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Mapping Host-Species Abundance of Three Major Exotic Forest Pests

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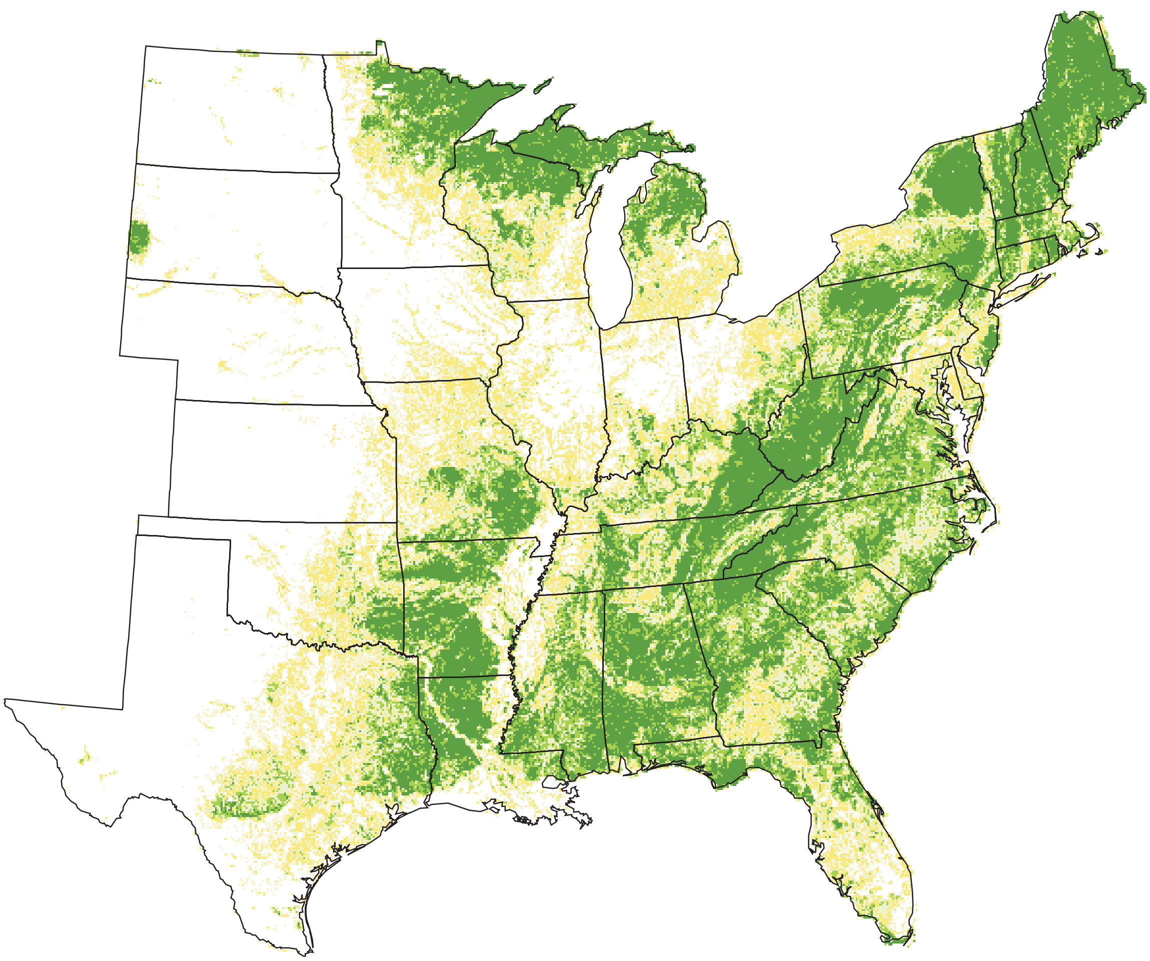

Abstract

Periodically over the last century, forests of the Eastern United States have been devastated by invasive pests. We used existing data to predict the geographical extent of future damage from beech bark disease (BBD), hemlock woolly adelgid (HWA), and gypsy moth. The distributions of host species of these alien pests were mapped in 1-km^2 cells by interpolating host basal area/ha from 93,611 forest-inventory plots in 37 states. The interpolated surfaces were adjusted for forest density (percent land cover) by multiplying values by an estimate of percent forest cover derived from existing land-cover maps (30-m^2 cells). According to our estimates, BBD currently occupies only about 27 percent of its potential range in land area, but has invaded more than 54 percent in total host density. HWA occupies nearly 26 percent of its potential range in land area, and about one-quarter in total host density. Gypsy moth occupies only 23 percent of its potential range in the Eastern United States, and only 26 percent in total host density.

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Cover: Map shows percent forest cover in the Eastern United States.

