CHAPTER 6.

A Forest Health Retrospective: National and Regional Results from 20 Years of Insect and Disease Survey Data

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INTRODUCTION

The Forest Health Monitoring (FHM) national program of the U.S. Department of Agriculture Forest Service determines status, changes, and trends in indicators of forest condition across all forested lands (ch. 1). One of the central objectives of the FHM annual national reports is to present forest health indicator information from a national perspective, or from a multi-State regional perspective when appropriate, using data collected by the Forest Health Protection (FHP) and Forest Inventory and Analysis (FIA) programs of the Forest Service, as well as from other sources. A standing chapter in each edition of the annual "Forest Health Monitoring: National Status, Trends, and Analysis" report, for example, quantifies forest area affected by insects and disease on a yearly basis using data from the FHP national Insect and Disease Survey (IDS) (FHP 2016, 2019) (ch. 2). This is particularly important because forest insects and diseases, particularly nonnative invasive agents, are among the most serious threats to the forests of the United States and are causing widespread ecological and economic impacts on the forests of the Nation (Logan and others 2003, Lovett and others 2016, Tobin 2015). Repeated analyses of regularly collected indicator data, such as from the national IDS, enable the detection of trends over time and can help establish a baseline for future comparisons (Riitters and Tkacz 2004).

Although the FHM reports address annual spatial extent and patterns of insect and disease detections (Coulston 2007, 2009; Potter 2012, 2013; Potter and Koch 2012; Potter and Paschke 2013, 2014, 2015a, 2015b, 2016, 2017; Potter and others 2018, 2019c; ch. 2 of this report), there has been no comprehensive medium-term analysis of insect and disease damage to forests in the FHM reports. Understanding these patterns will allow for better broad-scale decision making associated with the management of forests, and for detailed analyses of the ecological impacts of important insect and disease agents. Additionally, medium-term analyses of IDS data represent a highly useful component for the forest disturbance section of the Resources Planning Act (RPA) Assessment, which reports on status and trends of renewable resources on forest and rangelands every 10 years. Previous RPA Assessment reports (USDA Forest Service 2012, 2016) broadly summarized IDS mortality and defoliation data available in annual FHM reports. This chapter presents a more detailed and comprehensive retrospective analysis examining trends in different aspects of forest health in recent decades that will lay the foundation for developing future forest health projections in forthcoming RPA Assessment reports, as well as providing context to annual FHM reports and informing land management planning. Resources Planning Act Assessments summarize some indicators within four broad U.S. regions. These encompass areas that are similar but not identical to those of the five FHM regions (fig. 6.1).

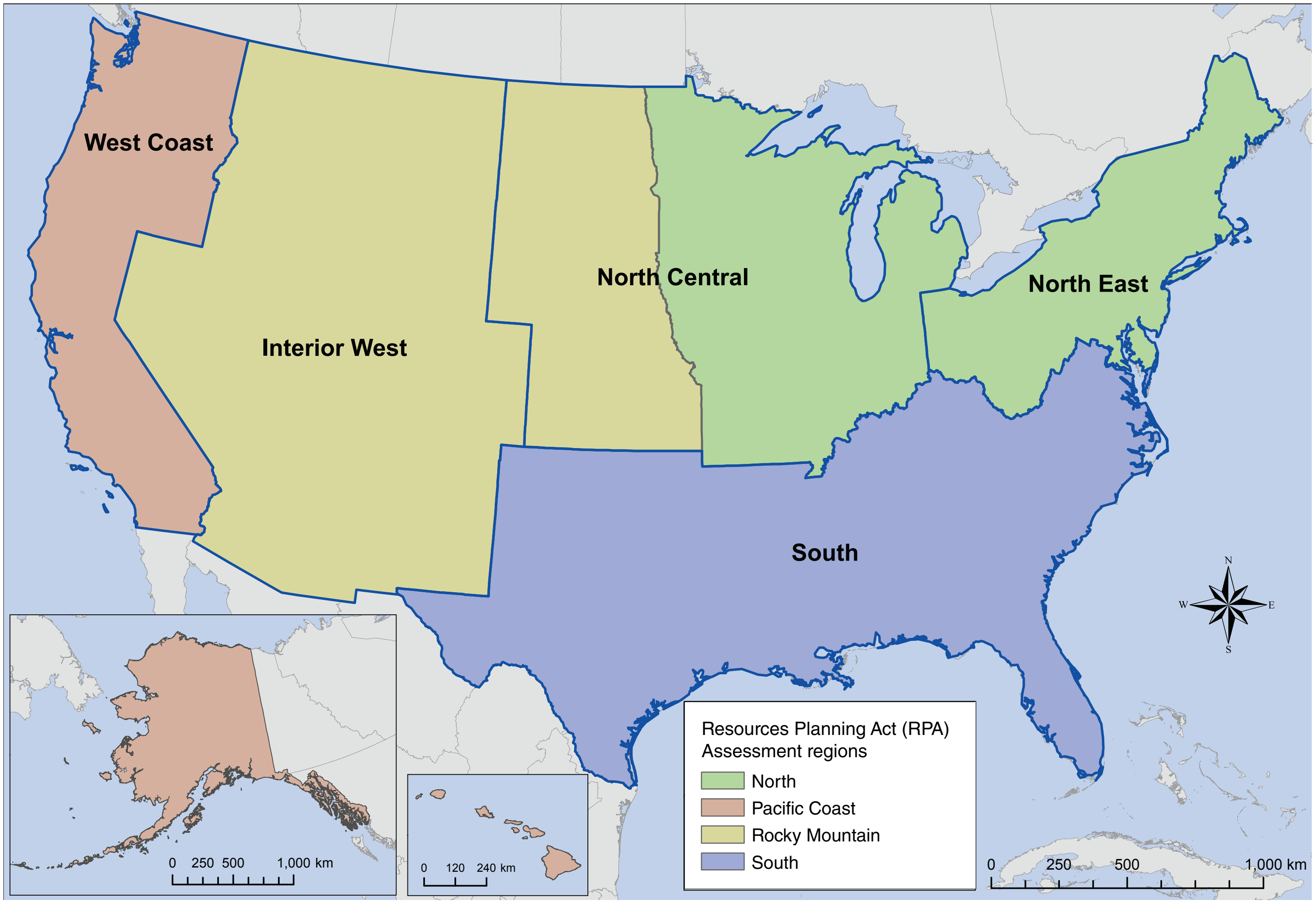


Figure 6.1—Comparison of the Forest Health Monitoring (FHM) and Resources Planning Act (RPA) Assessment regions. The blue lines delineate FHM regions, which are labeled on the map. The RPA Assessment regions are delineated by color, with labels in the legend. Alaska and Hawaii, which are part of the Pacific Coast RPA region, are not shown to scale with map of the conterminous United States.

METHODS

Data

Monitoring the occurrence of forest pest and pathogen activity at regional scales is important because understanding where it occurs, as well as the severity of associated damage, is important for decisions by land managers, including allocation of attention and response to the significant impact insects and diseases can have on forest health across landscapes, including on forest structure, composition, biodiversity, and species distributions (Castello and others 1995). Forest Health Protection national IDS data (FHP 2016, 2019) consist of information on forest disturbances and their causal agents recorded by trained aerial surveyors in low-altitude light aircraft as well as by ground observers. Geospatial IDS data are stored in the national IDS database. On average, the annual surveyed footprint area was 266 655 000 ha nationally for the period from 1999 (the first year that surveyed area was recorded nationally) to 2016, with a maximum of 320 712 000 ha in 2007 and a minimum of 225 928 000 ha in 2012 (fig. 6.2). Within regions, 93 475 000 ha were surveyed on average annually in the North RPA Assessment region, 59 470 000 in the South RPA region, 56 849 000 ha in the Rocky Mountain RPA region, and 55 425 000 ha in the Pacific Coast RPA region. Alaska and Hawaii are a part of the Pacific Coast region, with 14 259 000 ha

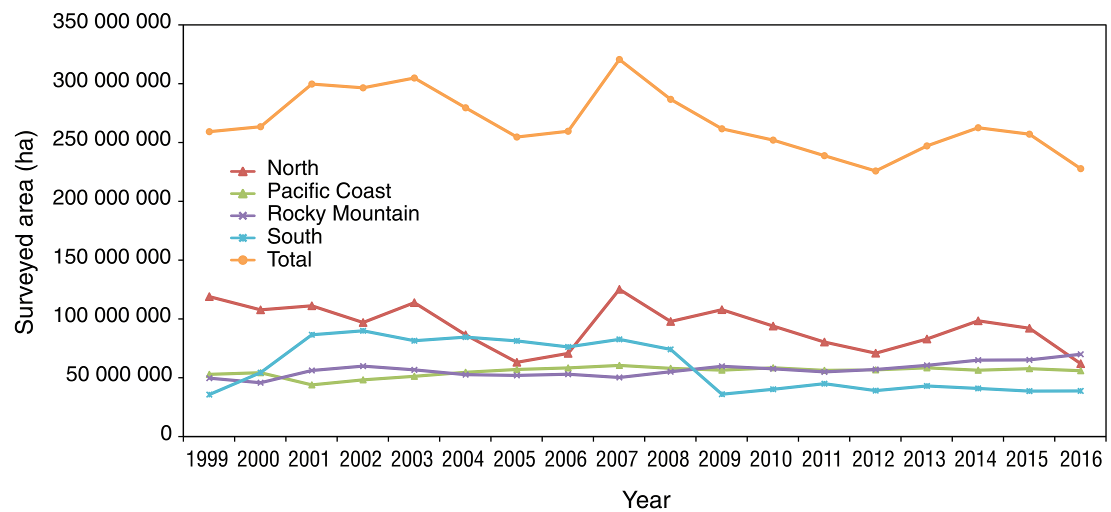


Figure 6.2—National Insect and Disease Survey (IDS) area surveyed by year, nationally and within four Resources Planning Act (RPA) Assessment regions.

surveyed on average each year in Alaska. In Hawaii, approximately 126 000 ha were surveyed in 2013 and 366 000 ha in 2015.

