Changes in Hardwood Sawtimber Growth, Mortality, and Removals in the Eastern United States

William G. Luppold,[a,*] and Matthew S. Bumgardner [b]

An examination of changes in growth, mortality, and removals of hardwood sawtimber in the eastern United States within the first two decades of the 21st century found large variations among regions and species groups. Changes in growth ranged from a 17% increase in the Lake States region to a statistically insignificant 1% in the Southern region. Most regions had relatively large increases in mortality. High levels of ash (*Fraxinus* spp.) mortality in the Northeast, Lake States, and Central regions likely were a result of the emerald ash borer (*Agrilus planipennis*). Hardwood sawtimber removals declined in all regions except the Lake States and Central regions, with the largest relative declines occurring in the Southern and Mid-Atlantic regions. With the exception of ash, there were no indications of immediate declines in eastern sawtimber volume. However, continual increases in mortality, a resurgence of removals, and reduced growth could cause sawtimber volume to plateau in the coming decades. The findings from this study indicated that there likely would be variations in these plateaus among the species groups and regions.

Keywords: United States; Eastern hardwoods; Growing stock, Sawtimber; Growth; Mortality; Removals

*Contact information: a: Northern Research Station, USDA Forest Service, 301 Hardwood Lane, Princeton, WV 24740 USA; b: Northern Research Station, USDA Forest Service, 359 Main Road, Delaware, OH 43015 USA; *Corresponding author: william.luppold@usda.gov*

INTRODUCTION

In a given forest region, hardwood growing stock volume is a function of growth, removals (primarily through harvest), and mortality. Since the late 1970s, hardwood growing stock volume in the eastern United States has steadily increased because a large portion of this resource grew into sawtimber-size trees (trees 11.0 inches dbh and larger, hereafter termed as sawtimber) of increasing diameter (Fig. 1). Between the 1970s and 1990s, annual removals (removals) of hardwood growing stock also increased (Fig. 2). Since the late 1990s, removals have decreased as hardwood roundwood (logs, bolts, pulpwood, *etc.*) production has declined (Howard and Liang 2019), allowing a greater portion of sawtimber trees to increase in volume through accretion.

Another source of forest change has been the 160% increase in annual mortality (mortality) of growing stock trees since the 1970s (Fig. 2). This increase in mortality has countered the impact of reduced removals. Yaussy *et al.* (2013) found that increased competition, due in part to a lack of removals, was increasing the mortality risk in eastern hardwood forests. In another study, conditions that resulted in slow growth increments were found to increase mortality in both red and white oak species (*Quercus* spp.), but red oak species were more affected (Shifley *et al*. 2006). Brooks (1994) found that overstocking, along with drought and insect defoliation, helped explain an increase in mortality and decrease in growth observed in western and central Pennsylvania. Environmental conditions, such as drought, can also negatively affect hardwood growth for some species and might interact with competition to increase tree mortality (Elliott and Swank 1994). However, for some species, wetter periods can lead to favorable conditions for disease vectors that also might increase mortality (Clinton *et al*. 2003).