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Introduction

Invasion by exotic insects and diseases threatens the productivity and stability of forest ecosystems around the world (Liebhold et al. 1995a; Vitousak et al. 1996; Pimentel et al. 2000). Forests of the Eastern United States seem to be particularly vulnerable to these invasions. Over the last century, they have been devastated by forest pests such as beech bark disease, chestnut blight, and gypsy moth (Mattson 1997), with subsequent secondary adverse effects throughout the invaded ecosystems (Redman and Scriber 2000). Assessing the likelihood of future damage from specific exotic organisms (risk assessment) is an important initial step in developing effective strategies for managing alien species (Reichard and Hamilton 1997; Byers et al. 2002) both before and after their arrival in new habitats (Liebhold et al. 1995a). A risk assessment for an invasive species that has not yet been established typically comprises estimates of: 1) the probability of arrival and establishment; 2) the geographical extent of its future range; and 3) the likely ecological, economical, and sociological impacts.

Maps representing the geographic extent of estimated future disturbance caused by exotic pests are an important component of risk assessment (Rouget et al. 2002). Predictions of disturbance risk in forest ecosystems are often limited by a lack of data and/or predictive models for specific pest species. We developed statistical models for predicting the abundance of host species for beech bark disease, hemlock woolly adelgid, and gypsy moth. The three disturbance agents have become established in North America and currently are expanding their range. Estimates of host-species abundance would be useful for long-range planning to both manage populations and implement cultural practices that minimize damage. In addition, abundance maps can serve as base layers that are a critical component of the USDA Forest Service's National Risk Map (Lewis 2002).

Beech bark disease (BBD), also known as beech scale-*Nectria* canker, is an insect-fungus complex involving the beech scale insect (*Cryptococcus fagisuga*) and the exotic canker fungus *Nectria coccinea* var. *faginata* or the native *Nectria galligena* that kills or injures American beech (*Fagus grandifolia*) (Houston 1994). The disease results when the *Nectria* fungus infects the bark through feeding wounds caused by beech scale, which was introduced accidentally into Nova Scotia from Europe around 1900. BBD has since spread southwest into New England, New York, Pennsylvania, West Virginia (Manion 1991), Ohio, Michigan, North Carolina, and Tennessee. Fungal invasion occurs about 3 to 5 years after the scale insects are evident. Mortality often is extensive in the year that *Nectria* is observed, though some trees can survive for several years.

First observed in the United States in the 1950's in Virginia, hemlock woolly adelgid (HWA) is a destructive insect pest of forest and ornamental hemlock trees. In the Eastern United States, HWA feeds only on the foliage of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*Tsuga caroliniana*), a less common species found in isolated areas of the southern Appalachians. Heavy infestations have killed trees in as few as 4 years, though some trees have survived infestations for more than 10 years (McClure et al. 2001).

Widely acknowledged as the most destructive defoliating forest insect in the United States (Davidson et al. 1999; Sharov et al. 2002), the gypsy moth was introduced accidentally around 1868 near Boston, Massachusetts. Outbreaks occurred in that area about 10 years later (Liebhold et al. 1992). The range of gypsy moth has been expanding gradually. Defoliating populations typically are found 5 to 6 years following establishment in a new location (Liebhold et al. 1994; Sharov and Liebhold 1998). In North America, gypsy moth feed on more than 300 species of trees and shrubs. There is considerable variation in susceptibility to defoliation among tree species (Liebhold et al. 1995b). Species preferred most by gypsy moth are in the genera *Quercus, Populus*, and *Larix*.

Methods

The geographic distribution of suitable habitats for BBD, HWA, and gypsy moth were mapped by interpolation of host-species abundance estimated from 93,611 forest-inventory plots in 37 states. Interpolation is a mathematical procedure by which values are estimated at positions between known values. The data were extracted from the Eastwide Database (Table 1), which at the time the project was executed was the most recent available source of USDA Forest Service Forest Inventory and Analysis (FIA) data for the 37 states in the study (Hansen et al. 1993). For our purposes, "Eastern United States" is used to describe the 37 states in the Eastwide Database. Host abundance for BBD, HWA, gypsy moth was measured as basal area/ha of American beech, basal area/ha of eastern and Carolina hemlock, and total basal area/ha of preferred tree species, respectively. A host species was considered preferred by the gypsy moth if it was in the "high" preference class developed by Liebhold et al. (1995b); this class included 79 species.

We used the ordinary kriging procedure (Deutsch and Journel 1998) to interpolate a surface of basal area/ha for the host species of each disease or insect. Kriging is a geostatistical method that provides estimates for unsampled locations by computing weighted averages of sampled values from nearby locations (Isaaks and Srivistava 1989; Cressie 1993). The weights are determined on the basis of the semivariogram, a statistical model of the relationship between spatial autocorrelation and distance between pairs of sampled values. A detailed explanation of kriging is available at: http://www.cee.vt.edu/program_areas/environmental/teach/smprimer/kriging/kriging.html. We generated maps from the plot data by calculating kriged estimates on a grid of 1- by 1-km cells. The GSLIB software library (Deutsch and Journel 1998) was used in performing the variography and kriging.

