

INTRODUCTION

Tree mortality is a natural process in all forest ecosystems. High mortality can be an indicator of forest health problems. On a regional scale, high mortality levels may indicate widespread insect or disease impacts. High mortality may also occur if a large proportion of the forest in a particular region is made up of older, senescent stands. The approach presented here seeks to detect mortality patterns that might reflect changes to ecosystem processes at large scales. In many cases, the proximate cause of mortality may be discernable. Understanding proximate causes of mortality *may* provide insight into whether the mortality is within the range of natural variation or reflects more fundamental changes to ecological processes.

DATA

Forest Inventory and Analysis (FIA) Phase 2 (P2) data were the basis of the mortality analysis. Forest Inventory and Analysis P2 data are collected across forested land throughout the United States, with approximately one plot per 6,000 acres of forest, using a rotating panel sample design (Bechtold and Patterson 2005). Field plots are divided into spatially balanced panels, with one panel being measured each year. A single cycle of measurements consists of measuring all panels. This “annualized” method of inventory was adopted, State by State, beginning in 1999. The cycle length (i.e., number of years required to measure all plot panels) ranges from 5 to 10 years.

An analysis of mortality requires data collected at a minimum of two points in time. Therefore, mortality analysis was possible for areas where data from repeated plot measurements using consistent sampling protocols were available (i.e., where one cycle of measurements had been completed and at least one panel of the next cycle had been measured, and where there had been no changes to the protocols affecting measurements of trees or saplings). In this report, as in recent years, the repeated P2 data were available for all of the Central and Eastern States. The most recent cycle of remeasurements for each State was used in this analysis.

In addition, mortality data have become available from parts of the Western United States. In the West, plots are remeasured on a 10-year cycle. Thus, estimates of growth and mortality from the Western States are based on less than a complete cycle of remeasurement. Working from an incomplete cycle of remeasurement, the effective sampling intensity for growth and mortality estimates is significantly lower than FIA’s standard of one plot per 6,000 acres (table 5.1). Therefore, the percent sampling error on growth and mortality estimates tends to be large. Results are not presented for ecoregions where fewer than 25 plots had been remeasured or where the percent error was unacceptably high. Nevertheless, results presented for the West should be viewed as preliminary. Because of this, results from the West are discussed separately from those from the Eastern and Central United States. The

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Tree Mortality

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division of Eastern/Central vs. Western States, as well as the forest cover within those States, is shown in figure 5.1.

METHODS

The Forest Inventory and Analysis program calculates the growth, mortality, and removal volume on each plot over the interval between repeated measurements. These values are

Table 5.1—Western States from which repeated Forest Inventory and Analysis Phase 2 measurements were available, the time period spanned by the data, and the effective sample intensity (based on the proportion of plots that had been remeasured) in the available datasets

State	Time period	Effective sample intensity
Arizona	2001–2017	one plot: 8,571 acres
California	2001–2017	one plot: 8,571 acres
Colorado	2002–2017	one plot: 10,000 acres
Idaho	2004–2017	one plot: 15,000 acres
Montana	2003–2017	one plot: 12,000 acres
Nevada	2004–2017	one plot: 15,000 acres
New Mexico	2005–2017	one plot: 20,000 acres
Oregon	2001–2016	one plot: 8,571 acres
Utah	2000–2017	one plot: 7,500 acres
Washington	2002–2016	one plot: 12,000 acres
Wyoming ^a	2000–2017	one plot: 8,571 acres

^a Mortality estimates for Wyoming are based on a comparison of annualized inventory data with data from the final periodic inventory.

stored in the FIA database (FIADB, version 8.0) (Burrill and others 2018). The FIA’s EVALIDator (ver. 1.8.0) is an online tool for querying the FIADB and generating area-based reports on forest characteristics (USDA Forest Service, FIA Program 2019). EVALIDator was used to obtain net growth rates and mortality rates over the most recent measurement cycle for each of 113 ecoregion sections (Cleland and others 2007, McNab and others 2007) covering the Eastern and Central United States and 23 ecoregion sections in the Western¹ United States. For most States, the most recent cycle of available data ran through 2017² (e.g., data collected from 2011 through 2017).

To compare mortality across forest types and climate zones, the ratio of annual mortality to gross growth (MRATIO) was used as a standardized mortality indicator (Coulston and others 2005).

The MRATIO has proven to be a useful indicator of forest health, but it can be a problematic indicator, especially when growth rates are very low. The MRATIO can also be difficult to interpret when there is high uncertainty to growth estimates. Both of these are the case with the data currently

¹ At the time that this analysis was being completed, updates being made to EVALIDator and FIADB made it impossible to generate growth estimates for the Interior West, so MRATIOS were only calculated for the West Coast States.

² Overall, the most recent data available for any State ranged from 2015 to 2018.