The IDS data identify areas of mortality and defoliation caused by insect and disease activity. Because of the general insect and disease aerial sketch-mapping process (i.e., recording of digital polygons by a human interpreter aboard an aircraft), all quantities are approximate "footprint" areas for each agent, 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 consistently reflected in the estimates of forest area affected. Depending on the level of damage to the forest in a given area and the convergence of other stress factors such as drought, a disease or insect might be considered a mortality-causing agent in one location and a defoliation-causing agent in another. Differences in data collection, attribute recognition, and coding procedures may exist among States and regions.

It is additionally important to note that some important forest insects are not easily detected nor thoroughly quantified through aerial detection surveys because they affect hosts that are widely dispersed throughout highly diverse forests or cause damage that is otherwise hard to detect. These pests include such insects as emerald ash borer (*Agrilus planipennis*) and hemlock woolly adelgid (*Adelges tsugae*), and such diseases as laurel wilt (*Raffaelea lauricola*), Dutch elm disease (*Ophiostoma novo-ulmi*), white pine blister rust (*Cronartium ribicola*), and thousand cankers disease (*Geosmithia morbida*), as well as mortality complexes (such as oak decline). At times, surveyors have drawn large polygons to encompass large or relatively large areas affected by dispersed insect or disease agents across diverse forested landscapes.

Recent years have seen a transition in how the IDS data are collected. Beginning in 2015, surveyors began to switch from the Digital Aerial Sketch Mapping (DASM) approach to the Digital Mobile Sketch Mapping (DMSM) approach (Berryman and McMahan 2019). This transition was complete for the 2018 survey season. The new DMSM approach allows surveyors to both define the extent of an area experiencing damage and to estimate percent range of the area within the polygon that is affected (1–3 percent, 4–10 percent, 11–29 percent, 30–50 percent, and >50 percent). With DMSM, it is therefore possible to generate an adjusted estimate of the area affected by each mortality or defoliation agent detection by multiplying the area of damage within each polygon (after masking by tree canopy cover) by the midpoint of the estimated range of percent affected (Berryman and McMahan 2019). To be consistent with the damage data collected throughout the 1997–2016 analysis window using the older DASM approach, however, DMSM data from 2015 and 2016 were treated as footprints of areas exposed to mortality or defoliation damage. Additionally, the DMSM data collection framework includes both polygon geometry, used for damage areas where boundaries are discrete and obvious from the air,

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. For our analyses, points were assigned an area of 0.8 ha (about 2 acres). Finally, DMSM allows for the use of grid cells (of 240-, 480-, 960-, or 1920-m resolution) to estimate the percent of trees affected by damages that may be widespread and diffuse. When calculating the total areas affected by each damage agent, we used the entire areas of these grid cells (e.g., 240-m cell = 5.76 ha).

Analyses

To examine medium-term trends in insect and disease damage to the forests of the United States, we organized and analyzed 20 years of IDS data, then produced an assessment of trends in forest area exposed to insects and disease in multiple timeframes and within the four RPA Assessment regions (fig. 6.1). This was done annually, in four 5-year time windows (1997–2001, 2002–2006, 2007–2011, and 2012–2016), and in two 10-year windows (1997–2006, 2007–2016). We chose 1997–2016 as the analysis period because it offered a 20-year window of time that was convenient for analysis and generally avoided complications associated with the switch from the DASM to the DMSM damage data collection framework.

Using ArcMap® (ESRI 2015), we assembled spatial data from the IDS database separately for mortality and for defoliation damage annually for each of the years from 1997 to 2016. For mortality, we further sorted the damage data into those attributed to insects versus those caused by diseases, those within each of three insect guilds, and those that were the result of infestation by nonnative invasive species and those that were not. Nonnative invasive species are defined as those with origins outside the United States. The insect agent guild assignments (foliage feeders, phloem- or wood-borers [hereafter referred to as "bark beetles"], and sap feeders) were based on Liebhold and others (2013). For defoliation, we sorted the damage data into those attributed to insects and those associated with diseases, and into those caused by nonnative invasive species and those that were not. The IDS database includes reports of general tree species declines (e.g., "oak decline" or "yellow-cedar decline"), but we did not include those in this set of analyses because the causes of declines are generally uncertain or complex and can be at least in part the result of abiotic factors. The IDS data additionally include some agents called "multi-agent complexes" because they include both a disease agent and one or more insect vectors (such as "beech bark disease complex" and "root disease and beetle complex" [formerly "subalpine fir mortality complex"]). For our purposes, we classified these as diseases. Finally, the IDS damage codes were revised in 2015 (and first used in the field the following year) to include new agents, reclassify agents into appropriate categories, and correct agent names. We adjusted our classifications of the data from before 2016 to reflect these changes.

We derived spatial footprints for each combination of damage type and group of agents for each year by dissolving the relevant damage polygons in ArcMap® (ESRI 2015). We next merged the dissolved data within temporal windows (5-year: 1997–2001, 2002–2006, 2007–2011, and 2012–2016, and 10-year: 1997–2006, 2007–2016) and dissolved the datasets again. Finally, we intersected these datasets with tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. The tree canopy data were resampled to 240 m from a 30-m raster dataset that estimates percent tree canopy cover (from 0 to 100 percent) for each grid cell; this dataset was generated from the 2011 National Land Cover Database (NLCD) (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). We treated any cell with >0 percent tree canopy cover as forest. Comparable tree canopy cover data were not available for Alaska, so we instead created a 240-m-resolution layer of forest and shrub cover from the 2011 NLCD. The data also were intersected with the RPA Assessment regions (fig. 6.1) to allow for broad regional comparisons.

RESULTS AND DISCUSSION

Mortality

Our analyses focused on determining the footprint of treed area affected by insect and disease agents within four 5-year and two 10-year increments based on IDS detections of agents of tree mortality and defoliation. We elected to report only the 5-year results here because of their higher temporal resolution. Across all insect and disease agents nationally, the treed area exposed to mortality-causing agents was relatively low, about 3.1 million ha, for the first 5-year period (1997–2001), followed by a dramatic increase to 14.2 million ha for the next period (2002–2006) and a subsequent decline over the last two intervals (9.9 million ha for 2007–2011 and 6.9 million ha for 2012–2016) (fig. 6.3A, table 6.1).

The peak for 2002–2006 is explained in part by the large polygons used to delineate diffuse emerald ash borer mortality in Michigan in 2004, 2005, and 2006 and balsam woolly adelgid (*Adelges piceae*) mortality in the balsam fir (*Abies balsamea*) forests of Maine in 2006 (Potter and Koch 2012). This is additionally reflected in the regional mortality footprint for the North region (fig. 6.4, table 6.1). Other than the 2002–2006 period, mortality was relatively low in the North, as it was in the South. The mortality footprints in both the Rocky Mountain and Pacific Coast regions were comparatively large, with the peak for the Rocky Mountain region occurring in the 2007–2011 interval, reflecting the particularly high impacts of bark beetles, especially mountain pine beetle (*Dendroctonus ponderosae*) during 2008, 2009, and 2010 (Potter 2012, 2013; Potter and Paschke 2013). Meanwhile, the Pacific Coast region had dual peaks during the 2002–2006 and 2012–2016 periods. Fir engraver (*Scolytus ventralis*) and western pine beetle (*Dendroctonus brevicomis*)

