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Potential Social and Economic Impacts of the Hemlock Woolly Adelgid in Southern New England

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Abstract: *Adelges tsugae* (Hemlock Woolly Adelgid; HWA) is a non-native forest insect that causes defoliation and mortality of hemlock in the eastern US. We quantified the extent to which people are potentially affected by the spread of HWA infestation where they live and where they recreate. We also considered how these impacts might change through time using data from 2007, 2009, and 2011. The study area included hemlock stands in a 7500-km^2 region of central Connecticut and central Massachusetts. We used sample-plot data on live basal area and vigor of hemlock stands to interpolate hemlock health characteristics for all hemlock stands in the study area. We estimated a loss of property values in the region of approximately $24.6 million USD. This estimate was conservative because there were insufficient data to fully quantify the economic losses associated with the death of hemlock trees and the degradation of recreational opportunities. The spatial extent of the HWA infestation suggests that both of the latter categories of economic losses are likely substantial. These data can be used to consider the economic efficacy of actions taken to ameliorate the effects of the HWA infestation.

Introduction

Adelges tsugae Annand (Hemlock Woolly Adelgid [HWA]) is an exotic forest pest that causes the decline and subsequent mortality of *Tsuga canadensis* L. (Eastern Hemlock) and *Tsuga caroliniana* Engelm. (Carolina Hemlock). HWA was accidentally introduced into Virginia from Japan in the early 1950s, and it has spread to hemlock forests throughout the northeastern US. The damage caused by this insect became widely evident in the 1990s; once infested, hemlocks often decline quickly, sometimes dying within four years (McClure 1990, 1991).

The damage to hemlock stands can be socially consequential because hemlock trees provide direct and indirect benefits for people and communities. Mature hemlocks are large trees that contribute to scenic beauty and the aesthetic value of landscapes (Brush 1979). Their dense shade contributes to the maintenance of cool stream temperatures and influences understory vegetation (Brantley et al. 2013). Hemlock forests on undeveloped land provide recreational opportunities for

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residents in nearby communities and non-residents who visit the forests (McConnell and Walls 2005).

Because hemlock stands provide these social benefits, the economic consequences of HWA invasion extend beyond the loss of harvestable timber. Holmes et al. (2010a) found that severely defoliated hemlocks in northern New Jersey reduced the value of residential parcels with HWA damage and reduced the value of properties located up to 0.5 km away from infestations. The economic losses were roughly 1–1.6% of the parcels' sales price. Such losses in property values also reduce annual property tax revenues and may cause communities to increase property-tax mill rates in order to maintain services. Moore et al. (2011) employed contingent valuation to examine the public's value of a program to control the HWA infestation in the southern Appalachian Mountains. They found that residents of North Carolina were willing to make a one-time payment of $122 per person to protect hemlock stands in western North Carolina public forests from HWA. This value was a measure of the loss to the public if the hemlock stands were not protected from HWA and were instead allowed to decline.

Managers face the challenge of determining how to interpret results of site-specific studies, predict infestation patterns and speed of spread, and consider management as it relates to regional economic consequences of HWA infestations. Holmes et al. (2010b) did an early extrapolation in which they predicted the intersection of hemlock forests and residential areas as HWA infestation spread spatially and temporally. These authors found that the largest economic losses due to hemlock defoliation were likely to occur in western Connecticut and Massachusetts, and southeastern New Hampshire.

In this study, we present a more refined approach to estimate the potential social impacts of HWA infestation. Using data on hemlock health from sampled stands in central Connecticut and Massachusetts, we scaled the damage to a regional area based on satellite imagery. We used kriging to interpolate HWA sample data on hemlock defoliation and live basal area to all hemlock stands in central Connecticut and Massachusetts. We then overlaid this HWA-damage data with GIS layers on human population, publicly and privately owned undeveloped land, and median home prices to identify HWA infestation intersections with places where people live and work (population) and places where people might recreate (undeveloped land), and to estimate losses in residential property values.

Our results indicated dramatic losses of healthy hemlock stands in the study area over time and space, with the infestation moving in a northeasterly direction. We found that the impact of HWA on people increased dramatically during the 5-year study period (2007–2011), during which the number of people living in close proximity to HWA-infested trees increased and, consequentially, there was a substantial accompanying decline in property values of as much as $105 million in the study area alone.

The effects of trees on property values

Previous hedonic studies have shown that healthy trees and forests could provide scenic and recreation value to residential properties (Anderson and Cordell

1985, Dombrow et al. 2000, Netusil et al. 2010, Tyrvainen and Miettinen 2000). For example, Dombrow et al. (2000) determined that sale prices of single-family homes increased by 2% when mature trees occurred on properties. This economic benefit of healthy forests indicates the potential significant loss from forest disturbances including forest fires and forest-pest outbreaks.

Forest-pest outbreaks are important factors that have negative effects on forest-ecosystem services (Holmes et al. 2009, Huggett 2008, Rosenberger et al. 2012). *Dendroctinus ponderosae* Hopkins (Mountain Pine Beetle), *Choristoneura fumiferana* (Clemens) (Spruce Budworm), *Lymantria dispar dispar* (L.) (Gypsy Moth), and HWA are all major forest pests that have caused significant damage to the forests in the eastern US. However, only a few studies have evaluated the economic impacts on property values from such forest pest outbreaks.

