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Spatial Distribution of Chesapeake Bay Riparian Hemlock Forests Threatened by Hemlock Woolly Adelgid

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Abstract

Landscape-scale maps of tree species densities are important tools for managing ecosystems threatened by forest pests. Eastern hemlock dominates riparian forests throughout its range. As a conifer in a deciduous landscape, hemlock plays an ecohydrological role, especially when other species are dormant. The nonnative, hemlock woolly adelgid has caused widespread hemlock decline and mortality. We used two existing basal area raster layers first to identify Chesapeake Bay subwatersheds with ≥6 percent hemlock basal area and second to quantify hemlock basal area densities within fixed-width riparian buffers of 50 m, 100 m, 250 m, and 500 m. Hemlock densities were higher in riparian zones compared with entire subwatersheds. In five subwatersheds, 50 m and 100 m zones had higher percentages of pixels with ≥25 percent hemlock basal area. We produced maps identifying hemlock riparian densities in the Pine Creek Watershed, which managers can use to prioritize sites for supplemental conifer planting under anticipated hemlock decline.

Study Implications: Forest inventory and satellite data were used to map riparian hemlock stands in the Pine Creek Watershed (Pennsylvania). Pine Creek is a subwatershed of the Chesapeake Bay and an important tributary of West Branch Susquehanna River. Pine Creek headwaters are a brook trout refuge, and hemlock shading along streams stabilizes water temperature. These fisheries provide recreational value and economic support to local communities. Hemlock woolly adelgid, an invasive insect, has recently entered the watershed and will cause hemlock decline and mortality. Our maps assist the Pine Creek Watershed Council in identifying riparian areas for supplemental planting of alternative conifer seedlings.

Keywords: eastern hemlock, Chesapeake Bay Watershed, riparian, hemlock woolly adelgid, geographic information systems

The nonnative insect, hemlock woolly adelgid (*Adelges tsugae*) (HWA) presents a landscape-scale threat to forest ecosystem health and economic viability of eastern hemlock (*Tsuga canadensis* Ehrh.) throughout eastern North America. Land managers require tools to assess hemlock's spatial distribution for monitoring HWA invasion and planning strategies to reduce ecological and hydrologic impacts from hemlock decline. Geographic information system (GIS) products can assist managers in synthesizing landscape-scale inventory data to address the HWA threat to forest ecosystem function (Pontius et al. 2010).

Eastern hemlock is distributed from the southern Appalachian Mountains to southeastern Canada and

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westward to the central Lake States (McWilliams and Schmidt 2000). It is a long-lived, shade tolerant conifer occurring in pure and mixed stands across a range of primarily mesic sites (Godman and Lancaster 1990). Because hemlock stands contribute unique structural and functional landscape attributes, hemlock is considered a foundation species with a specific role in ecosystem processes (Ellison et al. 2005). Hemlock's shade tolerance and slow growth habit result in dense, multilayered canopies (Fajvan and Seymour 1993), which are important to terrestrial and aquatic wildlife habitat (Snyder et al. 2002, Tingley et al. 2002, Witt and Webster 2010).

Throughout its range, hemlock dominates many riparian forests (Young et al. 2002, Vose et al. 2013), influencing hydrologic processes and aquatic ecosystems. It is commonly associated with stream terrain features such as steep, northerly facing slopes and concave topography (coves) in mountainous regions (Young et al. 2002). Abundant hemlock in riparian corridors contributes to lower stream temperatures and creates woody debris inputs. Compared with deciduous species, stream shading by hemlock reduces summer daily temperature maxima and increases winter daily minima (Snyder et al. 2002), which favors cold-water fish species. In addition, benthic assemblages can be more diverse where water temperatures are thermally stable (Kamler 1965). Headwater streams draining stands where hemlock composed 25–77 percent of total basal area supported more taxa than those of hardwood forests (Snyder et al. 2002).

