CHAPTER 2.

Large-Scale Patterns of Insect and Disease Activity in the Conterminous United States, Alaska, and Hawaii from the National Insect and Disease Survey, 2017

Kevin M. Potter
Jeanine L. Paschke
Frank H. Koch
Mark O. Zweifler

INTRODUCTION

Insects and diseases cause changes in forest structure and function, species succession, and biodiversity, which may be considered negative or positive depending on management objectives (Edmonds and others 2011). An important task for forest managers, pathologists, and entomologists is recognizing and distinguishing between natural and excessive mortality, a task that relates to ecologically based or commodity-based management objectives (Teale and Castello 2011). The impacts of insects and diseases on forests vary from natural thinning to extraordinary levels of tree mortality, but insects and diseases are not necessarily enemies of the forest because they kill trees (Teale and Castello 2011). If disturbances, including insects and diseases, are viewed in their full ecological context, then some amount can be considered "healthy" to sustain the structure of the forest (Manion 2003, Zhang and others 2011) by causing tree mortality that culls weak competitors and releases resources that are needed to support the growth of surviving trees (Teale and Castello 2011).

Analyzing patterns of forest insect infestations, disease occurrences, forest declines, and related biotic stress factors is necessary to monitor the health of forested ecosystems and their potential impacts on forest structure, composition, biodiversity, and species distributions (Castello and others 1995). Introduced nonnative insects and diseases, in particular, can extensively damage the biodiversity, ecology, and economy of affected areas (Brockerhoff and others 2006, Mack and others 2000). Few forests remain unaffected by invasive species, and their devastating impacts in forests are undeniable, including, in some cases, wholesale changes to the structure and function of an ecosystem (Parry and Teale 2011).

Examining insect pest occurrences and related stress factors from a landscape-scale perspective is useful, given the regional extent of many infestations and the large-scale complexity of interactions between host distribution, stress factors, and the development of insect pest outbreaks (Holdenrieder and others 2004, Liebhold and others 2013). One such landscape-scale approach is detecting geographic patterns of disturbance, which allows for the identification of areas at greater risk of significant ecological and economic impacts and for the selection of locations for more intensive monitoring and analysis.

METHODS

Data

Forest Health Protection (FHP) national Insect and Disease Survey (IDS) data (FHP 2018) consist of information from low-altitude aerial survey and ground survey efforts by FHP and partners in State agencies. These data can be used to identify forest landscape-scale patterns associated with geographic hot spots of forest insect and disease activity in the conterminous 48 States and to summarize insect and disease activity by ecoregion in Alaska (Potter 2012, 2013; Potter and Koch 2012; Potter and Paschke 2013, 2014, 2015a, 2015b, 2016, 2017;

Potter and others 2018) and by island in Hawaii (Potter and Paschke 2015b, 2017).

The IDS data identify areas of mortality and defoliation caused by insect and disease activity, although some important forest insects [such as emerald ash borer (*Agrilus planipennis*) and hemlock woolly adelgid (*Adelges tsugae*)], diseases [such as laurel wilt (*Raffaelea lauricola*), Dutch elm disease (*Ophiostoma novo-ulmi*), white pine blister rust (*Cronartium ribicola*), and thousand cankers disease (*Geosmithia morbida*)], and mortality complexes (such as oak decline) are not easily detected or thoroughly quantified through aerial detection surveys. Such pests may attack hosts that are widely dispersed throughout forests with high tree species diversity or may cause mortality or defoliation that is otherwise difficult to detect. A pathogen or insect might be considered a mortality-causing agent in one location and a defoliation-causing agent in another, depending on the level of damage to the forest in a given area and the convergence of other stress factors such as drought. In some cases, the identified agents of mortality or defoliation are actually complexes of multiple agents summarized under an impact label related to a specific host tree species (e.g., “beech bark disease complex” or “yellow-cedar decline”). Additionally, differences in data collection, attribute recognition, and coding procedures among States and regions can complicate data analysis and interpretation of the results.

In 2017, IDS surveys of the conterminous United States covered about 202.17 million ha, of which approximately 140.36 million ha were forested (about 55.1 percent of the total forested area of the conterminous States). A total of 161.87 million ha were surveyed using the new Digital Mobile Sketch Mapping (DMSM) approach (fig. 2.1), while an additional 52.29 million ha were surveyed in 2017 using the legacy Digital Aerial Sketch Mapping (DASM) approach. (These numbers exceed the total area surveyed because of overlaps in locations covered by the two methodologies.) In Alaska, roughly 5.94 million ha were surveyed in 2017, using the DMSM approach, of which 3.76 million ha were forested, about 7.3 percent of the total forested area of the State. For Hawaii, slightly >1 million ha were surveyed in 2017, with 530 500 ha forested, approximately 80.1 percent of the State’s total forested area.

Digital Mobile Sketch Mapping includes tablet hardware, software, and data support processes that allow trained aerial surveyors in light aircraft, as well as ground observers, to record forest disturbances and their causal agents. Digital Mobile Sketch Mapping is replacing the legacy DASM approach and will greatly enhance the quality and quantity of forest health data while improving safety by integrating with programs such as operational remote sensing (ORS), which uses satellite imagery to monitor disturbances in areas of higher aviation risk (FHP 2016). Geospatial data collected with DMSM and DASM are stored in the national Insect and Disease Survey (IDS) database. Digital Mobile Sketch Mapping includes both polygon geometry, used for damage areas where boundaries are discrete and obvious from the air,

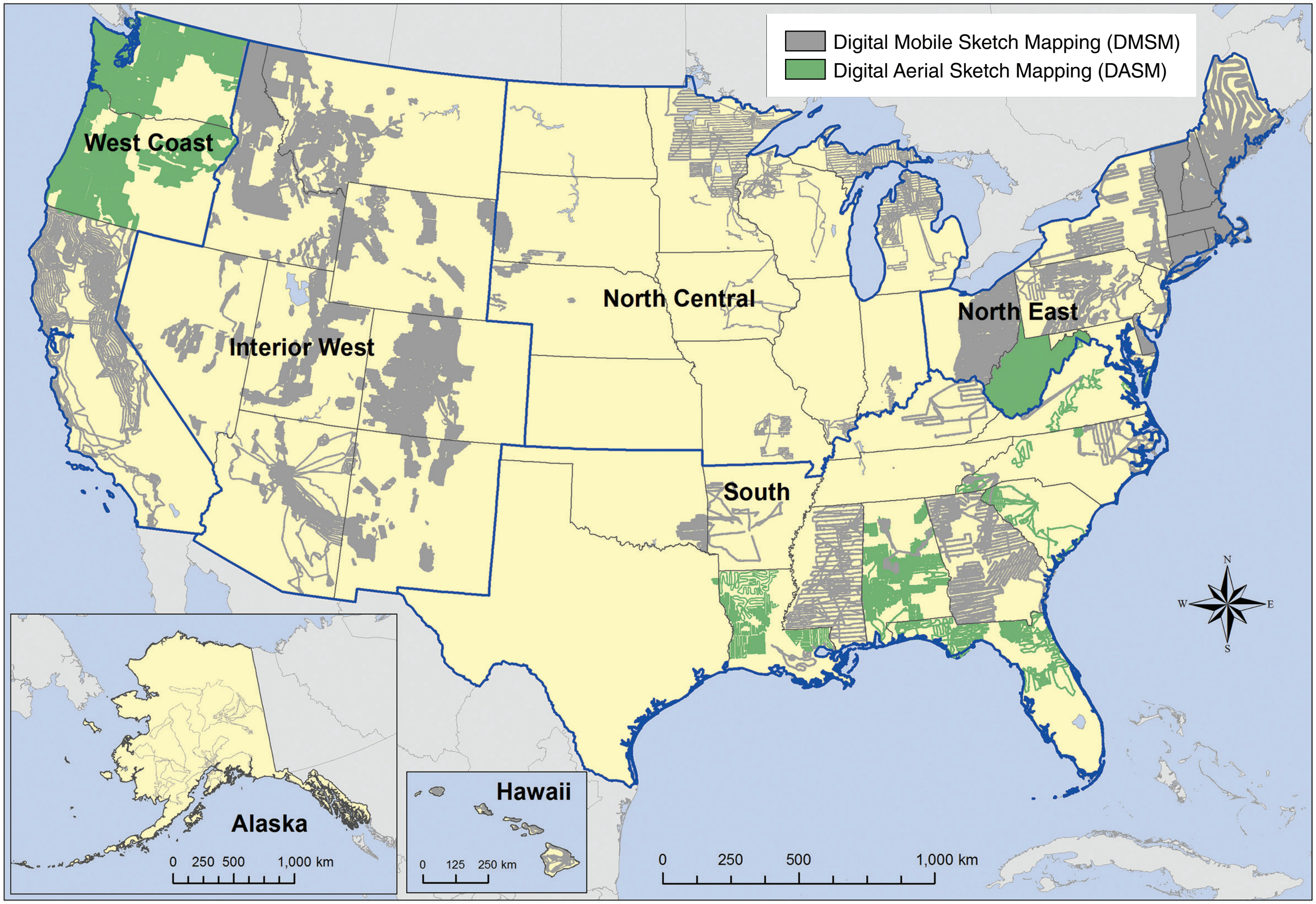


Figure 2.1—The extent of surveys for insect and disease activity conducted in the conterminous United States, Alaska, and Hawaii in 2017. Gray areas were surveyed using the new Digital Mobile Sketch Mapping (DMSM) platform, rather than the older Digital Aerial Sketch Mapping (DASM) approach, which is portrayed in green. The blue lines delineate Forest Health Monitoring regions. Note: Alaska and Hawaii are not shown to scale with map of the conterminous United States. For West Virginia, the survey was ground survey-based with assistance from remote sensing. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

and point geometry, used for small clusters of damage where the size and shape of the damage are less important than recording the location of damage, such as for sudden oak death, southern pine beetle (*Dendroctonus frontalis*), and some types of bark beetle damage in the West. For the 2017 data, most of the points that did not overlap with a damage polygon of the same type were assigned an area of 0.8 ha (about 2 acres). Additionally, DMSM allows for the use of grid cells (240-, 480-, 960-, or 1920-m resolution) to estimate the percent of trees affected by damages that may be widespread and diffuse, such as those associated with European gypsy moth (*Lymantria dispar dispar*) and emerald ash borer. For our analyses, the entire areas of these grid cells were used in summing damage areas (e.g., 240-m cell = 5.76 ha).

The 2017 mortality and defoliation polygons were used to identify the select mortality and defoliation agents and complexes causing damage on >5000 ha of forest in the conterminous United States in that year, and to identify and list the most widely detected mortality and defoliation agents for Alaska and mortality agents for Hawaii. Because of the insect and disease aerial sketch-mapping process (i.e., digitization of polygons by a human interpreter aboard the aircraft), all quantities are approximate “footprint” areas for each agent or complex, delineating areas of visible damage within which the agent or complex is present. Unaffected trees may exist within the footprint, and the amount of damage within the footprint is not reflected in the estimates of forest area affected. The sum of areas affected by all agents and complexes is not equal to the total affected area as a result of reporting multiple agents per polygon in some situations.

