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 (FHM 1994). 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 discernable. 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 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. 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 many 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.[2] 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 2015b). Thus, it would be very unusual to see any great changes in mortality patterns from one annual report to the next. The rotating panel design may also produce a time lag of several years in detecting extraordinary mortality. Nevertheless, it is important to look at mortality patterns every year so as not to miss detecting mortality patterns that may be indicative of forest health problems as soon as they become discernable.

[2] 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 (FIA) 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 datasets

Time period	States	Effective sample intensity	Proportion of plots measured 3 times
1999–2013	IN	1 plot: 6,000 acres	4/5
1999–2013	ME	1 plot: 6,000 acres	1.0
1999–2013	WI	1 plot: 3,000 acres[a]	4/5
1999–2014	MN	1 plot: 3,000 acres[a]	1.0
1999–2014	MO	1 plot: 6,000 acres[b]	1.0
2000–2013	MI	1 plot: 2,000 acres[c]	4/5
2000–2013	PA, VA	1 plot: 6,000 acres	1.0
2000–2014	AR	1 plot: 6,000 acres	4/5
2000–2014	IA	1 plot: 6,000 acres	1.0
2001–2013	GA, NE	1 plot: 6,000 acres	3/5
2001–2013	KS	1 plot: 6,000 acres	4/5
2001–2013	OH	1 plot: 6,000 acres	2/5
2001–2013	TX[d]	1 plot: 6,000 acres	1.0
2001–2012	TN	1 plot: 6,000 acres	2/5
2001–2013	LA	1 plot: 8,400 acres	0
2001–2014	AL	1 plot: 6,000 acres	2/7
2001–2014	IL, ND, SD	1 plot: 6,000 acres	4/5
2002-2012	KY	1 plot: 6,000 acres	0
2002–2013	FL	1 plot: 6,000 acres	0
2002–2013	NH, NY	1 plot: 6,000 acres	1/5
2002–2013	SC	1 plot: 6,000 acres	2/5
2003–2013	CT, MA, RI, VT	1 plot: 6,000 acres	1/5
2003–2014	NC	1 plot: 7,000 acres	0
2004–2013	DE, MD, NJ, WV	1 plot: 6,000 acres	0
2006–2014	MS	1 plot: 7,000 acres	0
2008–2013	OK[e]	1 plot: 7,500 acres	0

[a] In Minnesota and Wisconsin, the phase 2 inventory was done at twice the standard FIA sample intensity, approximately 1 plot per 3,000 acres.

[b] In Missouri, the phase 2 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 phase 2 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.

