CHAPTER 5.

Tree Mortality

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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. However, 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 West are based on less than a complete cycle of remeasurement. Remeasurement data were available for all western States in the conterminous United States except Wyoming. However, for several States, the proportion of plots that have been remeasured is small, making the effective sampling intensity for growth and mortality estimates 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 50 plots had been remeasured or where the percent error was unacceptably high. Nevertheless, results presented for the West

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 (on the proportion of plots that had been remeasured) in the available datasets

State	Time period	Effective sample intensity
Arizona	2001–2016	1 plot: 10,000 acres
California	2001–2016	1 plot: 10,000 acres
Colorado	2002–2015	1 plot: 15,000 acres
Idaho	2004–2015	1 plot: 30,000 acres
Montana	2003–2016	1 plot: 15,000 acres
Nevada	2004–2015	1 plot: 30,000 acres
New Mexico	2005–2015	1 plot: 60,000 acres
Oregon	2001–2016	1 plot: 8,571 acres
Utah	2000–2016	1 plot: 8,571 acres
Washington	2002–2016	1 plot: 12,000 acres

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 division of eastern/central vs. western States, as well as the forest cover within those States, is shown in figure 5.1.

METHODS

Forest Inventory and Analysis calculates the growth, mortality, and removal volume on each plot over the interval between repeated measurements. These values are stored in the FIA database (v. 7.0) (O'Connell and others 2017). The FIA EVALIDator (v. 1.6.0.03a) is an online tool for querying the FIA database and generating area-based reports on forest characteristics (Miles 2015). EVALIDator was used to obtain net growth rates and mortality rates over the most recent measurement cycle for each of 97 ecoregion sections (Cleland and others 2007, McNab and others 2007) covering the Eastern and Central United States and 47 ecoregion sections in the Western United States. For most States, the most recent cycle of available data ran through 2016 (e.g., data collected 2011 through 2016).

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). Because EVALIDator does not output gross growth directly, it must first be calculated as the sum of net growth and mortality. Thus, the MRATIO was calculated from the EVALIDator output for each ecoregion section, using the formula:

$$\text{MRATIO} = m / (m + g_n)$$

where

m = annual mortality (cubic feet/year)

g_n = net annual growth (cubic feet/year).