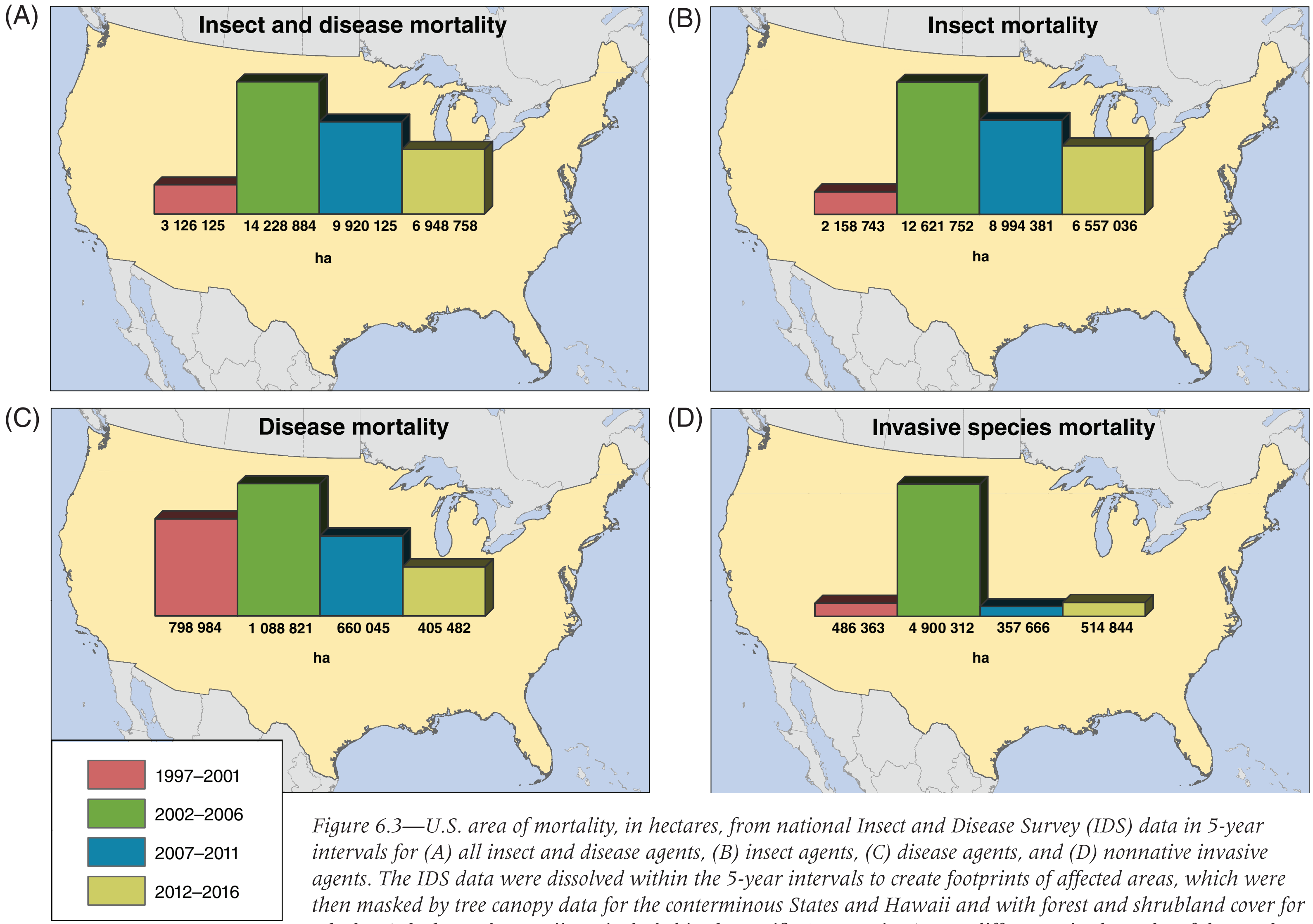


Figure 6.3—U.S. area of mortality, in hectares, from national Insect and Disease Survey (IDS) data in 5-year intervals for (A) all insect and disease agents, (B) insect agents, (C) disease agents, and (D) nonnative invasive agents. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.) Note differences in the scales of the results among the different groups of agents.

Table 6.1—Mortality attributed to three different insect guilds and to diseases from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) assessment regions and in 5-year intervals

		Area of mortality				
		RPA Region				
Agent	Years	North	Pacific Coast	Rocky Mountain	South	Total area of mortality
		ha				ha
Bark beetles	1997–2001	279	883 943	1 098 548	63 829	2 046 598
	2002–2006	1 824 430	2 263 292	4 522 989	69 796	8 680 507
	2007–2011	330 115	2 056 066	6 192 061	8635	8 586 878
	2012–2016	359 719	3 479 449	2 569 319	14 167	6 422 653
Foliage feeders	1997–2001	2914	14 582	22	0	17 517
	2002–2006	65 491	9200	32	75 876	150 599
	2007–2011	220 752	2120	0	10 251	233 122
	2012–2016	28 129	0	63	0	28 192
Sap feeders	1997–2001	485	3718	38 611	0	42 814
	2002–2006	2 627 102	3883	18 446	6395	2 655 826
	2007–2011	11 574	32 114	4711	11 908	60 307
	2012–2016	28 676	14 106	31 139	1795	75 717
Diseases	1997–2001	348 374	9520	440 394	697	798 984
	2002–2006	256 689	18 406	811 649	2077	1 088 821
	2007–2011	111 175	31 947	516 922	2	660 045
	2012–2016	74 212	96 171	234 723	376	405 482
Total	1997–2001	416 860	976 172	1 667 836	65 257	3 126 125
	2002–2006	4 807 773	3 579 073	5 687 672	154 366	14 228 884
	2007–2011	705 573	2 241 977	6 941 753	30 822	9 920 125
	2012–2016	510 420	3 608 089	2 806 249	24 001	6 948 758

Note: All values are "footprint" areas masked by treed canopy area. The sum of different types of agents may not equal the total within regions for a reporting period because of overlapping polygons of different types of damage.

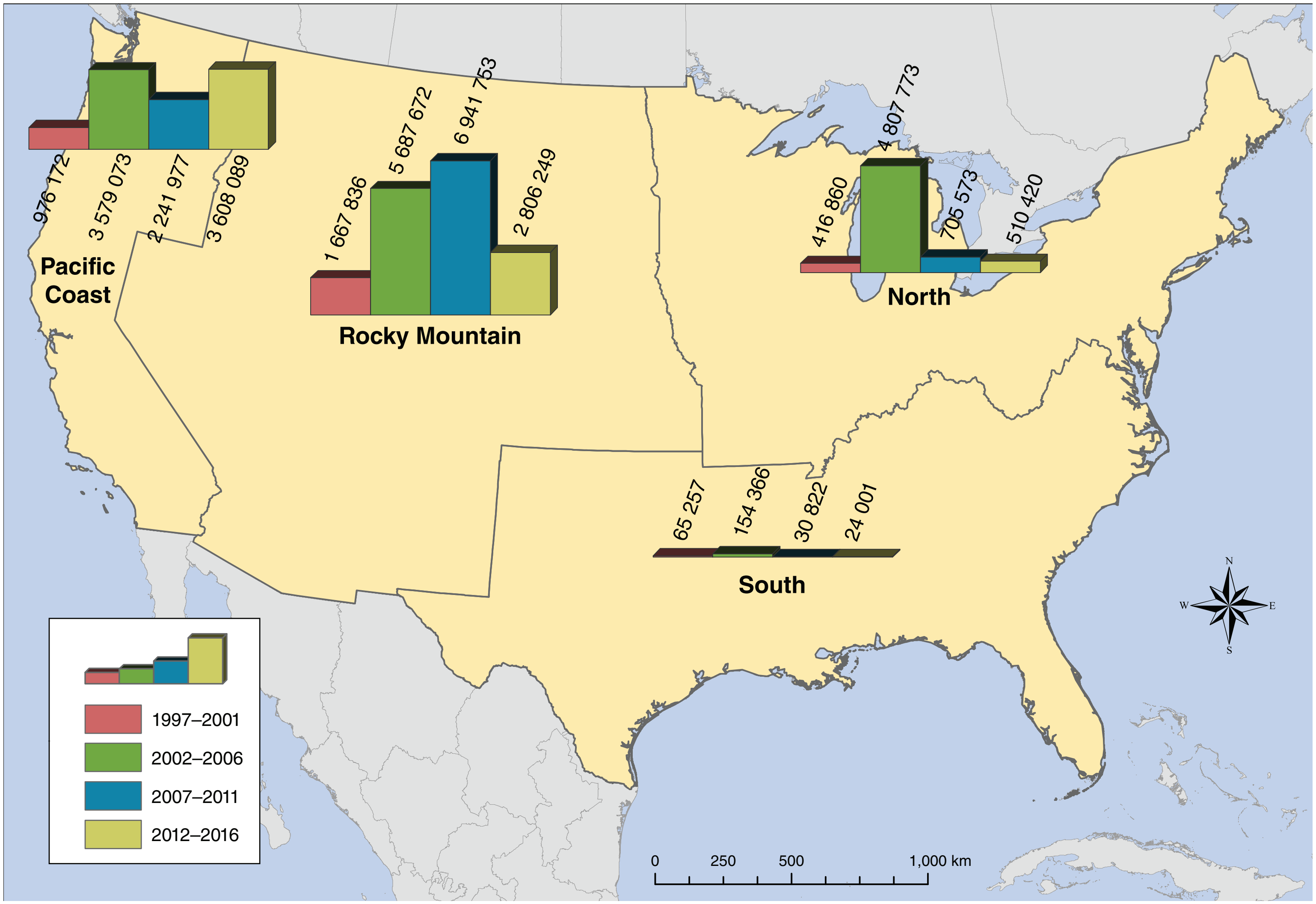


Figure 6.4—Area of mortality, in hectares, attributed to both insect and disease agents from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

were particularly damaging in 2015 and 2016, leading to the latter peak (Potter and Paschke 2017, Potter and others 2018). Bark beetles also were the main contributors to the earlier peak (Coulston 2007, 2009). Because the large majority of all mortality was caused by insects (between 69 and 94 percent across the four 5-year periods nationally, with similar regional percentages), the 5-year footprints of insect mortality were similar to the footprints across all agents, both nationally (fig. 6.3B) and regionally (fig. 6.5). The 2002–2006 timeframe represented the peak of insect-caused mortality nationally, with mortality recorded on approximately 12.6 million ha of treed area.