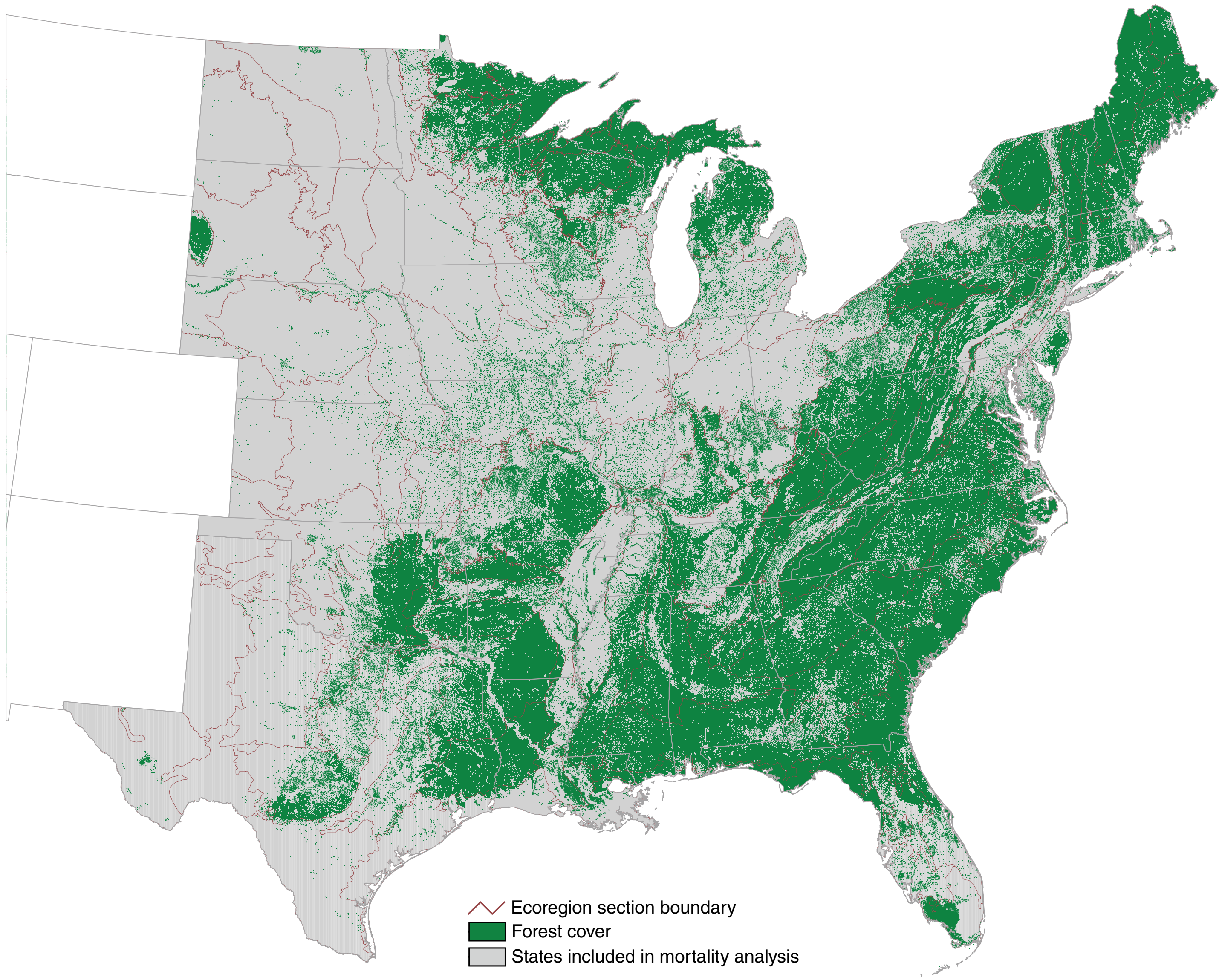

Figure 5.1—Forest cover in the States where mortality was analyzed by ecoregion section (Cleland and others 2007). Forest cover was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (USDA Forest Service 2008).

METHODS

The methods used in this analysis were developed for earlier FHM national reports (2001–2004), using FHM and FIA phase 3 (P3) data. FIA P2 tree (≥ 5 inches diameter at breast height, or 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 6.0 (USDA Forest Service 2014). The biomass represented by each tree was calculated by FIA and provided in the FIA Database (USDA Forest Service 2015). 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 of 98 ecoregion sections (Cleland and others 2007, McNab and others 2007) covering the Eastern United States 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 using data where not all plots have been measured over identical time intervals (Gregoire and others 1995), which is the case for the current FIA inventory methodology. 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 dead tree diameter to average surviving live tree diameter (DDLD ratio) was calculated for each plot where mortality occurred. Low DDLD ratios (much less than 1) usually indicate competition-induced mortality typical of young, vigorous stands, whereas high ratios (much greater than 1) indicate mortality associated with senescence or some external factors such as insects or disease (Smith and Conkling 2005). 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.

Finally, 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 mixed species stands. When the age of trees that die is relatively low compared with 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 = 1.73) in South Dakota and Nebraska, 332F–South-Central and Red Bed Plains (MRATIO = 1.53) in southern Kansas, and M334A–Black Hills (MRATIO = 1.32) in western South Dakota; in all three regions, mortality actually exceeded growth. Other areas of high mortality relative to growth were ecoregion sections 251F–Flint Hills (MRATIO = 0.95) in Kansas, 332D–North-Central Great Plains in South Dakota and Nebraska (MRATIO = 0.76), and 331M–Missouri Plateau (MRATIO = 0.67). Table 5.2 shows the tree species experiencing the greatest mortality in those ecoregions. 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.