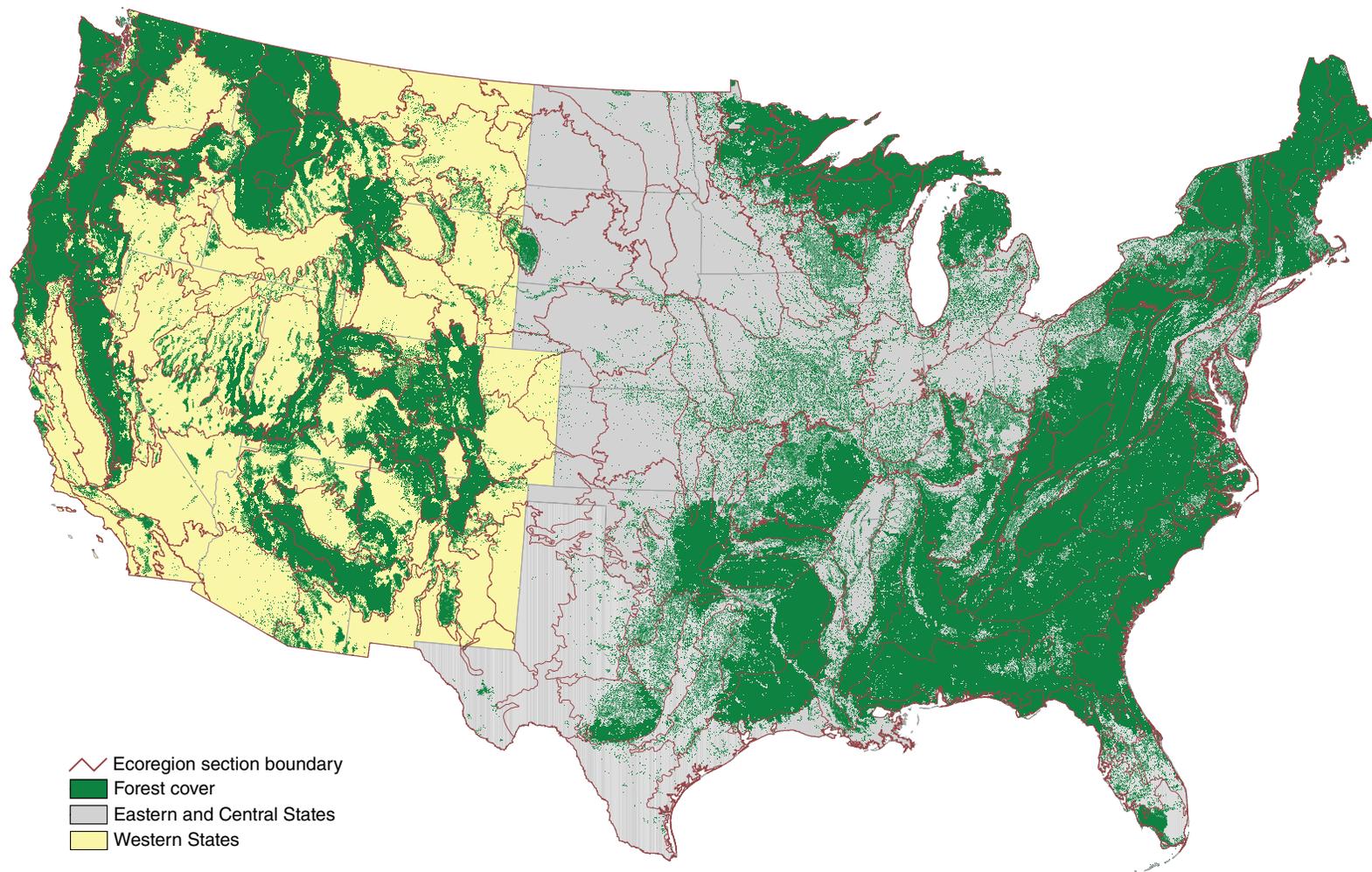


Figure 5.1—Forest cover in the States where mortality was analyzed by ecoregion section (Cleland and others 2007). Mortality in Eastern and Central States was analyzed using a complete remeasurement cycle; in most Western States, mortality was analyzed using a partial cycle of remeasurements, and results there should be considered preliminary. Forest cover was derived from MODIS satellite imagery (USDA Forest Service 2008).

available from the West. Therefore, mortality as a percentage of live growing stock also was calculated:

$$\text{Mortality percent} = m / v_1 * 100$$

where

m = annual mortality (cubic feet per year)

v_1 = total live tree volume (cubic feet)

When both this mortality percentage and the MRATIO are high, it suggests a possibly serious forest health concern.

To identify causal agents for the observed mortality, EVALIDator was also used to summarize by the reported “cause of death” associated with the observed mortality. Causes of death are reported as general categories (e.g., insects, fire, weather). For each ecoregion with a high MRATIO, EVALIDator was used to generate a table of annual mortality volume by FIA species group (Burrill and others 2018) and cause of death. From these tables, it is possible to make reasonable assumptions about the particular insects or diseases that may be affecting particular regions. Care must be used in interpreting these causes because tree mortality may actually be caused by a combination of factors such as drought and insects. Further information about the causes of mortality is provided by the aerial survey of insects and disease (see ch. 2 in this report). It is difficult to

directly match aerial survey data to mortality observed on FIA plots due to both the difference in timing when mortality is recorded and difficulty matching plot locations with aerial survey mortality polygons. However, aerial survey information has been incorporated into the discussion by referencing State Forest Health Highlights, which reflect in large part the results of aerial surveys.

In addition, mortality rates were derived for each forest type group (Burrill and others 2018, USDA Forest Service 2008) for each ecoregion section across the United States. At times, identifying the forest type experiencing high mortality can be more useful than identifying the species group, especially when the cause of death is abiotic. Results by forest type group are only reported when they help reveal a pattern that is not evident from analysis of species group alone.