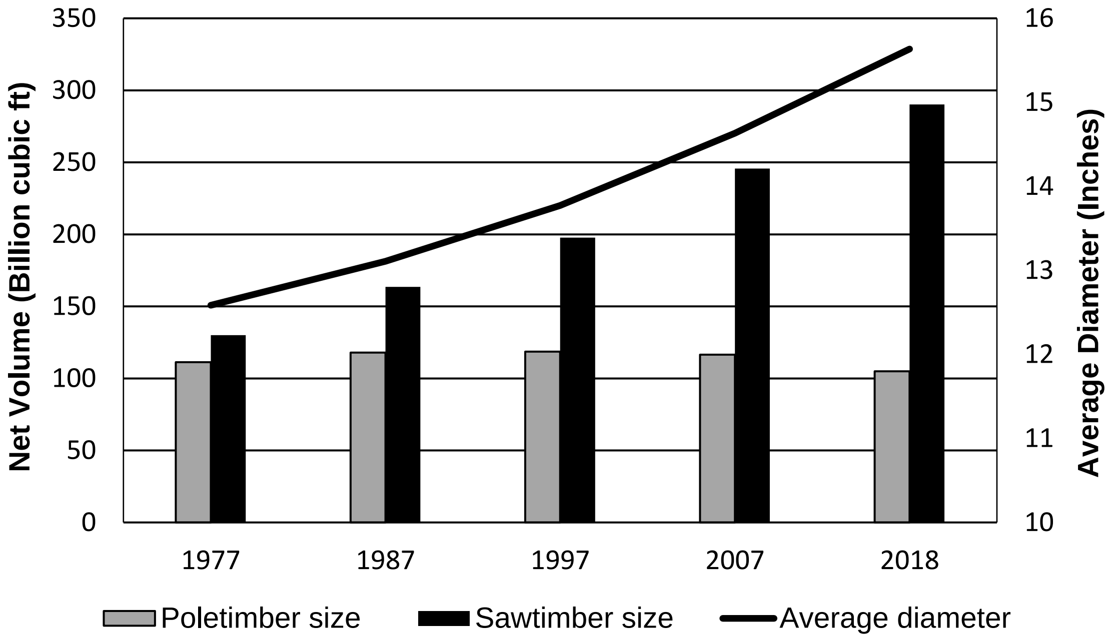

Fig. 1. Net volume of hardwood growing stock on timberland in the Eastern United States by tree size class and average diameter in 1977, 1987, 1997, 2007, and 2018 (Oswalt *et al*. 2019 for 1977 to 2007 data; USDA FS 2020 for 2018 data)

Even though mortality has been increasing in eastern hardwood forests, Ambrose (2018) found that mortality generally was low relative to growth in the forests of the eastern and central United States. However, large sections of the northern portion of the eastern United States had mortality rates of 30% or more of gross growth (growth in trees that remained alive between two survey periods) (Ambrose 2018). Understanding growing stock gross growth (hereafter termed growth unless otherwise specified), mortality, and removals is necessary to anticipate future changes in the eastern hardwood timber base. Knowledge of these changes is useful for long-term decisions on location of manufacturing facilities, timber investments, and research priorities.

Research is needed to assess recent relative changes in hardwood growing stock growth, removals, and mortality concurrently across different geographic regions and major species groups. Perhaps more importantly, what do such changes portend for future sawtimber volume? Compared to smaller trees, sawtimber-size trees provide logs that are less costly to process (Rast 1974) while yielding a greater proportional value of higher-grade material (Hanks *et al*. 1980). Thus, they are utilized by high-value primary manufacturing facilities (*i.e.*, sawmills, veneer- and plywood- mills). Knowledge concerning future sawtimber inventory, including composition and geographic location, is important for decision-making by the forest industry. The authors' objective is to examine recent changes in hardwood sawtimber growth, mortality, and removals for major hardwood species groups within five geographic regions of the eastern United States (Fig. 3).