Maps of forest susceptibility were then adjusted for forest density (percent forest cover). During the period of data collection, FIA plots were in effect located

Table 1.—Year and number of forest inventory plots in each of 37 states

State	Year	Number of plots
Alabama	1990	3,575
Arkansas	1995	3,090
Connecticut	1985	283
Delaware	1986	134
Florida	1995	3,822
Georgia	1997	5,789
Illinois	1998	1,586
Indiana	1986	1,976
Iowa	1990	636
Kansas	1994	1,548
Kentucky	1988	1,921
Louisiana	1991	2,233
Maine	1995	2,587
Maryland	1986	672
Massachussets	1985	371
Michigan	1993	9,933
Minnesota	1990	11,553
Mississippi	1994	2,960
Missouri	1989	4,664
Nebraska	1994	428
New Hampshire	1983	586
New Jersey	1987	251
New York	1993	2,850
North Carolina	1990	4,558
North Dakota	1995	265
Ohio	1991	1,587
Oklahoma	1993	862
Pennsylvania	1989	2,964
Rhode Island	1985	117
South Carolina	1993	3,358
South Dakota	1980	46
Tennessee	1999	2,348
Texas	1992	1,925
Vermont	1989	619
Virginia	1992	3,600
West Virginia	1989	2,491
Wisconsin	1996	5,423

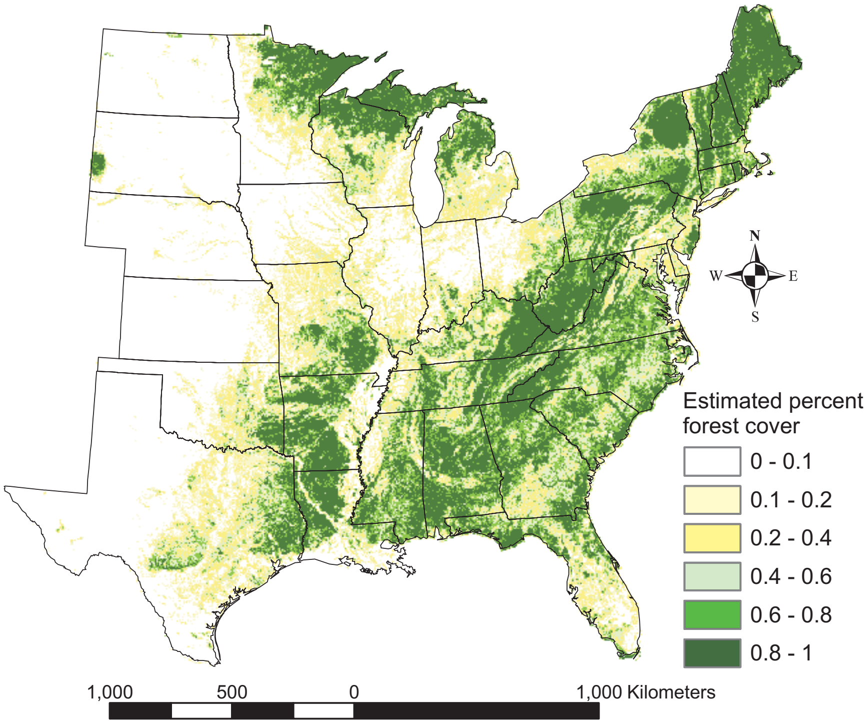

Figure 1.—Map of percent forest density from National Land Cover Data.

randomly, and tree data were collected only in forested areas. As a result, we had to adjust the estimates of host abundance in each cell for the proportion of the cell area that was forested. This was accomplished using a region-scale land-cover dataset (National Land Cover Data) acquired from the Multi-Resolution Land Characteristics Consortium as a raster matrix of 30- by 30-m cells that were placed into multiple land-cover classes (http://www.epa.gov/mrlc/nlcd.html) (Vogelmann et al. 2001). The data were aggregated to estimate percent forest cover for each 1- by 1-km cell (Fig. 1). A cell was considered forested if it was classified as deciduous, evergreen, mixed forest, or as forested wetland. Next, the kriged maps of host abundance were multiplied by the forest-density map (Fig. 1) to generate maps of forest susceptibility adjusted for percent forest cover.

When combined with current range maps, the host-density maps allow estimates of the current and potential ranges of BBD, HWA, and gypsy moth (Table 2). A 1-km^2 pixel was included in the estimates of land-area range if it was thought to contain host basal area.