Analyses

As an indicator of the extent of damaging insect and disease agents, we summarized the percent of surveyed area with tree canopy cover exposed to mortality and defoliation separately for ecoregions within the conterminous 48 States and Alaska, and for islands in Hawaii. This required first separately dissolving the mortality and defoliation polygon boundaries to generate an overall footprint of each general type of disturbance, and then masking the dissolved polygons using a forest cover map (1-km resolution) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center (USDA Forest Service 2008). The same process was undertaken with the polygons of the surveyed area. For the conterminous States, percent of surveyed area with tree canopy cover exposed to mortality and defoliation was calculated within each of 190 ecoregion sections (Cleland and others 2007). Similarly, the mortality and defoliation data were summarized by ecoregion section in Alaska (Nowacki and Brock 1995). In Hawaii, the percent of surveyed forest affected by mortality or defoliation agents was calculated by island with the exception of the Big Island, where this information was summarized for each of eight county council districts to better assess the prevalence of rapid ‘ōhi‘a death. Statistics were not calculated for analysis regions in the

conterminous United States or Hawaii with <5 percent of the forest surveyed, nor in Alaska with <2.5 percent surveyed.

Additionally, we used the Spatial Association of Scalable Hexagons (SASH) analytical approach to identify surveyed forest areas in the conterminous 48 States with the greatest exposure to the detected mortality-causing and defoliation-causing agents and complexes (from data collected using both DMSM and DASM). This method identifies locations where ecological phenomena occur at greater or lower frequency than expected by random chance and is based on a sampling frame optimized for spatial neighborhood analysis, adjustable to the appropriate spatial resolution, and applicable to multiple data types (Potter and others 2016). Specifically, it consists of dividing an analysis area into scalable equal-area hexagonal cells within which data are aggregated, followed by identifying statistically significant geographic clusters of hexagonal cells within which mean values are greater or less than those expected by chance. To identify these clusters, we employed a Getis-Ord (G_i*) hot spot analysis (Getis and Ord 1992) in ArcMap® 10.3 (ESRI 2015). We conducted two sets of hot spot analyses for both mortality-causing and defoliation-causing agents: one nationally, and one for each of the five Forest Health Monitoring (FHM) regions within the continental United States (West Coast, Interior West, North Central, North East, and South).

The units of analysis were 9,810 hexagonal cells, each approximately 834 km^2 in area, generated in a lattice across the conterminous United States using intensification of the Environmental Monitoring and Assessment Program (EMAP) North American hexagon coordinates (White and others 1992). These coordinates are the foundation of a sampling frame in which a hexagonal lattice was projected onto the conterminous United States by centering a large base hexagon over the region (Reams and others 2005, White and others 1992). This base hexagon can be subdivided into many smaller hexagons, depending on sampling needs, and serves as the basis of the plot sampling frame for the Forest Inventory and Analysis (FIA) program (Reams and others 2005). Importantly, the hexagons maintain equal areas across the study region regardless of the degree of intensification of the EMAP hexagon coordinates. In addition, the hexagons are compact and uniform in their distance to the centroids of neighboring hexagons, meaning that a hexagonal lattice has a higher degree of isotropy (uniformity in all directions) than does a square grid (Shima and others 2010). These are convenient and highly useful attributes for spatial neighborhood analyses. These scalable hexagons also are independent of geopolitical and ecological boundaries, avoiding the possibility of different sample units (such as counties, States, or watersheds) encompassing vastly different areas (Potter and others 2016). We selected hexagons 834 km^2 in area because this is a manageable size for making monitoring and management decisions in analyses that are national in extent (Potter and others 2016).

We used a different variable for this set of hot spot analyses than in previous reports, when we focused on the percentage of area with tree canopy cover in each hexagon exposed to either mortality-causing or defoliation-causing agents, based on the footprints of these disturbances. With the transition from the DASM to the DMSM data collection approach, the hot spot analyses need to account for the existence of three types of data: point geometry, polygon geometry, and grid cells (see above). We therefore used a point sampling approach that estimates the number of mortality or defoliation point occurrences per 100 km^2 of tree canopy coverage area within each hexagon. For this estimation, point detections remained as point occurrences. Polygons (including grid cells) were clipped by 240-m tree canopy cover data and converted from multipart to singlepart geometry. We derived the tree canopy cover data from a 30-m raster dataset that provides an estimate of the percent tree canopy cover (from 0 to 100 percent) for each grid cell and was generated from the 2011 National Land Cover Database (Homer and others 2015) through a cooperative project between the Multi-Resolution Land Characteristics Consortium and the Forest Service Geospatial Technology and Applications Center (Coulston and others 2012). For our purposes, we treated any cell with >0 percent tree canopy cover as forest. The mortality and defoliation polygons, after clipping by the tree canopy data, were then separated into two groups: small polygons <5.76 ha in area (the size of the smallest resolution [240-m] DMSM grid cells), and large polygons ≥5.76 ha in area. For the small polygons, we extracted the centroid points for each. For the large polygons, we employed a zonal statistics analysis to determine the number of 240-m tree canopy grid cells (i.e., center points) contained within each polygon, after we intersected them with the 834-km^2 hexagons. The zonal statistics approach has the additional advantage of accounting for overlapping polygons; that is, it can iteratively calculate the number of tree canopy grid center points contained within each of any number of stacked mortality or defoliation polygons. The three types of resulting point occurrence data (from the original point detections, from the centroids of the small polygons, and from the 240-m tree canopy grid center points from the large polygons) were added together for each hexagon, with the sum of mortality and defoliation point occurrences divided by the total tree canopy coverage area present in the hexagon.

The Getis-Ord G_i* statistic was then used to identify clusters of hexagonal cells in which the density of occurrences of mortality- or defoliation-causing insects and diseases was higher than expected by chance. This statistic allows for the decomposition of a global measure of spatial association into its contributing factors, by location, and is therefore particularly suitable for detecting instances of nonstationarity in a dataset, such as when spatial clustering is concentrated in one subregion of the data (Anselin 1992).

The Getis-Ord G_i* statistic for each hexagon summed the differences between the mean

values in a local sample, determined by a moving window consisting of the hexagon and its 18 first- and second-order neighbors (the 6 adjacent hexagons and the 12 additional hexagons contiguous to those 6) and a global mean. Our first analysis encompassed a global mean of all the forested hexagonal cells in the conterminous 48 States, while we conducted another set of analyses separately within each of the five FHM regions. The G_i* statistic was standardized as a *z*-score with a mean of 0 and a standard deviation of 1, with values >1.96 representing significant (p <0.025) local clustering of high values and values <-1.96 representing significant clustering of low values (p <0.025), since 95 percent of the observations under a normal distribution should be within approximately two (exactly 1.96) standard deviations of the mean (Laffan 2006). In other words, a G_i* value of 1.96 indicates that the local mean of the percentage of forest exposed to mortality-causing or defoliation-causing agents for a hexagon and its 18 neighbors is approximately two standard deviations greater than the mean expected in the absence of spatial clustering, while a G_i* value of -1.96 indicates that the local mortality or defoliation mean for a hexagon and its 18 neighbors is approximately two standard deviations less than the mean expected in the absence of spatial clustering. Values between -1.96 and 1.96 have no statistically significant concentration of high or low values. In other words, when a hexagon has a G_i* value between -1.96 and 1.96, mortality or defoliation damage within it and its 18 neighbors is not statistically different from a normal expectation. As described in Laffan (2006), it is calculated as

$$G_i^*\left(\boldsymbol{d}\right)=\frac{\sum_j w_{ij}(d)\,x_j - W_i^* \bar{x}^*}{s^*\sqrt{\dfrac{(ns^*_{1i})-W_i^{*2}}{n-1}}}$$

where

G_i* = the local clustering statistic (in this case, for the target hexagon)

i = the center of local neighborhood (the target hexagon)

d = the width of local sample window (the target hexagon and its first- and second-order neighbors)

x_j = the value of neighbor j

w_{ij} = the weight of neighbor j from location i (all the neighboring hexagons in the moving window were given an equal weight of 1)

n = number of samples in the dataset (the 9,810 hexagons)

W_i^* = the sum of the weights

s^*_{1i} = the number of samples within d of the central location (19: the focal hexagon and its 18 first- and second-order neighbors)

$\bar{x}^*$ = mean of whole dataset (in this case, for all 9,810 hexagons)

s^* = the standard deviation of whole dataset (for all 9,810 hexagons)

It is worth noting that the -1.96 and 1.96 threshold values are not exact because the correlation of spatial data violates the assumption of independence required for statistical significance (Laffan 2006). The Getis-Ord approach does not require that the input data be normally distributed because the local G_i^* values are computed under a randomization assumption, with G_i^* equating to a standardized *z*-score that asymptotically tends to a normal distribution (Anselin 1992). The *z*-scores are reliable, even with skewed data, as long as the distance band used to define the local sample around the target observation is large enough to include several neighbors for each feature (ESRI 2015).

The low density of survey data in 2017 from Alaska and the small spatial extent of Hawaii (fig. 2.1) precluded the use of Getis-Ord G_i^* hot spot analyses for these States.

RESULTS AND DISCUSSION

Conterminous United States Mortality

The national IDS survey data identified 63 different mortality-causing agents and complexes on approximately 3.27 million ha across the conterminous United States in 2017, similar to the combined land area of Massachusetts and Connecticut. By way of comparison, forests are estimated to cover approximately 252 million ha of the conterminous 48 States (Smith and others 2009). Twenty-three of the agents were detected on >5000 ha.

Emerald ash borer was the most widespread mortality agent in 2017, identified on 1.42 million ha (table 2.1). Four other mortality agents and complexes were detected on >100 000 ha: fir engraver (*Scolytus ventralis*) on 959 000 ha, western pine beetle (*D. brevicomis*) on 185 000 ha, mountain pine beetle (*D. ponderosae*) on 165 000 ha, and spruce beetle (*D. rufipennis*) on 157 000 ha. Mortality from the western bark beetle group, which encompasses 19 different agents in the IDS data (table 2.2), was detected on approximately 1.61 million ha in 2017, representing about half the total area on which mortality was recorded across the conterminous States.