RESULTS AND DISCUSSION

The MRATIO values are shown in figure 5.2. The MRATIO can be large if an over-mature forest is senescing and losing a cohort of older trees. If forests are not naturally senescing, a high MRATIO (>0.6) may indicate high mortality due to some acute cause (insects or pathogens) or due to generally deteriorating forest health conditions. The ecoregion sections with the highest MRATIOS are labeled on the map. In the discussion that follows, the focus is placed on the ecoregion sections having MRATIOS >0.6.

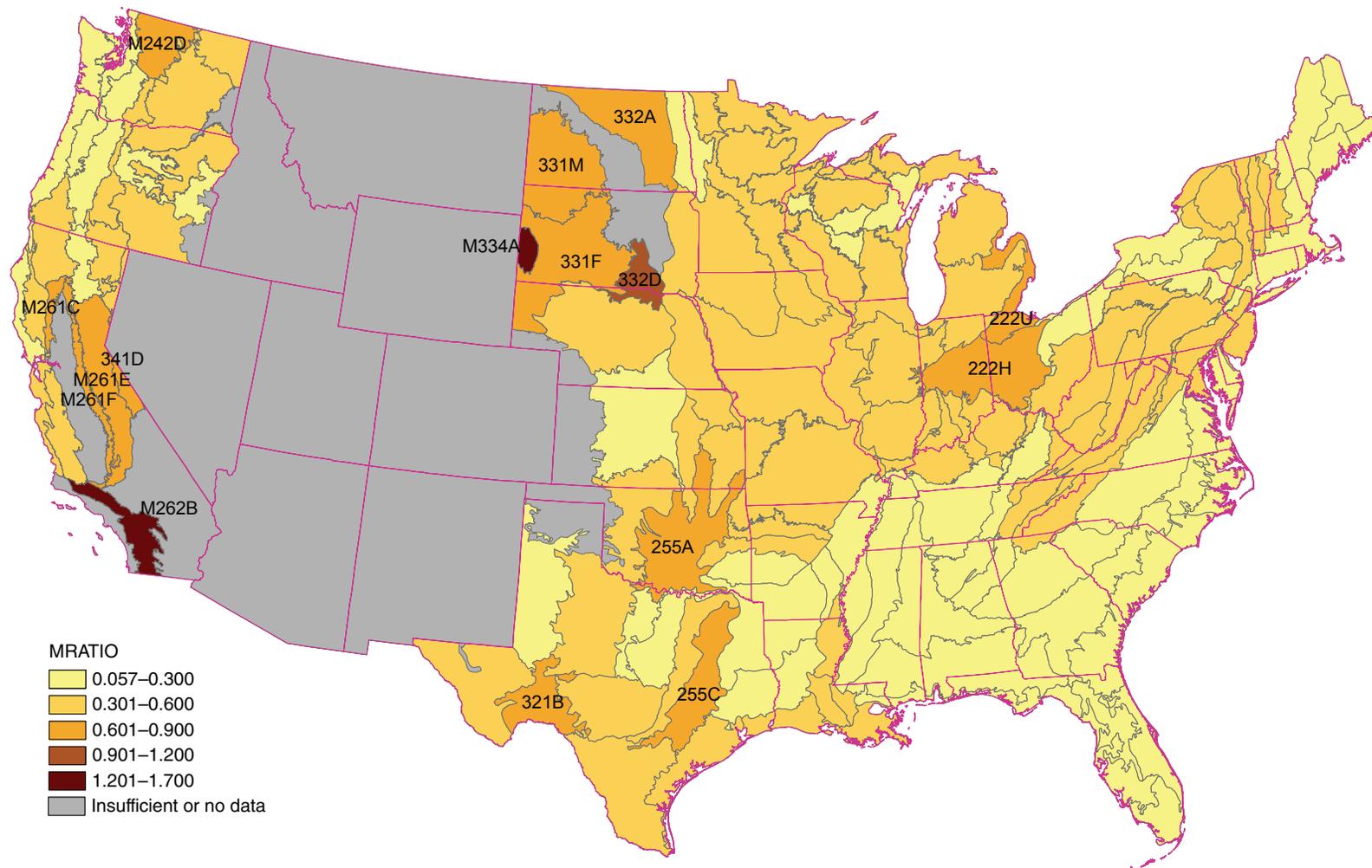


Figure 5.2—Tree mortality expressed as the ratio of annual mortality volume to gross annual growth volume (MRATIO) by ecoregion section (Cleland and others 2007). (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program)

Eastern and Central States

The highest MRATIOS occurred in ecoregion sections 332D–North-Central Great Plains (MRATIO = 1.08) in South Dakota and Nebraska and M334A–Black Hills (MRATIO = 1.21). Other areas of high mortality relative to growth on the Great Plains were ecoregions 331F–Western Great Plains (MRATIO = 0.81) in South Dakota and Nebraska, 331M–Missouri Plateau (MRATIO = 0.68) in North and South Dakota, and 332A–Northeastern Glaciated Plains (MRATIO = 0.80) in North Dakota. In these Great Plains ecoregions where mortality is high relative to growth, the predominant vegetation is grassland. Although the ecoregion sections are quite large, there was relatively little forest land to measure

(e.g., 135 forested plots in section 331F and 108 plots in section 331M). In the Plains, tree growth is generally slow because of naturally dry conditions. Where the number of sample plots is small and tree growth is naturally slow, care must be taken in interpreting mortality relative to growth.