Table 2.—Potential and current ranges and host densities of beech bark disease, hemlock woolly adelgid, and gyspy moth

Item	Beech bark disease	Hemlock woolly adelgid	Gypsy moth
Potential area of host habitat (km^2)	1,589,747	714,426	3,637,478
Current area of infested host habitat (km^2)	434,548	182,942	851,753
Proportion infested (%)	27.3	25.6	23.4
Potential density of host basal area (m^2)	606,734	522,653	10,331,781
Current density of host basal area (m^2)	348,311	128,425	2,685,118
Proportion infested (%)	57.4	24.6	26.0

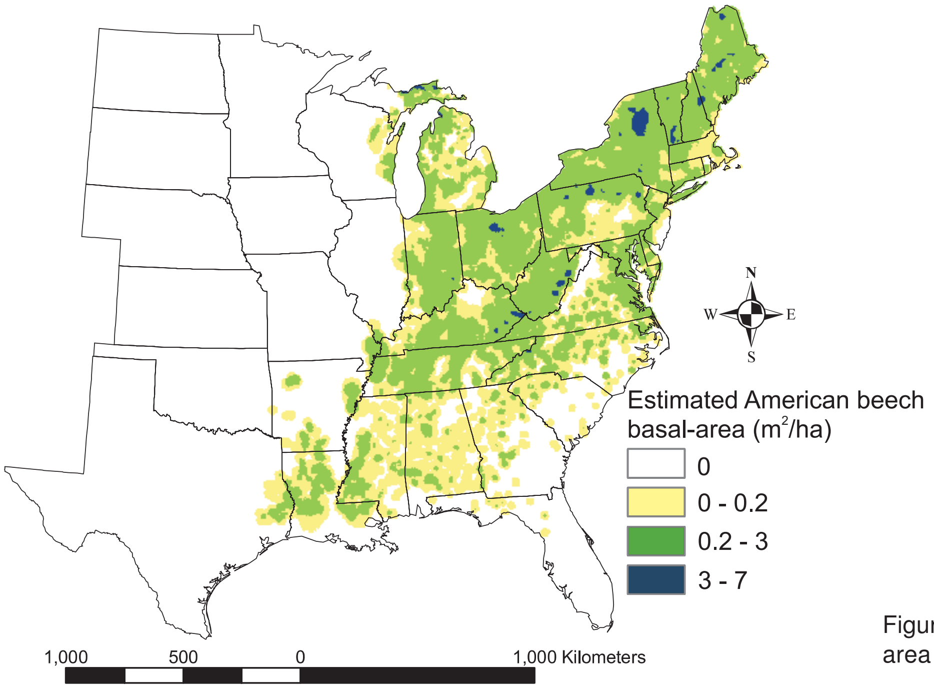

Figure 2.—Kriged map of estimated basal area of American beech.

Results

Beech Bark Disease

The basal area/ha of American beech was estimated (Fig. 2) and then multiplied by the forest-density map to create a map of beech abundance adjusted for forest density (Fig. 3). The greatest concentration of beech is in the Adirondack Mountain region of New York. There are smaller concentrations in Maine, New Hampshire, Vermont, West Virginia, and northern Pennsylvania. Beech also is found at low levels over a large range that extends through most of the forested regions of the Eastern United States. The current range of the beech scale insect is shown in Figure 4. Our estimates indicate that BBD currently occupies only about 27 percent of its potential range in land area, but already has invaded more than 54 percent of its potential area in total host density (Table 2).

Hemlock Woolly Adelgid

The basal area/ha of hemlock was estimated (Fig. 5) and then mulitiplied by the forest-density map to create a map of hemlock abundance adjusted for forest density (Fig. 6). Hemlock is distributed widely throughout the Northeast and the northern portions of Michigan and Wisconsin. Elsewhere, its distribution is limited to the higher elevations of the Appalachian Mountains. The current range of HWA is shown in Figure 7. Our estimates indicate that HWA currently occupies nearly 26 percent of its potential range land area and nearly 25 percent of its potential range in terms of total host density (Table 2).

Gypsy Moth

The basal area/ha of species preferred by gypsy moth was estimated (Fig. 8) and then was mulitiplied by the forest-density map to create a map of host species abundance adjusted for forest density (Fig. 9). Of the three disturbance agents, gypsy moth hosts were the most widely distributed. Also, maximum host densities (> 20 m^2/ha) were much higher than those of BBD and HWA. The current range of gypsy moth is shown in Figure 10. Our estimates indicate that gypsy moth currently occupies only 23 percent of its potential range in land area and only 26 percent of its potential range in total host density (Table 2).

Discussion

Planning forest pest management activities can be improved significantly with reliable mapped estimates of future disturbances. The methods and maps of host