The FHM North Central region had the largest area on which mortality agents and complexes were detected, about 1.54 million ha (table 2.3). Almost all of this area (1.41 million ha, or 91 percent of the total) was exposed to emerald ash borer mortality. Eighteen other mortality-causing agents and complexes were recorded, with the most widespread being eastern larch beetle (*D. simplex*) (5.6 percent of the mortality area), oak decline (1.3 percent), and beech bark disease complex (0.7 percent). As a result of emerald ash borer infestation, 24.1 percent of the surveyed forest in the 222K–Southwestern Great Lakes Morainal ecoregion section (along the western shore of Lake Michigan in Wisconsin and Illinois), and 14.2 percent of the neighboring 222L–North Central U.S. Driftless and Escarpment, were exposed to mortality (fig. 2.2). A geographic hot spot of extremely

Table 2.1—Mortality agents and complexes affecting more than 5000 ha in the conterminous United States during 2017

Agents/complexes causing mortality, 2017	Area
	ha
Emerald ash borer	1 424 453
Fir engraver	959 223
Western pine beetle	185 153
Mountain pine beetle	165 459
Spruce beetle	156 911
Eastern larch beetle	86 504
Douglas-fir beetle	85 637
Jeffrey pine beetle	55 337
Western balsam bark beetle	34 774
Unknown	27 722
Unknown bark beetle	24 284
Oak decline	21 186
Root disease and beetle complex	21 163
Balsam woolly adelgid	20 758
Southern pine beetle	13 788
Beech bark disease complex	12 222
Ips engraver beetles	10 760
Oak wilt	9573
Flatheaded fir borer	9240
Pinyon ips	8905
Flatheaded borer	7394
California fivespined ips	7020
Sudden oak death	6335
Other (40)	24 888
Total, all mortality agents	**3 266 598**

Note: All values are "footprint" areas for each agent or complex. The sum of the individual agents is not equal to the total for all agents due to the reporting of multiple agents per polygon.

Table 2.2—Beetle taxa included in the "western bark beetle" group

Western bark beetle mortality agents	
Common name	Scientific name
California fivespined ips	*Ips paraconfusus*
Cedar and cypress bark beetles	*Phloeosinus* spp.
Douglas-fir beetle	*Dendroctonus pseudotsugae*
Douglas-fir engraver	*Scolytus unispinosus*
Fir engraver	*Scolytus ventralis*
Flatheaded borer	Family Buprestidae
Ips engraver beetles	*Ips* spp.
Jeffrey pine beetle	*Dendroctonus jeffreyi*
Mountain pine beetle	*Dendroctonus ponderosae*
Pine engraver	*Ips pini*
Pinyon ips	*Ips confuses*
Root disease and beetle complex	N/A
Roundheaded pine beetle	*Dendroctonus adjunctus*
Silver fir beetle	*Pseudohylesinus sericeus*
Spruce beetle	*Dendroctonus rufipennis*
Unknown bark beetle	N/A
Western balsam bark beetle	*Dryocoetes confuses*
Western cedar bark beetle	*Phloeosinus punctatus*
Western pine beetle	*Dendroctonus brevicomis*

Table 2.3—The top five mortality agents or complexes for each Forest Health Monitoring region, and for Alaska and Hawaii, in 2017

Mortality agents and complexes, 2017	Area
	ha
Interior West	
Spruce beetle	152 625
Douglas-fir beetle	42 360
Fir engraver	42 055
Western balsam bark beetle	24 387
Unknown bark beetle	22 954
Other mortality agents (15)	59 732
Total, all mortality agents and complexes	**338 820**
North Central	
Emerald ash borer	1 408 766
Eastern larch beetle	86 504
Oak decline	20 556
Beech bark disease complex	11 490
Oak wilt	9561
Other mortality agents (14)	8327
Total, all mortality agents and complexes	**1 542 611**
North East	
Emerald ash borer	10 346
Unknown	6053
Gypsy moth	4954
Southern pine beetle	3230
Balsam woolly adelgid	2680
Other mortality agents (13)	4290
Total, all mortality agents and complexes	**31 497**

Mortality agents and complexes, 2017	Area
	ha
South	
Southern pine beetle	10 558
Ips engraver beetles	7487
Emerald ash borer	5341
Unknown	1700
Unknown bark beetle	139
Other mortality agents (4)	85
Total, all mortality agents and complexes	**25 309**
West Coast	
Fir engraver	917 168
Western pine beetle	182 265
Mountain pine beetle	146 312
Jeffrey pine beetle	55 269
Douglas-fir beetle	43 277
Other mortality agents (23)	88 219
Total, all mortality agents and complexes	**1 328 361**
Alaska	
Spruce beetle	164 281
Yellow-cedar decline	19 188
Northern spruce engraver	2428
Unknown	39
Western balsam bark beetle	16
Total, all mortality agents and complexes	**185 951**
Hawaii	
Unknown	30 320
Total, all mortality agents and complexes	**30 320**

Note: The total area affected by other agents is listed at the end of each section. All values are "footprint" areas for each agent or complex. The sum of the individual agents is not equal to the total for all agents due to the reporting of multiple agents per polygon.

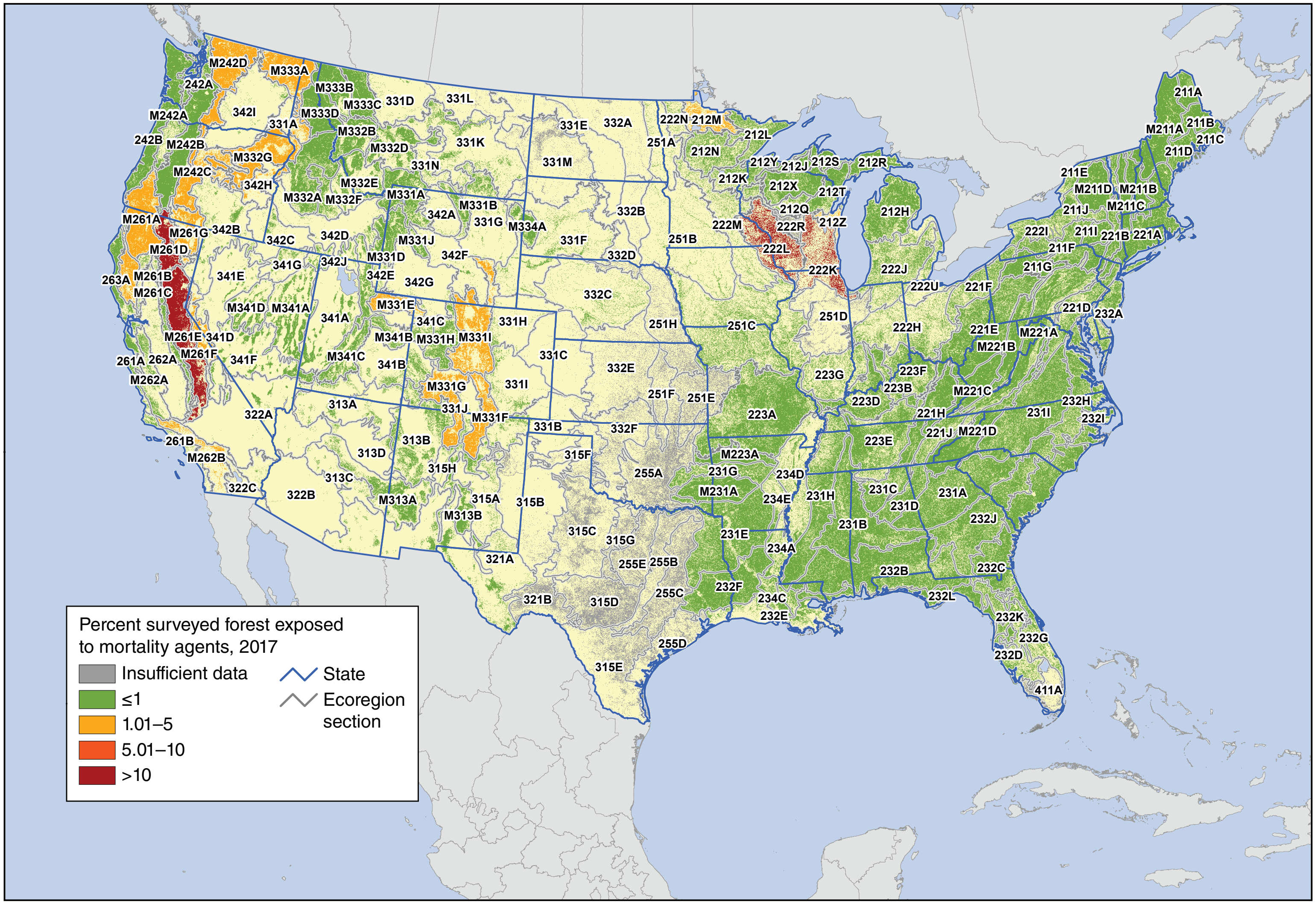


Figure 2.2—The percent of surveyed forest exposed to mortality agents, by ecoregion section within the conterminous 48 States, for 2017. The gray lines delineate ecoregion sections (Cleland and others 2007). The 240-m tree canopy cover is based on data from a cooperative project between the Multi-Resolution Land Characteristics Consortium (Coulston and others 2012) and the Forest Service Remote Sensing Applications Center using the 2011 National Land Cover Database. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

high density of mortality occurrences was detected in the first of these ecoregion sections in the conterminous United States analysis, and a hot spot of very high density was identified in the second (fig. 2.3A). Similar hot spots were identified in the analysis limited to the North Central FHM region (fig. 2.3B).

All the other North Central ecoregion sections had <1 percent forest exposure to mortality agents, with the exception of 4.5 percent in 212M–Northern Minnesota and Ontario (fig. 2.2), where surveyors found much mortality associated with eastern larch beetle. A national hot spot of moderate mortality occurrence density was detected in this ecoregion section as well (fig. 2.3A). Other national and regional mortality hot spots in the North Central region were associated with emerald ash borer, including in 251C–Central Dissected Till Plains (southeastern Iowa), and in 222M–Minnesota and Northeast Iowa Morainal-Oak Savannah (northeastern Iowa and southern Minnesota) with 212K–Western Superior Uplands.

In the FHM West Coast region, 28 mortality agents and complexes were detected on about 1.33 million ha (table 2.3). Fir engraver was the leading cause of mortality and was identified on about 917 000 ha, approximately 69 percent of the entire affected area. Other bark beetles, including western pine beetle, mountain pine beetle, Jeffrey pine beetle (*D. jeffreyi*), and Douglas-fir beetle (*D. pseudotsugae*), were also widespread causes of mortality in the region. The first two of these were detected on approximately 182 000 ha and 146 000 ha, respectively. As a result of bark beetle infestations, 14.7 percent of the surveyed forest in the M261E–Sierra Nevada ecoregion section and 10.2 percent of the forest in M261D–Southern Cascades were exposed to mortality (fig. 2.2). Several other ecoregion sections in the West Coast region had between 1 and 5 percent of their surveyed forest exposed to mortality agents.

At the same time, a hot spot of high mortality density was centered on the M261E–Sierra Nevada ecoregion section, and extended into several neighboring ecoregion sections, both for the national (fig. 2.3A) and regional (fig. 2.3B) analyses. An additional hot spot of high mortality density was identified in the M332G–Blue Mountains of eastern Oregon (in both the national and regional analyses), associated with mortality caused by fir engraver, mountain pine beetle, and western pine beetle. Similarly, the national analyses identified a high-density mortality hot spot in M333A–Okanogan Highland, caused by western pine beetle and several other bark beetles, including mountain pine beetle, Douglas-fir beetle, fir engraver, and Ips engraver beetles (*Ips* spp.). The same area was a moderate-density hot spot in the regional analysis.

