CHAPTER 5.
Tree Mortality

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INTRODUCTION

Tree mortality is a natural process in all forest ecosystems. However, extremely high mortality can be an indicator of forest health issues. On a regional scale, high mortality levels may indicate widespread insect or disease problems. High mortality may also occur if a large proportion of the forest in a particular region is made up of older, senescent stands.

The mission of the Forest Health Monitoring (FHM) Program is to monitor, assess, and report on the status, changes, and long-term trends in forest ecosystem health in the United States (USDA Forest Service 2003). Thus, the approach to mortality presented here seeks to detect mortality patterns that might reflect subtle changes to fundamental ecosystem processes (due to such large-scale factors as air pollution, global climate change, or fire-regime change) that transcend individual tree species–pest/pathogen interactions. However, sometimes the proximate cause of mortality may be discernible. In such cases, the cause of mortality is reported, both because it is of interest in and of itself to many readers and because understanding such proximate causes of mortality ***might*** provide insight into whether the mortality is within the range of natural variation or reflects more fundamental changes to ecological processes.

DATA

Mortality is analyzed using Forest Inventory and Analysis (FIA) phase 2 (P2) data. FIA P2 data are collected across forested land throughout the United States, with approximately 1 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. Any analysis of mortality requires data collected at a minimum of two points in time from any given plot. 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 measurement of trees or saplings). For this report, the repeated P2 data were available for all of the Central and Eastern States, and data for some States include a third cycle of measurements (i.e., a third measurement of the plots).

Once all P2 plots have been remeasured in a State, mortality estimates generally will be based on a sample intensity of approximately 1 plot:

6,000 acres of forest.[1] However, at this time not all plots have been remeasured in all the States included in this analysis. When not all plots have been remeasured, mortality estimates are based on a lower effective sample intensity. Table 5.1 shows the 37 States from which consistent, repeated P2 measurements were available, the time period spanned by the data, and the effective sample intensity. Also shown is the proportion of plots measured for a third time. The States included in this analysis, as well as the forest cover within those States, are shown in figure 5.1.

Because the data used here are collected using a rotating panel design and all available annualized data are used, the majority of data used in this mortality analysis were also used in the analysis presented in the previous FHM national report (Ambrose 2014). Using the data in this way, it would be very unusual to see any great changes in mortality patterns from one annual report to the next. Nevertheless, it is important to look at mortality patterns every year in order to observe emerging trends or sudden shifts that may indicate forest health problems.

[1]In some States more intensive sampling has been implemented. See table 5.1 for details.

Table 5.1—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 plot density and proportion of plots that had been remeasured) in the available data sets

Time period	States	Effective sample intensity	Proportion of plots measured 3 times
1999–11	IN	1 plot: 6,000 acres	2/5
1999–11	ME	1 plot: 6,000 acres	3/5
1999–11	WI	1 plot: 3,000 acres[a]	2/5
1999–12	MN	1 plot: 3,000 acres[a]	3/5
1999–12	MO	1 plot: 6,000 acres[b]	3/5
2000–11	PA, VA	1 plot: 6,000 acres	2/5
2000–12	IA	1 plot: 6,000 acres	3/5
2000–12	MI	1 plot: 2,000 acres[c]	3/5
2000–12	AR	1 plot: 6,000 acres	2/5
2001–11	OH	1 plot: 6,000 acres	0
2001–11	TX[d]	1 plot: 6,000 acres	3/5
2001–11	GA, KS, NE, TN	1 plot: 6,000 acres	1/5
2001–11	LA	1 plot: 14,000 acres	0
2001–12	AL	1 plot: 6,000 acres	0
2001–12	IL, ND, SD	1 plot: 6,000 acres	2/5
2002–11	FL	1 plot: 10,000 acres	0
2002–11	KY, SC	1 plot: 7,500 acres	0
2002–11	NY	1 plot: 7,500 acres	0
2002–12	NH	1 plot: 6,000 acres	0
2003–11	CT, MA, RI, VT	1 plot: 7,500 acres	0
2003–11	NC	1 plot: 14,000 acres	0
2004–11	DE, MD, NJ, WV	1 plot: 10,000 acres	0
2006–12	MS	1 plot: 10,500 acres	0
2008–11	OK[e]	1 plot: 15,000 acres	0

[a] In Minnesota and Wisconsin, the phase 2 (P2) inventory was done at twice the standard Forest Inventory and Analysis Program (FIA) sample intensity, approximately 1 plot per 3,000 acres.
[b] In Missouri, the P2 inventory was done at twice the standard FIA sample intensity, approximately 1 plot per 3,000 acres, on national forest lands, and at the standard intensity of 1 plot per 6,000 acres on all other lands.
[c] In Michigan, the P2 inventory was done at triple the standard FIA sample intensity, approximately 1 plot per 2,000 acres.
[d] Annualized growth and mortality data were only available for eastern Texas.
[e] Annualized growth and mortality data were only available for eastern Oklahoma.