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

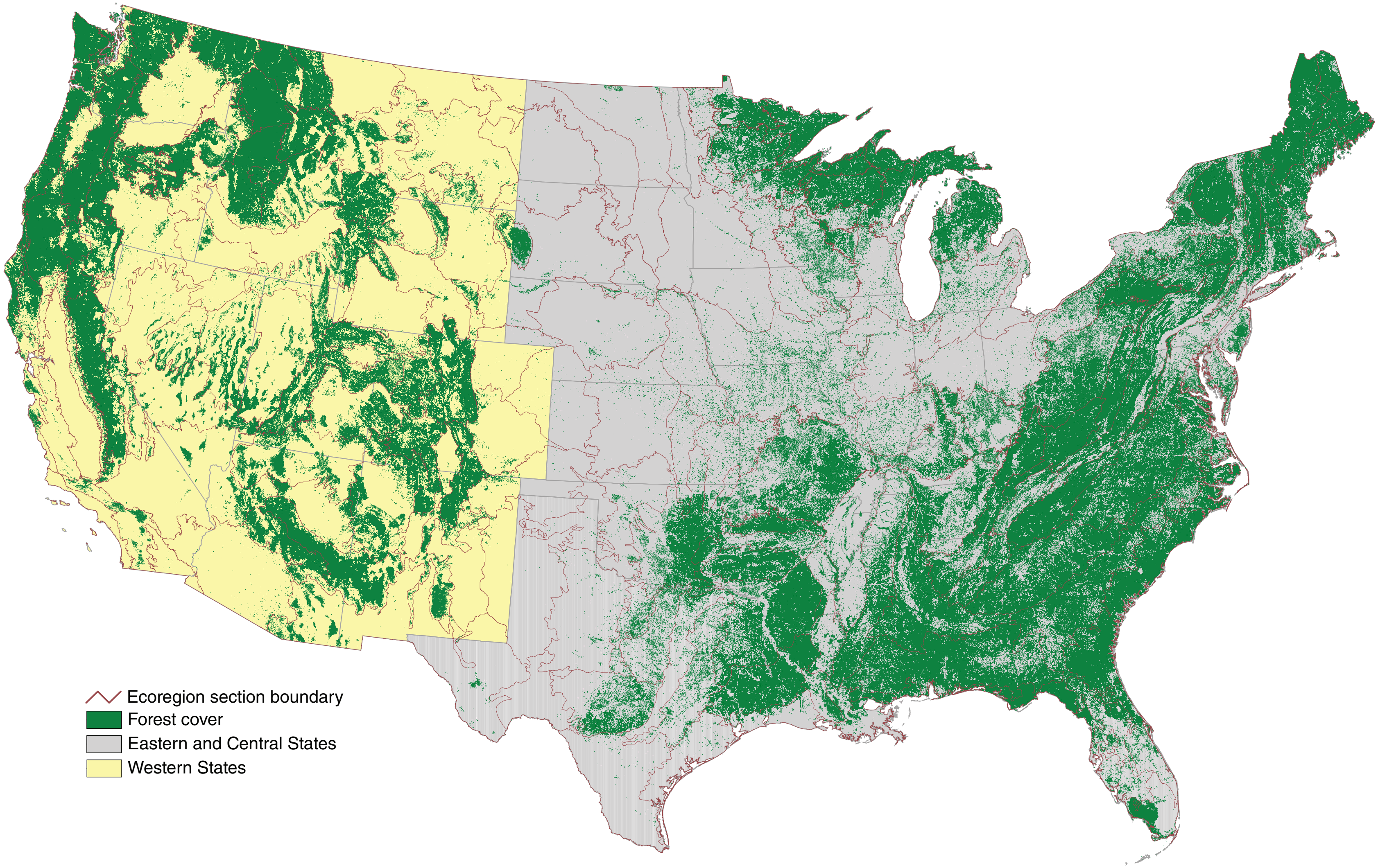

Figure 5.1—Forest cover in the States where mortality was analyzed by ecoregion section (Cleland and others 2007). Mortality in Eastern and Central States was analyzed using a complete remeasurement cycle; in Western States, mortality was analyzed using a partial cycle of remeasurements, and results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

are the case with the data currently available from the West. Therefore, we also calculated mortality as a percentage of live growing stock volume:

Mortality percent = $m / v_l * 100$

where

m = annual mortality (cubic feet/year)

v_l = total live tree volume (cubic feet).

When this value is high as well as the MRATIO, it suggests a possibly serious forest health concern.

In addition, mortality rates were derived for each forest type group (USDA Forest Service 2008) for each ecoregion section. Identifying the forest types experiencing high mortality in an ecoregion is a first step in identifying what forest health issue may be affecting the forests. Although determining particular causal agents associated with all observed mortality is beyond the scope of this report, often there are well-known insects and pathogens that are "likely suspects" once the affected forest types are identified.

To identify possible causal agents for the observed mortality, EVALIDator was also used to report disturbances that were recorded on plots where mortality occurred. Care must be used in interpreting these disturbances because disturbance is a location-level variable (e.g., recorded for each stand included on a plot) rather than a tree-level variable, so a given disturbance may not be directly related to the mortality of a particular tree. Similarly, mortality-causing agents may be present in a location but not recorded if their impact at the plot level is not significant enough to qualify as a "disturbance." Nevertheless, such disturbances may indicate stressors that played a role in the observed mortality. Further information about the cause of mortality is provided by the aerial survey of insects and disease (see chapter 2 in this report). It is difficult to directly match aerial survey data to mortality observed on FIA plots. However, I incorporate the results of this survey into the discussion by consulting State Forest Health Highlights, which reflect in large part the results of aerial surveys.

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.

Eastern and Central States

The seven ecoregion sections in the Eastern and Central States with the highest MRATIOs are labeled on the map. In the discussion that follows, I focus on the ecoregions having MRATIOs > 0.5 (i.e., where mortality was greater than half of gross growth).