The FHM Interior West region had approximately 339 000 ha on which 20 mortality-causing agents and complexes were detected in 2017 (table 2.3). About 45 percent of this was associated with spruce beetle (153 000 ha). Other bark beetles were also

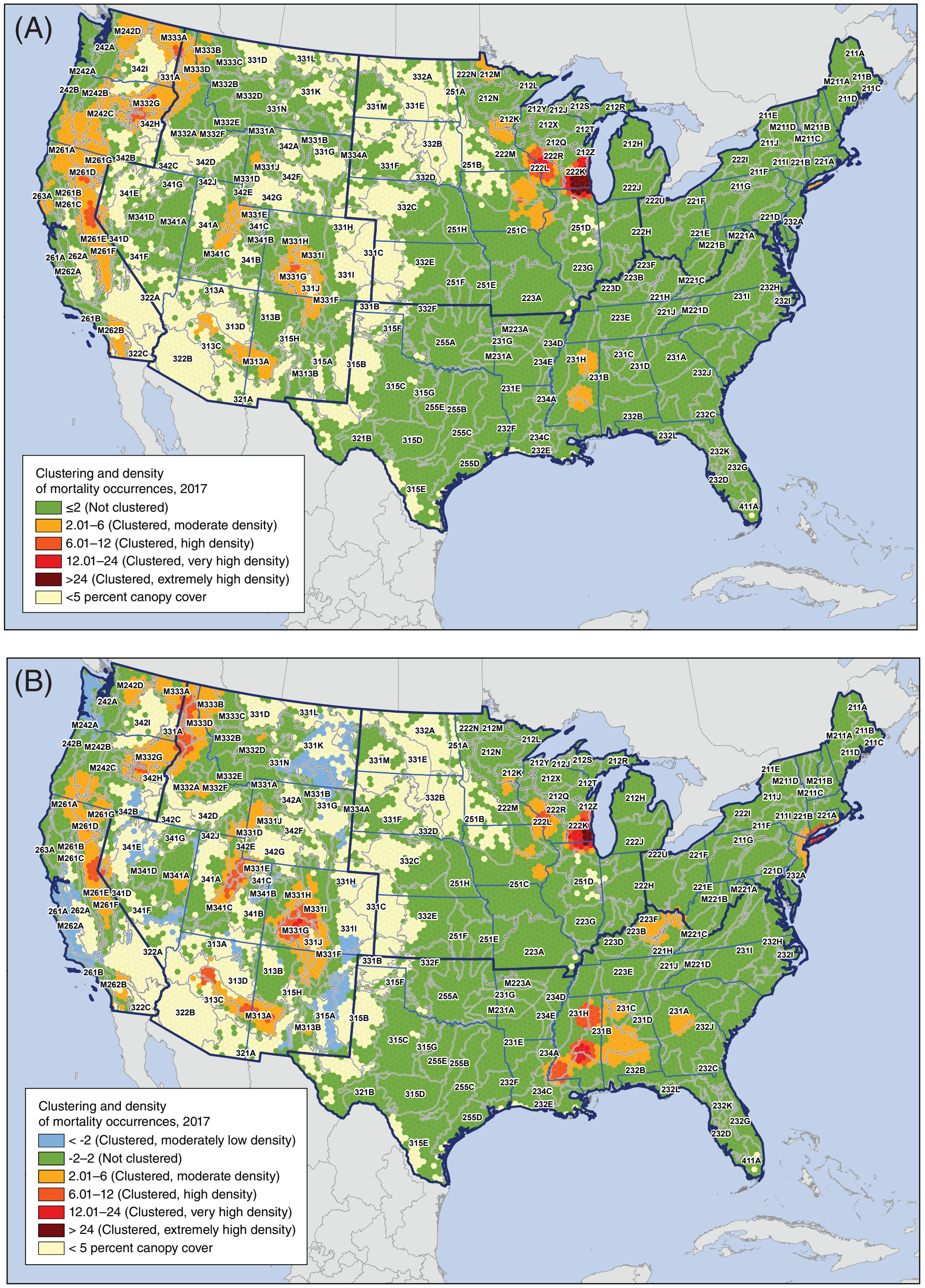


Figure 2.3—Hot spots of the density of occurrences of mortality-causing insects and diseases in 2017 for (A) the conterminous 48 States and (B) for separate Forest Health Monitoring regions, by hexagons containing >5 percent tree canopy cover. Values are Getis-Ord G_i scores, with values >2 representing significant clustering of high mortality occurrence densities and <-2 representing significant clustering of low mortality occurrence densities. The gray lines delineate ecoregion sections (Cleland and others 2007), and blue lines delineate Forest Health Monitoring regions. Tree canopy cover is based on data from a cooperative project between the Multi-Resolution Land Characteristics Consortium (Coulston and others 2012) and the Forest Service Remote Sensing Applications Center using the 2011 National Land Cover Database. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)*

widely detected, including Douglas-fir beetle and fir engraver (each about 42 000 ha, or 12 percent of the total) and western balsam bark beetle (*Dryocoetes confusus*) (24 000 ha, 7 percent).

As a result of bark beetle infestations, several ecoregion sections in the central Rocky Mountains experienced between 1 and 5 percent mortality in surveyed areas with tree canopy cover, including M331E–Uinta Mountains of northeastern Utah (3.4 percent), M331G–South-Central Highlands (2.5 percent) and M331F–Southern Parks and Rocky Mountain Range (1.4 percent) of southern Colorado and northern New Mexico, and M331I–Northern Parks and Ranges of northern Colorado and southern Wyoming (1.1 percent) (fig. 2.2). Most of the mortality in these areas was attributed to spruce beetle, although Douglas-fir beetle, western balsam bark beetle, and mountain pine beetle were also present.

The national Getis-Ord analysis revealed several geographic hot spots of mortality in the Interior West FHM region, one of which resulted from high mortality occurrence density (fig. 2.3A). This was caused by the spruce beetle outbreak in southern Colorado, and was centered on M331G–South-Central Highlands. The regional analysis (fig. 2.3B), meanwhile, identified four high mortality density hot spots that were classified as moderate density hot spots in the national analysis. These were located in:

- Northern Idaho (M333D–Bitterroot Mountains, 331A–Palouse Prairie, M333A–Okanogan Highland, and M332G–Blue Mountains) associated mainly with fir engraver as well as with mountain pine beetle, Douglas-fir beetle, spruce beetle, and pine engraver (*Ips pini*);
- North-central Utah (M331D–Overthrust Mountains, M331E–Uinta Mountains, M341C–Utah High Plateau, and M341B–Tavaputs Plateau), the result of spruce beetle in Engelmann spruce, Marssonina blight (*Drepanopeziza* spp.) in quaking aspen (*Populus tremuloides*), Douglas-fir beetle in Douglas-fir, root disease and beetle complex in subalpine fir (*Abies lasiocarpa*), and fir engraver in white fir (*A. concolor*); and
- Central Arizona, and southeastern Arizona and southwestern New Mexico, both within M313A–White Mountains-San Francisco Peaks-Mogollon Rim, and both associated with an unknown bark beetle in ponderosa pine (*Pinus ponderosa*).

Additionally, the national and regional analyses found a hot spot of moderate mortality exposure in northwestern Wyoming (M331D–Overthrust Mountains, M331A–Yellowstone Highlands, and M331J–Wind River Mountains) related to spruce beetle and subalpine fir mortality complex.

In the North East FHM region, mortality was recorded on approximately 32 000 ha, caused by 18 mortality agents and complexes. The cause of about a third of this mortality was emerald ash borer (10 000 ha). None of the ecoregion sections in the North East was exposed to >1 percent surveyed forest mortality (fig. 2.2). A hot spot of moderate mortality density in the national analysis (fig. 2.3A), and of very high mortality density in the regional analysis (fig. 2.3B), was identified in areas adjacent to Long Island Sound (in 221A–Lower New England), associated with southern pine beetle in pitch pine (*P. rigida*) stands and with oak decline in northern red oak (*Quercus rubra*) on Long Island, and with emerald ash borer in Connecticut.

In the South FHM region, mortality from nine agents was detected on about 25 000 ha (table 2.3). The most common causal agent was southern pine beetle, constituting 42 percent of the mortality (11 000 ha), followed by Ips engraver beetles (7000 ha, 30 percent) and emerald ash borer (5000 ha, 21 percent). No ecoregion sections in the South were exposed to >1 percent surveyed forest mortality (fig. 2.2). The national hot spot analysis identified two areas of moderately clustered mortality density in Mississippi (fig. 2.3A), both caused by the southern pine beetle outbreak in the region (box 2.1). One was located in the northeastern part of the State (231H–Coastal Plains-Loess and 231B–Coastal Plains-Middle), and the other in south-central Mississippi (231B–Coastal Plains-Middle and 232B–Gulf Coastal Plains and Flatwoods). In the regional analysis (fig. 2.3B), the second of these exhibited clustering of very high mortality density, while the first was of high mortality density. The regional analysis detected an additional hot spot of high mortality density, also associated with southern pine beetle, in the southwestern corner of Mississippi (231H–Coastal Plains-Loess). Hot spots of moderate southern pine beetle mortality density also appeared in neighboring Alabama and Georgia.

Eastern Kentucky (223F–Interior Low Plateau-Bluegrass, 221E–Southern Unglaciated Allegheny Plateau, and 221H–Northern Cumberland Plateau) was the location of a moderate mortality exposure hot spot in the regional analysis (fig. 2.3B). This was caused by emerald ash borer.

Conterminous United States Defoliation

In 2017, the national IDS survey identified 50 defoliation agents and complexes affecting approximately 2.34 million ha across the conterminous United States (table 2.4), an area slightly larger than the land area of New Hampshire. The most widespread defoliation agent was gypsy moth, which was detected on approximately 913 000 ha, or 39 percent of the

BOX 2.1

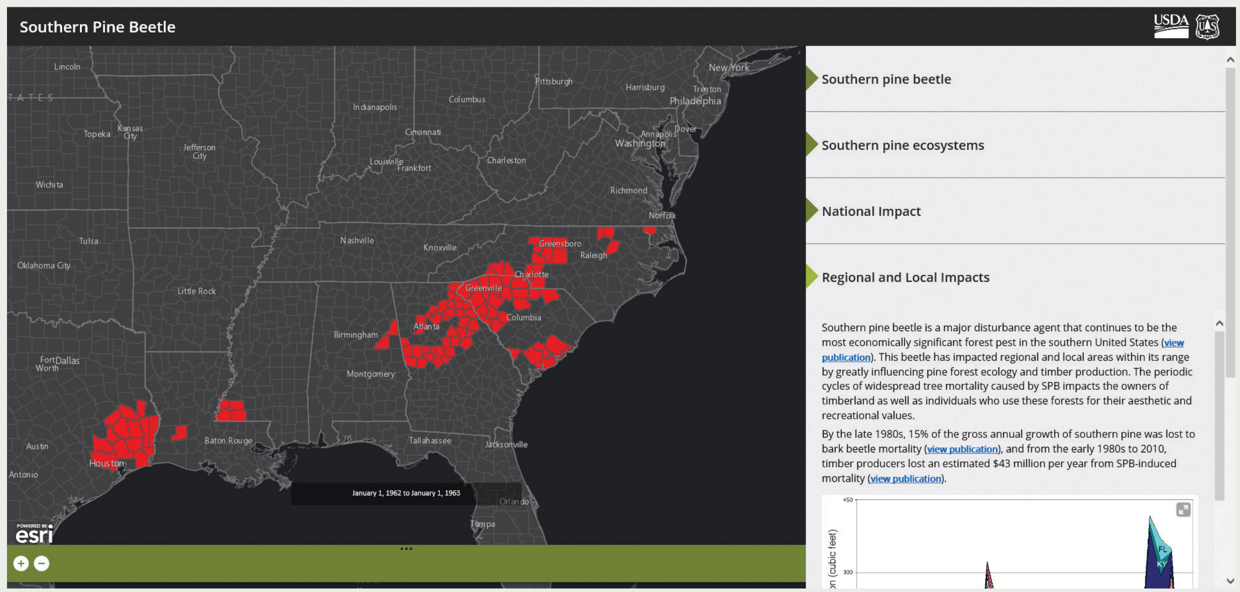
Southern pine beetle story map

Southern pine beetle (SPB, *Dendroctonus frontalis*) is the most economically significant pest in the Southern United States, where it impacts both southern yellow pine timber production and forest ecology. The host species of SPB, especially loblolly (*Pinus taeda*), shortleaf (*P. echinata*), pitch (*P. rigida*), and Virginia (*P. virginiana*) pines, play significant roles in the functioning of southern forest ecosystems and/or are important timber-producing species.