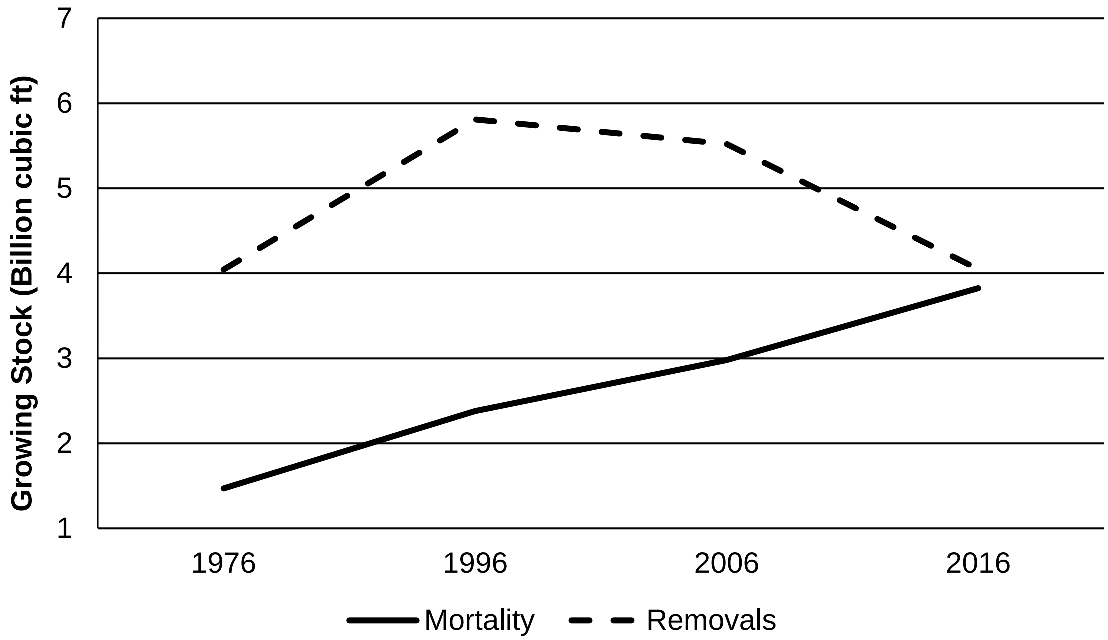

Fig. 2. Annual average mortality and removals of Eastern hardwood growing stock in 1976, 1996, 2006, and 2016 (Oswalt *et al*. 2019)

EXPERIMENTAL

Data Description and Analysis

The data analyzed in this study were collected by the USDA Forest Service Forest Inventory Analysis (FIA) and were accessed through the EVALIDator web application (USDA FS 2020). The data retrieved by EVALIDator were collected through multiyear survey panels described by Gillespie (1999) using data collection procedures presented in USDA FS (2017) and sampling and estimation procedures described in Bechtold and Patterson (2005). Plot selection and design are presented in the Appendix. Annual estimates of tree growth, mortality, and removals were developed at the regional level based on pooled forest inventory plots that were measured over two survey cycles (re-measured plots).

The multiyear survey panel process was initiated in most eastern states in the early 2000s, and the data allow for changes in growth, mortality, and removals to be examined in detail. This study focused on changes in average annual growth, mortality, and removals for the most recent set of survey panels (termed the “current period” ending in 2017 or 2018) and the previous set of panels (termed the “base period” ending in 2011). By examining these two sets of panels, changes within the first two decades of the 21st century can be isolated and analyzed. The specific panel sets used in this study by state are presented in the Appendix, Table A1.

Volume and error estimates provided by EVALIDator for growth, mortality, and removals were used to determine whether the base period volumes differed from the current period. One sample *t* tests were conducted using the standard errors of the base period. Significant findings at α levels of 0.05 and 0.01 (two-tailed) were noted, along with the estimated *p*-value associated with each significant test using a *t* score *p*-value calculator (Social Science Statistics 2020) since *p*-values had to be developed from the estimated *t* statistics and degrees of freedom. Tests were conducted if a species was observed on at least 30 plots for all three variables in both the base and current periods. This threshold reduced the potential of examining species that may have only existed on a small number of survey plots in a region. Although the tests were conducted on volumetric changes, scale differences in volume among the species and regions have dictated that changes should also be discussed in terms of percentages. While the use of percentages allows for a relative comparison of high value species that account for a low proportion of hardwood sawtimber volume such as black walnut (*Juglans nigra*), total regional sawtimber volume is most affected by absolute changes in the predominate species within the region.