Kovacs et al. (2011) investigated the economic losses from *Phytophthora ramorum* Werres, de Cock, & Man in't Veld (Sudden Oak Death) in Marin County, CA, and found that property values decreased 3–6% as a result of oak mortality. Price et al. (2010) conducted research to investigate the relationship between the number of trees killed by Mountain Pine Beetle and property prices in Grand County, CO. They estimated that property values decreased by \$648, \$43, and \$17 for every dead tree within a 0.1-, 0.5-, and 1.0-km buffer, respectively. However, these studies and others such as Holmes et al. (2010a) have focused on specific areas and forest pests. Thus, there is a need for further investigation as to how these price effects vary with infestation organism and region of the country.

In this study, we focused on the social impact of HWA infestation in central Connecticut and central Massachusetts. We also considered methods that could be used to scale-up the results from site-specific studies to larger geographic areas.

Study Area

Ecologists at the Harvard Forest (Petersham, MA) identified, mapped, and characterized Eastern Hemlock stands within a 7500-km^2 rectangular area extending from Long Island Sound in Connecticut north to the Massachusetts–Vermont border (Fig. 1; Orwig et al. 2002). They identified all stands of Eastern Hemlock greater than 1.3 ha in size using high-resolution aerial photographs that they then scanned and digitally transferred into a GIS overlay; a total of 6126 Eastern Hemlock stands were identified. Orwig et al. (2012) ground-truthed more than 300 stands across the study area and determined that they had correctly classified 93.5% of the visited sites in their aerial photograph interpretation.

Orwig et al. (2002) conducted field sampling in 1997–1998 to characterize Eastern Hemlock forest conditions in Connecticut (Orwig et al. 2002), the first New England state invaded by HWA, and continued their work in 2002–2004 to assess conditions in Massachusetts (Orwig et al. 2012). They included 142 Eastern Hemlock stands in their field surveys (Fig. 1).

Methods

For our analyses, we used Eastern Hemlock-health data collected by Preisser et al. (2011) when they revisited Orwig et al.'s (2002) stands in 2007, 2009, and 2011. We focused our analyses on measurements of Eastern Hemlock vigor and live basal area, which were the key variables we used to identify the effects of HWA infestation. HWA defoliates hemlocks, which reduces vigor, and when the hemlock trees die, the live basal area in the stand is reduced.

In the sampled Eastern Hemlock stands, data on live basal area (m^2/ha) and tree vigor were collected by sampling one 20 x 20-m fixed-area plot and 5–10 variable-radius plots spaced 30–50 m apart on a transect that crossed the long dimension of each stand (Orwig et al. 2002). In 2011, sampling efforts at 3 of the variable-radius plots used the Bitterlich method (Grosenbaugh 1952) to estimate the Eastern Hemlock live and mean basal area (m^2/ ha) (Preisser et al. 2011). Eastern Hemlock vigor was measured by estimating the amount of retained foliage in each stand using 4 categories: 4 = 0–25% foliar loss, 3 = 26–50% foliar loss, 2 = 51–75% foliar loss, and 1 = 76 –99% foliar loss (Preisser et al. 2011).

Mean and maximum values of Eastern Hemlock live basal area decreased from 2007 to 2011 due to mortality from the HWA (Table 1). The number of damaged Eastern Hemlock stands as measured by the extent of defoliation (vigor = 1, 2, or 3) increased through time, while the number of healthy hemlock stands (vigor = 4) decreased.