The periodic cycles of widespread tree mortality caused by SPB impact the owners of timberland as well as individuals who use these forests for their aesthetic and recreational values. Despite increases in the amount of intensively managed pine in the South, SPB activity across the South declined significantly since the late 1990s due, in part, to regional improvements in plantation silviculture, most notably stand thinning. In recent years, however, mostly localized but severe SPB activity has appeared in some areas, particularly across the national forests of Mississippi, Alabama, and Georgia. In these areas, thinning practices have fallen behind growth rates due to depressed markets for pine, resulting in a large concentration of overstocked stands.

A story map (https://arcg.is/rD01j, pictured below) provides an overview of SPB and its hosts. This includes interactive maps of SPB infestations from 1960 to 2017 and of the extent of its pine host species, background on the life cycle of the insect, discussion of its recent impacts on national forests in the South, and information about the management and monitoring of SPB outbreaks.

The story map was developed by the Forest Health Assessment and Applied Sciences Team of the U.S. Department of Agriculture, Forest Service, in association with the Forest Health Monitoring program and Forest Health Protection.



The Southern Pine Beetle story map provides interactive maps and background information on southern pine beetle, its hosts, and its management.

Table 2.4—Defoliation agents and complexes affecting more than 5000 ha in the conterminous United States in 2017

Agents/complexes causing defoliation, 2017	Area
	ha
Gypsy moth	912 678
Western spruce budworm	502 398
Forest tent caterpillar	286 962
Unknown gallmaker	183 583
Jumping oak gall wasp	147 456
Spruce budworm	122 257
Baldcypress leafroller	80 752
Unknown defoliator	35 691
White pine needle damage	27 471
Larch casebearer	25 891
Browntail moth	22 194
Winter moth	12 760
Cherry scallop shell moth	11 972
Unknown	9187
Pandora moth	7974
Other (35)	31 271
Total, all defoliation agents	**2 344 302**

Note: All values are "footprint" areas for each agent or complex. The sum of the individual agents is not equal to the total for all agents due to the reporting of multiple agents per polygon.

total. Five other insects were also detected on >100 000 ha each: western spruce budworm (*Choristoneura freemani*) on 502 000 ha, forest tent caterpillar (*Malacosoma disstria*) on 287 000 ha, an unknown gallmaker on 184 000 ha, jumping oak gall wasp (*Neuroterus saltatorius*) on 147 000 ha, and spruce budworm (*C. fumiferana*) on 122 000 ha (table 2.4).

The North East FHM region had by far the largest area on which defoliating agents and complexes were detected in 2017, slightly >1 million ha (table 2.5). Almost 87 percent of this (869 000 ha) was associated with gypsy moth (table 2.5). Seventeen other agents and complexes constituted the remaining defoliated area. The 221A–Lower New England ecoregion section had the highest percent of surveyed forest exposed to defoliation in the country, 17.9 percent (fig. 2.4), mostly as a result of the gypsy moth infestation, especially in Massachusetts, Connecticut, and Rhode Island. There was also white pine needle damage in southern Maine. Two neighboring ecoregion sections, 211D–Central Maine Coastal Embayment and M211C–Green-Taconic-Berkshire Mountains, had 1.3 percent and 1.1 percent of surveyed forest exposed to defoliators as a result of, respectively, white pine needle damage and browntail moth (*Euproctis chrysorrhoea*), and forest tent caterpillar.

Table 2.5—The top five defoliation agents or complexes for each Forest Health Monitoring region and for Alaska in 2017

Defoliation agents and complexes, 2017	Area
	ha
Interior West	
Western spruce budworm	486 076
Unknown defoliator	35 607
Pandora moth	7974
Marssonina blight	4097
Spruce aphid	2276
Other defoliation agents (15)	9250
Total, all defoliation agents and complexes	**544 363**
North Central	
Jumping oak gall wasp	147 456
Spruce budworm	122 257
Forest tent caterpillar	96 392
Gypsy moth	30 295
Larch casebearer	18 463
Other defoliation agents (7)	12 118
Total, all defoliation agents and complexes	**425 062**
North East	
Gypsy moth	868 644
Forest tent caterpillar	53 663
White pine needle damage	27 471
Browntail moth	22 194
Winter moth	12 760
Other defoliation agents (13)	16 793
Total, all defoliation agents and complexes	**1 000 820**

Defoliation agents and complexes, 2017	Area
	ha
South	
Unknown gallmaker	183 583
Forest tent caterpillar	136 705
Baldcypress leafroller	80 752
Gypsy moth	13 739
Unknown	2843
Other defoliation agents (2)	394
Total, all defoliation agents and complexes	**345 593**
West Coast	
Western spruce budworm	16 321
Larch casebearer	7428
Needlecast	2511
Unknown	570
Swiss needle cast	555
Other defoliation agents (12)	1308
Total, all defoliation agents and complexes	**28 464**
Alaska	
Aspen leafminer	59 713
Unknown defoliator	42 331
Willow leaf blotchminer	29 325
Speckled green fruitworm	14 872
Birch aphid	1318
Other defoliation agents (6)	805
Total, all defoliation agents and complexes	**146 212**

Note: The total area affected by other agents is listed at the end of each section. All values are "footprint" areas for each agent or complex. The sum of the individual agents is not equal to the total for all agents due to the reporting of multiple agents per polygon.

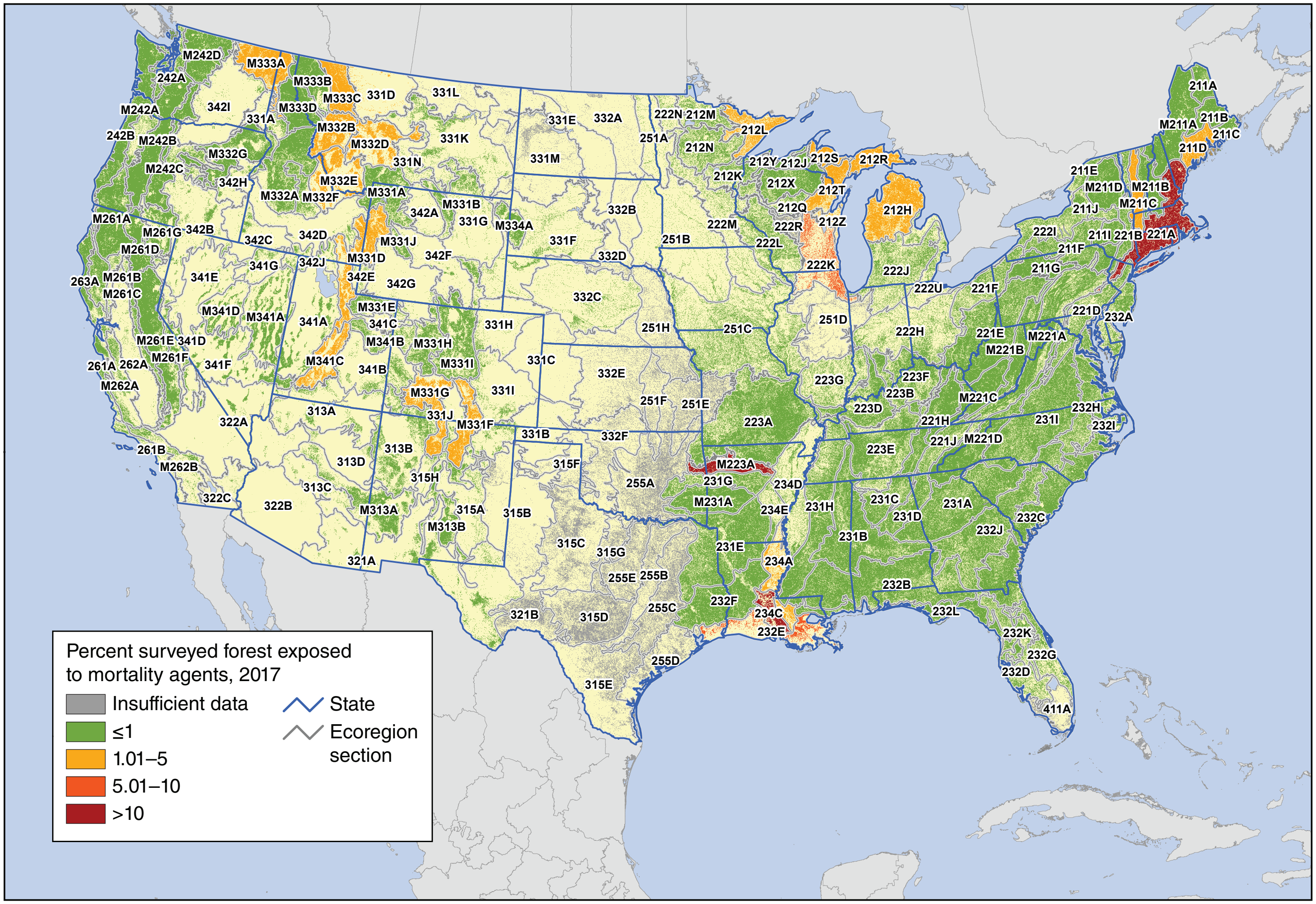


Figure 2.4—The percent of surveyed forest exposed to defoliating agents, by ecoregion section within the conterminous 48 States, for 2017. The gray lines delineate ecoregion sections (Cleland and others 2007). The 240-m tree canopy cover is based on data from a cooperative project between the Multi-Resolution Land Characteristics Consortium (Coulston and others 2012) and the Forest Service Remote Sensing Applications Center using the 2011 National Land Cover Database. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

Three hot spots of defoliation were detected in the North East region. One, of extremely high defoliation density in the national analysis (fig. 2.5A) and of very high defoliation density in the regional analysis (fig. 2.5B), was associated with the gypsy moth infestation in 221A–Lower New England. A hot spot of high and moderate defoliation density in the national analysis, and of moderate density in the regional analysis, was associated with white pine needle damage and browntail moth in 211D–Central Maine Coastal Embayment and 221A–Lower New England. Finally, the national analysis revealed a hot spot of moderate forest tent caterpillar defoliation density in northern Vermont (M211C–Green-Taconic-Berkshire Mountains, M211B–New England Piedmont, and M211A–White Mountains).