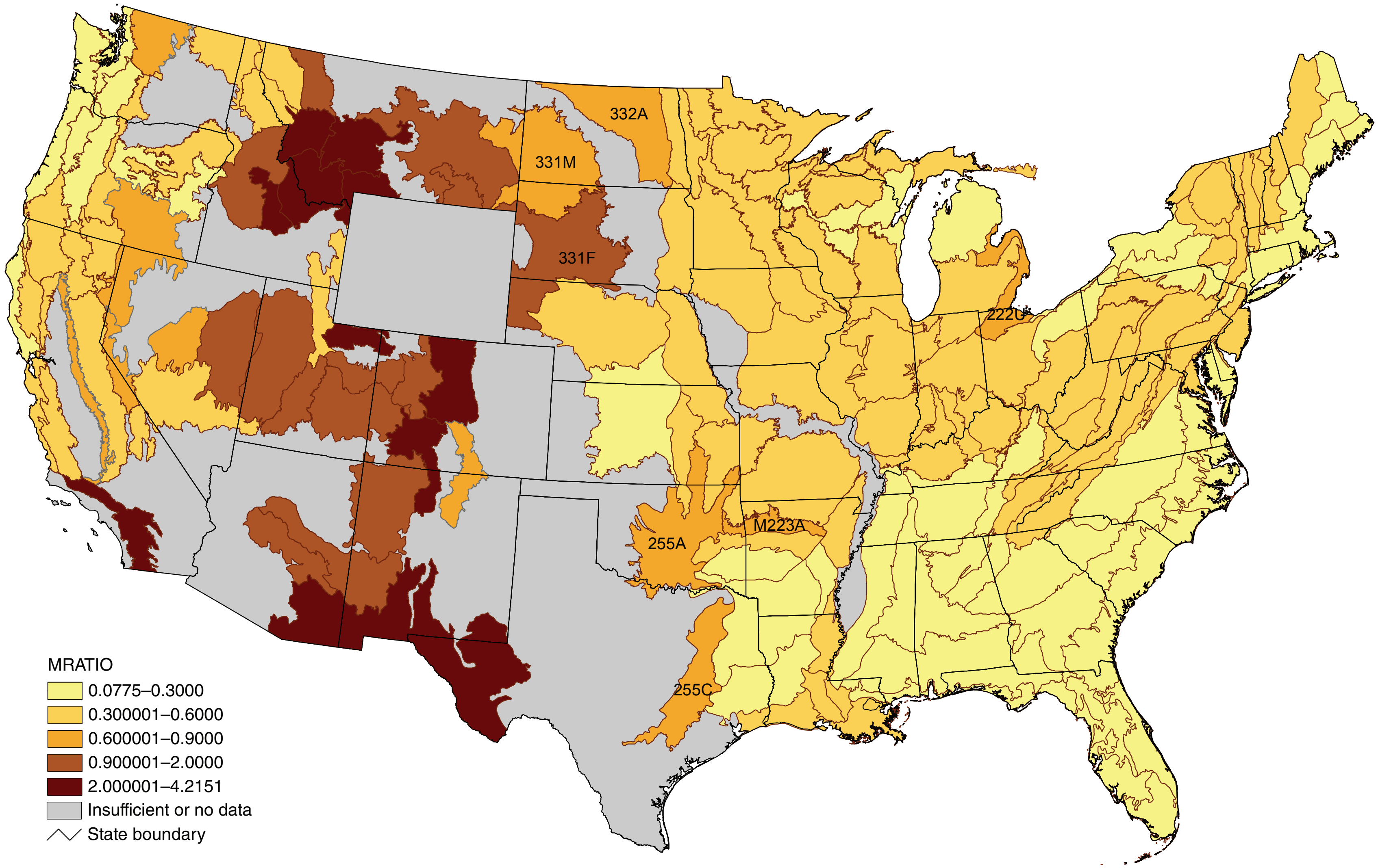

Figure 5.2—Tree mortality expressed as the ratio of annual mortality volume to gross annual volume growth (MRATIO) by ecoregion section (Cleland and others 2007). (Data source: U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program)

The highest MRATIOs occurred in ecoregion section 331F–Western Great Plains (MRATIO = 1.32) in South Dakota and Nebraska (and Montana). Other areas of high mortality relative to growth on the Great Plains were sections 331M–Missouri Plateau (MRATIO = 0.73) in North and South Dakota and 332A–Northeastern Glaciated Plains (MRATIO = 0.62) in North Dakota. In these Great Plains ecoregions where mortality is high relative to growth, the predominant vegetation is grassland. Although the ecoregions are quite large, there was relatively little forest land to measure (e.g., 113 plots in section 331F and 93 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.

Both ecoregion sections 331F and 331M have had high mortality relative to growth in recent years (Ambrose 2013, 2014, 2015a, 2015b, 2016, 2017), so the observed mortality is **not a new phenomenon**. Tree growth rates in these sections (especially in 331F) are quite low, so the high MRATIOSs are due to a combination of low growth and high mortality. Much of the forest in these sections is riparian, and most of the species experiencing greatest mortality are commonly found in riparian areas. The major exception was high ponderosa pine mortality in ecoregion section 331F. Ponderosa pine is not a riparian tree species, but like the riparian species, it only occurs in a relatively small area of the ecoregion, on discontinuous mountains, plateaus, canyons, and breaks in the plains (Burns and Honkala 1990). In both of these ecoregion sections, damage from domestic animals was associated with large proportions of the mortality (table 5.2).