In ecoregion section M334A–Black Hills (MRATIO = 1.21), the vast majority (93 percent) of mortality occurred in the ponderosa and Jeffrey pine species group. For the entire ecoregion section, 72 percent of mortality was caused by insects, while 16 percent was caused by fire (table 5.2); for ponderosa/ Jeffrey pine, insects and fire were responsible for 75 percent and 17 percent of mortality,

Table 5.2—Ecoregion sections in the Eastern and Central United States having the highest mortality relative to growth (MRATIO), annual growth and mortality rates, and associated causes of mortality

Ecoregion section	Average annual mortality	Average annual gross growth	MRATIO	Major causes of mortality ^a
	----- cubic feet per year -----			
M334A–Black Hills	49,157,466	40,643,847	1.21	Insects (72%), fire (16%)
332D–North-Central Great Plains	12,841,746	11,919,536	1.08	Weather-related (46%), fire (24%)
255C–Oak Woods and Prairies	116,902,469	141,752,979	0.82	Weather-related (69%), disease (14%)
321B–Stockton Plateau	7,685,163	9,381,332	0.82	Weather-related (67%), fire (32%)
331F–Western Great Plains	11,966,303	14,721,800	0.81	Fire (48%), weather-related (21%)
332A–Northeastern Glaciated Plains	8,029,281	10,033,026	0.80	Weather-related (45%), animals (12%), disease (10%)
222U–Lake Whittlesey Glaciolacustrine Plain	47,912,169	64,702,192	0.74	Insects (73%)
255A–Cross Timbers and Prairie	18,731,996	27,304,630	0.69	Disease (44%), weather-related (29%), fire (14%)
331M–Missouri Plateau	6,131,103	8,955,926	0.68	Weather-related (70%), disease (11%)
222H–Central Till Plains-Beech-Maple	112,895,664	173,456,876	0.65	Insects (44%), weather-related (12%)

^a Agents identified as causing at least 10 percent of the mortality.

respectively. Mortality in this ecoregion is most likely related to mountain pine beetle (*Dendroctonus ponderosae*). There had been an ongoing pine beetle outbreak in the Black Hills region (Ball and others 2015, 2016; South Dakota Department of Agriculture 2011, 2012, 2013, 2014). Pine beetle activity has declined dramatically in the region since 2015 (Ball and others 2017, Wyoming State Forestry Division 2017). The pine beetle outbreak has ended, but reported mortality remains high because results, based on the most recent cycles of FIA data, reflect mortality over the period that includes the peak of the outbreak in 2015.

In 332D–North-Central Great Plains (MRATIO = 1.08), 46 percent of mortality was weather-related, while another 24 percent of mortality was due to fire (table 5.2). Almost half of the mortality occurred in the cottonwood and aspen species group. Mortality was also high in the white oak, ponderosa and Jeffrey pine, and other eastern soft hardwoods species groups. Adverse weather was responsible for almost all of the cottonwood/aspen mortality. However, the majority of oak and pine mortality was due to fire. Adverse weather conditions, including both droughts and excessively wet conditions, occurred multiple times during the remeasurement cycle. These included a drought that affected almost all of Nebraska in 2012 and 2013 and a major drought in South Dakota in 2017 (Ball and others 2017; Nebraska Forest Service 2012, 2013; South Dakota Department of Agriculture 2012). A number of other agents may have contributed to the mortality, including

oak decline, which has been reported in northern and eastern Nebraska (Nebraska Forest Service 2017, 2018), bur oak blight (*Tubakia iowensis*), and Dutch elm disease (*Ophiostoma novo-ulmi*) (Ball and others 2017, 2018).

In ecoregion section 331F–Western Great Plains (MRATIO = 0.81), fire caused 48 percent of mortality; another 21 percent of mortality was weather-related (table 5.2). In this ecoregion, most of the mortality (about 75 percent) occurred in the ponderosa and Jeffrey pine species group. In this species group, 52 percent of mortality was due to fire, and 27 percent was due to adverse weather. Only 9 percent of pine mortality was related to insects. Adverse weather events included a drought in 2012 and 2013, affecting much of South Dakota and Nebraska (South Dakota Department of Agriculture 2012; Nebraska Forest Service 2012, 2013). In western Nebraska, ips beetles have caused pine mortality, especially in trees stressed by drought or fire (Nebraska Forest Service 2015, 2016, 2017).

In ecoregion section 331M–Missouri Plateau (MRATIO = 0.68), about 71 percent of the mortality (by volume) occurred in the cottonwood and aspen species group. About 70 percent of total mortality (table 5.2) and 89 percent of cottonwood/aspen mortality was identified as weather-related. Adverse weather conditions, including both drought and excessively wet conditions, occurred during the remeasurement cycle (Ball and others 2017; Johnson 2017; North Dakota Forest Service 2012, 2013; South Dakota Department

of Agriculture 2012). Multiple tree-damaging storm events, including both hail storms and tornadoes, also occurred over that period (Johnson 2017; North Dakota Forest Service 2016). About 11 percent of total mortality (table 5.2) and 5 percent of cottonwood/aspen mortality was caused by disease. Cottonwood canker fungi have been identified as a problem throughout North Dakota (North Dakota Forest Service 2014, 2015); these fungi may be contributing to the observed cottonwood mortality.