The ecohydrological importance of hemlock-dominated riparian forests can be seasonally influenced by disturbances that reduce hemlock leaf area in a deciduous landscape (Ford and Vose 2007, Brantley et al. 2013, 2014). As an evergreen, hemlock transpires year-round but at lower rates than deciduous associates (Catovsky et al. 2002) except in northernmost ranges where transpiration may be reduced during extremely cold winter periods (Hadley 2000). In the southern part of hemlock's range, riparian and cove hemlocks conduct approximately 50 percent of their annual transpiration during winter and spring (Ford and Vose 2007). Alternatively, potential transpiration from deciduous species is greater than hemlocks during the summer (Daley et al. 2007, Ford and Vose 2007, Brantley et al. 2013). Structurally, dense, multilayered hemlock canopies have a higher leaf area index and higher mean precipitation interception rates compared with deciduous species (Guswa and Spence 2011). The structural and transpirational characteristics of riparian hemlock stands can ameliorate the effects of extreme storm/flooding watershed events coinciding with winter and early spring deciduous dormancy (Brantley et al. 2014).

Since its introduction in the 1950s, HWA has spread 5–20 miles per year (Evans and Gregoire 2007, Morin et al. 2009), infesting hemlock in at least 18 states (USDA Forest Service 2010). Widespread decline and mortality typically occur within 4–10+ years (McClure 1991, Eschtruth 2006). Chemical HWA controls are not economically feasible at a landscape scale and biological controls have limited effectiveness (Vose et al. 2013). Widespread HWA-mortality causes permanent reductions in winter transpiration rates because of canopy replacement with deciduous species (Orwig and Foster 1998) or understory *Rhododendron* sp. (Brantley et al. 2014).

In a southern Appalachian watershed studied by Brantley et al. (2014), hemlock mortality contributed to permanent reductions in water yield and transient increases in peak flow during large-flow events. They found significant relationships between hemlock mortality and water yield where hemlock basal area was at least 6 percent of total forest cover and 26 percent was concentrated in riparian areas. Hence, as hemlock decline progresses, streams draining headwater catchments with at least 26 percent riparian hemlock basal area have potential for increased storm flow events. Mapping riparian hemlock concentrations could assist planning of mitigation strategies in watersheds with anticipated hemlock decline.

Management of forest stands with hemlock basal areas of ≥30 ft^2/ac are sufficiently stocked for silvicultural prescriptions (Lancaster 1985) focusing on reducing stand density to improve hemlock health under threat from HWA (Fajvan 2008, Ford Miniat et al. 2020). Because basal area is calculated directly from tree diameter, it is generally correlated with crown area (Stout and Nyland 1986), which can be estimated from remotely sensed satellite data. Forest inventory plots and spatial layers of ecological characteristics have been combined to create raster surfaces of tree species densities across landscapes (Ellenwood and Krist 2007, Nelson et al. 2009, Wilson et al. 2012, Ellenwood et al. 2015). These spatially explicit species estimates can be used for designing mitigation strategies of ecosystem processes threatened by forest pests.

Study Area: Hemlock in Subwatersheds of the Chesapeake Bay

The Chesapeake Bay Watershed (CBW) encompasses more than 44 million acres and is 55 percent forested (Horton 2003, Sprague 2006). The CBW includes parts of six states (Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia) and contains the largest estuary in the United States (Horton 2003). The bay is a highly productive ecosystem and extremely sensitive to forest cover changes (Claggett et al. 2004, Lister and Perdue 2011). Hemlock is more prevalent in the northern region of the CBW (Lister and Lister 2012) where HWA exists in isolated stands (USDA Forest Service 2015). Hemlock density specific to riparian areas in the CBW has not been previously quantified.

HWA mitigation strategies, such as planting supplemental conifer species (Faulkenberry et al. 2019), are being planned by the Pine Creek Watershed Council (Tioga, Potter, Lycoming Counties) in Pennsylvania, to maintain thermal refuges for naturally reproducing trout populations. Pine Creek is a subwatershed of the CBW and the second largest tributary of the West Branch Susquehanna River. The Pine Creek Watershed covers 981 square miles with 17 subbasins and a total of 1623 miles of streams. More than half of the land is publicly owned and approximately 93 percent is forested.