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. Interestingly, the same pattern of mean and median DDLD close to one and some high DDLD values was observed in nearly all ecoregions, regardless of the overall mortality level. With the exception of M334A–Black Hills, in all of the ecoregion sections exhibiting high mortality relative to growth, the predominant vegetation is grassland (see the forest cover in fig. 5.1). In most of them, though the ecoregions were quite large, there were

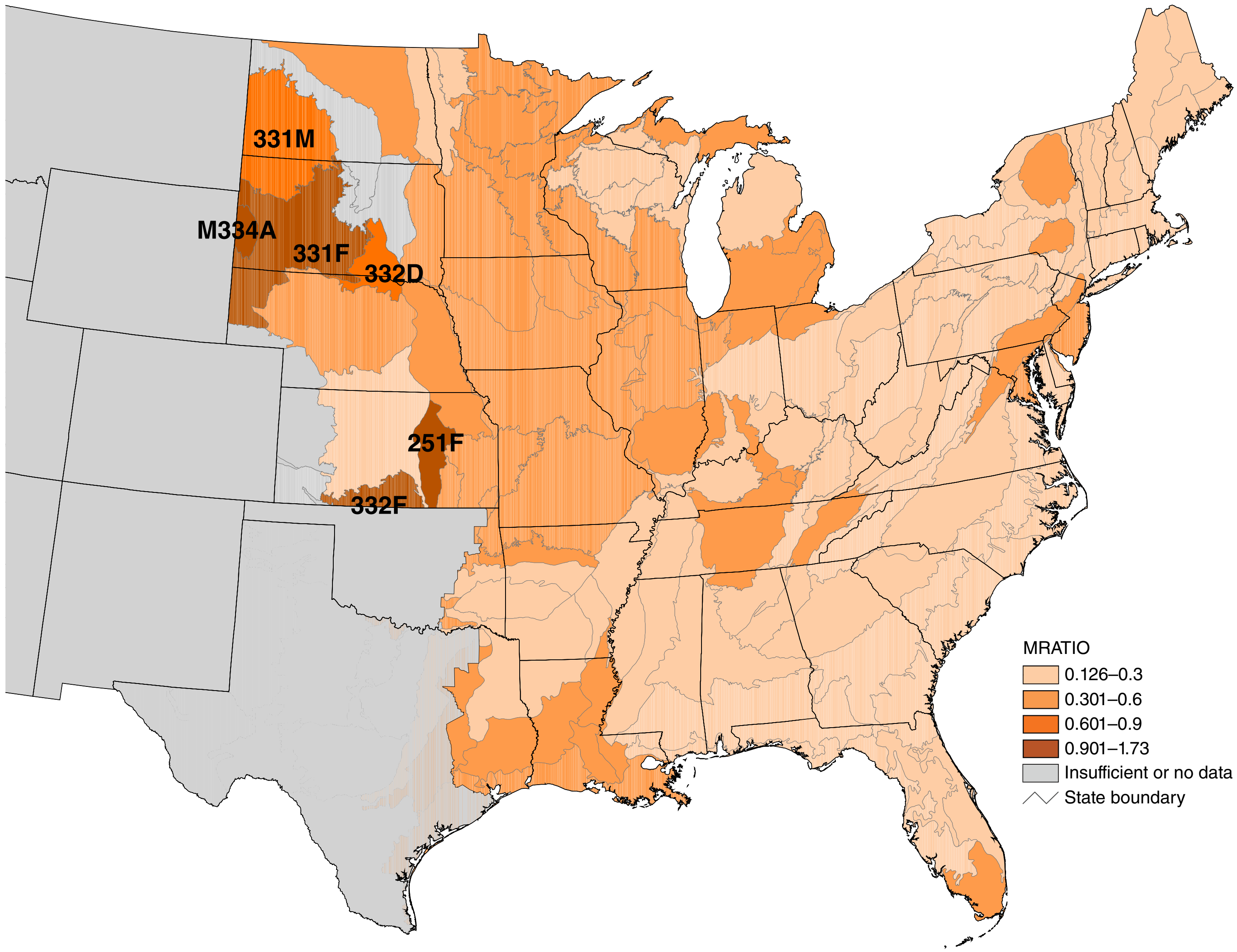

Figure 5.2—Tree mortality expressed as the ratio of annual mortality of woody biomass to gross annual growth in woody biomass (MRATIO) by ecoregion section (Cleland and others 2007). Ecoregions with high MRATIOs are identified by section number. (Data source: U.S. Department of Agriculture, Forest Service,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