The majority of the mortality in ecoregion 332A–Northeastern Glaciated Plains (MRATIO = 0.80) of North Dakota was split among the cottonwood and aspen (48 percent), ash (13 percent), white oak (20 percent), and other eastern soft hardwoods (19 percent) species groups. About 45 percent of the mortality overall (table 5.2) and 38 percent of cottonwood/aspen mortality was related to adverse weather. North Dakota experienced numerous storm events over the past several years, including 435 hail events and 66 tornadoes during the 2015 and 2016 growing seasons. Damage due to hail storms can make trees susceptible to a number of fungal diseases (North Dakota Forest Service 2015, 2016). About 12 percent of mortality was attributed to animals; almost all of this occurred in the cottonwood/aspen species group.

Mortality relative to growth was also rather high (MRATIO = 0.74) in ecoregion section 222U–Lake Whittlesey Glaciolacustrine Plain. There the majority of the mortality (73 percent) was ash. About 73 percent of mortality in that

ecoregion was caused by insects (table 5.2), and insects were responsible for 97 percent of ash mortality. Most of this mortality was due to emerald ash borer (*Agrilus planipennis*), which has produced extremely high ash mortality throughout Ohio and Michigan (Michigan Department of Natural Resources 2014, 2015, 2016, 2017; Ohio Department of Natural Resources, Division of Forestry 2014, 2015). In fact, emerald ash borer has caused the death of the “vast majority” of native ash in northwestern Ohio (Ohio Department of Natural Resources, Division of Forestry 2016, 2017).

Similarly, in the adjacent ecoregion 222H–Central Till Plains-Beech-Maple (MRATIO = 0.65) in Ohio and Indiana, much of the mortality (48 percent) was ash and 91 percent of ash mortality was due to insects, most likely emerald ash borer. Indeed, emerald ash borer has been confirmed throughout the ecoregion as well as throughout Indiana (Marshall, 2017, 2018; Ohio Department of Natural Resources, Division of Forestry 2016, 2017). For species other than ash, adverse weather was the single most important mortality-causing agent, accounting for 12 percent of mortality overall (table 5.2).

Ecoregion 255C–Oak Woods and Prairies in Texas also had relatively high mortality (MRATIO = 0.82). About 53 percent of the mortality occurred in the red and white oak species groups, and another 16 percent occurred in the loblolly and shortleaf pine species group. The majority (69 percent) of mortality in this ecoregion section was identified

as weather-related (table 5.2). Weather was responsible for 75 percent of oak mortality and 52 percent of pine mortality. A record-setting drought in 2011 affected Oklahoma and Texas (Oklahoma Forestry Services 2014, 2015, 2016). It was reported as weakening both pines and hardwoods in Texas, making them susceptible to a variety of pests and pathogens (Smith 2013, 2014). Disease was the reported cause of another 14 percent of mortality (table 5.2). Oak wilt has been a major problem in oak woodlands in central Texas (Smith 2014; Texas A & M Forest Service 2015, 2016) and probably contributed to the red and white oak mortality. Pine engraver beetle (*Ips* spp.) has been a problem in Texas' pine forests and may have contributed to mortality in the loblolly and shortleaf pine (Smith 2014; Texas A & M Forest Service 2015, 2016, 2017).

Ecoregion 255A—Cross Timbers and Prairie experienced relatively high mortality (MRATIO = 0.69). About 52 percent of the mortality occurred in the red and white oak species groups. Disease was the reported cause of 44 percent of mortality; 29 percent of mortality was weather-related; 14 percent of mortality was due to fire (table 5.2). Among the oaks, disease was responsible for about 67 percent of the mortality, while weather was responsible for 19 percent. As mentioned above, a record drought in 2011 and 2012 affected Oklahoma and Texas, stressing trees. Oklahoma has been working with Texas to monitor the impacts of drought on forest health in both States (Oklahoma Forestry Services 2014, 2015, 2016). Oaks have been especially strongly affected by the drought

(Oklahoma Forestry Services 2017). Following the drought, Hypoxylon canker, caused by the fungus *Biscogniauxia atropunctata*³ (McBride and Appel 2016), has become a problem on the drought-stressed trees (Oklahoma Forestry Services 2017).

In ecoregion section 321B—Stockton Plateau (MRATIO = 0.82), 67 percent of mortality was related to adverse weather and another 32 percent was due to fire (table 5.2). About 89 percent of mortality occurred in the western woodland softwoods species group. Most of this mortality probably was related to the previously discussed drought that affected Texas beginning in 2011.

Western States

As mentioned above, in all Western States, less than the full panel of plots have been remeasured. Thus, the mortality results presented here should be considered preliminary. Also, one must be aware that, because of the longer 10-year measurement cycle in the West, results shown represent mortality that may have occurred any time during the period spanned by the data (see table 5.1), which may have been as long as 17 years.

For a large portion of the West, no MRATIO could be calculated. At the time this chapter was being written, due to changes being made to the

³ The fungal pathogen *Hypoxylon atropunctatum* has recently been moved to the genus *Biscogniauxia*, but the term “Hypoxylon canker” remains in common usage.

FIADB, growth estimates were not available for the Interior West FIA region. Thus, no MRATIOS were calculated for ecoregions in those States. MRATIOS were also not calculated for some ecoregions in West Coast States. This was because either (1) fewer than 25 plots had been remeasured in an ecoregion, or (2) the percent sampling error for the growth estimate was too high (>100 percent). One expects that as the first cycle of plot remeasurements is completed in future years, it will be possible to estimate MRATIOS for most of the West.