Our objectives are to use data from the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, spatially explicit hemlock density data, and geospatial hydrology data to (1) identify CBW subwatersheds with ≥6 percent mean hemlock basal areas and compare with hemlock percentages in their riparian zones; (2) quantify riparian zones in the identified CBW subwatersheds that contain ≥25 percent hemlock basal area to determine those zones most vulnerable to HWA impacts; (3) identify the location of CBW riparian stands with a significant hemlock component (containing ≥30 ft^2/ac hemlock basal area; previously defined as stocking threshold for management purposes) for HWA management purposes; and (4) use these techniques to map riparian hemlock stands in headwater tributaries of the Pine Creek Watershed. In objective 2, the ≥25 percent hemlock basal area threshold was based on the 26 percent riparian hemlock basal area concentrations found to impact hydrologic processes in HWA-disturbed hemlock stands (Brantley et al. 2014).

Methods

For the first part of our analyses, we used FIA inventories of forest attributes. FIA samples the United States based on a tessellation into hexagons of approximately 6,000 acres, containing at least one permanent plot (Bechtold and Patterson 2005). Eight, hydrologic unit code 8 (HUC8) subwatersheds where hemlock basal area was ≥6 percent of the total forest basal area were identified in the CBW according to the FIA plot data.

Secondly, we used two different raster data sets for a more spatially explicit examination of subwatershed basal areas and hemlock distribution relative to riparian areas. The major difference between the two modeled basal area layers is the resolution: 250 m versus 30 m. The 250 m resolution product was derived from moderate resolution imaging spectroradiometer (MODIS) (Justice et al. 1998) imagery. MODIS data images were collected during the 2001 to 2006 growing seasons (Wilson et al. 2012) to estimate hemlock basal area across the United States using a pixel size of 250 m (Figure 1). Geospatial data are publicly available in the Forest Service Research Data Archive (Wilson et al. 2013). The 30 m hemlock basal area surfaces were spatially derived using three-season Landsat imagery and modeled individually within US Geological Survey (USGS) National Land Cover Dataset mapping zones (Ellenwood et al. 2015) and are available upon request from the USDA Forest Health Assessment and Applied Sciences Team (Ellenwood and Krist 2007).

The two map products were created by applying a spatial model to a stack of geospatial layers including the FIA plots, satellite imagery, and other ecological variables, such as slope, aspect, and soil characteristics. Because basal area is correlated with crown area, it is also correlated with spectral forest characteristics measured with satellite-based sensors (Wilson et al. 2012). FIA full-cycle plot data ending in the year 2009 were used as model inputs and included trees ≥1 inch in diameter measured at breast height (dbh) (Wilson et al. 2013). Both modeled products (250 m and 30 m)[1] included accuracy assessments where species without adequate FIA samples for model parameterization were removed (Wilson et al. 2012, Ellenwood et al. 2015).

MODIS-based raster layers (250 m) of hemlock basal area (per acre), and the National Hydrography Dataset (NHD) (USGS 2016) were used to categorize total forest basal area, hemlock basal area, and percent hemlock basal area. The eight "high hemlock" HUCs were further examined according to geographic features associated within increasing distances from first-order and higher perennial streams (riparian zones) (Figure 2). These same data were buffered at 250 m and 500 m (inclusive) from streams and the mean percentage hemlock basal areas