The species groups examined in this study accounted for at least 2% of the hardwood sawtimber composition in a specific region (Table 1). Species groups reported in the study regions (Tables 2 through 6) were included if changes in one or more of the three forest change measures were statistically different. The order of analysis was to first test for significant changes in growth for all species in a region followed by testing by the species groups shown in Table 1. The remaining species were tested for significant changes in mortality and those with significant changes were included. The remaining species groups with nonsignificant changes in growth and mortality were then examined for significant changes in removals.

Table 1. Percentage Composition of Hardwood Sawtimber Volume by Species Group for the Five Eastern Regions[a] in the Current Period (Ending in 2017 or 2018 Depending on State, See Appendix 2)

Species Group	Northeast	Lake States	Central	Mid-Atlantic	Southern
			(%)		
Select white oaks	4.2	7.5	14.6	11.9	11.4
Select red oaks	14.5	12.8	7.3	6.7	6.5
Other white oaks	3.7	t[b]	7.7	9.3	6.9
Other red oaks	5.1	5.6	11.9	11.3	25.0
Hickory	2.7	t	9.5	5.1	6.4
Yellow birch	3.7	t	t	t	t
Hard maple	13.7	16.3	5.1	t	t
Soft maple	19.8	16.2	6.6	7.0	2.1
Beech	3.4	t	2.4	2.0	t
Sweetgum	t	t	t	6.8	14.2
Tupelo/blackgum	t	t	t	3.6	8.1
Ash	6.6	6.1	3.7	2.1	2.9
Aspen/cottonwood	4.0	17.0	2.0	t	t
Basswood	t	7.1	t	t	t
Yellow-poplar	3.4	t	13.0	26.7	8.8
Walnut	t	t	2.1	t	t
Cherry	7.4	2.6	2.5	t	t
Total of region [c]	92.0	91.2	88.4	92.3	92.3

[a] See Fig. 3 for description of regions;
[b] Trace (under 2% of composition);
[c] Total percentage volume of species examined in region

The following species groups were examined:

- Select white oaks, primarily *Quercus alba*, bur oak (*Q. macrocarpa*), and chinkapin oak (*Q. muehlenbergii*);
- Select red oaks, primarily northern red (*Q. rubra*) and cherrybark oak (*Q. falcata* var. *pagodifolia*);
- Other white oaks, primarily chestnut oak (*Q. prinus*), post oak (*Q. stellate*), and overcup oak (*Q. lyrata*);
- Other red oaks, primarily black oak (*Q. velutina*), water oak (*Q. nigra*), scarlet oak (*Q. coccinea*), southern red oak (*Q. falcata* Michx. var. *falcata*), laurel oak (*Q. laurifolia*), willow oak (*Q. phellos*), and pin oak (*Q. palustris*);
- Yellow birch (*Betula alleghaniensis*);
- Hard maple, primarily sugar maple (*Acer saccharum*);
- Soft maple, primarily red maple (*A. rubrum*) and silver maple (*A. saccharinum*);
- Ash, primarily white ash (*Fraxinus americana*), green ash (*F. pennsylvanica*), and black ash (*F. nigra*);
- Tupelo/blackgum, primarily swamp tupelo (*Nyssa sylvatica* var. *biflora*), blackgum (*N. sylvatica*), and water tupelo (*N. aquatica*);
- Aspen/cottonwood, primarily quaking aspen (*Populus tremuloides*), bigtooth aspen (*P. grandidentata*), and eastern cottonwood (*P. deltoides*);
- Hickory (*Carya* spp.);
- Basswood (*Tilia americana*);
- Beech (*Fagus grandifolia*);
- Sweetgum (*Liquidambar styraciflua*);
- Yellow-poplar (*Liriodendron tulipifera*);
- Walnut
- Cherry (*Prunus serotina*).

Delineation of the Five Eastern Regions

The five regions examined in this study (Fig. 3) were based on differences in hardwood sawtimber-size growing stock (sawtimber) composition in the current period (Table 1).