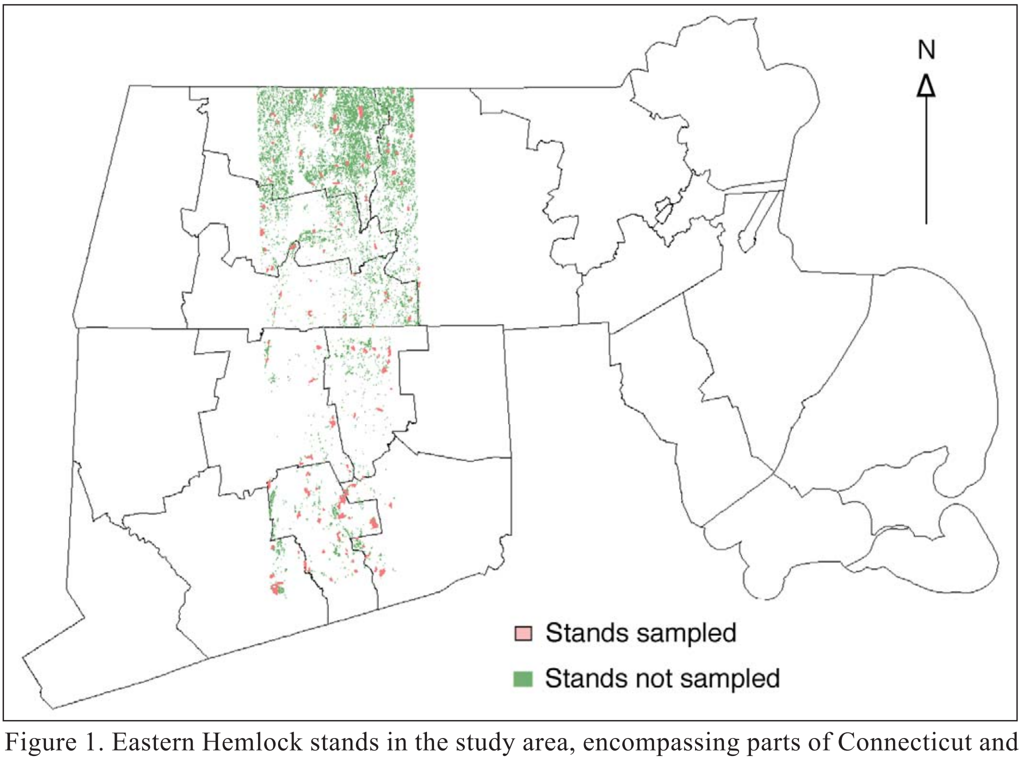

Figure 1. Eastern Hemlock stands in the study area, encompassing parts of Connecticut and Massachusetts. Red and green areas indicate locations of stands sampled and not sampled, respectively, by Orwig et al. (2002, 2012).

Spatial interpolation and potential prediction errors

Spatial interpolation methods, such as kriging, have been widely applied in forestry applications (Gunnarsson et al. 1998, Jansen et al. 2002). Kriging is a geostatistical interpolation methodology that is used to predict the value of spatially distributed variables at unsampled locations using a weighted average of observations at neighboring locations (Cressie 1993, Goovaerts 1997, Isaaks and Srivastava 1989). For example, Biondi et al. (1994) employed kriging to interpolate number and size of forest tree stems. Köhl and Gertner (1997) applied this methodology to tree needle losses. Wulff et al. (2006) used kriging to estimate the geographical distribution and dispersal of forest damage from an outbreak of *Gremmeniella* (a canker). We employed kriging to interpolate Eastern Hemlock damage from HWA infestations in central Connecticut and Massachusetts.

Spatial interpolation of live Eastern Hemlock basal area was accomplished using ordinary kriging, which is the most common spatial interpolation procedure. We used simple kriging to spatially interpolate Eastern Hemlock vigor because it facilitated geostatistical simulation to investigate the robustness of impact projections. We assumed that spatial correlation was isotropic over the study area, depending only on the distance between two points, but not the direction of their separation, and we used semivariogram analysis to identify the pattern of spatial correlation between neighboring points (Cressie 1985, Stein 1999). We used this approach to interpolate live Eastern Hemlock basal area and vigor for the >6000 stands in the study area for each of the 3 sampling years. Our intent was to develop a spatial picture of the effects of HWA infestation throughout the study area and how these effects changed over time.

To obtain the best predictions, a kriging model should have a mean standardized prediction error (MSE) close to 0 and a root mean-squared standardized error (RMSE) close to 1. We determined that the exponential model fit best for live basal area (Table 2), and the best model for vigor varied.

Table 1. Live basal area and vigor for sampled hemlock stands (Preisser et al. 2011). SD = standard deviation. Note: the number of sampled sites decreased through time as hemlock stands died or access for sampling was denied. Vigor ratings (as percent foliar loss): 1 = 76–99%, 2 = 51–75%, 3 = 26–50%, 4 = 0–25%.

	2007	2009	2011
Live basal area (m^2/ha)			
Mean	38.23	27.83	15.31
SD	27.59	16.29	11.89
Min	0	0	0
Max	125.45	73.34	54.04
n	140	138	122
Hemlock vigor (# of stands)			
1	8	11	9
2	18	19	23
3	33	37	44
4	82	71	47
n	141	138	123

We conducted cross validation of the interpolations by comparing predicted and actual values for live basal area from each of the sample sites. If there were no data-interpolation errors, all points would fall along a 45-degree line (Fig. 2).

Results and Discussion

Our model over-estimated Eastern Hemlock live basal area for stands with small live basal areas and under-estimated it for stands with large live basal area (Fig. 2). We may have obtained this result, in part, because the distribution of sampled values was skewed to stands with small live basal areas. The over-estimation for stands with large live basal areas was most pronounced in the 2011 data (denoted by the flatness of the blue trend line in Fig. 2). As Eastern Hemlocks die from HWA infestation, the live basal area of stands becomes smaller, a result that supports our suggested effect of data skewness.

To place these prediction errors in context, we developed 95% confidence intervals along the 45-degree lines in each plot in Figure 2. We computed the 95% confidence intervals using the difference between the data points and the corresponding points on the 45-degree lines for the measured basal areas, and the confidence intervals are shown by the dotted lines in each plot in Figure 2. The 95% confidence intervals are ± 37.5, 25.3, and 19.6 m^2/ha for 2007, 2009, and 2011, respectively.

These results do not invalidate the kriging results, but suggest that caution must be used when interpreting the empirical predictions. As a first step to consider the robustness of predictions, we used the first, second, and third quartiles of live basal area in 2007—14.475 m^2/ha, 34.74 m^2/ha, and 55.005 m^2/ha—to investigate the potential variability of HWA impacts. The values we used for evaluate our results for interpolated vigor were 1.5, 2.5, and 3.5, which are the mid-points between the levels for this index variable. To account for error in the kriging predictions, we further employed a geostatistical simulation method when we predicted property value losses from HWA damage (Chiles and Delfiner 1999).