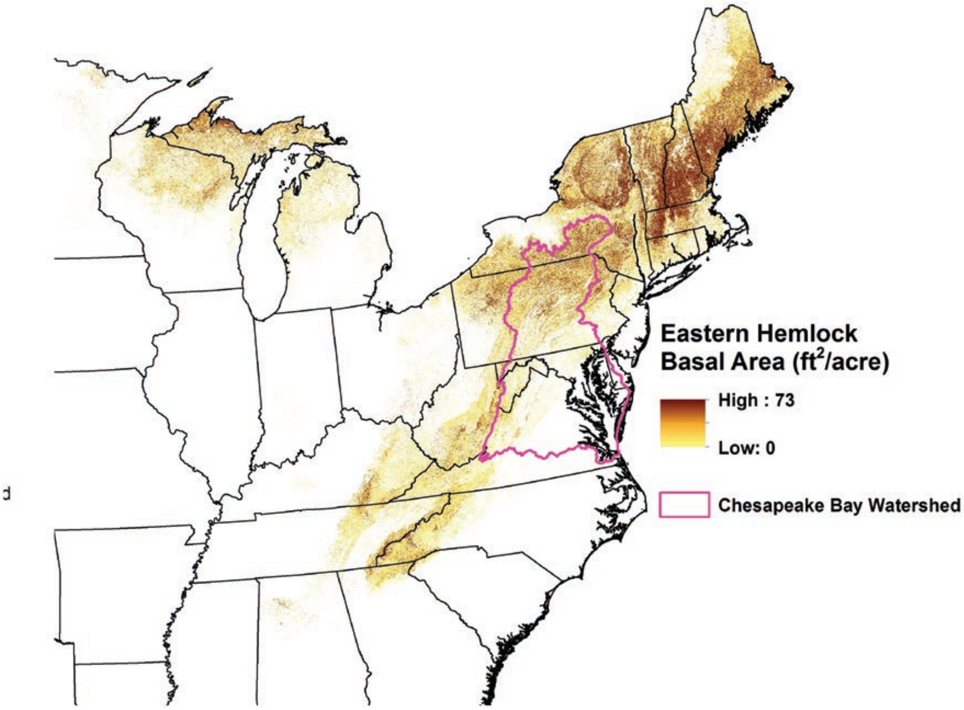

Figure 1. Percent eastern hemlock basal area from raster data modeled using 2009 Forest Inventory and Analysis plot data and a pixel size of 250 m (Wilson et al. 2012). Hemlock density within Chesapeake Bay Watershed is indicated.

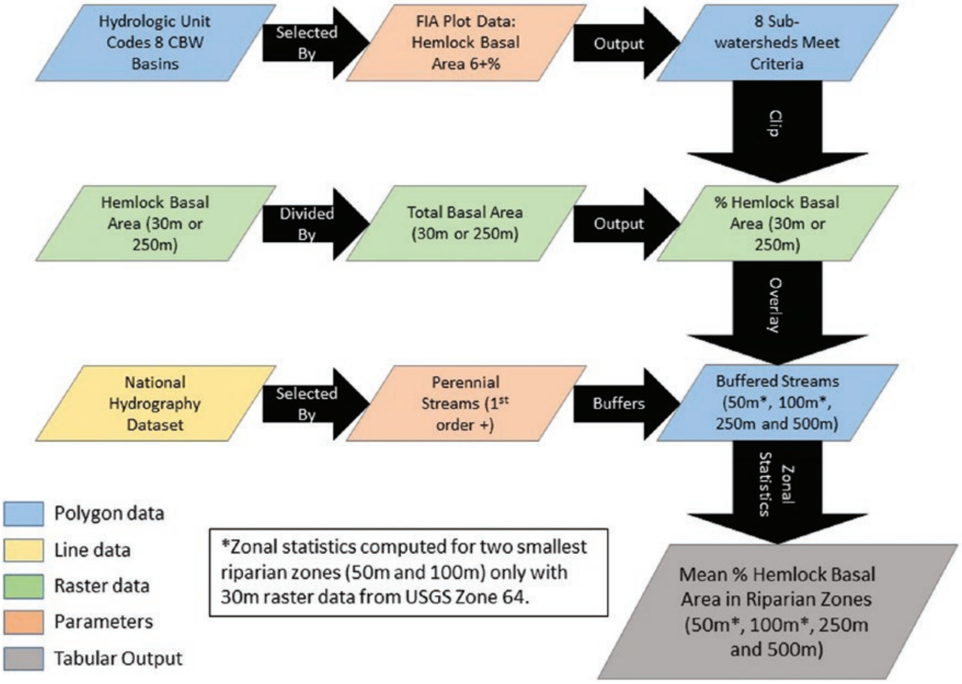

Figure 2. GIS procedure for estimating percent hemlock basal area per acre in riparian zones (50 m, 100 m, 250 m, 500 m) of Chesapeake Bay subwatersheds with at least 6 percent hemlock basal area. Raster layers of 250 m and 30 m were used to model basal area at two spatial scales.