As with insect-related mortality, the tree canopy area exposed to disease-caused mortality also was highest during the 2002–2006 period with approximately 1.1 million ha (fig. 6.3C), though this was <8 percent of the total area of recorded mortality during this timeframe. Much of the disease mortality was associated with subalpine fir (*Abies lasiocarpa*) mortality complex, which was used to document mortality caused by the interaction of root diseases (primarily those caused by *Armillaria* spp.) and infestation by western balsam bark beetle (*Dryocoetes confusus*) in spruce/fir forest types.[1] This resulted in the Rocky Mountain region having the greatest area of mortality attributed to disease agents in each of the 5-year periods, with the maximum in 2002–2006 (fig. 6.6). During that timeframe, oak wilt (*Ceratocystis fagacearum*) was a widespread issue repeatedly in the North and during 2005 in the South, while large areas of beech bark disease infestations were identified in 2002 and 2003 in the North. Nationally, disease mortality increased from about 800 000 ha in 1997–2001 to the 1.1 million-ha peak in 2002–2006, which was then followed by declines over the next two reporting periods, to about 660 000 ha in 2007–2011 to 400 000 ha in 2012–2016. This was also the pattern in the Rocky Mountain region, but the Pacific Coast region saw a modest increasing trend over time while the North had a steady decline (fig. 6.6). For the Pacific Coast region, this is attributable to the combination of an increase in sudden oak death mortality of tanoak (*Notholithocarpus densiflorus*) in northern California and southwestern Oregon caused by the pathogen *Phytophthora ramorum*, and the 2015 and 2016 detection in Hawaii of rapid ‘ōhi‘a death (Potter and Paschke 2015a, 2015b, 2016, 2017; Potter and others 2018). Rapid ‘ōhi‘a death, a wilt disease caused by the fungal pathogens *Ceratocystis lukuohia* and *C. huliohia* (Barnes and others 2018), affects ‘ōhi‘a lehua (*Metrosideros polymorpha*), a highly ecologically and culturally important tree in Hawaiian native forests (University of Hawai‘i 2019). For the North, meanwhile, detections of beech bark disease, which is the primary disease mortality agent in the region, has declined in recent years. Meanwhile, very little disease mortality was reported in the South during any of the reporting intervals.

[1] In 2015, the “subalpine fir mortality complex” aerial survey damage agent code was retired and replaced with “root disease and beetle complex.” It was primarily used in Forest Service Region 2.

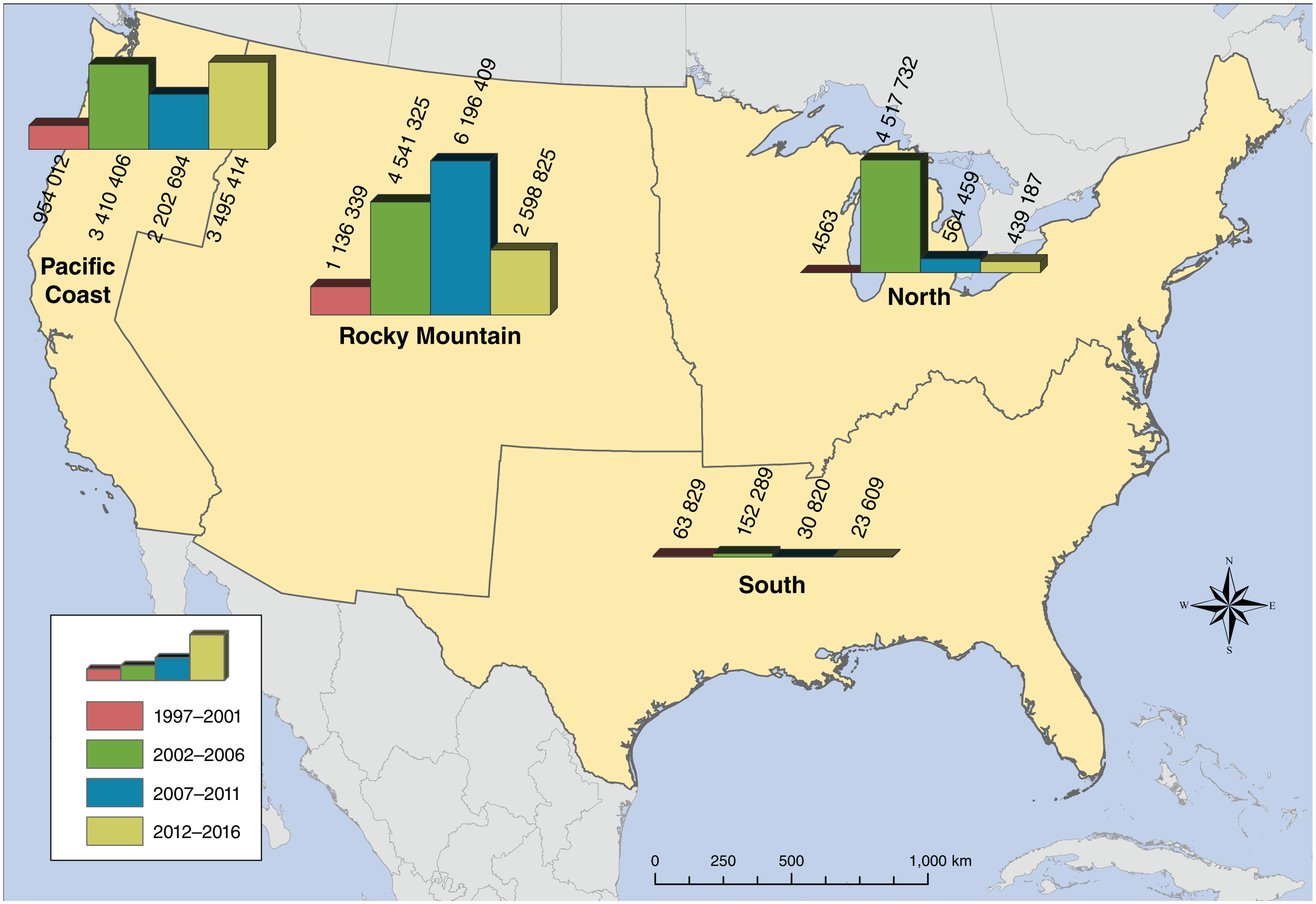


Figure 6.5—Area of mortality, in hectares, attributed to insect agents from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

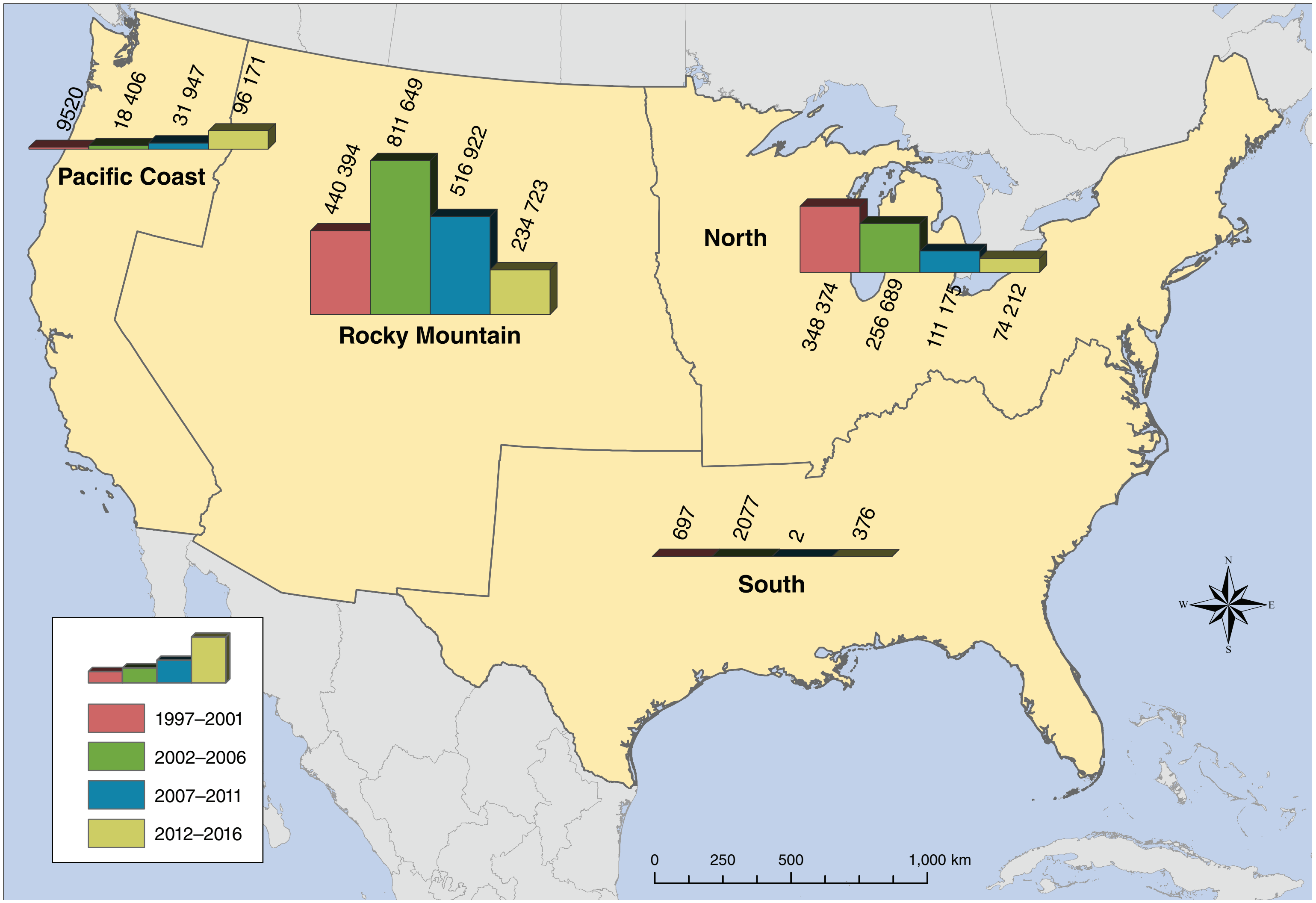


Figure 6.6—Area of mortality, in hectares, attributed to disease agents from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