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

Ecoregion section	MRATIO	Tree species	Percent of total ecoregion mortality biomass	Mean age of dead trees[a]	Species percent mortality (biomass)	(stems)
251F–Flint Hills	0.95	American elm *(Ulmus americana)*	20.53	36	16.05	18.64
		Eastern redbud *(Cercis canadensis)*	15.4	58	59.16	32.59
		Green ash *(Fraxinus pennsylvanica)*	9.36	59	9.19	3.84
		White mulberry *(Morus alba)*	9.2	--	63.53	46.64
		Hackberry *(Celtis occidentalis)*	8.12	73	2.58	6.56
331F–Western Great Plains	1.73	Ponderosa pine *(Pinus ponderosa)*	61.91	51	7.97	11.14
		Green ash *(Fraxinus pennsylvanica)*	13.08	44	11.73	7.52
		Eastern cottonwood *(Populus deltoides)*	9.22	61	3.61	21.16
		Bur oak *(Quercus macrocarpa)*	5.92	61	4.82	12.84
331M–Missouri Plateau	0.67	Eastern cottonwood *(Populus deltoides)*	37.28	51	11.21	8.16
		Bur oak *(Quercus macrocarpa)*	24.81	60	7.49	6.24
		Green ash *(Fraxinus pennsylvanica)*	21.94	63	5.47	6.5
		American elm *(Ulmus americana)*	6.43	71	12.98	3.3
332D–North-Central Great Plains	0.76	American elm *(Ulmus americana)*	24.72	48	24.33	24.58
		Eastern cottonwood *(Populus deltoides)*	24.28	85	10.64	4.5
		Ponderosa pine *(Pinus ponderosa)*	15.99	44	20.37	30.72
		Green ash *(Fraxinus pennsylvanica)*	9.81	63	11.82	14.25
		Bur oak *(Quercus macrocarpa)*	9.29	64	2.06	4.2
		Eastern redcedar *(Juniperus virginiana)*	5.78	34	3.63	7.58
		Hackberry *(Celtis occidentalis)*	5.26	60	4.15	0.38
332F–South-Central and Red Bed Plains	1.53	Black willow *(Salix nigra)*	20.35	51	40.09	44
		Black locust *(Robinia pseudoacacia)*	18.56	40	22.93	39.95
		Eastern cottonwood *(Populus deltoides)*	16.36	39	6.34	7.3
		Eastern redcedar *(Juniperus virginiana)*	10.3	45	17.31	12.15
		Hackberry *(Celtis occidentalis)*	8.67	8	13.23	7.82
		Red mulberry *(Morus rubra)*	7.96	43	4.68	2.38
		American elm *(Ulmus americana)*	7.18	39	15.27	2.69
M334A–Black Hills	1.32	Ponderosa pine *(Pinus ponderosa)*	85.24	63	5.73	10.46
		Quaking aspen *(Populus tremuloides)*	5.94	72	22.15	24.84

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 FIA 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 or greater

Ecoregion section	Mean DDLD	Maximum DDLD	Median DDLD	Minimum DDLD
251F–Flint Hills	1.04	4.77	0.79	0.25
331F–Western Great Plains	1.00	3.29	0.91	0.08
331M–Missouri Plateau	1.04	2.45	0.90	0.14
332D–North-Central Great Plains	1.12	5.38	0.91	0.15
332F–South-Central and Red Bed Plains	1.11	3.11	1.08	0.14
M334A–Black Hills	1.05	7.02	0.84	0.16

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

relatively few forested plots measured (67 plots in region 251F, 103 plots in region 331F, 83 plots in region 331M, 59 plots in region 332D, and 31 plots in region 332F).

In ecoregion section M334A-Black Hills, by far the largest amount of biomass that died was ponderosa pine (*Pinus ponderosa*) (table 5.2); however, this represented a relatively small proportion of the ponderosa pine in the ecoregion (about 10 percent of ponderosa pine stems and 6 percent of biomass). In the adjacent ecoregion section 331F–Western Great Plains, where the MRATIO was highest, ponderosa pine also made up the vast majority of trees that died (62 percent). Here, too, this mortality represented a relatively small proportion of the ponderosa pine (biomass and stems) in the region. The pine mortality in both ecoregions is very likely related to mountain pine beetle (*Dendroctonus ponderosae*). There has been an ongoing pine beetle outbreak in the Black Hills (South Dakota Department of Agriculture 2011, 2012, 2013, 2014), and mountain pine beetle–related mortality 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 more recently (Nebraska Forest Service 2014). Drought in 2012 and 2013, affecting much of South Dakota and Nebraska (Nebraska Forest Service 2012, 2013; South Dakota Department of Agriculture 2012), may also have contributed to pine mortality, as well as that of other species, in these ecoregions.