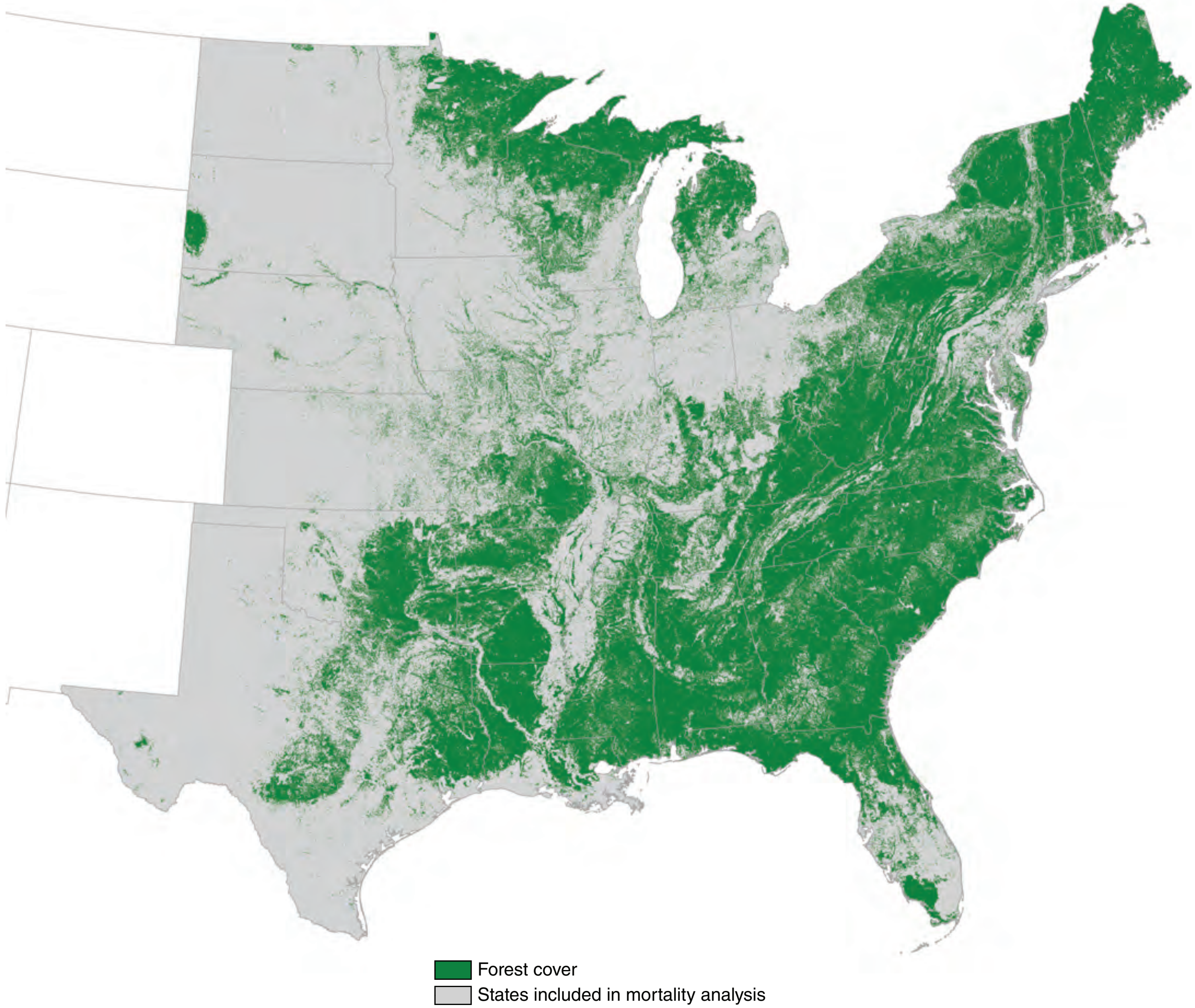

Figure 5.1—Forest cover in the States where mortality was analyzed. Forest cover was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (USDA Forest Service 2008).

