mausel et al. 2010). The spatial maps provided as a part of this project will help identify early decline (decline class 1–2) areas to target biological control releases and potential development of long-term predator insectaries. A network of potential insectary locations can allow land managers the opportunity to prioritize management based on their resource needs. A network of these optimal and repeated release sites should also promote eventual population convergence through establishment and natural dispersal. The recommended network of eight points from this work would provide ~60 % coverage of the 84,500-ha study area if a 5-km radial predator dispersal is achieved and complete coverage of the study area if a 10-km radial predator dispersal is achieved. Areas in moderate–severe decline are

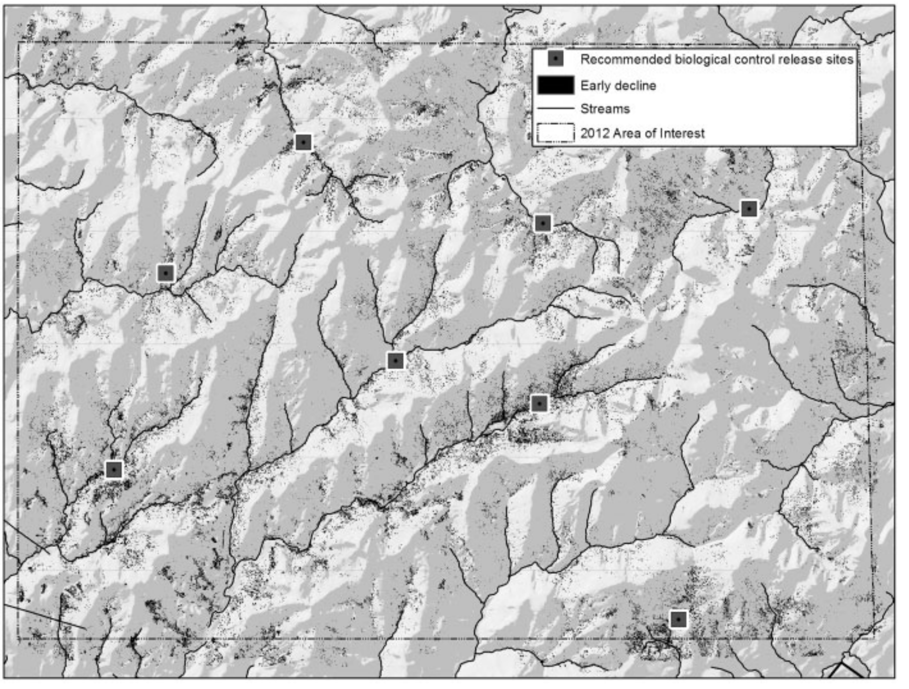

Fig. 6. Recommended biological control long-term release sites based on decline classification and proximity to roads water and high-use recreation areas.

typically too unhealthy to be used for successful biological control establishment. These stands are unlikely to have healthy overstory hemlocks in the foreseeable future.

The promising results from this study suggest remote sensing estimates for hemlock condition, and change detection are equivalent to results from field monitoring efforts, and could provide a larger-scale detailed assessment of the hemlock resource across the landscape while assisting land managers in prioritizing practical management applications. This pilot in the Catskills region indicates that while a strong shift from healthy to decline conditions have been observed over the 10-yr study, a majority of the decline pixels remain in the "early decline" category and widespread mortality has not yet occurred in this region of higher elevation hemlock and colder winter temperatures. The slow decline across the region shows promise for the successful long-term implementation of biological control and the results from this work are in line with other long-term monitoring studies (Eschtruth et al. 2013). Armed with the spatial techniques described in this study, targeted *A. tsugae* management strategies can be developed at the landscape scale and deployed to individual stands based on tree health. A truly integrated pest management plan could be developed that included coordinated treatments with silviculture, biological control, and insecticides targeting appropriate and suitable stands. These techniques could improve control strategies and reduce further decline of hemlock in the region.

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