Interpolation results

Interpolated live basal area declined over time (Table 3), as was observed for the sample data (Table 1). Figure 3 presents a spatial representation of these results: the red, orange, and yellow shaded areas (larger basal areas) disappear

Table 2. Kriging summary statistics

Variables	Year	Model	Mean standardized error	Root mean square standardized error
Live basal area				
	2007	Exponential	0.0002	0.924
	2009	Exponential	-0.011	1.046
	2011	Exponential	-0.017	1.027
Vigor				
	2007	Gaussian	-0.006	1.025
	2009	Gaussian	-0.013	1.029
	2011	K-Bessel	0.018	1.027

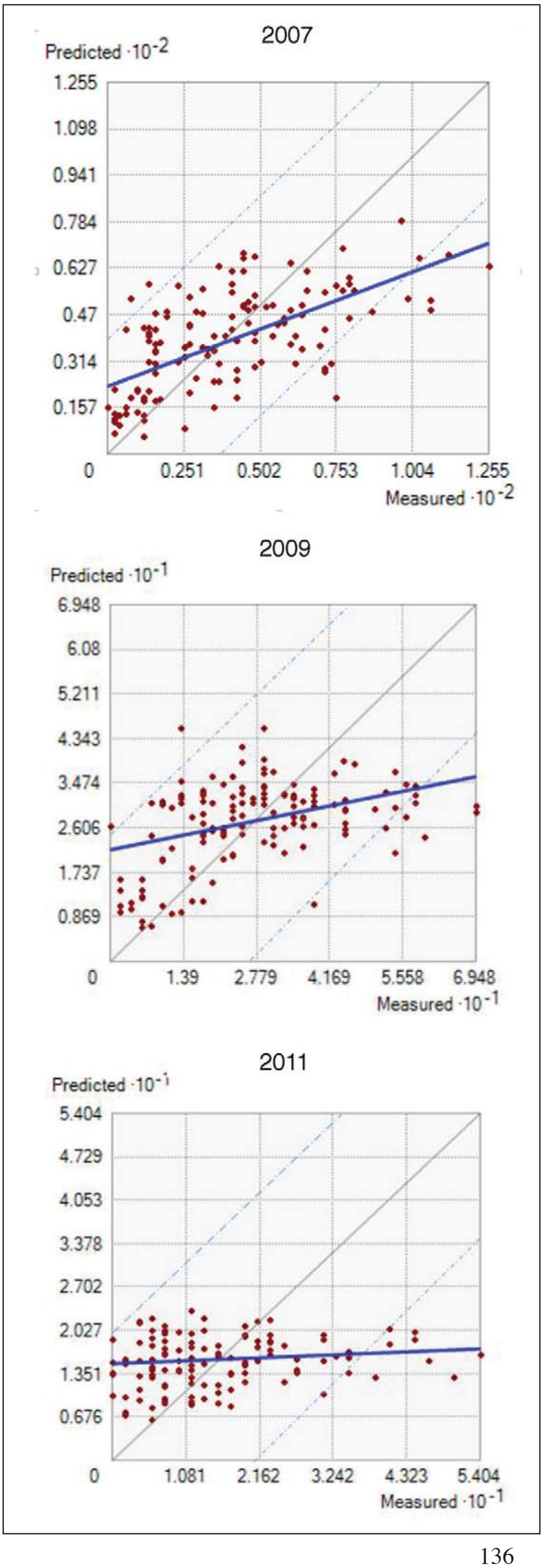

Figure 2. Results of cross validation for live basal area (m^2/ha). Red dots are interpolations of 142 sites sampled by Orwig et al. (2002, 2012), blue line is best-fit trend line, and dotted lines are 95% confidence intervals.

through time and the green and blue areas (smaller basal areas) expand. Sites with lower basal areas are shown to expand from the southern extreme of the study area to the north through time. The maximum interpolated live basal area was about 96 m^2/ha in 2007 and declined to 25 m^2/ha in 2011.

Mean interpolated Eastern Hemlock vigor also declined through time (Table 3, Fig. 4). The spatial change of Eastern Hemlock vigor followed the same pattern as live basal area; the data initially indicated diminished vigor in the south and a progression of decreased vigor northward from southern Connecticut to northern Massachusetts over time. In 2011, there was a decrease in seriously damaged Eastern Hemlocks in southern Connecticut because of mortality in trees that had

Table 3. Summary statistics for interpolated damage to hemlock stands (n = 6126). SD = standard deviation. Vigor = continuous vigor based on kriging projections.