Maple species account for 36% of the hardwood sawtimber volume in the Northeast region and oak species account for an additional 23%. The Northeast region also contains relatively large volumes of ash species and cherry. The Lake States region contains large volumes of maple and oak species and contains over 60% of the eastern aspen/cottonwood volume (USDA FS 2020). The Central region contains large qualities of oak and maple species, hickory, ash, and yellow-poplar. The Central region also contains 70% of the eastern walnut sawtimber volume, 44% of the select white oak volume, and 27% of the cherry volume.

The Mid-Atlantic region has a considerable oak resource and has relatively high proportions of yellow-poplar and sweetgum. Over 45% of the Southern region hardwood timber base is oak species, with other red oaks accounting for over half of this volume. The Southern region also contains over 65% of the eastern sweetgum and tupelo/blackgum resource (USDA FS 2020).

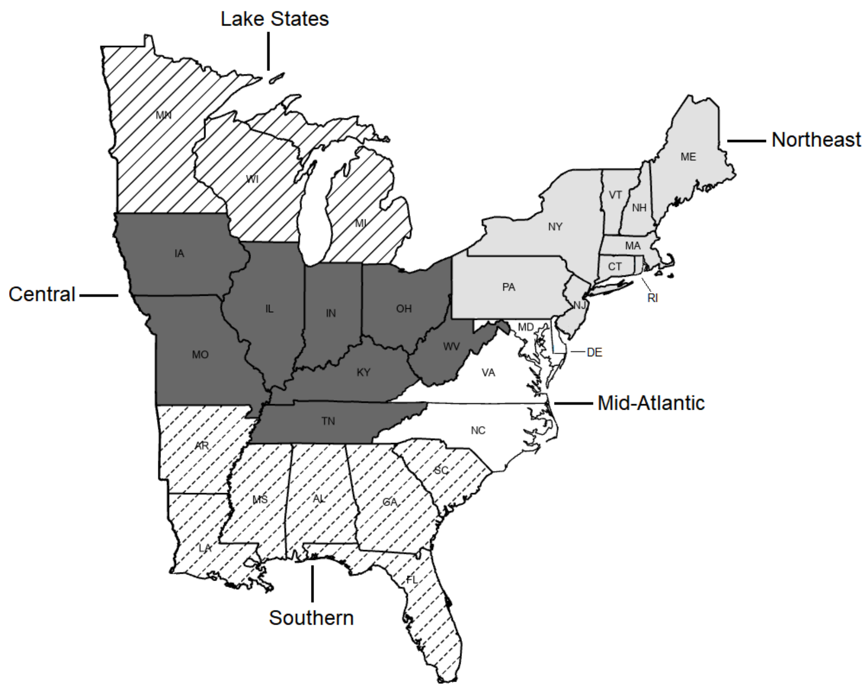

Fig. 3. States included in the Northeast, Lake States, Central, Mid-Atlantic, and Southern Regions

RESULTS AND DISCUSSION

Northeast Region

Total Northeast region hardwood sawtimber growth increased 6.9%, mortality increased 15.6%, and removals declined 13.2% between the base and current periods; all these changes were statistically significant (Table 2).

Table 2. Volumetric and Percentage Changes in Annual Growth, Mortality, and Removals of Hardwood Sawtimber between the Base and Current Periods[a] for Species with Statistically Significant Increases in at Least One of the Volume Measures in the Northeast Region

Northeast Region	Change in Growth		Change in Mortality		Change in Removals	
	Million CF	Percent	Million CF	Percent	Million CF	Percent
Total	73.6**	6.9	58.3**	15.6	-94.5**	-13.2
Select red oaks	22.1**	12.2	-0.9	-3.7	-22.6*	-26.9
Yellow birch	5.3**	17.9	-4.5	-24.6	-5.8	-15.2
Soft maple	11.8*	6.0	11.8*	21.8	-6.1	-5.1
Cherry	9.6**	13.6	12.0**	75.4	-9.0	-15.6
Ash	-2.8	-3.5	38.6**	178.8	7.9	16.6