West Coast ecoregion sections having the highest MRATIOS are shown in table 5.3 with the major causes of mortality identified. Seeing

that fire and weather as well as insects and disease were responsible for significant mortality, for these West Coast ecoregions we examined mortality numbers both by forest type group and species group. We would expect that patterns of mortality caused by biotic factors (insects, disease) would be most apparent when looking at species groups affected, while patterns of mortality caused by abiotic factors (weather, fire) would be most apparent when looking at forest types affected.

Of the ecoregions of the West Coast States where the MRATIO could be calculated, ecoregion section M262B–Southern California Mountain and Valley (MRATIO = 1.67)

Table 5.3—Ecoregion sections in West Coast States having the highest mortality relative to growth (MRATIO), annual growth and mortality rates, and associated causes of mortality

Ecoregion section	Average annual mortality	Average annual gross growth	MRATIO	Major causes of mortality ^a
	----- cubic feet per year -----			
M262B–Southern California Mountain and Valley	19,950,233	11,961,582	1.67	Fire (57%), insects (14%)
341D–Mono	6,203,870	7,534,619	0.82	Insects (47%), fire (39%)
M242D–Northern Cascades	289,680,840	369,562,663	0.78	Insects (36%), fire (25%), weather-related (16%), disease (13%)
M261E–Sierra Nevada	390,937,815	548,833,831	0.71	Fire (32%), disease (30%), weather-related (13%), insects (13%)
M261C–Northern California Interior Coast Ranges	5,057,305	7,112,102	0.71	Fire (48%), disease (23%), weather-related (13%)
M261F–Sierra Nevada Foothills	18,375,520	29,763,584	0.62	Disease (23%), weather-related (18%), fire (13%)

^a Agents identified as causing at least 10 percent of the mortality.

stands out. This is the highest MRATIO found anywhere in the United States. Fire was responsible for 57 percent of this mortality (table 5.3). Insects were responsible for another 14 percent of mortality. About half of the mortality in this ecoregion section occurred in the western oak forest type group, and most of that mortality was due to fire. Fire was also responsible for most of the mortality in the pinyon/juniper forest type group, where 9 percent of the ecoregion's mortality occurred. Insects were responsible for almost all the mortality in the ponderosa pine forest type group and about 44 percent of the mortality in the California mixed conifer forest type group (about 33 percent of the mortality occurred in the ponderosa and Jeffrey pine species group and about 22 percent in the other western softwoods species group).

In ecoregion section 341D–Mono (MRATIO = 0.82), about 60 percent of mortality occurred in the western woodland softwoods species group, and about 23 percent was in the lodgepole pine species group. All of the lodgepole pine mortality was attributed to insects, while for western woodland softwoods about 57 percent of mortality was due to fire, and about 30 percent was due to insects.

In M261E–Sierra Nevada (MRATIO = 0.71), mortality occurred in a large number of species groups, with the highest mortality suffered by true firs (43 percent), ponderosa and Jeffrey pine (17 percent), and sugar pine (12 percent). A variety of agents (insects, disease, fire, and weather) contributed to the observed mortality.

Disease was the single most important cause of mortality in the true fir and sugar pine species groups.

In M261C–Northern California Interior Coast Ranges (MRATIO = 0.71), almost all of the mortality occurred in the western oak forest type group. About 40 percent of the mortality was oaks, and about 60 percent was other western softwoods. Just over half of the oak mortality and about 40 percent of the softwood mortality was due to fire.

Similarly, in M261F–Sierra Nevada Foothills (MRATIO = 0.62), almost all of the mortality occurred in the western oak forest type group. About 63 percent of the mortality was oaks, about 18 percent was other western softwoods, and 9 was ponderosa/Jeffrey pine. However, in this ecoregion section, a variety of agents (disease, weather, fire, and insects) all contributed to the observed mortality (table 5.3) and about 41 percent of mortality could not be definitely attributed to a known causal agent.

At a broad scale, we see that, in much of California, tree mortality is often related to a combination of prolonged drought (2011–2015 statewide; 2011–2017 in parts of the State), bark beetles, and fire (California Forest Pest Council 2015, 2016, 2017). These factors have interacted, leading to high mortality, especially in southern California. Overstocked stands in many parts of the State have contributed to the drought stress and susceptibility of forests to insects and wildfires (California Forest Pest Council 2015, 2016, 2017). It should also be

noted that the same drought which led to high mortality (directly or indirectly) would also have reduced growth over the measurement period; reduced growth also contributes to a high MRATIO (see Methods section).

Aside from California, the highest MRATIO (0.78) occurred in ecoregion section M242D—Northern Cascades. There, mortality occurred in a large number of species groups, including Engelmann and other spruces (27 percent), true firs (23 percent), lodgepole pine (15 percent), and Douglas-fir (15 percent). While insects and fire were the most significant mortality-causing agents, other factors, including disease and adverse weather, also contributed to the observed mortality (table 5.3).

Figure 5.3 shows the ratio of annual mortality to standing live tree volume for the United States. In most of the country, the ecoregion sections having high mortality relative to standing volume are the same regions that had high MRATIOs (fig. 5.2).

Focusing on the Interior West, we see clusters of ecoregion sections where mortality is high relative to standing live tree volume: a cluster of mountain ecoregion sections in western Montana, central Idaho, and northwestern Wyoming (M331A, M331J, M332A, M332B, M332D, M332E, M332F, and M333C); in the Front Range of Colorado and southern Wyoming (M331I) and the South-Central Highlands of Colorado and northern New Mexico (M331G) together with the Uinta Mountains of Utah (M331E); and in northeastern Nevada (341G).