In ecoregion section 331F, where the MRATIO was highest, the vast majority (~83 percent) of the mortality occurred in the ponderosa pine forest type group. However, this mortality represented a relatively small proportion of the growing stock in the ponderosa pine forest type (0.47 percent) in the region. The pine mortality in this ecoregion is very likely related to mountain pine beetle (*Dendroctonus ponderosae*). There has been an ongoing pine beetle outbreak in the adjacent Black Hills region (Ball and others 2015, 2016; South Dakota Department of Agriculture 2011, 2012, 2013, 2014). Mountain pine beetle-related mortality also has been reported in western Nebraska (Nebraska Forest Service 2011, 2012), with an outbreak that began in 2009, though pine beetle-related mortality there has fallen significantly recently (Nebraska Forest Service 2014, 2015, 2016). More recently, several other agents have been reported as affecting ponderosa pine in western Nebraska, including *Ips* beetles and *Diplodia* blight (Nebraska Forest Service 2015, 2016). Drought in 2012 and 2013, affecting much of South Dakota and Nebraska (South Dakota Department of Agriculture 2012; Nebraska Forest Service 2012, 2013), may also have contributed to pine mortality, as well as that of other species, in these ecoregions.

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 disturbances associated with areas of mortality

Ecoregion section	Average annual net growth	Average annual mortality	MRATIO	Major disturbances associated with areas with mortality[a]
	------- *cubic feet/year* -------			
331F–Western Great Plains	-3,662,068	15,227,903	1.32	Domestic animals (62%), bear (35%), fire (23%)
331M–Missouri Plateau	2,457,206	6,789,208	0.73	Weather-related (57%), domestic animals (27%), animal damage (14%)
222U–Lake Whittlesey Glaciolacustrine Plain	19,166,504	48,660,341	0.72	Insects (17%)
255C–Oak Woods and Prairies	22,472,645	53,525,386	0.70	Weather-related (11%)
255A–Cross Timbers and Prairie	8,376,354	16,526,241	0.66	Weather-related (17%), domestic animals (10%)
332A–Northeastern Glaciated Plains	4,109,748	6,668,929	0.62	Animals (26%), insects (21%), weather-related (17%), domestic animals (16%)

[a] Percentages are the percent of mortality volume occurring on forested conditions that were affected by the given disturbance type.

In ecoregion section 331M–Missouri Plateau, about 64 percent of the mortality (by volume) occurred in the elm-ash-cottonwood forest type group, and about 23 percent of mortality occurred in the oak-hickory forest type group. Prior analyses identified three species: eastern cottonwood, bur oak, and green ash as suffering high mortality in this region (Ambrose 2015b). Green ash have been affected by ash/lilac borer (*Podosesia syringae*), as well as other native ash borers, in both North and South Dakota (Ball and others 2015, 2016; North Dakota Forest Service 2012; South Dakota Department of Agriculture 2012). 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. Adverse weather conditions, including both drought and excessively wet conditions, both of which occurred during the remeasurement cycle (North Dakota Forest Service 2012, 2013; South Dakota Department of Agriculture 2012), may have contributed to mortality by stressing trees. Adverse weather was associated with 57 percent of the observed mortality (table 5.2).

The majority of the mortality in ecoregion section 332A was split about evenly between the elm-ash-cottonwood and aspen-birch forest type groups (about 40 percent in each). As in ecoregions 331F and 331M, a large proportion of the mortality (about 16 percent) was associated with domestic animal damage (table 5.2). This ecoregion includes the Turtle Mountains, where thousands of acres of forest tent caterpillar

(*Malacosoma disstria*) and large aspen tortrix (*Choristoneura conflictana*) defoliation have occurred in recent years (North Dakota Forest Service 2014). Overmaturity of aspen stands in North Dakota has led to increasing insect and disease issues (North Dakota Forest Service 2015), and 4,000 acres of aspen decline related to over-mature stands have been identified in this ecoregion (North Dakota Forest Service 2014). The defoliation together with the aspen decline may be the cause of most of the mortality in the aspen-birch forest type. Cottonwood canker fungi have been a problem throughout North Dakota (North Dakota Forest Service 2014, 2015) and may be a cause of the mortality in the elm-ash-cottonwood forest type.