Surveyors in the Interior West FHM region, meanwhile, detected defoliation by 20 agents and complexes on 544 000 ha (table 2.5). Most commonly found, by far, was western spruce budworm (486 000 ha, or 89 percent). Several ecoregion sections in the Interior West experienced between 1 and 5 percent of surveyed area defoliation (fig. 2.4), almost entirely attributed to western spruce budworm:

- M331G–South-Central Highlands (3.8 percent)
- M331F–Southern Parks and Rocky Mountain Range (3.1 percent)
- M331D–Overthrust Mountains (2.4 percent)
- M332E–Beaverhead Mountains (2.3 percent)
- M332B–Northern Rockies and Bitterroot Valley (2.1 percent)
- M332D–Belt Mountains (2.1 percent)
- M341C–Utah High Plateau (1.3 percent)

The 2017 Getis-Ord analysis detected hot spots of defoliation density in many of these same ecoregion sections, both in the national (fig. 2.5A) and regional (fig. 2.5B) analyses.

Meanwhile, 12 agents and complexes were associated with about 425 000 ha with defoliation in the North Central FHM region (table 2.5). Jumping oak gall wasp and spruce budworm were the most commonly detected defoliation agents, identified on 147 000 ha and 122 000 ha, respectively, representing 35 and 29 percent of the total area of defoliation in the region. Other widespread defoliators were forest tent caterpillar (96 000 ha), gypsy moth (30 000 ha), and larch casebearer (*Coleophora laricella*) (18 000 ha).

Several ecoregion sections bordering the Great Lakes had moderately high exposure to defoliation agents. The highest percentage of surveyed forest exposed to defoliators (5.2 percent) was in 222K–Southwestern Great Lakes Morainal in Wisconsin and Illinois, where a high concentration of jumping oak gall wasp was identified (fig. 2.4). The other ecoregion sections with >1 percent defoliation of surveyed forest were:

- 212Z–Green Bay-Manitowoc Upland (5.0 percent): jumping oak gall wasp
- 212R–Eastern Upper Peninsula (4.6 percent): spruce budworm and forest tent caterpillar

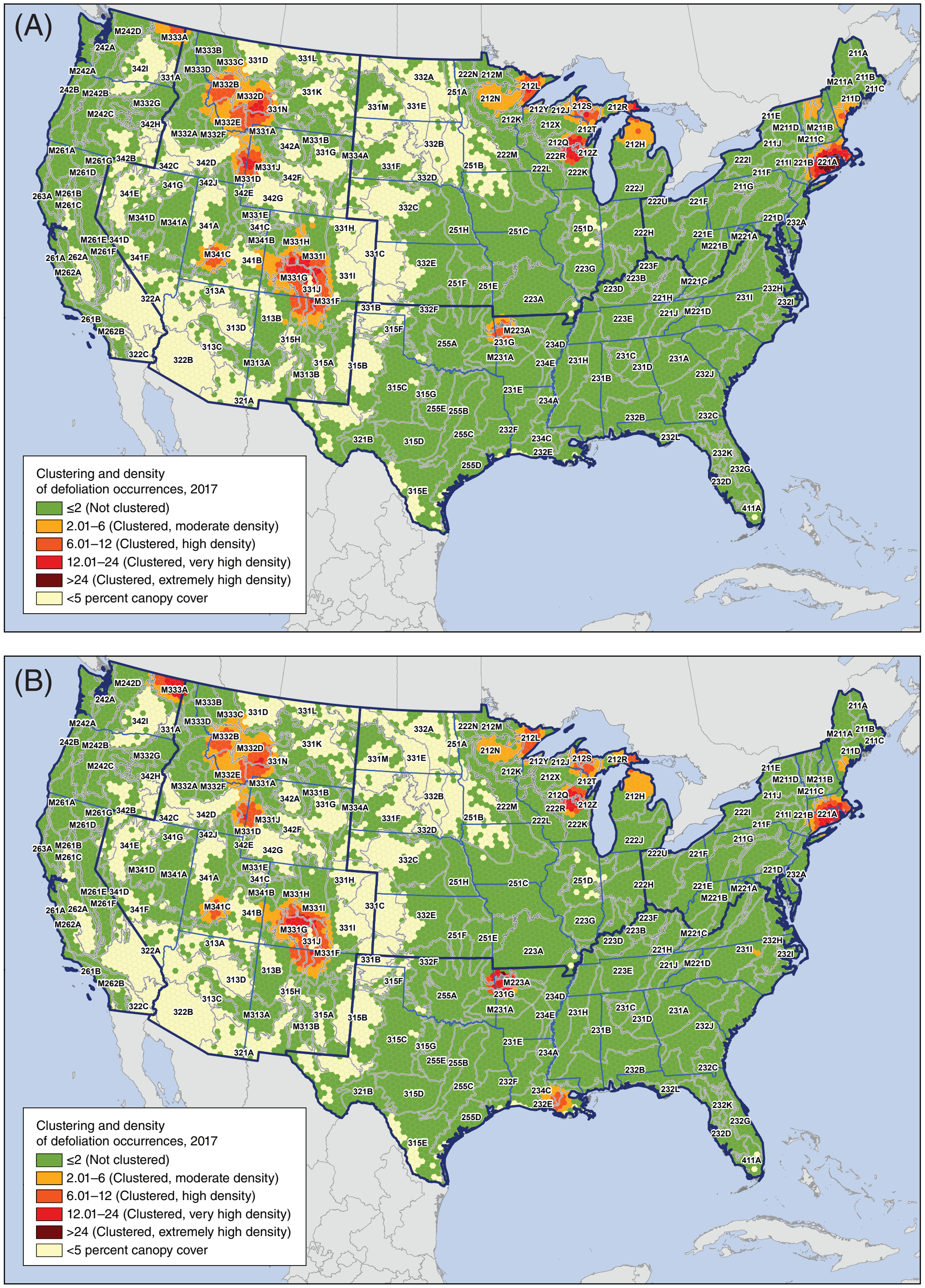


Figure 2.5—Hot spots of the density of occurrences of defoliation-causing insects and diseases in 2017 for (A) the conterminous 48 States and (B) for separate Forest Health Monitoring regions, by hexagons containing >5 percent tree canopy cover. Values are Getis-Ord G_i^* scores, with values >2 representing significant clustering of high defoliation occurrence densities. (No areas of significant clustering of low densities, <-2, were detected.) The gray lines delineate ecoregion sections (Cleland and others 2007), and blue lines delineate Forest Health Monitoring regions. Tree canopy cover is based on data from a cooperative project between the Multi-Resolution Land Characteristics Consortium (Coulston and others 2012) and the Forest Service Remote Sensing Applications Center using the 2011 National Land Cover Database. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

- 212S–Northern Upper Peninsula (3.1 percent): spruce budworm and forest tent caterpillar
- 212T–Northern Green Bay Lobe (2.4 percent): spruce budworm, large aspen tortrix, and larch casebearer
- 212H–Northern Lower Peninsula (2.1 percent): gypsy moth and forest tent caterpillar
- 212L–Northern Superior Uplands (1.2 percent): spruce budworm and forest tent caterpillar

The national (fig. 2.5A) and regional (2.5B) analyses revealed hot spots of similar extent within these ecoregion sections bordering the Great Lakes.

Approximately 346 000 ha of defoliation were documented in the South FHM region during 2017. Slightly more than half of this (53 percent, 184 000 ha) was attributed to an unknown gallmaker (table 2.5). Forest tent caterpillar was associated with an additional 40 percent (137 000 ha), and baldcypress leafroller (*Archips goyerana)* with about 23 percent (81 000 ha). As a result of an infestation by the unknown gallmaker, 12.7 percent of the surveyed forest in the M223A–Boston Mountains ecoregion section in northwestern Arkansas was exposed to defoliation (fig. 2.4), and this area was the location of a hot spot of high defoliation density nationally (fig. 2.5A) and very high defoliation density regionally (fig. 2.5B). Similarly, baldcypress leafroller and forest tent caterpillar resulted in a regional hot spot of high defoliation density (fig. 2.5B) in ecoregion sections of southern Louisiana that also had high percentages of surveyed forest exposed to defoliators: 234C–Atchafalaya and Red River Alluvial Plains (12 percent) and 232E–Louisiana Coastal Prairie and Marshes (7.9 percent) (fig. 2.4).

Finally, 17 defoliating agents and complexes were identified in the FHM West Coast region, with western spruce budworm accounting for about 57 percent of the approximately 28 000 ha with defoliation (table 2.5). The only ecoregion section with at least 1 percent of surveyed forest exposed to defoliating agents was M333A–Okanogan Highland (1.0 percent) of northeastern Washington, where outbreaks of western spruce budworm and larch casebearer were detected (fig. 2.4). This ecoregion section was the site of a hot spot of high defoliation density nationally (fig.2.5A) and of very high defoliation density regionally (fig. 2.5B).

Alaska and Hawaii

In Alaska, mortality was recorded on nearly 186 000 ha in 2017, attributed to five agents and complexes (table 2.3). Spruce beetle was the most widely detected mortality agent, representing 88 percent of the total area with mortality (164 000 ha). Yellow-cedar (*Chamaecyparis nootkatensis*) decline was detected on 19 000 ha, 10 percent of the total. The ecoregion section with the highest percent of surveyed forest exposed to mortality (21 percent) was 213B–Cook Inlet Lowlands in the south-central part of the State (fig. 2.6), where surveyors detected extensive mortality due to spruce beetle. The infestation carried over into