In all of these ecoregion sections, annual mortality exceeded 2.5 percent of live volume (table 5.4).

In northeastern Nevada's ecoregion section 341G—Northeastern Great Basin, fire was the major cause of mortality (table 5.4). About 56 percent of the mortality occurred in the true fir species group, and about 70 percent of the fir mortality was due to fire.

In Colorado and Wyoming's ecoregion section M331I—Northern Parks and Ranges, 64 percent of the mortality was lodgepole pine, and another 19 percent was the Englemann and other spruces species group; almost all of this mortality was attributed to insects. The ecoregion includes areas that have experienced major outbreaks of mountain pine beetle as well as spruce beetle (*D. rufipennis*) (Colorado State Forest Service 2016; Wyoming State Forestry Division 2016, 2017). These same pests, as well as fir engraver beetle (*Scolytus ventralis*), have been affecting ecoregion M331E—Uinta Mountains (USDA Forest Service, Uinta-Wasatch-Cache National Forest, no date; Utah Department of Natural Resources, Forestry, Fire, & State Lands 2016), where 66 percent of mortality was lodgepole pine and 13 percent was Englemann and other spruces. Here, also, most of the mortality was caused by insects. In ecoregion section M331G—South-Central Highlands, about two-thirds of mortality overall was caused by insects. In this ecoregion, about 61 percent of mortality was Englemann and other spruces; 96 percent of spruce mortality was due to insects. In this area, spruce beetle has caused significant mortality

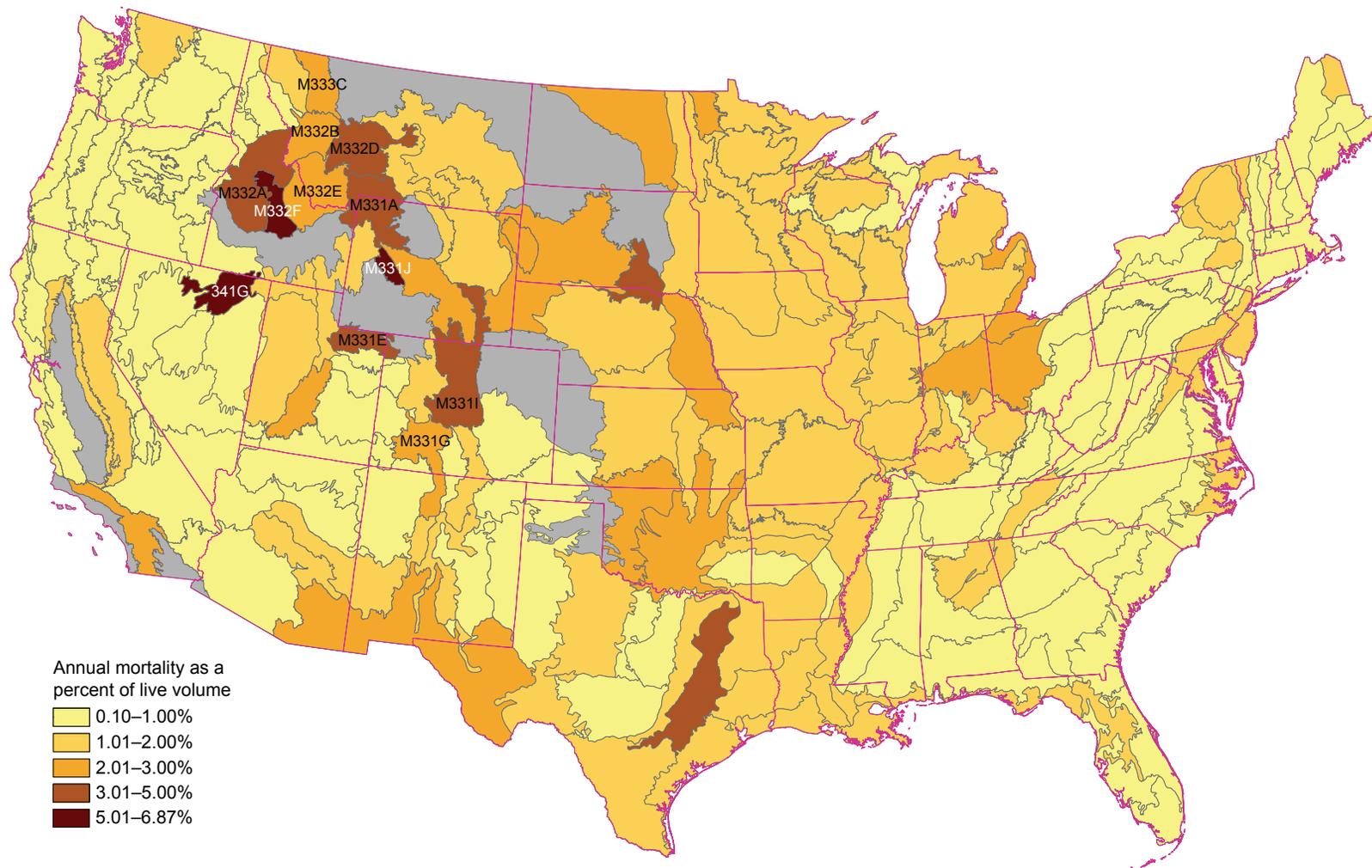


Figure 5.3—Annual tree mortality expressed as a percentage of standing live tree volume by ecoregion section (Cleland and others 2007). (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program)