METHODS

The methods used in this analysis were originally developed for earlier FHM national reports (2001–2004) using FIA phase 3 (P3) data. In this report, FIA P2 tree [≥ 5 inches diameter at breast height (d.b.h.)] and sapling (1 inch ≤ d.b.h. < 5 inches) data were used to estimate average annual tree mortality in terms of tons of aboveground biomass per acre. The data were obtained from the public FIA Database-version 5.1 (USDA Forest Service 2013). The biomass represented by each tree was calculated by FIA (USDA Forest Service 2011). To compare mortality rates across forest types and climate zones, the ratio of annual mortality to gross growth (MRATIO) is used as a standardized mortality indicator (Coulston and others 2005b). Gross growth rate and mortality rate, in terms of tons of biomass per acre, were independently calculated for each ecoregion section (Cleland and others 2007, McNab and others 2007) using a mixed modeling procedure where plot-to-plot variability is considered a random effect and time is a fixed effect. The mixed modeling approach has been shown to be particularly efficient for estimation when using data where not all plots have been measured over identical time intervals (Gregoire and others 1995). In the estimation procedure, within-plot temporal correlation was modeled using a Toeplitz matrix. MRATIOs were then calculated from the growth and mortality rates. For details on the method, see Appendix A–Supplemental Methods in *Forest Health Monitoring 2001 National Technical Report* (Coulston and others 2005c) and Appendix A–Supplemental Methods in *Forest Health Monitoring 2003 National Technical Report* (Coulston and others 2005a).

In addition, the ratio of average diameter of trees that died between plot measurements to average surviving live tree diameter (DDLD ratio) was calculated for each plot where mortality occurred. Low DDLD ratios (much < 1) usually indicate competition-induced mortality typical of young, vigorous stands, while high ratios (much > 1) indicate mortality associated with senescence or some external factors such as insects or disease (Smith and Conkling 2004). Intermediate DDLD ratios can be hard to interpret because a variety of stand conditions can produce such DDLD values. The DDLD ratio is most useful for analyzing mortality in regions that also have high MRATIOs. High DDLD values in regions with very low MRATIOs may indicate small areas experiencing high mortality of large trees or locations where the death of a single large tree (such as a remnant pine in a young hardwood stand) has produced a deceptively high DDLD.

To further analyze tree mortality, the number of stems and the total biomass of trees that died also were calculated by species within each ecoregion. Identifying the tree species 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 tree species are identified.

In addition, a biomass weighted mean mortality age was calculated by ecoregion and species. For each species experiencing mortality in an ecoregion, the mean stand age was calculated, weighted by the dead biomass on the plot. This value gives a rough indicator of the average age of the stands in which trees died. However, the age of individual trees may differ significantly from the age assigned to a stand by FIA field crews, especially in stratified mixed stands (i.e., stands consisting of multiple cohorts of different ages). When the age of trees that die is relatively low compared to the age at which trees of a particular species usually become senescent, it suggests that some pest, pathogen, or other forest health problem may be affecting the forest.

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. An MRATIO value >1 indicates that mortality exceeds growth and live standing biomass is actually decreasing.

The highest MRATIOs occurred in ecoregion sections 331F–Western Great Plains (MRATIO = 1.42) and 332C–Nebraska Sand Hills (MRATIO = 1.40) in South Dakota and Nebraska, where mortality actually exceeded growth. Other areas of high mortality relative to growth were sections 332D–North-Central Great Plains, also in South Dakota and Nebraska (MRATIO =0.65), M334A–Black Hills (MRATIO = 0.87) in South Dakota, and 234A–Southern Mississippi Alluvial Plain in Louisiana, Mississippi, and Arkansas (MRATIO = 0.86). Table 5.2 shows the tree species experiencing the greatest mortality in those ecoregions.

The results of the analysis of the relative sizes of trees that died to those that lived, the DDLD ratio, are shown in table 5.3. The DDLD ratio is a plot-level indicator, so I obtained summary statistics for the ecoregions where mortality relative to growth was highest. In all cases, the mean and median DDLDs were rather close to one, meaning that the trees that died were similar in size to the trees that survived. However, there were some plots with extremely high DDLD values. This same pattern of mean and median DDLD being close to one with some high DDLD values was observed in nearly all ecoregions, regardless of the overall mortality level.