[a] See Appendix Table A1 for applicable years in each period;
* Significant at the 0.05 level. Growth: Soft maple (p=0.024); Mortality: Soft maple (p=0.047); Removals: Select red oaks (p=0.016);
** Significant at the 0.01 level. Growth: Total (p<0.001), Select red oaks (p<0.001), Yellow birch (p<0.001), Cherry (p=0.003); Mortality: Total (p<0.001), Cherry (p<0.001), Ash (p<0.001); Removals: Total (p=0.003)

Select red oaks, yellow birch, soft maple, and cherry had significant increases in growth. Soft maple, ash, and cherry had significant increases in mortality. The increases in ash and cherry mortality were large relative to the other species groups examined. While total Northeast removals declined significantly, select red oak was the only species group with a significant decline.

Because cherry has not experienced any widespread disease issues, mortality might be related to age. However, cherry is known to be impacted by periodic insect defoliation events, which have been associated with growth reduction and irregular growth ring formation (Long *et al*. 2019). A reduction in cherry regeneration also has been noted in the Allegheny plateau region of Pennsylvania, with several possible causes cited (Turcotte *et al*. 2018).

Lake States Region

The Lake States region sawtimber growth increased 16.7% in the study period, with relatively large and significant increases in all major species groups examined (Table 3). Mortality also increased significantly overall, with significant increases occurring for other red oak, soft maple, ash, and basswood. In contrast, mortality for the aspen/cottonwood species group (primarily aspen species) decreased. Total Lake States removals did not significantly change during the study period as other red oaks, soft maple, and ash had significant increases, while select red oaks had a significant decrease. Similar to the Northeast region, ash had the largest percentage increase in mortality (over 280%).

Table 3. Volumetric and Percentage Changes in Annual Growth, Mortality, and Removals of Hardwood Sawtimber between the Base and Current Periods[a] for Species with Statistically Significant Increases in at Least One of the Volume Measures in the Lake States Region

Lake States Region	Change in Growth		Change in Mortality		Change in Removals	
	Million CF	Percent	Million CF	Percent	Million CF	Percent
Total	88.3**	16.7	70.9**	27.5	7.4	1.9
Select white oaks	5.3**	16.1	0.5	7.5	-1.4	-9.9
Select red oaks	13.6**	16.4	2.6	22.5	-11.1*	-24.5
Other red oaks	7.3**	24.3	5.4**	51.7	6.2**	44.3
Hard maple	9.5**	13.6	2.4	25.3	6.9	14.2
Soft maple	22.1**	29.0	3.8*	33.4	9.6*	25.7
Ash	4.2**	12.1	65.8**	280.3	9.5**	58.5
Aspen/cottonwood	10.9**	9.9	-10.4*	-9.1	-16.2	-11.4
Basswood	4.9**	16.0	6.3**	74.3	0.2	0.8

[a] See Appendix Table A1 for applicable years in each period;
* Significant at the 0.05 level. Mortality: Soft maple (p=0.030), Aspen/cottonwood (p=0.038); Removals: Select red oak (p=0.042), Soft maple (p=0.017);
** Significant at the 0.01 level. Growth: Total (p<0.001), Select white oaks (p<0.001), Select red oaks (p<0.001), Other red oak (p<0.001), Hard maple (p<0.001), Soft maple (p<0.001), Ash (p=0.004), Aspen/cottonwood (p<0.001), Basswood (p<0.001); Mortality: Total (p<0.001), Other red oaks (p=0.001), Ash (p<0.001), Basswood (p<0.001); Removals: Other red oaks (p=0.004), Ash (p<0.001)

Ash species alone accounted for over a quarter of the total mortality in the Lake States region in the current period (Fig. 4), even though ash constitutes less than 7% of the hardwood sawtimber base in the region. Other studies have documented the high rates of ash mortality and live ash volume reduction associated with emerald ash borer (*Agrilus planipennis*; EAB) expansion in eastern U.S. forests (Morin *et al*. 2017; Ambrose 2018).