	2007	2009	2011
Live basal area (m^2/ha)			
Mean	50.69	32.01	16.34
SD	16.25	5.28	3.68
Min	4.71	6.07	4.74
Max	95.69	41.81	25.47
Vigor			
Mean	3.791	3.736	3.198
SD	0.383	0.459	0.320
Min	1.584	1.177	1.192
Max	4.093	4.152	3.910

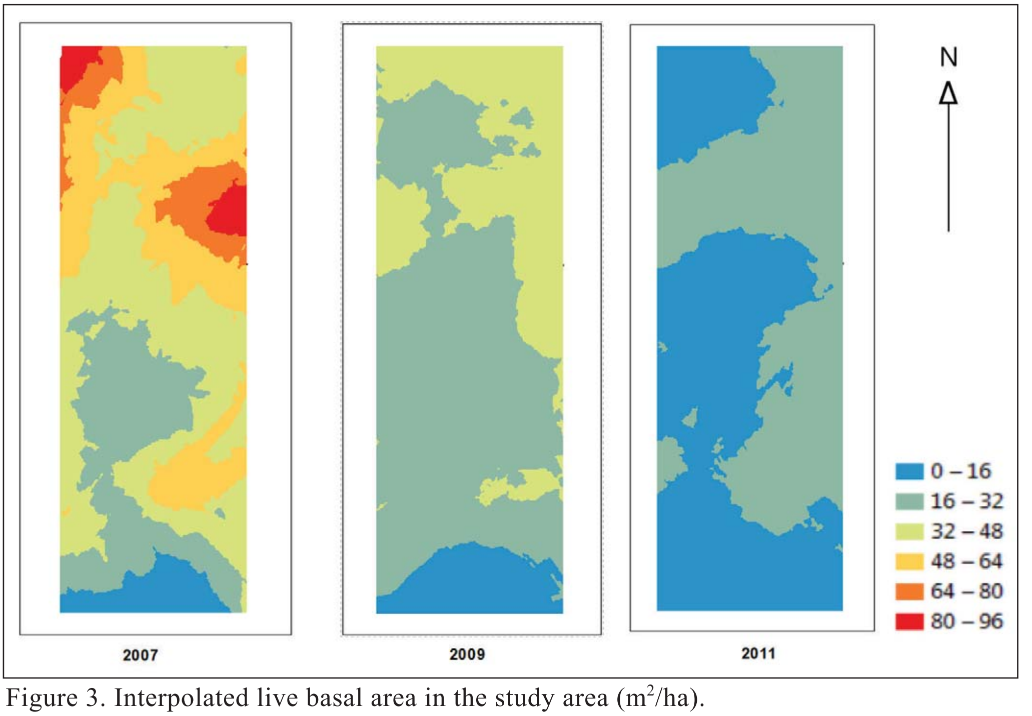

Figure 3. Interpolated live basal area in the study area (m^2/ha).

previously been experiencing reduced vigor; dead trees were no longer counted, so there were fewer low-vigor trees present in the samples. The change reflects mortality, not an overall increase in vigor.

Potential social and economic impacts

Affected households. The study area included 9 counties, 5 in Connecticut (Hartford, Middlesex, New Haven, New London, and Tolland) and 4 in Massachusetts (Franklin, Hampden, Hampshire, and Worcester). Residents of these counties were potentially affected by HWA infestation based on where they lived, worked, shopped, and recreated. If residential properties were located within or near Eastern Hemlock stands, then residents might have observed defoliated stands of live and dead Eastern Hemlock trees during their daily activities.

We overlaid the layer of interpolated Eastern Hemlock-health data with 2010 census-block population data (Fig. 5; US Census Bureau 2010). The affected census blocks indicated areas where households were likely to see HWA damage during their daily activities. The estimated number of households affected by HWA infestation increased substantially through time (Table 4) via the northern expansion of the infestation into an area with a high density of Eastern Hemlock stands (Fig. 1). Based on the thresholds of median live basal area or vigor ≤3.5, the number of people affected by HWA damage tripled from 2007 to 2011 (Table 4).