(per acre) for these zones were calculated (Figure 2). Five-hundred meters was the maximum distance tested because of potential overlap with adjacent tributaries.

Five subwatersheds were further examined at a finer spatial resolution (30 m) to determine riparian zone sizes most likely to contain ≥25 percent hemlock basal area. Because the 30 m data are available for download for individual USGS mapping zones, we used zone 64, which contained the Pine Creek Watershed (for our case study) and four adjacent HUC8 subwatersheds. For these five subwatersheds, we used the interpolated raster layers to estimate hemlock basal area in riparian zones at four spatial scales. Perennial streams from the NHD were buffered at distances of 50, 100, 250, and 500 meters (Figure 2). We also compared riparian zone locations of forest patches containing hemlock basal areas of ≥30 ft^2/ac.

Results

Hemlock basal area in the CBW is concentrated in northern Pennsylvania and southern New York, where HWA has had minor impacts to date (USDA Forest Service 2015). Our study area is defined as the eight subwatersheds with mean percent hemlock basal areas from 6.2 to 10.2, which met the criteria of ≥6 percent (Figures 3 and 4). Mean percent hemlock basal area remained generally the same as riparian zone size increased from 250 m to 500 m and was similar to the overall average (Table 1).

For the five watersheds evaluated at 30 m resolution, the percentages of riparian zone pixels containing ≥25 percent hemlock basal area were always higher than mean percentages for the entire watershed (Table 2). The 50 m and 100 m riparian zones had higher percentages of pixels meeting these criteria and decreased as pixels in the 250 m and 500 m zones were included (Table 2, Figure 5). At 500 m, the percentages of pixels were similar to the overall averages for the watersheds.

Comparisons of riparian zones with mean hemlock basal areas ≥30 ft^2/ac did not show a similar pattern to percent basal area. Mean basal areas for each zone were very similar to the overall watershed mean (Table 3). Maximum total watershed hemlock basal areas ranged from 70 to 99 ft^2/ac, suggesting the presence of some overstocked stands. Mixed hemlock-hardwood stands can be considered fully to overstocked if there is at least 30 percent hemlock basal area of a total ranging from 140 to 200 ft^2/ac depending on mean stand diameter (Lancaster 1985).

Discussion

Natural resource managers typically integrate chemical, biological, and silvicultural applications to slow