In three of the ecoregion sections exhibiting highest mortality relative to growth (331F–Western Great Plains, 332C–Nebraska Sand Hills, and 332D–North-Central Great Plains), the predominant vegetation is not forest land, but rather grassland (see the forest cover in

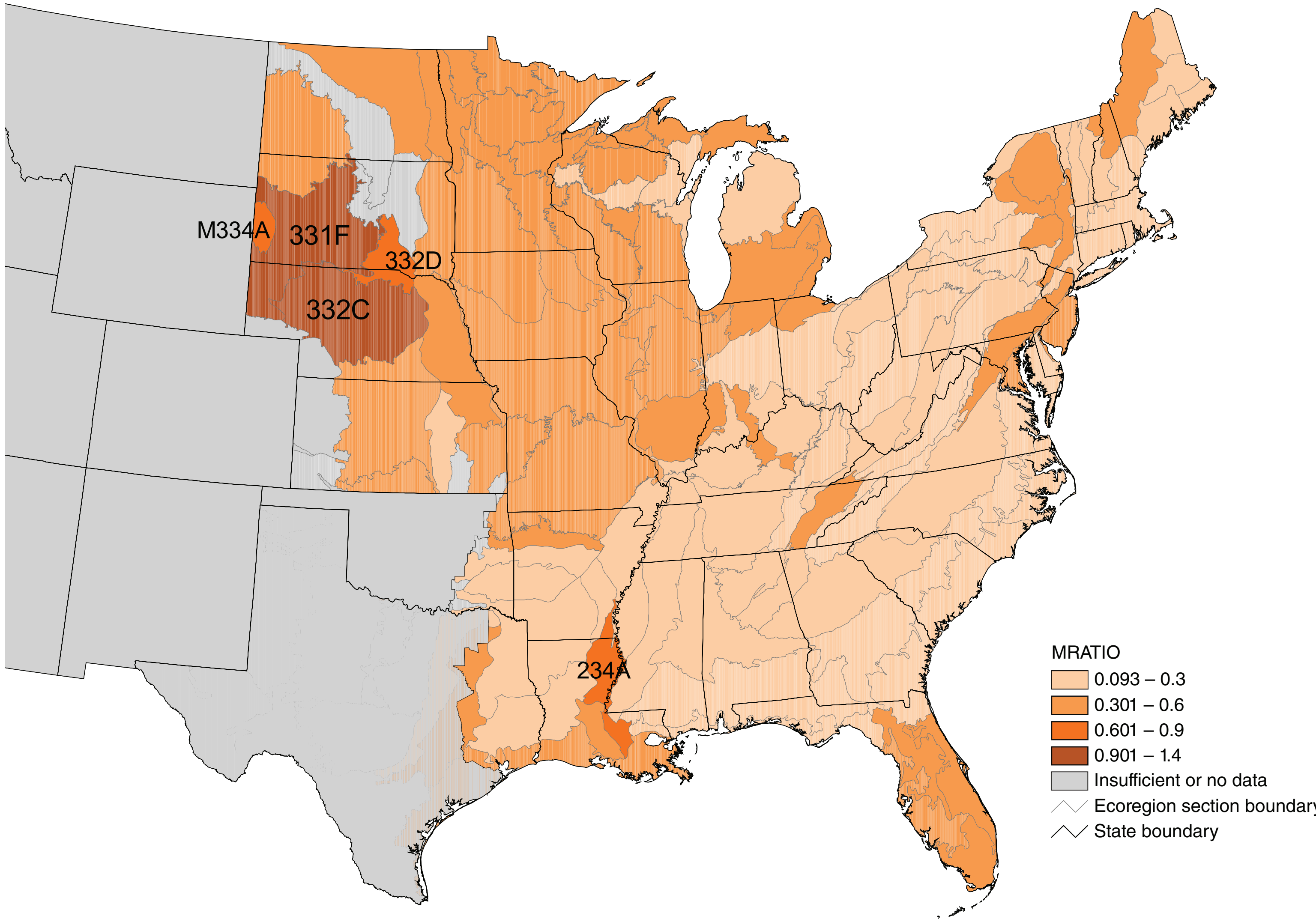

Figure 5.2—Tree mortality expressed as the ratio of annual mortality of woody biomass to gross annual growth in woody biomass (MRATIO) by ecoregion section (Cleland and others 2007). (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program)