Mortality was split almost evenly between the oak-hickory and elm-ash-cottonwood forest type groups in ecoregion section 222U–Lake Whittlesey Glaciolacustrine Plain (MRATIO = 0.72). About 17 percent of the mortality in this ecoregion was associated with insects (table 5.2). Much of the mortality in the elm-ash-cottonwood group is likely 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; 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). The cause of mortality in the oak-hickory forest type group is less clear. Several oak pests were reported in Ohio as well as "leaf-curl syndrome" of unknown origin (Ohio Department of Natural Resources, Division of Forestry 2015, 2016), while in Michigan oak wilt (caused by the pathogen *Ceratocystis fagacearum*) has been confirmed in at least part of the ecoregion (Michigan Department of Natural Resources 2015, 2016).

Ecoregion section 255C–Oak Woods and Prairies in Texas had relatively high mortality (MRATIO = 0.70). About 51 percent of the mortality occurred in the oak-hickory forest type group, and another 12 percent occurred in the oak-gum-cypress forest type group. About 18 percent of mortality occurred in the loblolly-shortleaf pine type group. A record-setting drought in 2011 affected Oklahoma and Texas. It was reported as weakening both pines and hardwoods in Texas, making them susceptible to a variety of pests and pathogens (Smith 2013, 2014). This drought probably contributed to the mortality in this ecoregion. 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 mortality in the oak-hickory and oak-gum-cypress forest types. Pine engraver beetle (*Ips* spp.) has been a problem in Texas' pine forests, and may have contributed to mortality in the loblolly-shortleaf pine forests.

Ecoregion section 255A–Cross Timbers and Prairie experienced relatively high mortality (MRATIO = 0.66). However, the majority of the ecoregion is located in western Oklahoma, where mortality data are not yet available. Therefore, the results shown are based on data collected in the relatively small portion of the ecoregion located in eastern Oklahoma and southeastern Kansas. About 77 percent of the mortality (in terms of tree volume) occurred in the oak-hickory forest type group; another 14 percent of the mortality occurred in the elm-ash-cottonwood forest type group. Disturbances associated with mortality included adverse weather and domestic animal damage. As mentioned above, a record drought in 2011 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).

Western States

As mentioned above, in much of the West, only a small proportion 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 be as long as 15 years.

The Western United States presents a very different picture from the East in terms of mortality. For large portions of the West, no MRATIO has been calculated. This is because either (1) fewer than 50 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 an MRATIO for most of the West.

In much of the Interior West as well as southern California, where the MRATIO was calculated, mortality exceeded growth, sometimes by a factor of two to four (fig. 5.2). This is not surprising. In such dry regions, trees grow very slowly. Live tree volume is decreasing in regions where major mortality events are occurring. Because of the low growth rates, it will take quite a long time to recover the tree volume lost.

Figure 5.3 shows annual mortality as a percentage of total live tree volume. We see three clusters of mountain ecoregion sections where mortality is high relative to standing live volume: eastern Montana and central Idaho (M332A–Idaho Batholith, M332B–Northern Rockies and Bitterroot Valley, M332D–Belt Mountains, M332E–Beaverhead Mountains, M332F–Challis Volcanics, and M333C–Northern Rockies), the Front Range of Colorado (M331I–Northern Parks and Ranges and M331G–South-Central Highlands) together with section M331E–Uinta Mountains of Utah, and M262B–Southern California Mountain and Valley section. In all of these sections, annual mortality exceeded 3 percent of live volume.

In California, the mortality is most likely related to a combination of drought, bark beetles, and fire (California Forest Pest Council