The amount of treed area exposed to nonnative invasive mortality agents nationally was generally about half a million ha during the 5-year reporting periods, with the exception of 2002–2006 (fig. 6.3D). As noted above, surveyors delineated large polygons of diffuse mortality associated with balsam woolly adelgid in Maine in 2006 and with emerald ash borer in Michigan in 2004, 2005, and 2006. Both of these are nonnative invasive insects, so this resulted in a tenfold increase in the amount of detected forest mortality attributed to invasive species. Nationally, the proportion of the total mortality footprint associated with invasive insects and diseases decreased from 14.8 percent in 1997–2001 and 34.4 percent in 2002–2006 to 3.6 percent in 2007–2011 and 7.4 percent in 2012–2016. Among the RPA Assessment regions, only in the North was a large proportion of the 5-year mortality footprints consistently attributed to nonnative invasive agents (fig. 6.7). This ranged from 35.1 percent in 2007–2011 (when outbreaks of several native insects occurred) to 98.5 percent in 2002–2006. The suite of agents associated with this mortality has evolved over time in the North. In the first assessment period (1997–2001), the most commonly detected invasive agents were beech bark disease, European gypsy moth (*Lymantria dispar dispar*), oak wilt, and hemlock woolly adelgid. In the second and third assessment periods (2002–2006 and 2007–2011), these agents were joined by balsam woolly adelgid, emerald ash borer, and Dutch elm disease, with emerald ash borer detected in an increasingly large number of States. This emerald ash borer trend continued for the final period (2012–2016), and a single new invasive agent, red pine scale (*Matsucoccus resinosae*), was detected. In the South, relatively small areas and percentages of invasive agents (specifically, hemlock woolly adelgid and oak wilt) were detected during the first two assessment periods (1.1 percent and 5.5 percent). These increased in the final two periods (71.8 percent and 21.9 percent) as hemlock woolly adelgid was more widely identified and as emerald ash borer was included in the aerial survey data for the first time in 2016. Invasive agents were the cause of only a very small proportion of the mortality footprint area in the two western regions (between 0.3 percent and 7.2 percent in the Rocky Mountain region and between 0.7 percent and 3.0 percent in the Pacific Coast region). In the Rocky Mountains, either balsam woolly adelgid or white pine blister rust was detected every year, with both found in some years. In the Pacific Coast region, meanwhile, Port-Orford-cedar root disease (*Phytophthora lateralis*) was detected every year, and sudden oak death was found annually beginning in 2008. Mortality attributed to balsam woolly adelgid was also found in most years, and rapid ʻōhiʻa death was detected in Hawaii in 2015 and 2016.

When comparing the relative importance of agents categorized in one of three insect feeding guilds (foliage feeders, bark beetles, and sap feeders) or as diseases, bark beetles nationally encompassed the largest area (table 6.1) and proportion of treed mortality area during each of the four assessment periods: 65.5 percent

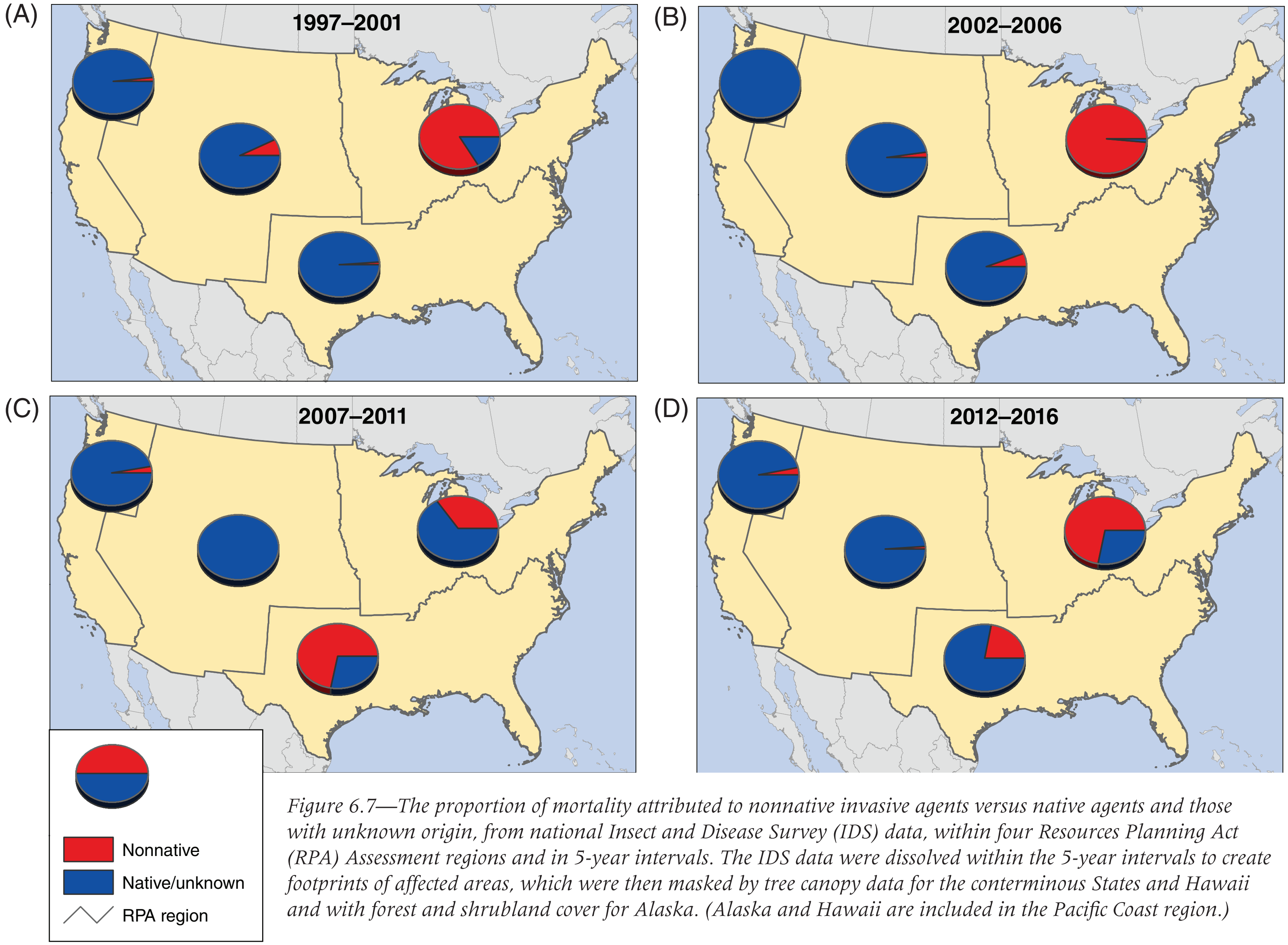


Figure 6.7—The proportion of mortality attributed to nonnative invasive agents versus native agents and those with unknown origin, from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

for 1997–2001, 61.0 percent for 2002–2006, 86.6 percent for 2007–2011, and 92.4 percent for 2012–2016. The only period during which another guild accounted for >10 percent of the treed mortality area was 2002–2006, which included the large polygons of diffuse mortality associated with balsam woolly adelgid, a sap feeder. Sap feeders represented 18.7 percent of detected mortality area that period. Otherwise, sap feeders and foliage feeders accounted for a very small amount of mortality. During most intervals, diseases were the second most widely detected nationally (5.8 to 25.6 percent).

In the two western regions (Pacific Coast and Rocky Mountain), bark beetles make up the large majority of mortality detected in all the 5-year intervals (fig. 6.8, table 6.1). The proportion of mortality associated with diseases in the Rocky Mountain region was relatively high (7.4 percent to 26.4 percent), attributed to subalpine fir mortality complex and, to a lesser degree, white pine blister rust. Bark beetles also encompassed an increasingly large proportion of the mortality in the North over time, reflecting the increasing extent and impact of emerald ash borer and, to much lesser degree, of eastern larch beetle (*Dendroctonus simplex*). (Almost all of the mortality in the North during the first 5-year period was associated with disease, specifically beech bark disease, while the majority of the 2002–2006 mortality was associated with balsam woolly adelgid, a sap feeder.) Bark beetles were important in the South in the first and last assessment periods, and to a lesser degree in the second period, because of southern pine beetle (*Dendroctonus frontalis*) infestations. During 2007–2011, foliage feeders had a relatively large mortality footprint in the South because of a severe gypsy moth infestation in Virginia. Infestation of hemlock woolly adelgid in the Southern Appalachians resulted in a relatively large sap feeder footprint during that same timeframe as well as the following one (2012–2016).