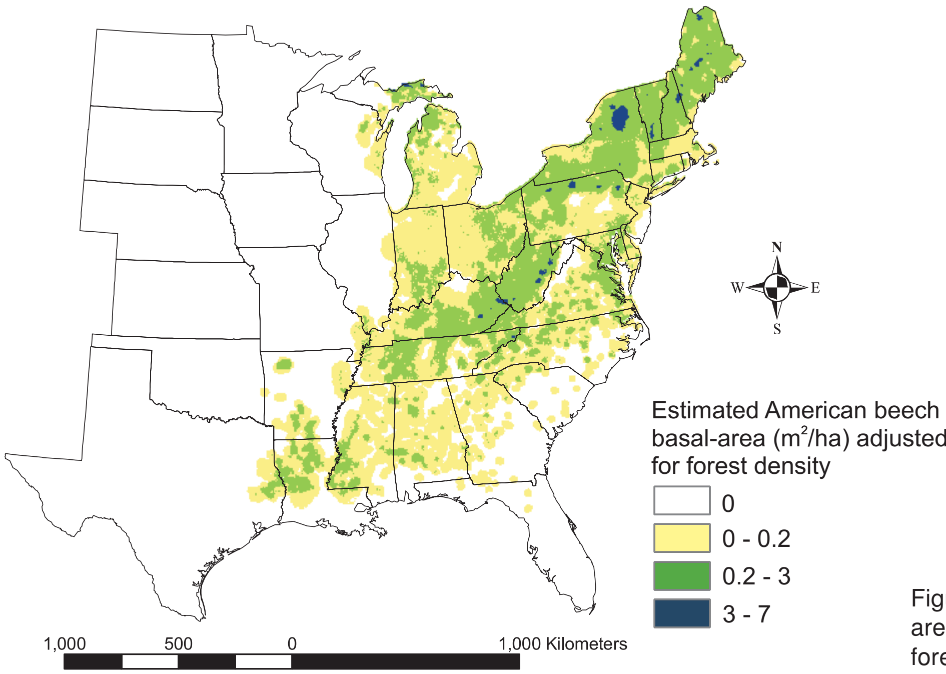

Figure 3.—Kriged map of estimated basal area of American beech adjusted for forest density.

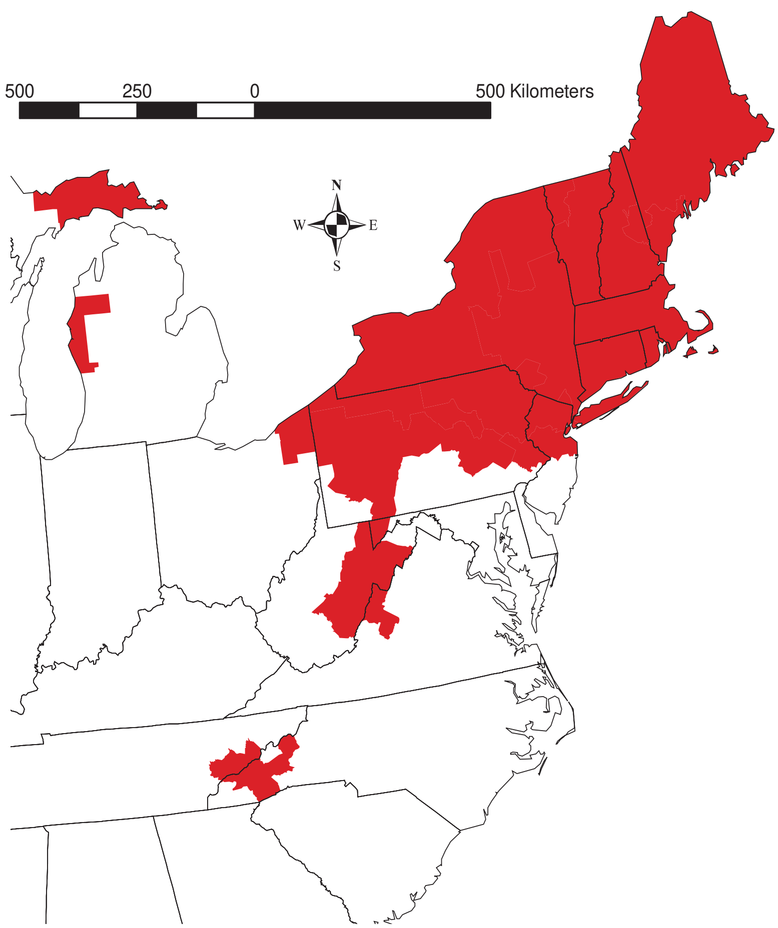

Figure 4.—Map of range of beech bark disease (2003).