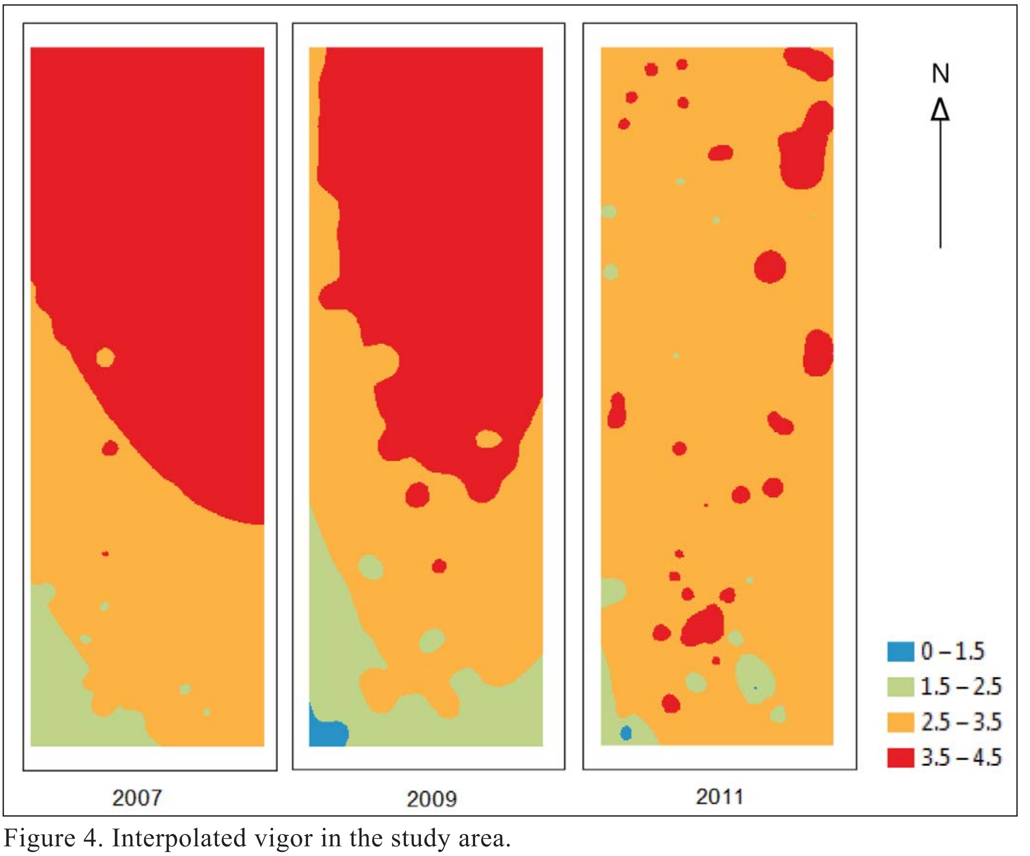

Figure 4. Interpolated vigor in the study area.

Undeveloped land. Undeveloped land, including Eastern Hemlock stands, provide natural areas where people may recreate; these stands also contribute to the aesthetic quality of landscapes (Earnhart 2006, Fausold and Lilieholm 1999, Irwin 2002). We overlaid GIS maps of publicly and privately owned open space (Ceep

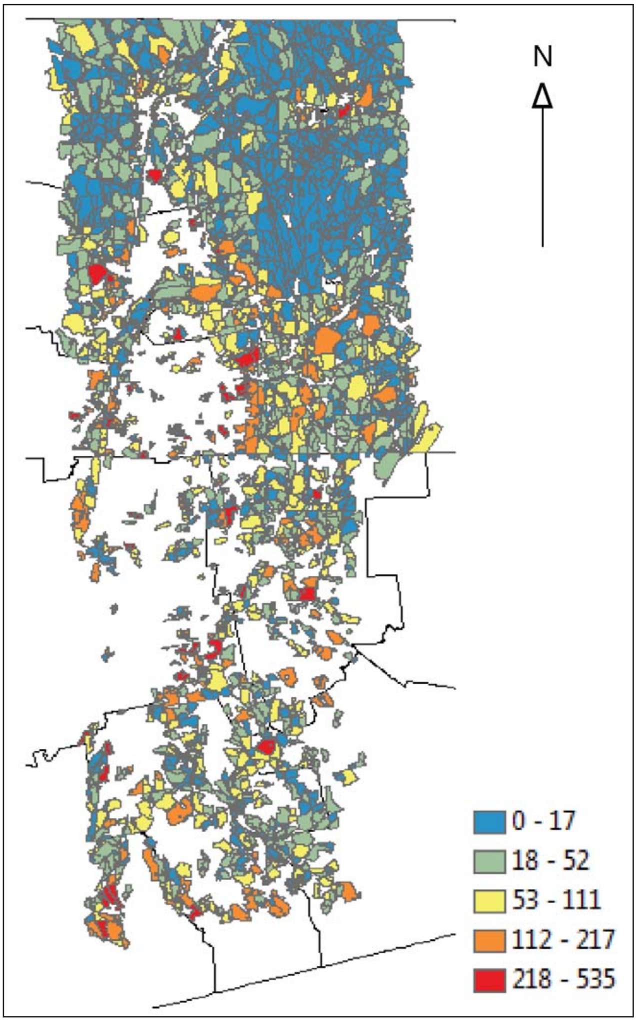

Figure 5. Number of households in census blocks that intersect with Eastern Hemlock stands.

Table 4. Predicted number of households affected by HWA damage.

	2007	2009	2011
Live basal area			
≤14.475 m^2/ha	5426	6383	50,927
≤34.74 m^2/ha	38,264	92,394	107,450
≤55.005 m^2/ha	91,341	107,450	107,450
Vigor			
≤1.5	0	1296	938
≤2.5	7373	10,986	5146
≤3.5	39,265	45,856	101,735

2011, MassGIS 2013) with the layer of Eastern Hemlock stands. Using these overlays, we were able to identify the areas of undeveloped land potentially affected by HWA infestation. About 38% of the Eastern Hemlock stands were located on publicly and privately owned undeveloped land (green shaded area in Fig. 6); most of these stands were located in northern Massachusetts.

After overlaying the interpolated HWA-infestation data with the Eastern Hemlock stands on undeveloped lands, we observed that the effects of the infestation were potentially quite dramatic (Table 5). The area of public land with Eastern Hemlock stands with live basal area of less than 34.74 m^2/ha increased by a factor of ≈14 from 2007 to 2011. The area of public land with interpolated Eastern Hemlock vigor ≤3.5 increased by 10-fold from 2007 to 2011. The magnitude of these increases was due to the confluence of a larger number of Eastern Hemlock stands in the northern portion of the study area, a large amount of undeveloped land in this area, and the northern expansion of HWA infestation through time. The impact of HWA infestation affecting undeveloped land likely extended beyond local residents