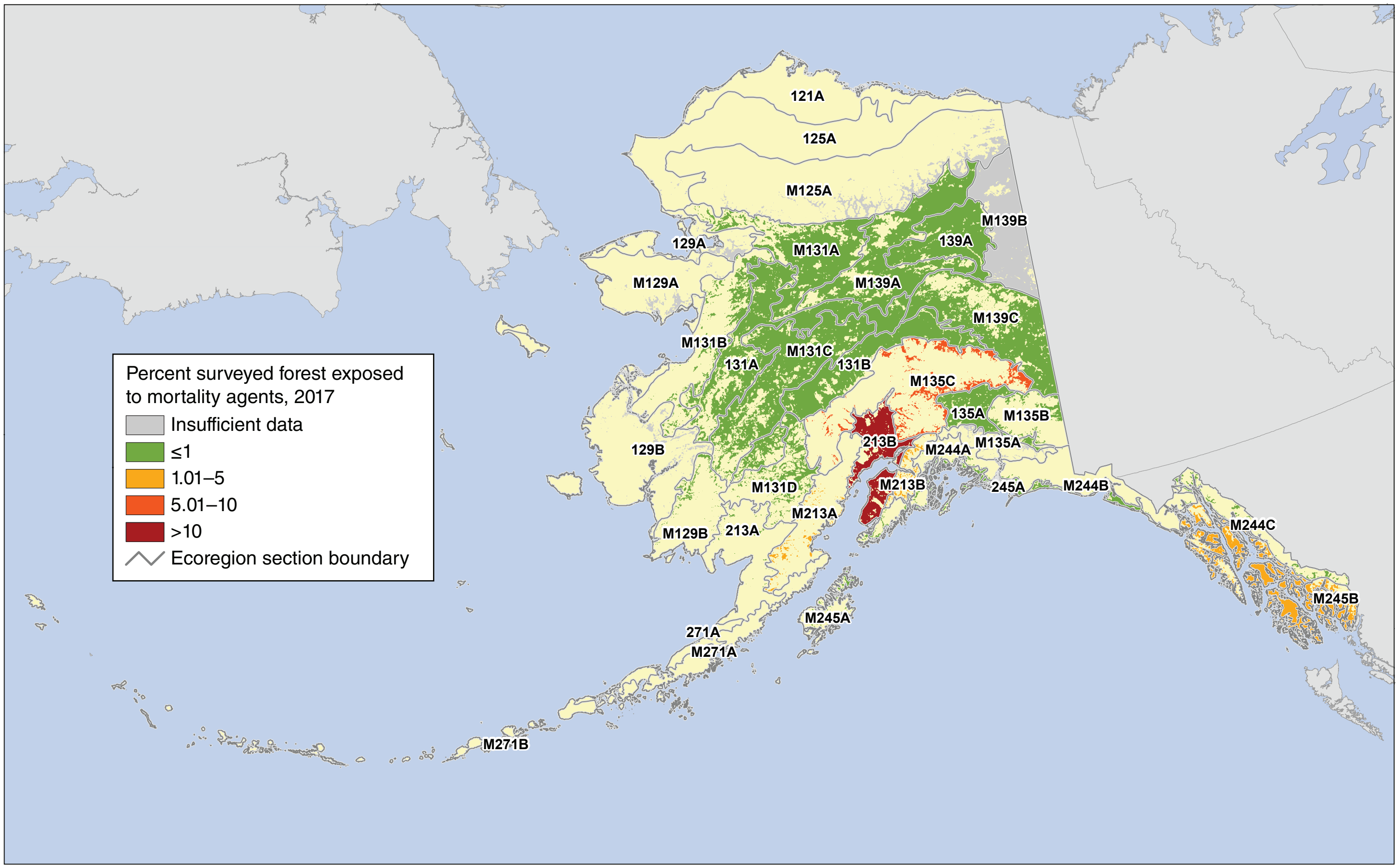


Figure 2.6—Percentage of surveyed forest in Alaska ecoregion sections exposed to mortality-causing insects and diseases in 2017. The gray lines delineate ecoregion sections (Nowacki and Brock 1995). Background forest cover is derived from MODIS imagery by the Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

the neighboring M135C–Alaska Range, where 9.8 percent of surveyed forest was exposed to mortality, as well as M213A–Northern Aleutian Range (3.9 percent) and M213B–Kenai Mountains (2.2 percent). In the panhandle of Alaska, the percent of surveyed forest exposed to mortality was 2.0 in M245B–Alexander Archipelago, location of extensive yellow-cedar decline.

At the same time, 11 defoliators in Alaska were detected on 146 000 ha (table 2.5). Of this area, about 41 percent (60 000 ha) was attributed to aspen leafminer (*Phyllocnistis populiella*). Meanwhile, willow leaf blotchminer (*Micrurapteryx salicifoliella*) was recorded on 29 000 ha (20 percent) and speckled green fruitworm (*Orthosia hibisci*) on about 15 000 ha (10 percent). The Alaska ecoregion section with the highest proportion of surveyed forest area affected by defoliators in 2017 was 139A–Yukon Flats (12.7 percent of surveyed forest) (fig. 2.7), where willow leaf blotchminer and aspen leafminer were commonly reported in willow (*Salix* spp.) and quaking aspen stands. Aspen leafminer was also commonly detected in neighboring M139C–Dawson Range (8.1 percent defoliation in surveyed forest). Several other ecoregion sections in central Alaska had defoliation detected on 1 to 5 percent of their surveyed forest, while surveyors detected defoliation, caused by unknown defoliators, on 12.2 percent of the surveyed forest in 245A–Gulf of Alaska Forelands.

In 2017, approximately 30 000 ha with mortality were recorded in Hawaii (table 2.3), which are officially labeled as having an unknown cause but may be associated with rapid ‘ōhi‘a death, a wilt disease caused by the fungal pathogens *Ceratocystis lukuohia* and *C. huliohia* (Barnes and others 2018) that affects ‘ōhi‘a lehua (*Metrosideros polymorpha*), a highly ecologically and culturally important tree species in Hawaiian native forests (University of Hawai‘i 2017). All of this mortality was on the Big Island, with higher percentages of surveyed forests affected on the windward (eastern) side of the island, especially in council districts 2, 5, and 3 (12.1, 11.4, and 11 percent, respectively) (fig. 2.8), which encompass much of the Puna and Hilo areas. Mortality did not exceed 1 percent of surveyed forest on any of the other islands in the State. No defoliation was recorded in Hawaii during 2017.

CONCLUSION

Continued monitoring of insect and disease outbreaks across the United States will be necessary for determining appropriate follow-up investigation and management activities. Due to the limitations of survey efforts to detect certain important forest insects and diseases, the pests and pathogens discussed in this chapter do not include all the biotic forest health threats that should be considered when making management decisions and budget allocations. However, large-scale assessments of mortality and defoliation exposure, including geographical hot spot detection analyses, offer a useful approach for identifying geographic areas where the concentration of monitoring and management activities might be most effective.

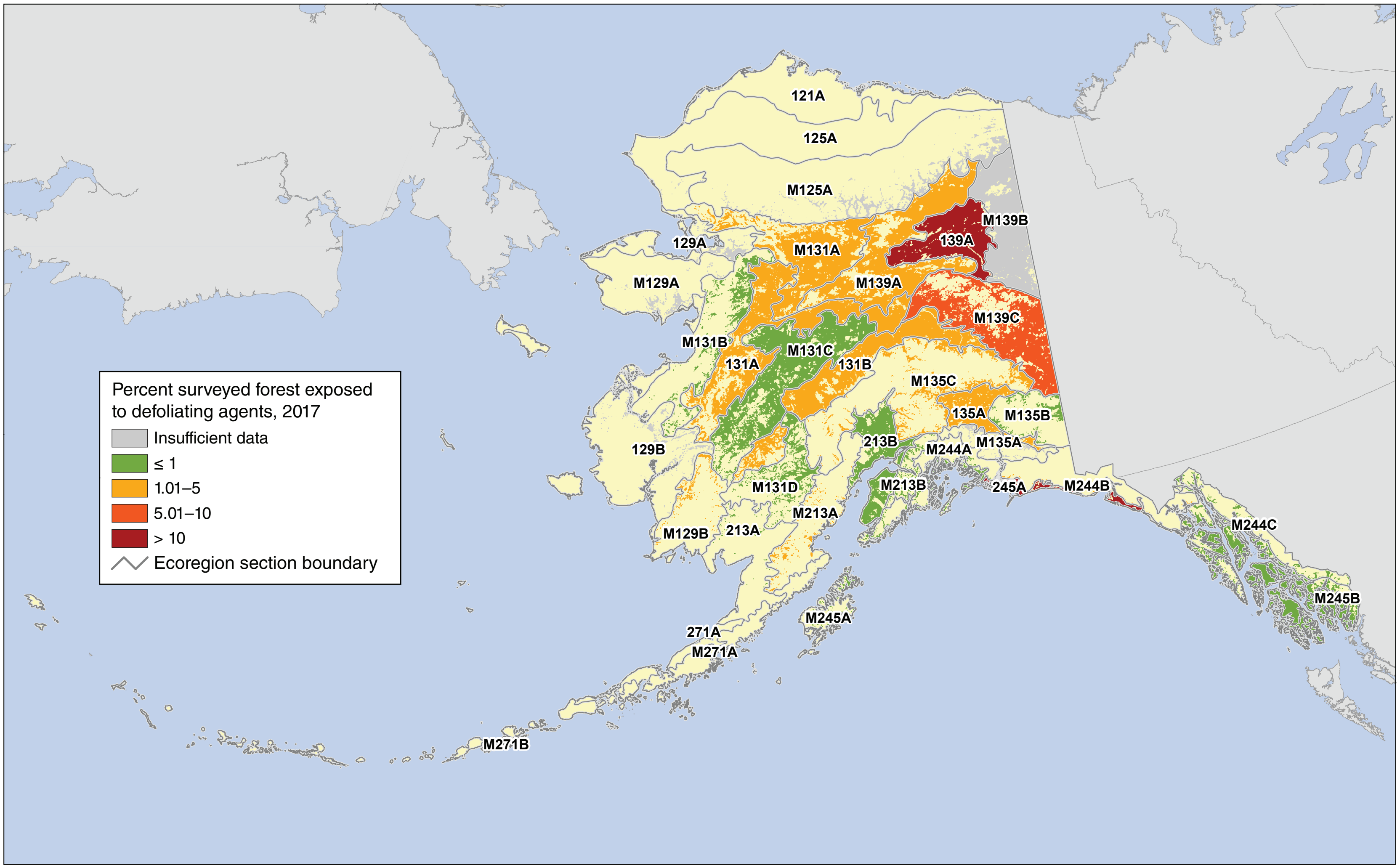


Figure 2.7—Percentage of surveyed forest in Alaska ecoregion sections exposed to defoliation-causing insects and diseases in 2017. The gray lines delineate ecoregion sections (Nowacki and Brock 1995). Background forest cover is derived from MODIS imagery by the Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