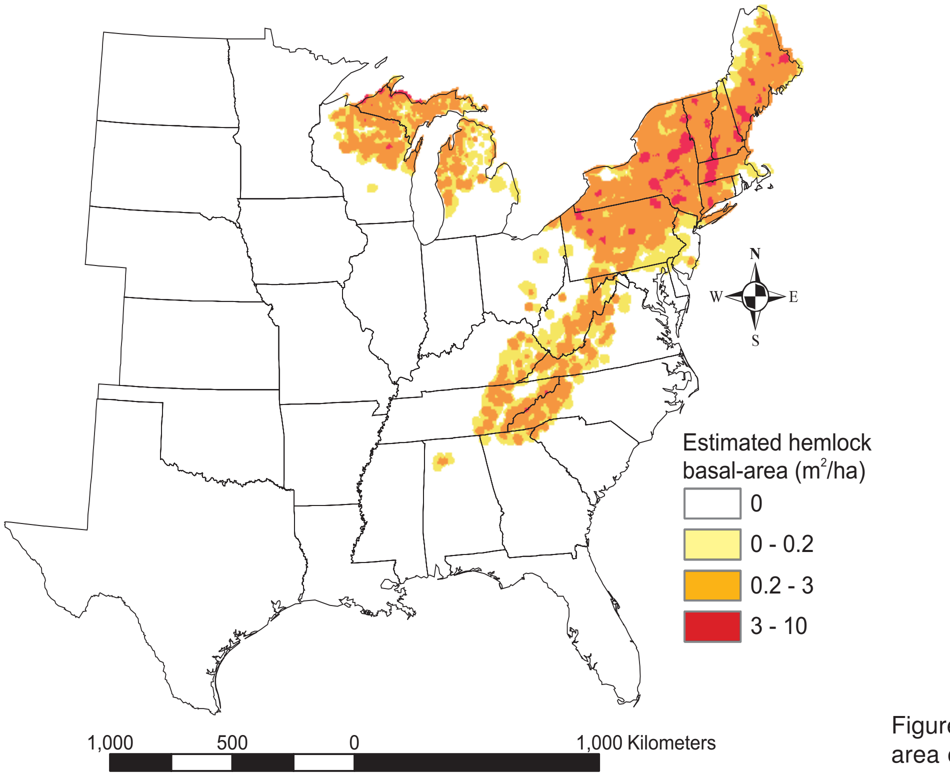

Figure 5.—Kriged map of estimated basal area of hemlock.

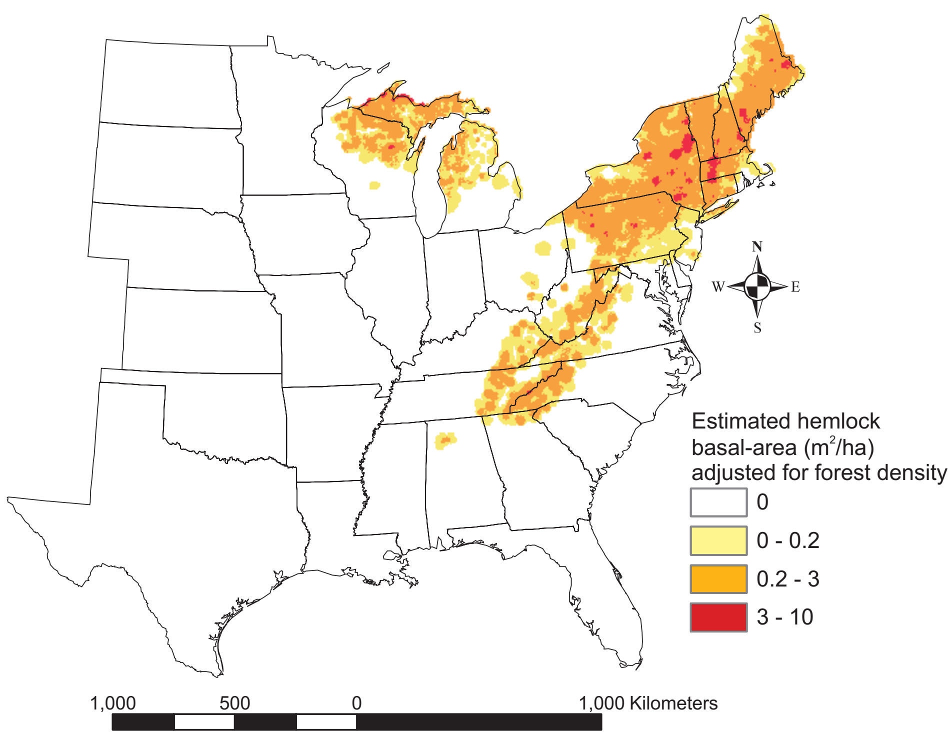

Figure 6.—Kriged map of estimated basal area of hemlock adjusted for forest density.