It is worth noting that forest mortality (as well as defoliation) may be underrepresented in the South in these datasets. This is partly due to the heterogeneity of the landscape, more intense management cycles (particularly pine plantations), and higher growth and decay rates leading to more rapid forest recovery after disturbance and, ultimately, signatures that are less persistent and more difficult to detect during aerial surveys. For example, mortality from southern pine beetle is notably underrepresented during the 1997–2001 and 2002–2006 time periods, which coincided with the second largest outbreak of this insect since 1960 that culminated in almost 400 000 ha of damaged timber and over $1 billion in economic losses (Nowak and others 2008). The FHM program traditionally records southern pine beetle infestations as “spots” of activity, often before these spots expand and envelop larger areas. Furthermore, the availability of markets often leads to rapid response in the form of salvage clearcutting, thinning, and clearcutting ahead of an active spot to disrupt it from further expansion. Thus, ubiquitous management regimes across the South routinely limit

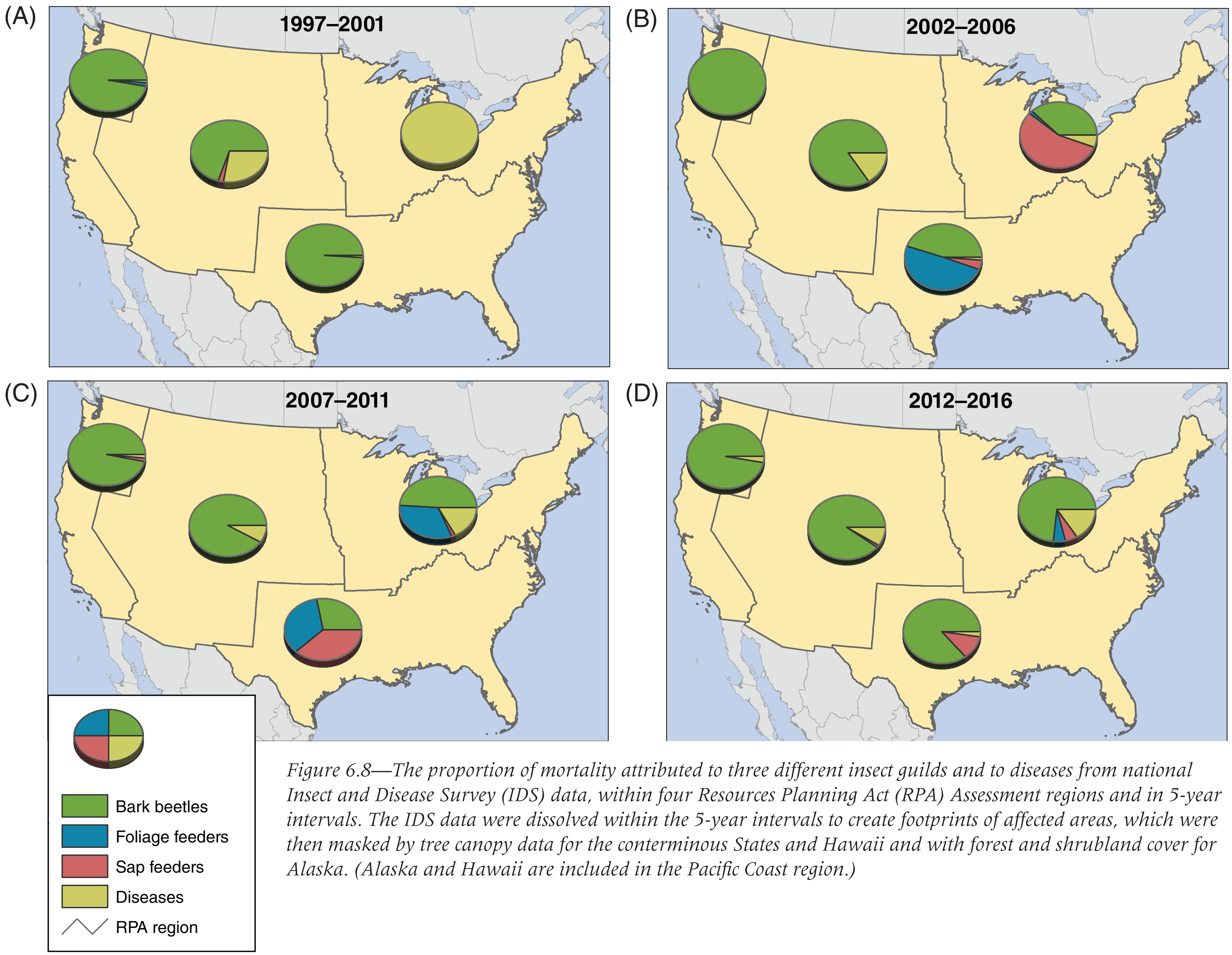


Figure 6.8—The proportion of mortality attributed to three different insect guilds and to diseases from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

bark beetle mortality to small areas with short-lived disturbance signatures. Typically, the impact of bark beetles in the region is much larger than what is reflected in outright beetle-induced mortality because many more healthy trees end up being cut to disrupt the expansion of a spot infestation or as part of salvage sales.

Defoliation

In addition to mortality, the IDS data include the spatial extent and putative causal agents of forest defoliation. The area affected by defoliation in most 5-year windows exceeded that affected by mortality and was relatively consistent over time: 13.2 million ha in 1997–2001, 11.0 million ha in 2002–2006, 9.7 million ha in 2007–2011, and 11.4 million ha in 2012–2016 (fig. 6.9A).

Regionally, the North experienced the most defoliation for the first two timeframes, but the defoliation footprint there declined across assessment periods while the area of defoliation grew in the Rocky Mountains in the final two assessment windows (fig. 6.10). The earlier defoliation in the North was attributed to a variety of agents, the most commonly detected of which included forest tent caterpillar (*Malacosoma disstria*), mostly in quaking aspen (*Populus tremuloides*) stands in the Great Lakes States and later in New England hardwood stands; gypsy moth in oak (*Quercus* spp.) and other hardwood stands in the Northeast; spruce budworm (*Choristoneura fumiferana*) in white spruce (*Picea glauca*) and balsam fir forests in Great Lakes States; large aspen tortrix (*Choristoneura conflictana*) in Great Lakes States; and jack pine budworm (*Choristoneura pinus*) in jack pine (*Pinus banksiana*) and fir stands in Michigan. Defoliation area during the first assessment periods was inflated somewhat by large polygons of diffuse defoliation, including forest tent caterpillar in northern Wisconsin, northern Minnesota, and the Upper Peninsula of Michigan, and locust leafminer (*Odontota dorsalis*) in southern Indiana in 2001. In the later assessment periods, gypsy moth was often a widely detected agent in the Northeast, along with a suite of other defoliators that included forest tent caterpillar, winter moth (*Operophtera brumata*), fall cankerworm (*Alsophila pometaria*), and oak leafroller (*Archips semiferana*), while spruce budworm and forest tent caterpillar were often widely detected in the Great Lakes States, along with jack pine budworm, large aspen tortrix, and several other agents.

In the Rocky Mountains, meanwhile, the large majority of defoliation has been caused by western spruce budworm, with particularly large outbreaks in recent years (Potter and Paschke 2015a, 2015b, 2016, 2017; Potter and others 2018). During the earlier assessment periods, these outbreaks were only identified in the southern Rockies, but they began also to be detected in the northern Rockies beginning in 2002 and 2003, becoming more widespread there in later assessment periods while continuing in the southern Rockies. In the South, the area on which defoliation was recorded was relatively small for the first three 5-year periods but increased by >400 percent in the final period relative to the average for the previous windows (fig. 6.10). This was the result of large polygons of diffuse fall cankerworm defoliation in eastern Virginia in 2012 and 2013 and of yellow poplar