Table 5.2—Tree species comprising at least 5 percent of the mortality (in terms of biomass) for ecoregions where the MRATIO was ≥ 0.60

Ecoregion section	MRATIO	Tree species	Percent of total ecoregion mortality biomass	Mean age of dead trees[a]	Species percent mortality	
					Biomass	Stems
				years		
234A–Southern Mississippi Alluvial Plain	0.86	Black willow *(Salix nigra)*	36.49	38	52.66	66.05
		Water oak *(Quercus nigra)*	8.88	65	10.67	20.73
		Sugarberry *(Celtis laevigata)*	7.45	52	6.53	7.93
		Green ash *(Fraxinus pennsylvanica)*	6.99	50	11.30	14.35
		Eastern cottonwood *(Populus deltoides)*	6.00	54	23.40	16.89
		Swamp chestnut oak *(Quercus michauxii)*	5.88	63	43.64	80.00
331F–Western Great Plains	1.42	Ponderosa pine *(Pinus ponderosa)*	67.04	52	8.53	10.70
		Green ash *(Fraxinus pennsylvanica)*	14.37	44	13.86	12.45
		Eastern cottonwood *(Populus deltoides)*	8.18	79	3.87	7.69
332C–Nebraska Sand Hills	1.40	Eastern cottonwood *(Populus deltoides)*	40.08	56	55.21	33.86
		Green ash *(F. pennsylvanica)*	14.61	52	15.14	14.09
		Eastern redcedar *(Juniperus virginiana)*	12.45	40	6.91	21.22
		American elm *(Ulmus americana)*	6.43	54	22.01	31.88
332D–North-Central Great Plains	0.65	Ponderosa pine *(Pinus ponderosa)*	25.45	44	24.90	34.60
		American elm *(U. americana)*	20.55	49	22.75	25.22
		Bur oak *(Quercus macrocarpa)*	17.85	61	3.57	4.63
		Green ash *(F. pennsylvanica)*	12.69	62	15.17	18.00
		Hackberry *(Celtis occidentalis)*	10.59	60	11.24	0.72
		Eastern redcedar *(J. virginiana)*	6.51	37	4.22	6.53
M334A–Black Hills	0.87	Ponderosa pine *(Pinus ponderosa)*	61.28	22	19.80	45.58
		Quaking aspen *(Populus tremuloides)*	5.22	16	28.83	59.51

MRATIO = ratio of annual mortality of woody biomass to gross annual growth in woody biomass.
[a] Ages are estimated from the stand age as determined by the Forest Inventory and Analysis field crew. It is possible, especially in mixed-species stands, that the age of individual trees that died differed significantly from the stand age.

Table 5.3—Dead diameter–live diameter (DDLD) ratios for ecoregion sections where the MRATIO was ≥0.60

Ecoregion section	Mean DDLD	Maximum DDLD	Median DDLD	Minimum DDLD
234A–Southern Mississippi Alluvial Plain	0.97	3.72	0.77	0.18
331F–Western Great Plains	0.98	3.29	0.91	0.08
332C–Nebraska Sand Hills	1.16	6.75	0.87	0.16
332D–North-Central Great Plains	0.93	2.17	0.91	0.29
M334A–Black Hills	1.04	7.02	0.77	0.16

MRATIO = ratio of annual mortality of woody biomass to gross annual growth in woody biomass.

fig. 5.1), and subsequently there were relatively few forested plots measured (98 plots in region 331F, 85 plots in region 332C, and 57 plots in region 332D). Both ecoregions 331F and 332D have had high mortality relative to growth in recent years (Ambrose 2013, 2014), so the observed mortality is not a new phenomenon. Tree growth rates in these regions (especially in 331F) are quite low, so the high MRATIOs are due to a combination of low growth and high mortality. Much of the forest in these sections is riparian forest, and, indeed, most of the species experiencing greatest mortality (table 5.2) are commonly found in riparian areas. The one exception was high ponderosa pine mortality in ecoregion section 331F–Western Great Plains. Ponderosa pine is not a riparian species, but like the riparian tree species, it occurs in a relatively small area of the ecoregion, only on discontinuous mountains, plateaus, canyons, and breaks in the plains (Burns and Honkala 1990).