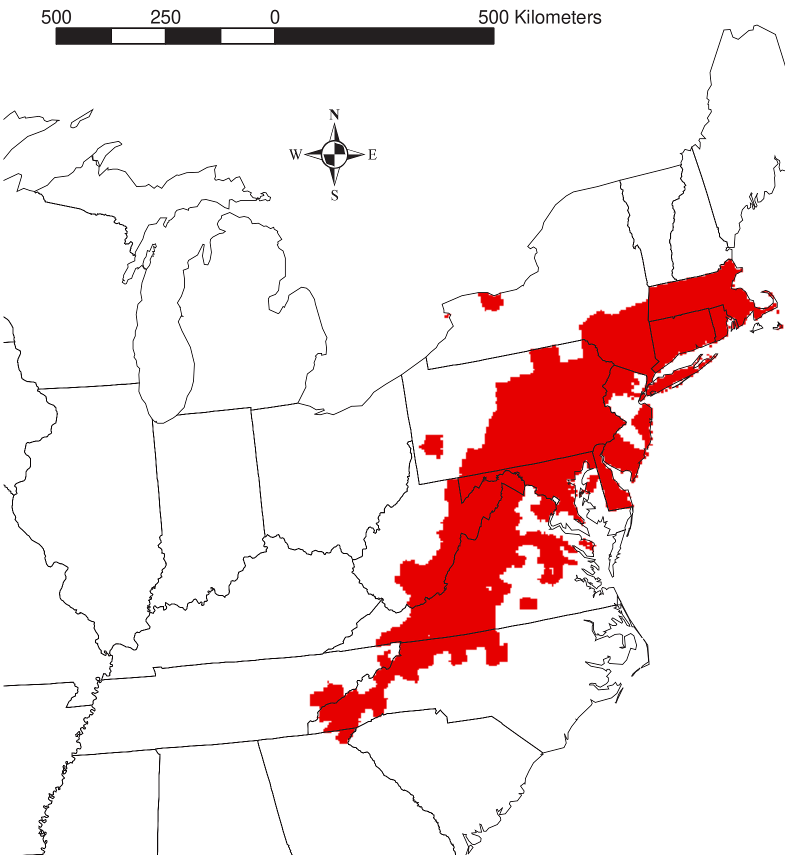

Figure 7.—Map of range of hemlock woolly adelgid (2003).

abundance described here should aid land managers in deciding where pest surveys should be conducted and silvicultural treatments should be located.

BBD has invaded areas with the greatest concentration of beech, though vast portions of the range of beech remain uninvaded. That beech is still abundant in many regions where BBD has already invaded illustrates that while significant mortality can occur, the disease generally does not eliminate all beech from stands (Houston 1994; Morin et al. 2001). Figure 3 highlights eastern Kentucky, northern Ohio, and northern Indiana as areas with the highest risk that are currently uninfested.

By contrast, HWA has invaded areas with a large component of hemlock only recently. Estimated hemlock abundance was highest in a large portion of New England, New York, and northern Pennsylvania (Fig. 6).

Gypsy moth is currently occupying less than one-quarter of its favorable habitat. Areas that have not been invaded by gypsy moth but have the highest densities of host species include the Ozark Mountains in Arkansas and Missouri, central Appalachians in Virginia, West Virginia, and North Carolina, and Wisconsin and northern Minnesota (Fig. 9).

A limitation that might affect the accuracy of our predictions is that while the abundance of host species is a major factor in determining susceptibility, it is not the only factor that determines vulnerability of a forest to a pest. For example, local site characteristics such as climate and soils (e.g. Houston and Valentine 1977) also can affect forest susceptibility. Another limitation concerns the geographic distribution of FIA plots. The FIA inventory data include sufficient spatial information with which to summarize these data by spatial units

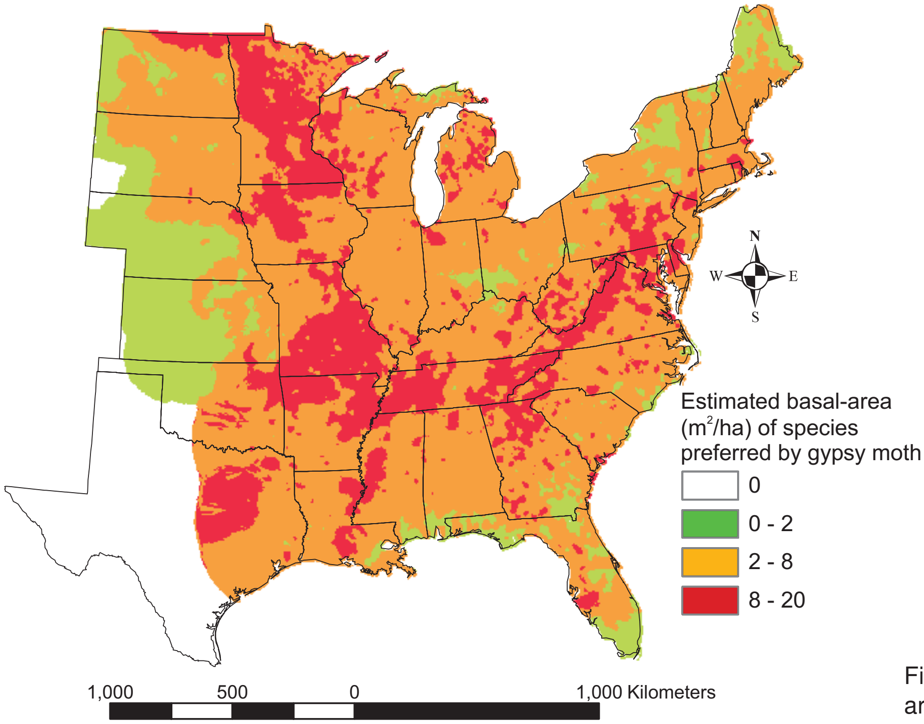

Figure 8.—Kriged map of estimated basal area of species preferred by gypsy moth.