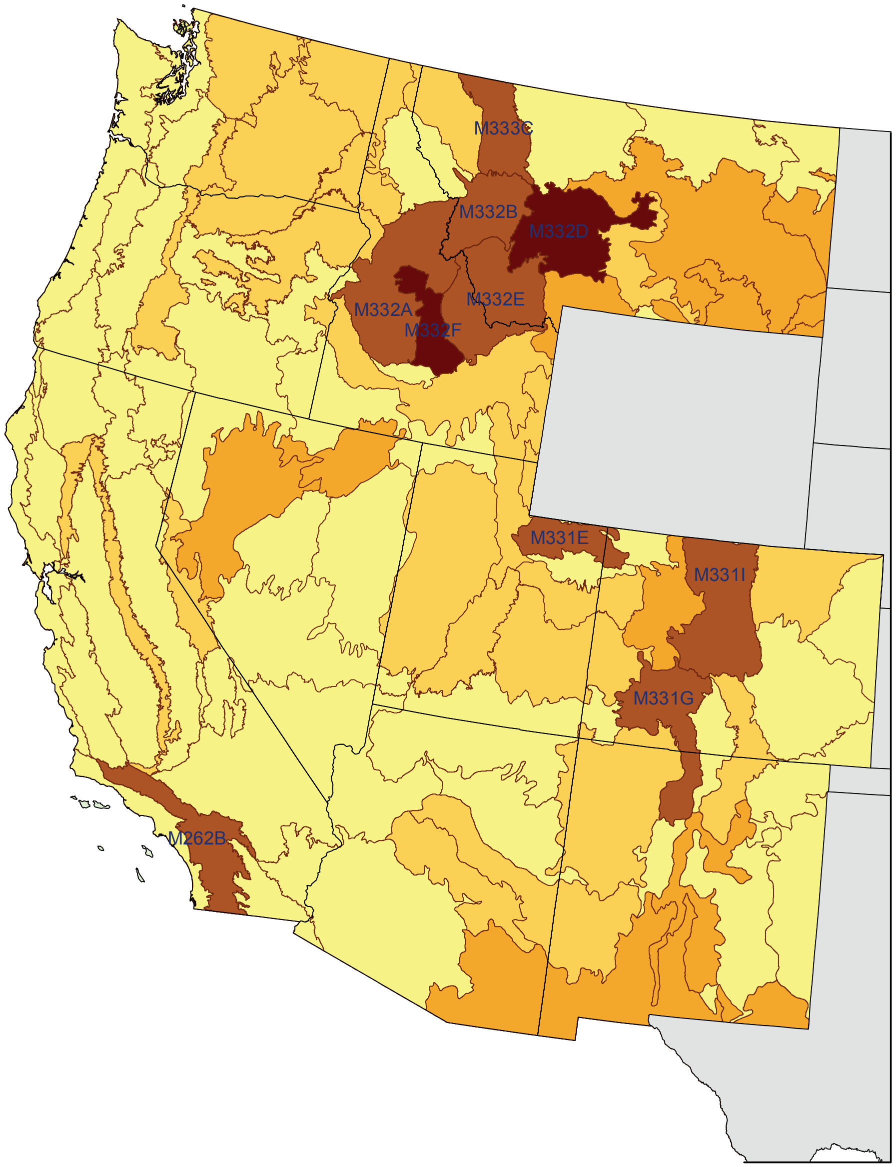

Figure 5.3—Annual tree mortality expressed as a percentage of gross live tree volume by ecoregion section (Cleland and others 2007) for the Western United States. (Data source: U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Program). Mortality was analyzed using a partial cycle of remeasurements, and results from the region should be considered preliminary.

2016). In Colorado, ecoregion sections M331G and M331I include areas that have experienced major outbreaks of mountain pine beetle as well as spruce beetle (*Dendroctonus rufipennis*) (Colorado State Forest Service 2016). These same pests have been affecting ecoregion M331E (USDA Forest Service, Uinta-Wasatch-Cache National Forest [no date]; Utah Department of Natural Resources, Forestry, Fire, and State Lands 2016). The areas of high mortality in Montana and Idaho include 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.

SUMMARY

This analysis shows that mortality is low relative to tree growth in most of the Eastern and Central United States. The areas of highest mortality occur in the mostly riparian forests of Great Plains ecoregions. A common characteristic of most of these 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.

The preliminary analysis of the Western United States shows that, almost everywhere in the Interior West, mortality relative to growth is higher than in most of the Eastern and Central United States. In several parts of the West, mortality is also very high as a percent of live volume. These areas correspond to regions where insect outbreaks (see chapter 2) as well as fire (chapter 3) and/or severe drought (chapter 4) have occurred.

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, should a particular species be dying due to a pest or pathogen in mixed-species forests where other species are growing vigorously, these analyses are unlikely to detect it. This is especially true of species (e.g., ash) that make up a relatively small proportion of many eastern forests.

To gain a more complete understanding of mortality, one should consider the results of this analysis together with other indicators of forest health. FIA tree damage data (O'Connell and others 2017) as well as Evaluation Monitoring projects that focus on particular mortality-causing agents (chapters 8–15) can provide insight into smaller scale or species-specific mortality issues. Large-scale analyses of forest-damaging events, including insect and disease activity (chapter 2) and fire (chapter 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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