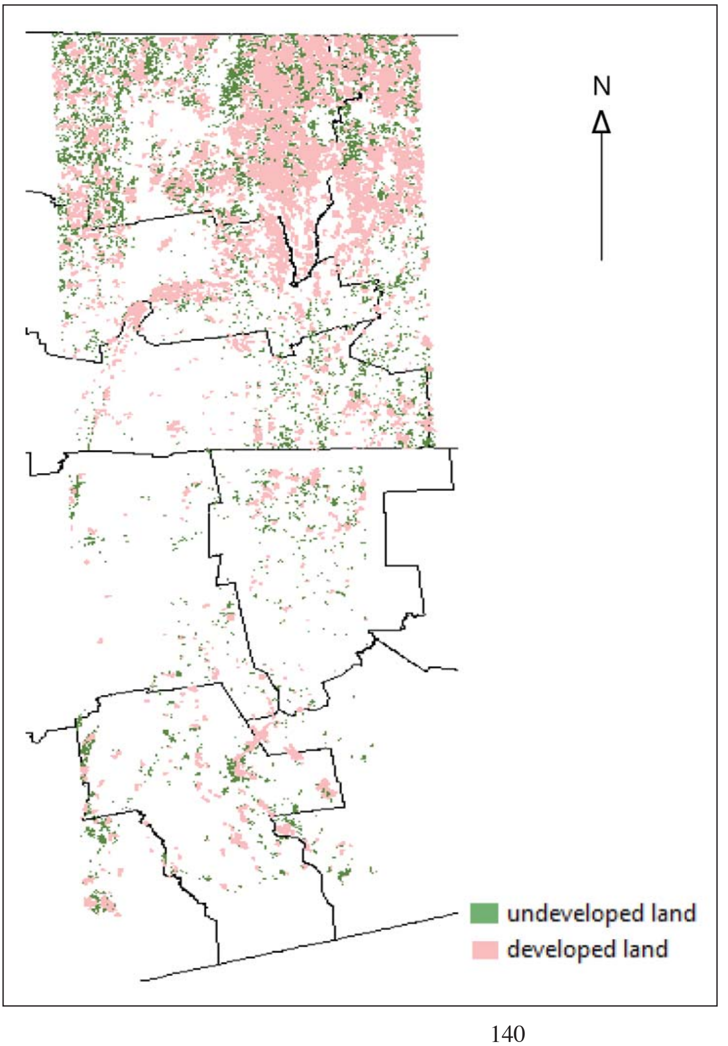

Figure 6. Publicly or privately owned undeveloped land that intersects with Eastern Hemlock stands.

to people who reside outside the study area, i.e., those who live in nearby urban areas (e.g., Boston and New York) and visit the study area to recreate.

Economic losses. Holmes et al. (2010b) estimated that severe (>75%) Eastern Hemlock defoliation, which is comparable to our vigor ≤1.5, resulted in a 1% decrease (conservatively) in residential property values of parcels that had Eastern Hemlocks on the property. Our aggregation included more properties than were included in Holmes et al. (2010b) because we did not restrict effects solely to properties that contained Eastern Hemlock trees; rather, we also included properties adjacent to Eastern Hemlock stands because mortality would affect values. Applying this property-value diminution to median property values in affected census-block groups (US Census Bureau 2011) provided an estimate of the decrease in property values due to the effects of the HWA infestation (Fig. 7). We multiplied the number of households in each census block intersected by Eastern Hemlock stands with vigor ≤1.5 by the median property value for the census block, and then multiplied this result by 0.01 to estimate the property-value losses in each census block. We computed aggregate losses by summing the losses for each census block (Table 6). We assumed a constant marginal damage function applied, and thus the housing markets had recalibrated to new hedonic equilibria following the extensive damage in the study area as reported by Holmes et al. 2006.

Based on the simple kriging interpolation results of Eastern Hemlock vigor, we used a geostatistical simulation to generate 500 realizations of Eastern Hemlock vigor for the study area. We calculated the total economic loss for each realization to develop an empirical distribution of potential property-value losses. The potential capitalized property-value loss due to severely defoliated Eastern Hemlock

Table 5. Predicted area (in km^2) of undeveloped land affected by HWA damage.

	2007	2009	2011
Live basal area (≤14.475 m^2/ha)			
Publicly owned	1.7	5.2	47.5
Public + private	4.0	7.6	72.2
Live basal area (≤34.74 m^2/ha)			
Publicly owned	22.8	202.6	316.0
Public + private	31.5	258.6	390.9
Live basal area (≤55.005 m^2/ha)			
Publicly owned	259.0	316.0	316.0
Public + private	311.8	390.9	390.9
Vigor (≤1.5)			
Publicly owned	0.0	1.2	0.1
Public + private	0.0	2.4	1.2
Vigor (≤2.5)			
Publicly owned	2.8	3.7	5.0
Public + private	6.6	8.7	8.4
Vigor (≤3.5)			
Publicly owned	25.3	32.1	273.6
Public + private	35.6	46.5	328.3

stands (vigor ≤1.5) was roughly \$3.6 million in 2007 (SD = \$1.8 million). The spread of HWA between 2007 and 2011 caused an additional loss of about \$21.0 million, for a total estimated loss of \$24.6 million by 2011 (SD = \$4.4 million) (Table 6). We did not have any information on the losses in property values due to the Eastern Hemlock mortality and removal. Thus, our estimates of property losses of \$24.6 million are conservative.