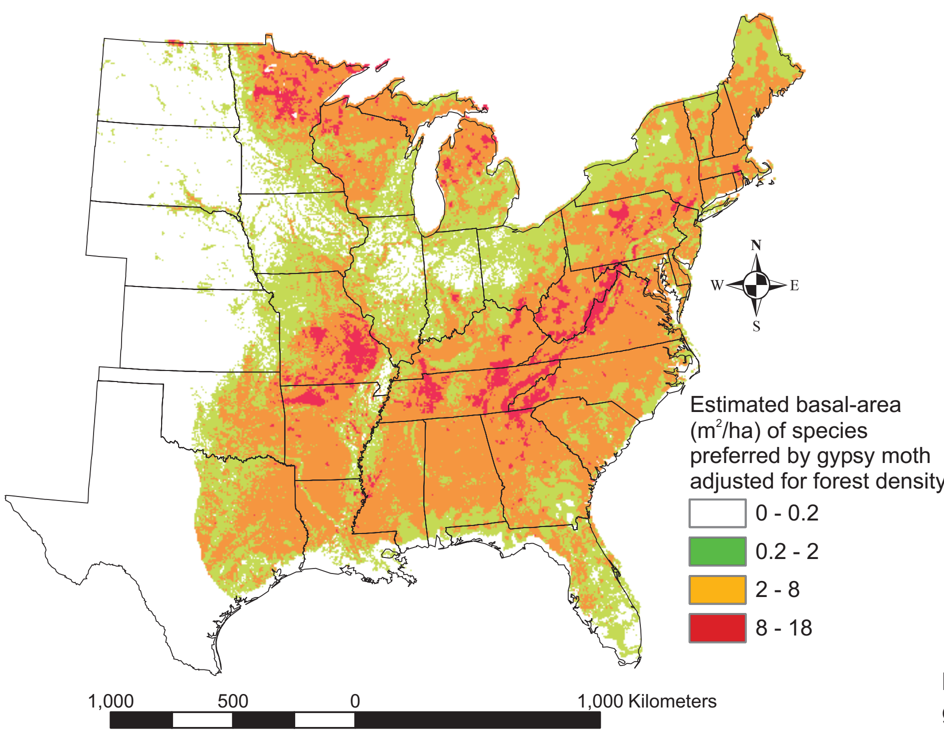

Figure 9.—Kriged map of estimated basal area of species preferred by gypsy moth adjusted for forest density.

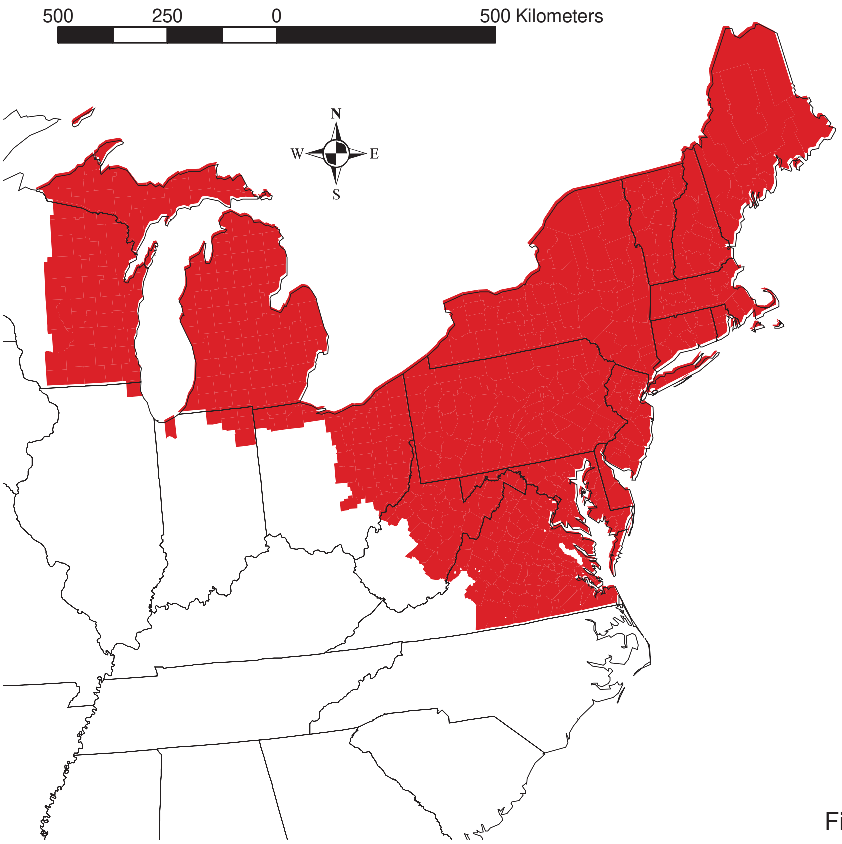

Figure 10.—Map of range of gypsy moth (2003).

smaller than counties (Hershey and Reese 1999). Although more than 93,000 plots were used to interpolate host density, plot data provide only a coarse resolution of geographic distribution of host trees. For example, fine-scale variations in aspect, slope position, elevation, and soil depth affect the location of a species within a specific area. The methodologies employed here thus represents a first approximation of the geographic distribution of pest risk and these methods can be elaborated in the future to generate improved estimates of forest risk to these and other pests.

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Keywords: Beech bark disease; hemlock woolly adelgid; gypsy moth

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