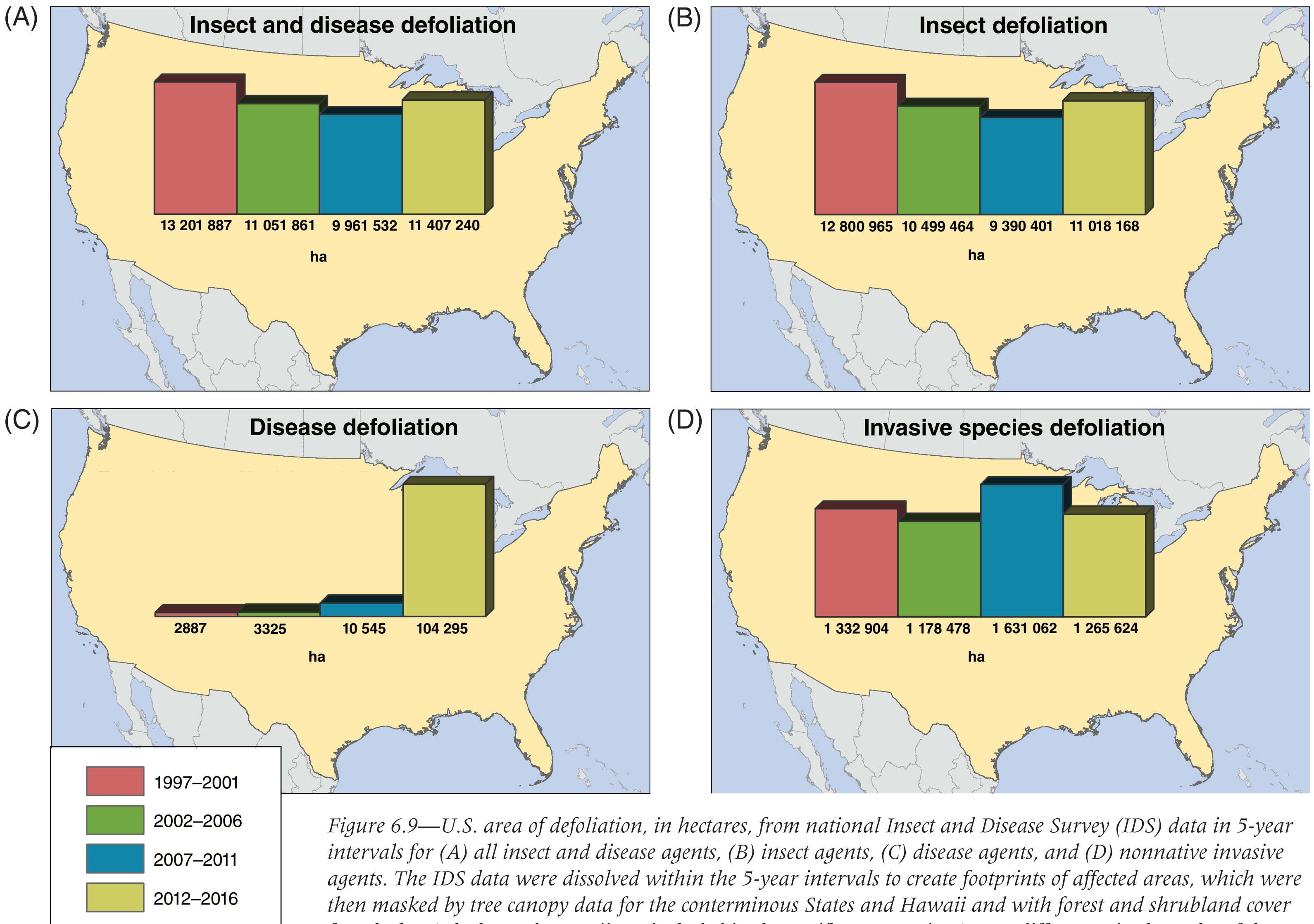


Figure 6.9—U.S. area of defoliation, in hectares, from national Insect and Disease Survey (IDS) data in 5-year intervals for (A) all insect and disease agents, (B) insect agents, (C) disease agents, and (D) nonnative invasive agents. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.) Note differences in the scales of the results among the different groups of agents.

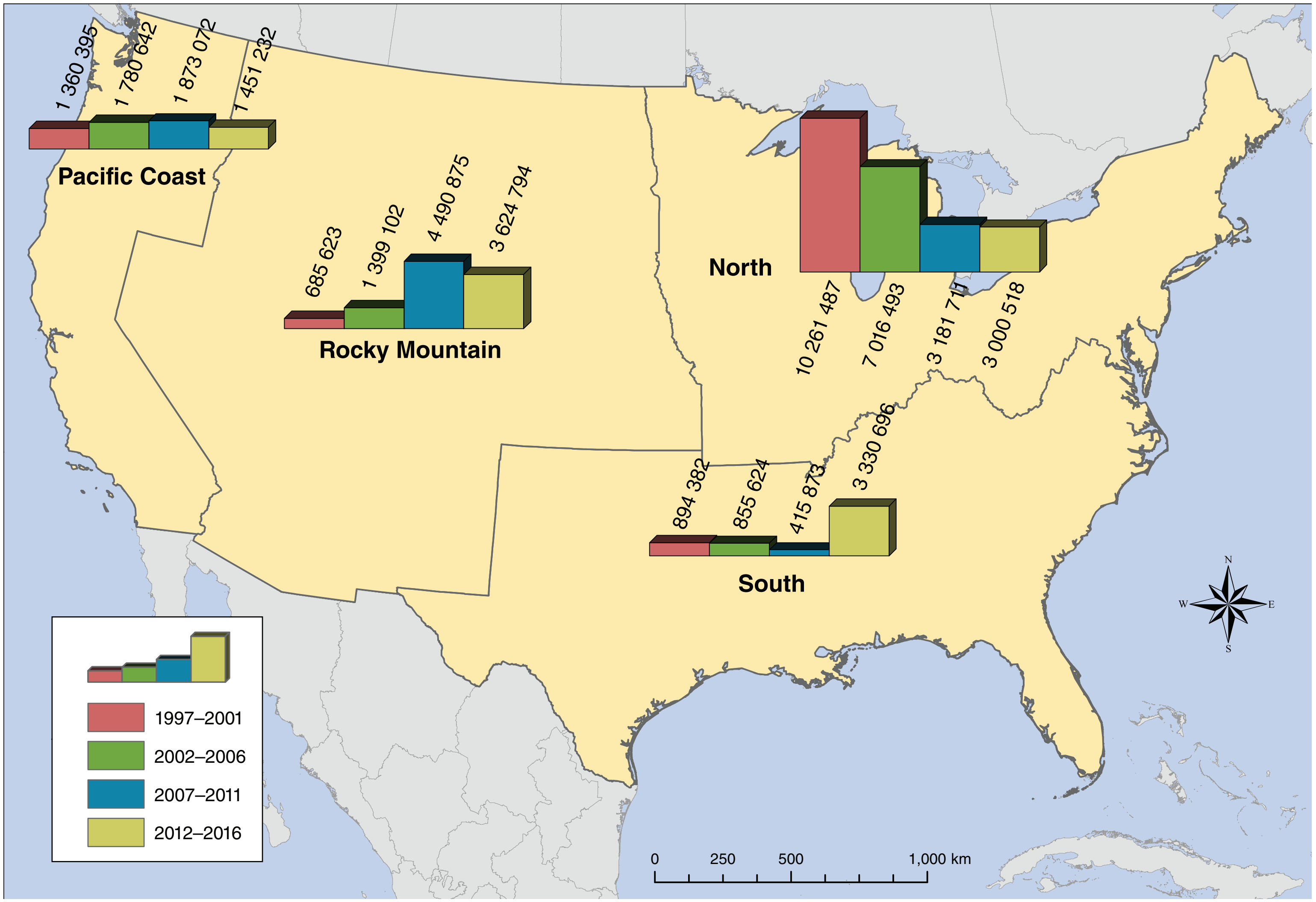


Figure 6.10—Area of defoliation, in hectares, attributed to both insect and disease causes from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

weevil (*Odontopus calceatus*) in western North Carolina in 2015. Across the 20 years of IDS data, forest tent caterpillar was consistently widely recorded across large areas of the South, particularly in Louisiana and South Carolina. Leafrollers (baldcypress leafrollers [*Archips goyerana*] after 2004 and fruittree leafrollers [*Archips argyrospila*] before that) were consistently detected in Louisiana baldcypress (*Taxodium distichum*) stands. Gypsy moth was regularly recorded in hardwood forests of Virginia from 2001 to 2009.

Finally, a moderate level of defoliation was recorded consistently in the Pacific Coast region across the four 5-year timeframes. In most years, the majority of the defoliation in the region was detected in Alaska. This defoliation was attributed to a variety of causal agents, with aspen leafminer (*Phyllocnistis populiella*) the agent most widely detected in many years. Other common defoliators included willow leaf blotchminer (*Micrurapteryx salicifoliella*) in willows, larch sawfly (*Pristiphora erichsonii*) in western larch (*Larix occidentalis*), and spruce aphid (*Elatobium abietinum*) in Sitka spruce (*Picea sitchensis*). Meanwhile, in the three conterminous States included in the Pacific Coast region, defoliation by western spruce budworm was commonly delineated in Washington State, with especially large infestations in 2011 and 2012. Swiss needlecast (caused by the pathogen *Phaeocryptopus gaeumannii*) was an issue for Douglas-fir (*Pseudotsuga menziesii*) in both Oregon and Washington during early years of IDS data collection, while larch casebearer (*Coleophora laricella*) was often detected in Oregon. A very extensive outbreak of pine butterfly (*Neophasia menapia*) occurred in ponderosa pine (*Pinus ponderosa*) stands in eastern Oregon in 2011 and, to a lesser degree, in 2012.

The large majority of defoliation nationally across the assessment periods was attributed to insects (fig. 6.9B) rather than diseases (fig. 6.9C). The amount of insect defoliation was consistent across time, while disease defoliation was mostly negligible until the 2012–2016 timeframe, when it increased tenfold from 2007–2011. The increase in the detection of disease defoliation occurred in three of the four RPA Assessment regions, with the exception of the South. In the North, this was the result of an infestation of white pine needle damage in 2016 along with an outbreak of anthracnose in 2013. Surveyors in recent years also detected Lophodermium needle cast (*Lophodermium* spp.) in Oregon and Washington ponderosa pine stands in the Pacific Coast region and Marssonina blight (*Drepanopeziza* spp.) in quaking aspen stands of the northern Rocky Mountain region. Meanwhile, regional patterns of insect defoliation (not shown) largely matched those of total defoliation (fig. 6.10).