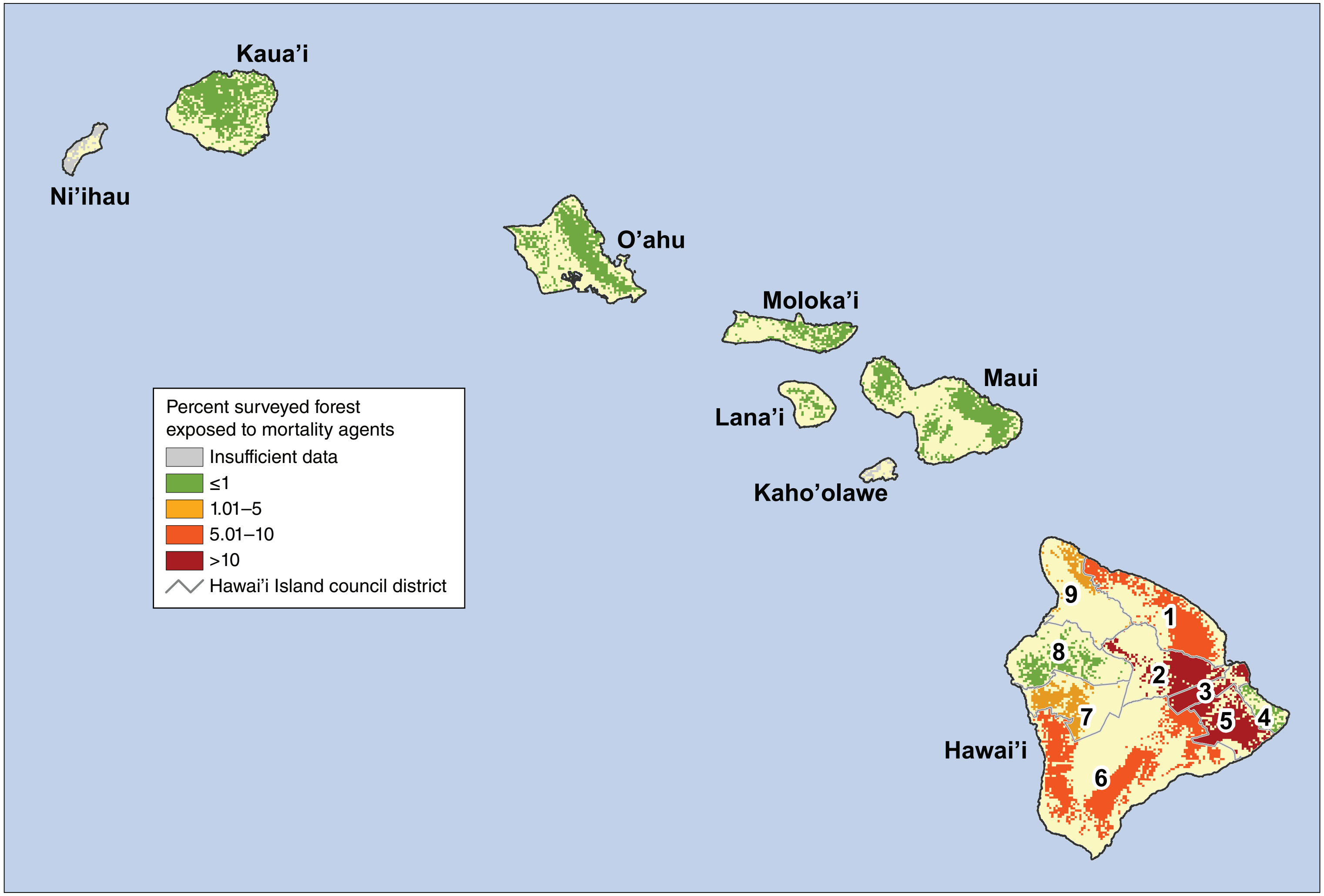


Figure 2.8—Percentage of surveyed forest on Hawaii islands (and by county council district on the Big Island of Hawai'i) exposed to mortality-causing insects and diseases in 2017. Background forest cover is derived from the LANDFIRE program (LANDFIRE 2014). (Data source: U.S. Department of Agriculture Forest Service, Forest Health Protection)

LITERATURE CITED

Anselin, L. 1992. Spatial data analysis with GIS: an introduction to application in the social sciences. Tech. Rep. 92-10. Santa Barbara, CA: National Center for Geographic Information and Analysis. 53 p.

Barnes, I.; Fourie, A.; Wingfield, M.J. [and others]. 2018. New *Ceratocystis* species associated with rapid death of *Metrosideros polymorpha* in Hawaii. Persoonia-Molecular Phylogeny and Evolution of Fungi. 40(1): 154–181.

Brockerhoff, E.G.; Liebhold, A.M.; Jactel, H. 2006. The ecology of forest insect invasions and advances in their management. Canadian Journal of Forest Research. 36(2): 263–268.

Castello, J.D.; Leopold, D.J.; Smallidge, P.J. 1995. Pathogens, patterns, and processes in forest ecosystems. BioScience. 45(1): 16–24.

Cleland, D.T.; Freeouf, J.A.; Keys, J.E. [and others]. 2007. Ecological subregions: sections and subsections for the conterminous United States. Gen. Tech. Report WO-76D. Washington, DC: U.S. Department of Agriculture Forest Service. Map; Sloan, A.M., cartographer; presentation scale 1:3,500,000; colored. Also on CD-ROM as a GIS coverage in ArcINFO format or at http://data.fs.usda.gov/geodata/edw/datasets.php. [Date accessed: July 20, 2015].

Coulston, J.W.; Moisen, G.G.; Wilson, B.T. [and others]. 2012. Modeling percent tree canopy cover: a pilot study. Photogrammetric Engineering and Remote Sensing. 78(7): 715–727.

Edmonds, R.L.; Agee, J.K.; Gara, R.I. 2011. Forest health and protection. Long Grove, IL: Waveland Press, Inc. 667 p.

ESRI. 2015. ArcMap® 10.3. Redlands, CA: Environmental Systems Research Institute, Inc.

Forest Health Protection (FHP). 2016. Detection surveys. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Forest Health Technology Enterprise Team. http://www.fs.fed.us/foresthealth/technology/detection_surveys.shtml. [Date accessed: July 23, 2016].

Forest Health Protection (FHP). 2018. Insect and Disease Detection Survey Database (IDS). [Online database]. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Forest Health Technology Enterprise Team. https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/gis-spatial-analysis/detection-surveys.shtml#idsdownloads. [Date accessed: October 24, 2018].

Getis, A.; Ord, J.K. 1992. The analysis of spatial association by use of distance statistics. Geographical Analysis. 24(3): 189–206.

Holdenrieder, O.; Pautasso, M.; Weisberg, P.J.; Lonsdale, D. 2004. Tree diseases and landscape processes: the challenge of landscape pathology. Trends in Ecology & Evolution. 19(8): 446–452.

Homer, C.G.; Dewitz, J.A.; Yang, L. [and others]. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States: representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing. 81(5): 345–354.

Laffan, S.W. 2006. Assessing regional scale weed distributions, with an Australian example using *Nassella trichotoma*. Weed Research. 46(3): 194–206.

LANDFIRE. 2014. Existing vegetation type layer, LANDFIRE 1.4.0. U.S. Department of the Interior, Geological Survey. https://www.landfire.gov/evt.php. [Date accessed: May 2, 2014].

Liebhold, A.M.; McCullough, D.G.; Blackburn, L.M. [and others]. 2013. A highly aggregated geographical distribution of forest pest invasions in the USA. Diversity and Distributions. 19: 1208–1216.

Mack, R.N.; Simberloff, D.; Lonsdale, W.M. [and others]. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecological Applications. 10(3): 689–710.

Manion, P.D. 2003. Evolution of concepts in forest pathology. Phytopathology. 93: 1052–1055.

Nowacki, G.; Brock, T. 1995. Ecoregions and subregions of Alaska [EcoMap]. Version 2.0. Juneau, AK: U.S. Department of Agriculture Forest Service, Alaska Region. Map; presentation scale 1:5,000,000; colored.

Parry, D.; Teale, S.A. 2011. Alien invasions: the effects of introduced species on forest structure and function. In: Castello, J.D.; Teale, S.A., eds. Forest health: an integrated perspective. New York: Cambridge University Press. 115–162.

Potter, K.M. 2012. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national insect and disease detection survey database, 2007 and 2008. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring 2009 national technical report. Gen. Tech. Rep. SRS-167. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 63–78.

Potter, K.M. 2013. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national insect and disease detection survey, 2009. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2010. Gen. Tech. Rep. SRS-176. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 15–29.

Potter, K.M.; Koch, F.H. 2012. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska, 2006. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring 2008 national technical report. Gen. Tech. Rep. SRS-158. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 63–72.

Potter, K.M.; Koch, F.H.; Oswalt, C.M.; Iannone, B.V. 2016. Data, data everywhere: detecting spatial patterns in fine-scale ecological information collected across a continent. Landscape Ecology. 31: 67–84.

Potter, K.M.; Paschke, J.L. 2013. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national Insect and Disease Detection Survey Database, 2010. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2011. Gen. Tech. Rep. SRS-185. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 15–28.

Potter, K.M.; Paschke, J.L. 2014. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national Insect and Disease Survey Database, 2011. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2012. Gen. Tech. Rep. SRS-198. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 19–34.

Potter, K.M.; Paschke, J.L. 2015a. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national insect and disease survey, 2012. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2013. Gen. Tech. Rep. SRS-207. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 19–36.

Potter, K.M.; Paschke, J.L. 2015b. Large-scale patterns of insect and disease activity in the conterminous United States, Alaska, and Hawaii from the national insect and disease survey, 2013. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2014. Gen. Tech. Rep. SRS-209. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 19–38.

Potter, K.M.; Paschke, J.L. 2016. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national insect and disease survey, 2014. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2015. Gen. Tech. Rep. SRS-213. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 21–40.

Potter, K.M.; Paschke, J.L. 2017. Large-scale patterns of insect and disease activity in the conterminous United States and Alaska from the national insect and disease survey, 2015. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2016. Gen. Tech. Rep. SRS-222. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 21–42.

Potter, K.M.; Paschke, J.L.; Zweifler, M. 2018. Large-scale patterns of insect and disease activity in the conterminous United States, Alaska and Hawai'i from the national insect and disease survey, 2016. In: Potter, K.M.; Conkling, B.L., eds. Forest Health Monitoring: national status, trends, and analysis, 2017. Gen. Tech. Rep. SRS-233. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 23–44.

Reams, G.A.; Smith, W.D.; Hansen, M.H. [and others]. 2005. The Forest Inventory and Analysis sampling frame. In: Bechtold, W.A.; Patterson, P.L., eds. The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 11–26.

Shima T.; Sugimoto S.; Okutomi, M. 2010. Comparison of image alignment on hexagonal and square lattices. 2010 IEEE International Conference on Image Processing: 141–144. DOI: 10.1109/icip.2010.5654351.

Smith, W.B.; Miles, P.D.; Perry, C.H.; Pugh, S.A. 2009. Forest resources of the United States, 2007. Gen. Tech. Rep. WO-78. Washington, DC: U.S. Department of Agriculture Forest Service. 336 p.

Teale, S.A.; Castello, J.D. 2011. Regulators and terminators: the importance of biotic factors to a healthy forest. In: Castello, J.D.; Teale, S.A., eds. Forest health: an integrated perspective. New York: Cambridge University Press: 81–114.

University of Hawai'i, College of Tropical Agriculture and Human Resources. 2017. Rapid 'Ōhi'a Death/*Ceratocystis* Wilt of 'Ōhi'a. http://rapidohiadeath.org. [Date accessed: July 17, 2017].

U.S. Department of Agriculture (USDA) Forest Service. 2008. National forest type data development. http://svinetfc4.fs.fed.us/rastergateway/forest_type/. [Date accessed: May 13, 2008].

White, D.; Kimerling, A.J.; Overton, W.S. 1992. Cartographic and geometric components of a global sampling design for environmental monitoring. Cartography and Geographic Information Systems. 19(1): 5–22.

Zhang, L.; Rubin, B.D.; Manion, P.D. 2011. Mortality: the essence of a healthy forest. In: Castello, J.D.; Teale, S.A., eds. Forest health: an integrated perspective. New York: Cambridge University Press: 17–49.