DDLD values vary widely within each of these sections. There are a small number of plots with high DDLDs, and these plots represent most of the biomass that died in these sections. However, on many of these plots the overall level of mortality is comparatively low, as would be the case when remnant larger trees die, leaving younger stands behind. Tree growth is generally slow in these ecoregion sections because of naturally dry conditions. Where the number of sample plots is small and tree growth is slow, care must be taken in interpreting mortality relative to growth over short time intervals.

In ecoregion section M334A–Black Hills, by far the largest amount of biomass that died was ponderosa pine (table 5.2). In section M334A, this mortality represented nearly half of the ponderosa pine stems and nearly 20 percent of the biomass. There has been an ongoing mountain pine beetle (*Dendroctonus ponderosae*) outbreak in the Black Hills (South Dakota Department of Agriculture 2011, 2012), so this pine mortality is very likely related to the outbreak.

In the adjacent ecoregion section 331F, where the MRATIO was highest, ponderosa pine also made up the vast majority of trees that died (67 percent), but this mortality represented a relatively small proportion of the ponderosa pine (biomass and stems) in the region. Scattered mountain pine beetle-related mortality has been reported in the Wildcat Hills and Pine Ridge areas of western Nebraska (Nebraska Forest Service 2010, 2011), which are part of this ecoregion. Green ash, although with an ecoregion mortality less than one quarter that of ponderosa pine, suffered a slightly larger proportional loss of the total ash stock.

In ecoregion section 332D–North-Central Great Plains, six species experienced the highest total mortality in terms of biomass and together represent over 90 percent of the mortality in the ecoregion: ponderosa pine, American elm, bur oak, green ash, hackberry, and eastern redcedar (table 5.2). Of these, ponderosa pine and American elm made up the largest proportion of total mortality and suffered the largest proportional loss in terms of both biomass and number of stems. There is not a lot of ponderosa pine in this region, and much of it is located in shelterbelts. The pine mortality is mostly related to three factors: over-mature trees, drought, and *Diplodia* tip blight. Many of the pines that died were 50 to 100 years old, which is quite old for this species when growing out of its native range and in the harsh environment of the Great Plains. In 2011 and 2012, the region experienced a severe drought that may be a cause of much of the mortality in the region, including that of ponderosa pine. Finally, *Diplodia* tip blight, which has been widely reported in shelterbelts in South Dakota (South Dakota Department of Agriculture 2011) was a third stressor, which finally killed the already severely stressed pines.[2] The elm mortality is probably related to Dutch elm disease, which is reported to be a problem throughout Nebraska (Nebraska Forest Service 2010, 2011). In the case of hackberry, the mortality in terms of biomass (11.24 percent) was much higher than the mortality in terms of number of stems (0.72 percent), which means that the trees that died were a relatively small number of very large trees.

In ecoregion section 234A–Southern Mississippi Alluvial Plain, a number of hardwood species experienced high mortality, including black willow, water oak, sugarberry, green ash, swamp chestnut oak, and eastern cottonwood. The cause of mortality in this wide range of species is not immediately obvious. However, willow, oak, and cottonwood are among the genera preferred by the forest tent caterpillar (*Malacosoma disstria*), which has affected parts of Louisiana and Arkansas in recent years (Arkansas Forestry Commission 2011; Louisiana Department of Agriculture 2009, 2010), so this defoliator may have played some role in the observed mortality. In addition, the growth and mortality of trees in flood plains can be strongly

[2] Personal Communication. 2013. John Ball, South Dakota Dept. of Agriculture, Resource Conservation and Forestry Division, 523 East Capitol, Pierre, SD 57501.

affected by river and groundwater levels. Thus, the observed mortality may be related to either flooding or drought. This may warrant further investigation.

The mortality patterns shown in these analyses do not immediately suggest large-scale forest health issues. Mortality is relatively low in most of the areas for which data are available. The areas of highest mortality occur in the mostly riparian forests of Great Plains ecoregions. A characteristic of most of these Great Plains ecoregions with high mortality is that they are on the margins of land suitable for forest growth. As a result, the implications of the high mortality are unclear. Trees growing in these marginal situations may be especially susceptible to new or changed biotic or abiotic stressors. Because of the small number of forested plots used to analyze these ecoregions, it is difficult to determine whether the mortality is localized or more widespread. Therefore, further study of the health of these forests may be warranted.

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