The amount of defoliation attributable to nonnative invasive species was largely consistent across reporting periods, ranging between 1.2 million ha and 1.6 million ha (fig. 6.9D). Nationally, invasive agents accounted for 10.4 percent of defoliated area in 1997–2001, 11.2 percent in 2002–2006, 17.4 percent in 2007–2011, and 11.5 percent in 2012–2016. Invasive defoliating agents were more important in the

East than in the West, particularly in the North region, where invasive agents accounted for a greater share of defoliation in recent periods (48.1 percent and 42.9 percent) compared to the first two timeframes (11.2 percent and 15.7 percent) (fig. 6.11). Gypsy moth was a major invasive defoliating agent throughout much of the North in all four periods. Other important agents were winter moth in the Northeast, larch casebearer in tamarack (*Larix laricina*) stands of the Great Lakes States, birch leafminer (*Fenusa pusilla*) in New England, and balsam woolly adelgid in Maine (especially in 2002–2006). The South exhibited relatively high proportions of invasive defoliators for the first three timeframes (8.4 percent to 20.0 percent), mostly the result of gypsy moth detections in Virginia. A small percentage of defoliation in the Pacific Coast region (0.3 percent to 3.8 percent) was the result of invasive agents, specifically larch casebearer affecting western larch in Oregon and Washington, and birch leafminer in Alaska. Less than 1 percent of defoliation in the Rocky Mountain region was ever attributed to invasive agents.

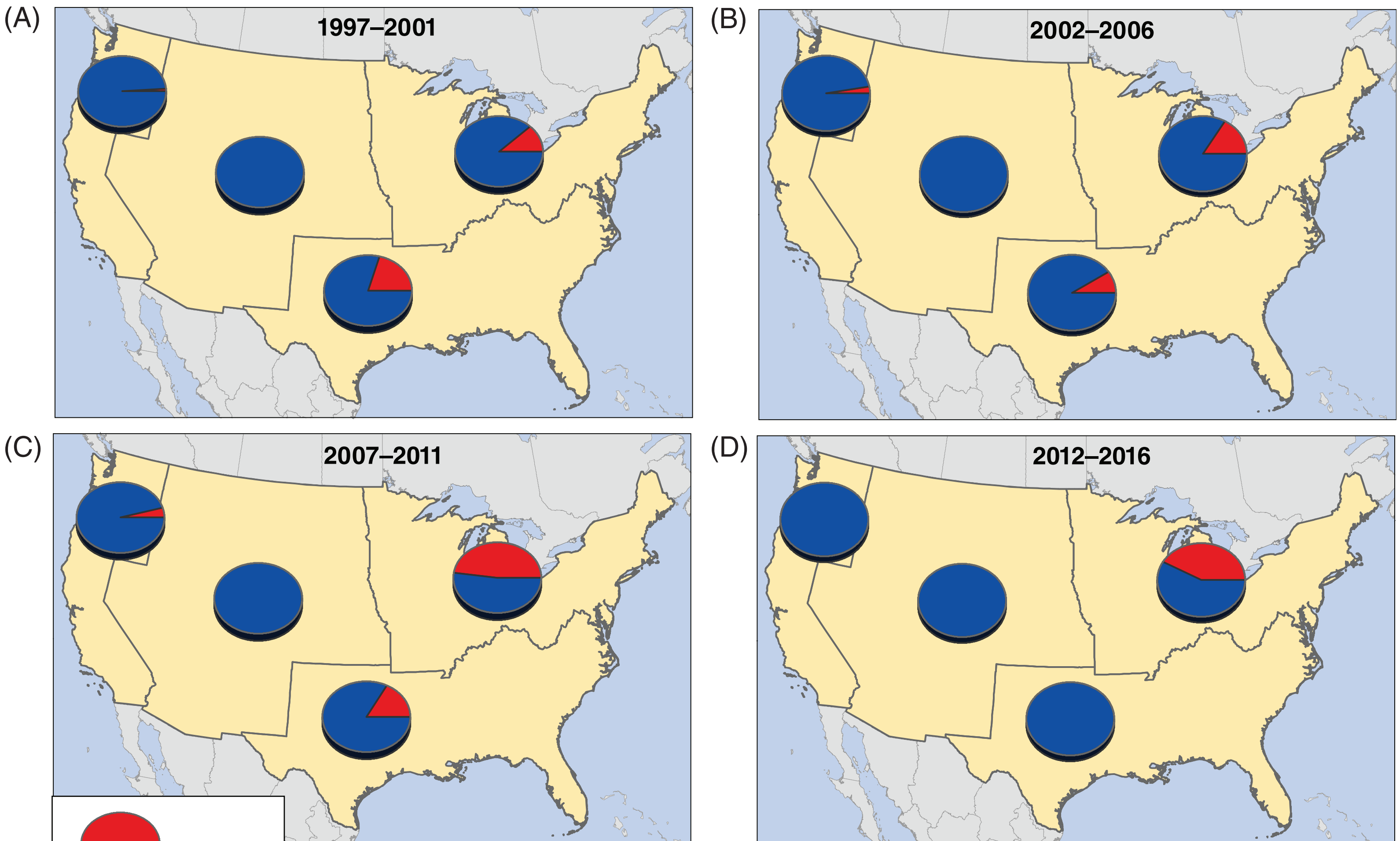
CONCLUSIONS

Insects and diseases affect a variety of aspects of forest structure and function and can be considered either negative or positive depending on management objectives (Edmonds and others 2011). Generally, mortality by insects and diseases that exceeds baseline conditions is considered undesirable and unhealthy. Nearly all native tree species of the conterminous United States are affected by at least one harmful insect or disease agent, with invasive insects and diseases on average considerably more severe than native ones (with some important exceptions such as native bark beetles) (Potter and others 2019a) and most likely to negatively affect the genetic integrity of the host species they infest (Potter and others 2019b).

This chapter presents results from a national retrospective analysis of pest and pathogen detections using annual data from the FHP national IDS. Specifically, the project aims to evaluate trends in the extent, severity, and periodicity of major insect and disease threats, providing context for the annual FHM reports. Understanding these trends will allow for future analyses that focus on developing better attribution of tree mortality and volume loss to the corresponding threats, as well as generating future forest health impact projections. Incorporating these products into the national RPA Assessment will allow for analyses within a framework of social and economic trends and projections.

Key findings of this overview of 20 years of IDS data include:

- The tree canopy area affected by mortality agents has been consistently large across the three most recent 5-year assessment periods, with the most mortality reported in 2002–2006.



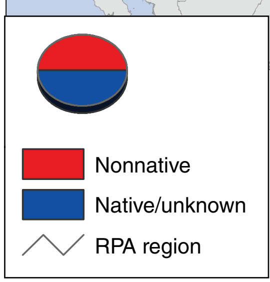


Figure 6.11—The proportion of defoliation attributed to nonnative invasive agents versus native agents and those with unknown origin, from national Insect and Disease Survey (IDS) data, within four Resources Planning Act (RPA) Assessment regions and in 5-year intervals. The IDS data were dissolved within the 5-year intervals to create footprints of affected areas, which were then masked by tree canopy data for the conterminous States and Hawaii and with forest and shrubland cover for Alaska. (Alaska and Hawaii are included in the Pacific Coast region.)

- The four RPA Assessment regions exhibit different temporal patterns of area exposed to mortality: the North had the most in 2002–2006, the Pacific Coast had mortality peaks in 2002–2006 and 2012–2016, the Rocky Mountains had the most mortality in 2007–2011 followed by 2002–2006, and the South had comparatively limited areas exposed to mortality.
- Insects have been much more widespread agents of mortality than diseases, with bark beetles consistently the most important mortality agents across regions and over time, especially in the West.
- The tree canopy area affected by defoliation agents has remained relatively consistent over time and has usually exceeded or equaled the area affected by mortality agents.
- Insects are much more important agents of defoliation, but disease defoliation increased markedly during the final 5-year assessment period.
- Nonnative invasive insects and diseases had a larger relative impact on forests in the North, through both mortality and defoliation, than elsewhere in the United States. At the same time, nonnative invasive agents are having significant impacts elsewhere as well, including Hawaii, where rapid ‘ōhi‘a death is causing considerable mortality to one of the State’s most ecologically and culturally important tree species.
- Nationally, the tree canopy area affected by invasive agents of mortality and defoliation has remained relatively consistent over time.
- The use of large polygons to encompass broad areas of diffuse damage complicates the interpretation of mortality and defoliation spatial data. Newer aerial survey protocols are likely to avoid these problems (Berryman and McMahan 2019), but appropriately incorporating these large polygons from earlier survey efforts may present a challenge.

By looking across different threats to forest health over time, this retrospective analysis addresses forest mortality and defoliation, as well as the impacts of invasive species. Evaluating trends in these threats at a national scale provides context to managers attempting to understand the implications and scope of current forest health threats. Future projections will provide managers with information to assist in land management planning and decision making.

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