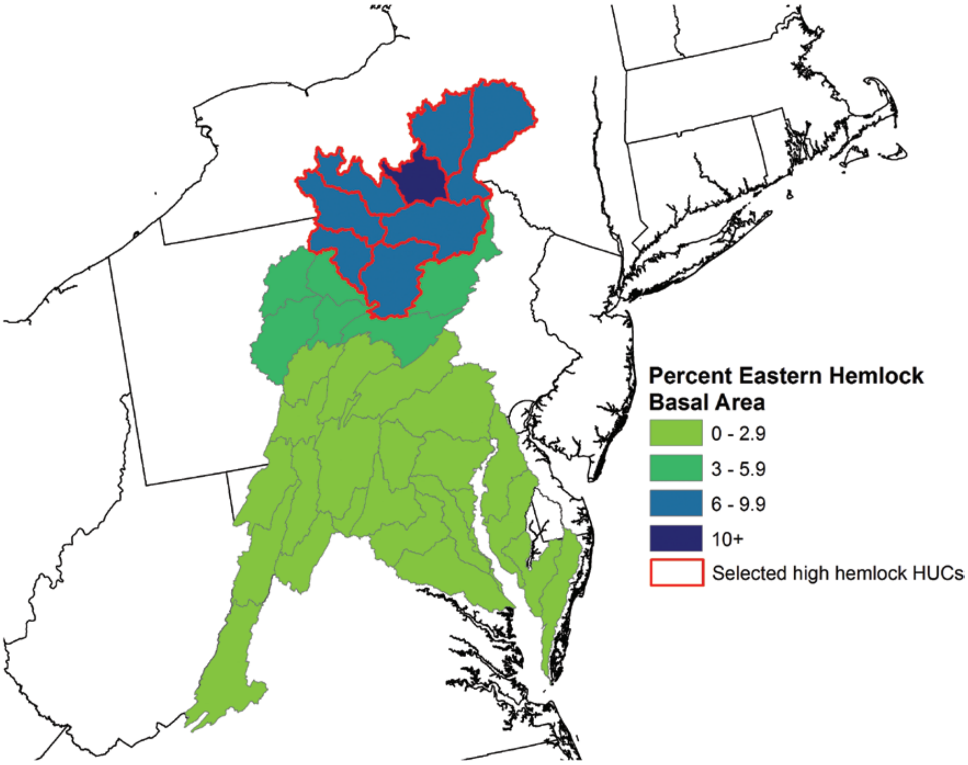

Figure 3. Percent eastern hemlock basal area per acre by hydrologic unit code 8 (HUC8) subwatersheds in Chesapeake Bay Watershed. The study area includes the eight subwatersheds outlined in red because each met the criteria of ≥6 percent hemlock basal areas as identified from Forest Inventory and Analysis plot data.

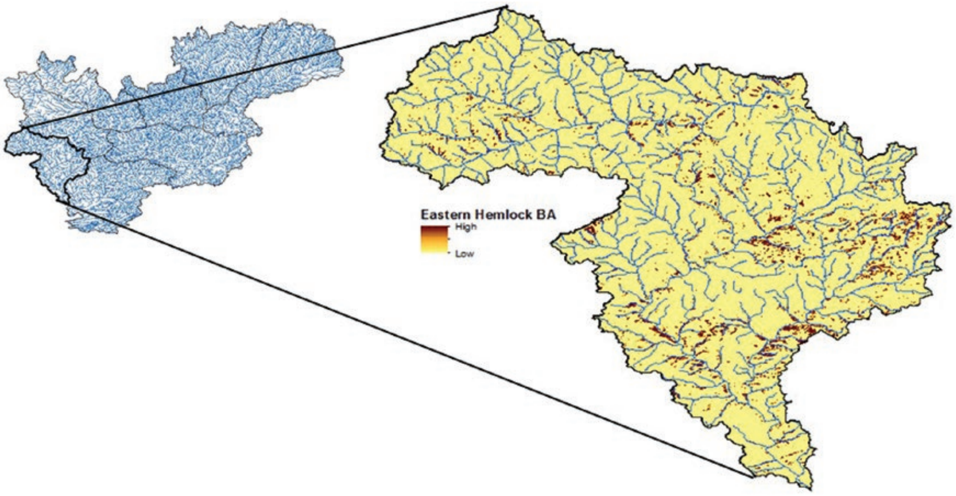

Figure 4. Perennial streams identified on the eight hydrologic unit code 8 (HUC8) subwatersheds with hemlock basal areas ≥6 percent. The mean percentage hemlock basal areas per acre for riparian zones were calculated (250 m resolution). Pine Creek Watershed displayed as example of mapping percent hemlock basal area in riparian zones (30 m resolution) ranging from high (≥25 percent) to low (zero).

Table 1. Mean basal areas per acre (BA) (±STD) for all species (total) and for hemlock in eight subwatersheds of the Chesapeake Bay evaluated at 250 m pixel resolution. Mean percent hemlock basal areas per acre (±STD) for entire subwatershed and two riparian buffer zones (inclusive).