Both ecoregions 331F and 332D have had high mortality relative to growth in recent years (Ambrose 2013, 2014, 2015a, 2015b), 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, and, indeed, most of the species experiencing greatest mortality (table 5.2) are commonly found in riparian areas. The major exception was high ponderosa pine mortality in ecoregion section 331F–Western Great Plains. 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 ecoregion section 332D–North-Central Great Plains, seven species experienced high total mortality in terms of biomass and together represent over 90 percent of the mortality in the ecoregion: American elm (*Ulmus americana*), eastern cottonwood (*Populus deltoides)*, ponderosa pine, bur oak (*Quercus macrocarpa*), green ash (*Fraxinus pennsylvanica*), hackberry (*Celtis occidentalis*), and eastern redcedar (*Juniperus virginiana*) (table 5.2). Of these, ponderosa pine and American elm suffered the largest proportional loss in terms of both biomass and number of stems and, together with eastern cottonwood, made up the largest proportion of total mortality. In the case of hackberry, the mortality in terms of biomass (4.15 percent) was much higher than the mortality in terms of number of stems (0.38 percent), which means that the trees that died were a relatively small number of very large trees. A number of different factors may be responsible for the high mortality in the ecoregion. The drought in 2012 and 2013, as well as associated winter desiccation, has been reported as severely stressing trees in much of South Dakota and Nebraska. Dutch elm disease has been responsible for elm mortality in both States (Nebraska Forest Service 2012, 2013; South Dakota Department of Agriculture 2012). Cedar bark beetle (*Phloesinus* spp.) combined with drought stress have been reported as causing mortality in juniper (redcedar) in South Dakota (South Dakota Department of Agriculture 2012, 2013). Green ash has been affected by ash/lilac borer (*Podosesia syringae*) in South Dakota (South Dakota Department of Agriculture 2012). Also, a variety of insects and diseases have been reported as affecting ponderosa pine in the South Dakota and Nebraska; their activity may have produced increased mortality in trees stressed by drought conditions.

In ecoregion 332F–South-Central and Red Bed Plains, in south-central Kansas, a wide range of species suffered high mortality, including black willow (*Salix nigra*), black locust (*Robinia pseudoacacia*), eastern cottonwood, eastern redcedar, hackberry, red mulberry (*Morus rubra*), and American elm. It is unlikely that a single pest or pathogen would produce mortality in this range of species. The most likely factor associated with this mortality is drought: 2011 through 2013 were extremely dry years in most of Kansas, with the areas of most severe drought including this ecoregion (Kansas Forest Service 2011, 2012, 2013), and drier than normal conditions persisted through 2014 (Kansas Forest Service 2014). Such severe drought could lead to tree mortality either directly or by stressing the trees so that they succumb to pests or pathogens that would normally be nonlethal.

In ecoregion 251F–Flint Hills, several species experienced high mortality: American elm, eastern redbud (*Cercis canadensis*), green ash, white mulberry (*Morus alba*), and hackberry. Most of the biomass that died was American elm, and the mortality represented 16 percent of the biomass and 19 percent of the stems of that species (table 5.2). Here also, Dutch elm disease may have been responsible for this mortality. The severe drought in Kansas, mentioned above, likely contributed to the mortality in all species.

In ecoregion 331M–Missouri Plateau, three species, eastern cottonwood, bur oak, and green ash, represented more than three-fourths of the mortality (biomass). Green ash have been affected by ash/lilac borer as well as other native ash borers, in both North and South Dakota (North Dakota Forest Service 2012, South Dakota Department of Agriculture 2012). Adverse weather conditions, including both drought and excessively wet conditions, both of which occurred during the past remeasurement cycle (Bergdahl 2013, 2014; South Dakota Department of Agriculture 2012), may have contributed to mortality by stressing trees.

This analysis shows that in most of the Eastern and Central United States, mortality has been low relative to tree growth. Mortality has been rather low in most of the areas for which data are available. The areas of highest recent mortality occurred in the mostly riparian forests of Great Plains ecoregions. A common characteristic of most of the ecoregions with high mortality is that, being very dry, they are on the margins of land suitable for forest growth. 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 the mortality observed.

It is also important to realize that this analysis alone cannot tell the complete story regarding tree mortality. Mortality that is concentrated in highly fragmented areas or areas adjacent to human development may not be detected because areas classified as nonforest are not included in the FIA sample. Also, should a particular species be dying due to a pest or pathogen in mixed-species forests where other species are growing vigorously, this analysis is 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, including insect and disease activity (chapter 2) and Evaluation Monitoring projects that focus on particular mortality-causing agents (chapters 7–17).

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