Table 5.4—Ecoregion sections in Interior West States having the highest mortality relative to standing live tree volume and associated causes of mortality

Ecoregion section	Average annual mortality	Standing live tree volume	Mortality relative to standing volume	Major causes of mortality ^a
	<i>cubic feet per year</i>	<i>cubic feet</i>		
341G—Northeastern Great Basin	6,774,796	98,564,467	6.87%	Fire (57%), insects (29%)
M332F—Challis Volcanics	137,664,825	2,176,648,229	6.32%	Fire (50%), insects (42%)
M331J—Wind River Mountains	51,789,732	938,456,464	5.52%	Insects (72%), fire (18%)
M331I—Northern Parks and Ranges	531,523,774	12,437,622,452	4.27%	Insects (85%)
M332D—Belt Mountains	202,524,949	4,892,340,858	4.14%	Insects (86%)
M331A—Yellowstone Highlands	340,716,778	8,247,943,183	4.13%	Insects (57%), fire (28%)
M331E—Uinta Mountains	102,559,418	2,845,948,640	3.60%	Insects (66%), disease (22%)
M332A—Idaho Batholith	539,075,204	17,585,337,151	3.07%	Fire (55%), insects (26%)
M331G—South-Central Highlands	295,137,741	9,861,651,126	2.99%	Insects (66%), disease (12%), fire (12%)
M332B—Northern Rockies and Bitterroot Valley	180,135,382	6,083,853,253	2.96%	Insects (51%), fire (38%)
M332E—Beaverhead Mountains	141,598,785	5,386,335,877	2.63%	Insects (76%), fire (16%)
M333C—Northern Rockies	202,302,538	7,766,591,480	2.60%	Fire (53%), disease (25%), insects (15%)

^a Agents identified as causing at least 10 percent of the mortality.

(Colorado State Forest Service 2016, 2017; Norlander 2013; Zegler 2015, 2016; Zegler and Formby 2017).

In the areas of high mortality in Montana, Idaho, and northwestern Wyoming (ecoregion sections M331A, M331J, M332A, M332B, M332D, M332E, M332F, and M333C), insects and fire were the most significant causes of mortality (table 5.4). This region includes areas suffering outbreaks of mountain pine beetle (Montana Department of Natural Resources and

Conservation 2014, 2016) as well as major fires (Idaho Department of Lands 2014). However, several other insect and disease issues have been identified in this region and may have contributed to the mortality. In most of these ecoregion sections (M331A, M331J, M332A, M332B, M332D, and M332E), the lodgepole pine species group suffered the highest mortality, most of which was due to insects. However, many other species groups, including Douglas-fir, true firs, and Englemann and other spruces also suffered non-trivial mortality.

SUMMARY

This analysis shows that, in most of the Eastern and Central United States, mortality is low relative to tree growth. The areas of highest mortality occur in the mostly riparian forests of Great Plains ecoregions. A common characteristic of most of the ecoregions having high mortality is that they are on the margins of land suitable for forest growth, being very dry. Thus, they tend to be extremely vulnerable to changes in weather patterns that might produce prolonged and/or extreme drought. Drought, combined with a variety of other biotic and/or abiotic stressors, is likely responsible for much of the mortality observed.

However, one insect pest issue does stand out in the East. In ecoregion sections 222H—Central Till Plains-Beech-Maple and 222U—Lake Whittlesey Glaciolacustrine Plain, ash mortality due to emerald ash borer is extremely high.

The preliminary analysis of the Western United States shows that, in many parts of the Interior West, mortality is very high as a percent of standing live tree volume and that several West Coast ecoregion sections have high MRATIOS. All of these areas correspond to regions where insect outbreaks (ch. 2) as well as fire (ch. 3) and/or severe drought (ch. 4) have occurred. These three mortality-causing agents are related in that drought stresses trees, making them more susceptible to insect attack, while both drought and insect-killed trees create conditions favorable for wildfires.

It is also important to realize that the analyses presented in this chapter alone cannot tell the complete story regarding tree mortality. Mortality that is concentrated in highly fragmented forest or nonforest areas adjacent to human development may not be detected because the available FIA data do not cover most urban areas or other places not defined as forest by FIA. Also, these analyses are unlikely to detect a pest or pathogen attacking a particular tree species in a mixed-species forest where other species are growing vigorously. This is especially true of species (e.g., ash) that make up a relatively small proportion of many eastern forests. For example, it is known that emerald ash borer has been causing very high ash mortality in many Eastern and Central States in recent years (USDA APHIS 2018; Ohio Department of Natural Resources, Division of Forestry 2016). Yet, this mortality stands out only in ecoregion sections 222H—Central Till Plains-Beech-Maple and 222U—Lake Whittlesey Glaciolacustrine Plain. Elsewhere in the East, though ash mortality is known to be extremely high, the mortality is masked because ash is a relatively minor component of the forest.

To gain a more complete understanding of mortality, one should consider the results of this analysis together with other indicators of forest health. Forest Inventory and Analysis tree damage data (Burrill and others 2018), as well as Evaluation Monitoring projects that focus on particular mortality-causing agents (ch. 8–9), can provide insight into smaller scale or species-specific mortality issues. Large-scale analyses

of forest-damaging events, including insect and disease activity (ch. 2) and fire (ch. 3), are also important for understanding mortality patterns. This can be especially important in the West, where mortality data are limited.

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