			Percent Hemlock Basal Area		
Watershed	Total BA (ft^2/ac)	Hemlock BA (ft^2/ac)	Entire Watershed	250 m (820 ft)	500 m (1,640 ft)
Chemung	60.3 (35.9)	5.8 (8.6)	8.1 (9.7)	7.9 (9.6)	8.1 (9.7)
Chenango	67.6 (37.7)	7.3 (10.1)	9.2 (9.8)	9.3 (9.7)	9.2 (9.8)
Low West Branch Susquehanna	70.6 (42.6)	4.8 (7.5)	6.2 (8.2)	6.9 (8.6)	6.5 (8.4)
Owego-Wappasening	66.3 (36.6)	7.8 (9.9)	10.2 (10.5)	10.4 (10.8)	10.4 (10.6)
Pine Creek	94.7 (34.8)	5.9 (7.7)	6.5 (7.7)	6.5 (7.8)	6.3 (7.6)
Tioga	66.6 (38.1)	5.7 (7.8)	7.7 (9.0)	7.8 (9.3)	7.8 (9.1)
Upper Susquehanna	70.6 (37.8)	7.1 (9.4)	8.7 (9.3)	9.3 (9.5)	8.9 (9.4)
Upper Susquehana-Tunkhannock	64.1 (37.2)	5.8 (7.6)	8.6 (9.5)	8.6 (9.7)	8.6 (9.6)

Note: STD, standard deviation.

Table 2. Mean percentage of pixels containing ≥25 percent hemlock basal area for the five subwatersheds evaluated using 30 m pixel resolution. Pixels were evaluated for the entire watershed and four riparian buffer zones (inclusive).

Watershed	Total Watershed	50 m (164 ft)	100 m (328 ft)	250 m (820 ft)	500 m (1,640 ft)
Chemung	5.1	6.6	7.1	6.4	5.2
Owego-Wappasening	11.0	19.0	18.7	14.8	11.8
Pine Creek	5.3	12.3	11.1	8.3	6.3
Tioga	5.7	12.7	11.8	8.9	6.6
Upper Susquehana-Tunkhannock	12.9	22.6	21.5	17.3	14.0

HWA spread and reduce ecological impacts (Ford Miniat et al. 2020). HWA management efforts are easier to facilitate at the stand level (e.g., Pontius et al. 2010) and more challenging across land ownerships within the larger forested landscape of hemlock's range. We initially assessed the extent of hemlock abundance

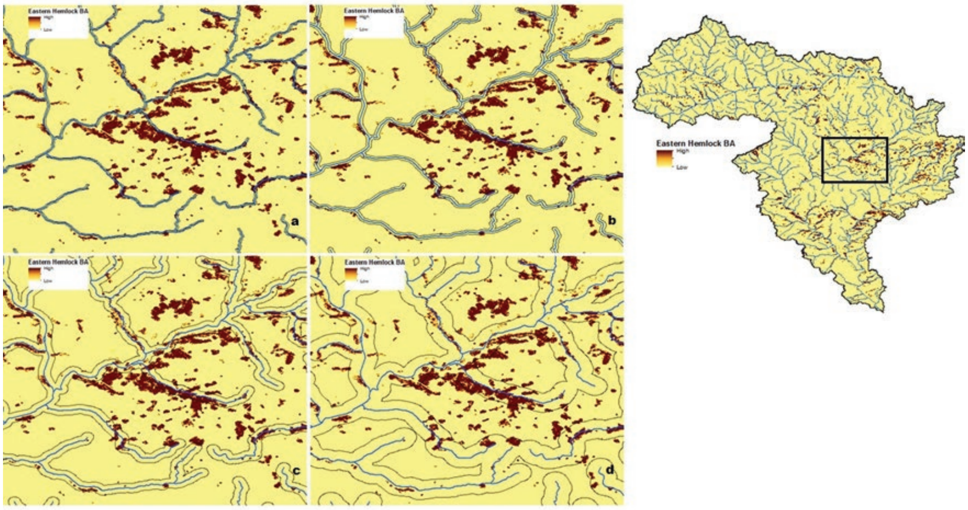

Figure 5. Hemlock basal area (30 m resolution) in riparian zones of the Pine Creek Watershed (from left to right): 50 m, 100 m, 250 m, and 500 m. For all five watersheds evaluated at this scale, the percentage of pixels with ≥25 percent basal area was concentrated within 100 m.

Table 3. Mean hemlock basal areas (±STD) for pixels containing ≥30 ft^2/ac in five subwatersheds evaluated using 30 m pixel resolution. Pixel were evaluated for the entire watershed and four riparian buffer zones (inclusive) using 30 ft^2/ac (minimum) and maximum values as indicated.