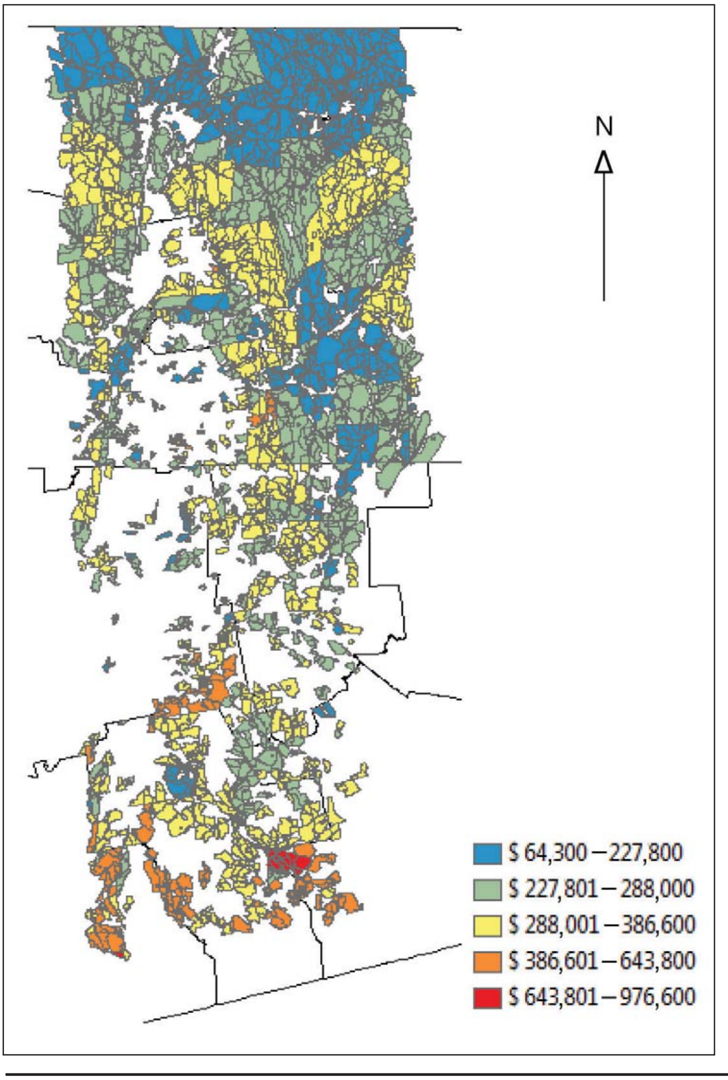

Figure 7. Median residential property values in census blocks that intersect with Eastern Hemlock stands.

Table 6. Potential capitalized property-value losses from HWA damage (x \$1000). SD = standard deviation.

	2007 total damage	2009 total damage	2011 total damage
Vigor ≤1.5			
Mean	\$3581	\$8370	\$24,564
SD	1832	2559	4441

Conclusions

We infer that the spread of HWA infestation has substantial social effects as trees are defoliated and die where people live, work, and play. Using data from portions of Connecticut and Massachusetts, we estimated that the losses in property values were as much as $24.6 million during the study period.

Placing our estimates in context, Holmes et al. (2010b) estimated HWA property-value losses for Connecticut and Massachusetts at $9.4 million for the period 1999–2008. This estimate was for a much larger geographic region than we address, but their estimate is within the 90% confidence interval of the potential economic losses that we calculated for 2009 ($4.9 million–$13.0 million). We likely have more accurate data and extrapolations of the HWA infestation than those available to Holmes et al. (2010b). Thus, our more refined approach to interpolate the expansion of HWA infestation suggests that the aggregate losses in property values across regions of the US that may potentially experience HWA damage likely exceeds the $20.2 million in aggregate property-value losses estimated by Holmes et al (2010b); our 2011 estimate that includes only portions of Connecticut and Massachusetts exceeds the Holmes et al. (2010b) national estimate.

Further, our analysis shows that HWA infestation affects places where people recreate. This result suggests that there is likely a loss in economic values from diminished recreation experiences. These losses could arise because the loss of the Eastern Hemlock overstory can affect stream temperatures and, therefore, fishing quality. The defoliation and loss of Eastern Hemlock trees could also affect the quality of recreational hiking experiences. Although we know of no existing studies to impute this category of potential economic losses resulting from hemlock mortality, it is a topic of interest for future studies that could make estimates using travel-cost recreation-demand modeling. In addition, a stated-preference study such as the one conducted by Moore et al. (2011) could be undertaken for the entire geographic area potentially affect by HWA infestation.

The Connecticut and Massachusetts data demonstrate that focusing solely on defoliation may provide a misleading underestimate of economic losses because it does not capture the economic losses as Eastern Hemlock trees die. That is, defoliation does not account for a decreased number of trees in the future, only diminished foliage. Thus, it is important to consider multiple dimensions of pest infestations, including HWA, if accurate characterizations of social and economic effects are to be developed. Further, the analysis presented here documents recent economic losses due to HWA. We suggest that forest pest and disease infestation-related losses may increase with climate change and that the costs will go far beyond simply the losses of commercial timber, and include decreases in property values, tax revenue, and revenue from recreational activities.

Acknowledgments

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