Watershed	Total Watershed	50 m (164 ft)	100 m (328 ft)	250 m (820 ft)	500 m (1,640 ft)
Chemung	35.9 (6.7)	35.8 (6.3)	35.8 (6.5)	35.6 (6.4)	35.9 (6.7)
Maximum	70	65	65	69	69
Owego-Wappasening	36.3 (7.0)	36.7 (7.4)	36.6 (7.3)	36.4 (7.1)	36.4 (7.1)
Maximum	89	89	89	89	89
Pine Creek	36.6 (7.4)	36.9 (7.5)	37.1 (7.7)	36.9 (7.7)	36.7 (7.5)
Maximum	79	73	77	77	77
Tioga	36.3 (7.1)	37.0 (7.5)	37.0 (7.4)	36.7 (7.3)	36.4 (7.0)
Maximum	79	69	75	75	75
Upper Susquehana-Tunkhannock	38.6 (8.8)	39.2 (9.0)	39.2 (9.1)	39.0 (9.0)	38.7 (8.8)
Maximum	99	82	88	99	99

Note: STD, standard deviation.

within the CBW by mapping species density at a broad landscape scale (250 m) (Wilson et al. 2013). Analysis of FIA data allowed us to identify subwatersheds with high overall hemlock densities. Further delineation of high hemlock concentrations in riparian areas was accomplished using existing remote sensing–based maps. Although some spatial detail was initially lost by using MODIS compared with Landsat data (250 m versus 30 m resolution), MODIS data allow users to efficiently produce maps of larger geographic areas with fewer cloud contamination issues (Nelson et al. 2009).

The first stage of the analyses used FIA plot data to identify hemlock densities in CBW subwatersheds that met the >6 percent basal area criteria. Results identified the eight most northern subwatersheds where HWA infestations are light (Sarah Johnson, pers. commun., PA Bureau of Forestry, 2017–2019 regional survey data), primarily because frequent colder minimum temperatures contribute to HWA population crashes (Evans and Gregoire 2007, Morin et al. 2009). However, temporal variations in annual HWA winter survival rates because of climate warming have accelerated its northward progression into New York and New England (USDA Forest Service 2015) where high hemlock densities (Figure 1) increases the urgency for management.

Other studies examining the influence of hemlock densities (≥25 percent basal area) on hydrologic processes focused on stand-level water budgets and did not examine hemlock density and distribution specific to riparian zones (Ford and Vose 2007, Brantley et al. 2014). We compared hemlock densities in zone sizes from 50 to 500 m at two spatial scales. At the finer spatial resolution (30 m), we detected higher hemlock densities within 100 m of streams. This zone is more likely to have negative HWA-caused hydrologic/ecological impacts and could be targeted for mitigation efforts. Depending on the watershed, there were some riparian hemlock clusters/stands with sufficient hemlock basal areas for silvicultural thinnings. Hemlock density reductions in fully to overstocked hemlock-hardwood stands increases sunlight to hemlock crowns (Fajvan 2008) and improves resistance to HWA (Ford Miniat et al. 2020).

The maps/data we provided to the Pine Creek Watershed Council were used to prioritize riparian areas for digital field reconnaissance of hemlock densities using ArcGIS Survey 123 (Esri 2019). A custom spatial vegetation smart form linking GPS information with forest inventory parameters was designed for data collection. The council is devising a protocol for proactive, supplemental riparian planting of other shade-tolerant conifers based on species recommendations from Pennsylvania's hemlock conservation plan (Faulkenberry et al. 2019). Their goal is to protect thermal refuges of native brook trout and other aquatic species and retain watershed ecological and economic values under threat from HWA.

Endnotes

1. The Landsat and MODIS sensors collect data at resolutions defined in term of meters. English conversions for the rest of the manuscript: 30 m = 98.4 ft; 50 m = 164.0 ft; 100 m = 328.1 ft; 250 m = 820.2 ft; 500 m = 1,640.4 ft.

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