The changes in ash growth and mortality in the Lake States region demonstrate an important aspect of the measurements used in this study and the difference between gross growth (termed growth in this paper) and net growth (gross growth minus mortality). Annual ash growth increased because the volume of sawtimber-size trees re-measured in the study period increased at a greater annual rate in the current period than the base period. However, the increase in mortality was considerably greater than the increase in growth, causing net growth to change from a positive 11 million cubic feet in the base period to a negative 50 million board feet in the current period (USDA FS 2020). These changes have resulted in the total volume of ash sawtimber to decline 9% between the base and current periods, and this decline was significant at the 0.01 level.

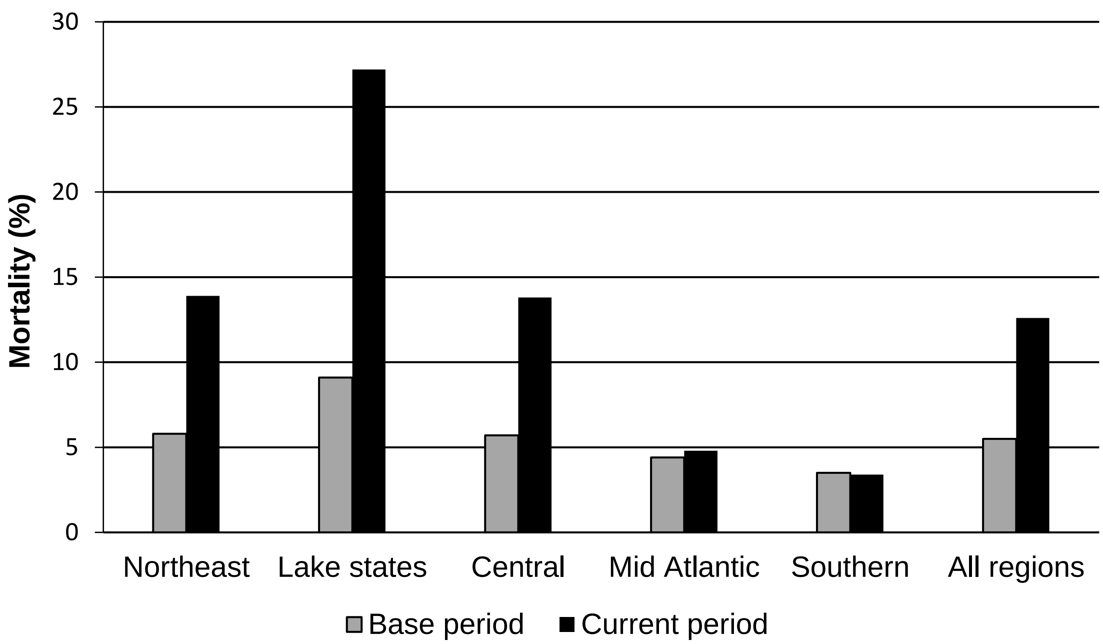

Fig. 4. Percent of total mortality attributable to ash species by region in the base and current periods (USDA FS 2020)

Central Region

The change in growth in the Central region was a statistically significant 6.8% with the growth in select red oaks, hickory, soft maple, and walnut being significant (Table 4). Overall mortality in this region increased by a statistically significant 27.4%; the largest percentage increases occurred for select white oaks, ash, and cherry. Unlike the Lake States region, ash in the Central region had no significant change in growth but did have large increases in mortality and removals similar to the Lake States. Similar to the Northeast region, the percentage increase in cherry mortality in the Central region was surpassed only by the percentage increase in ash mortality.

The Central region contains over 40% of the eastern select white oak volume (USDA FS 2020). In the study period, select white oak growth has been relatively constant while mortality increased 67%. This species group has been historically important in the export market (Luppold and Bumgardner 2013) and is the only group that contains species that can be used in the production of barrels and staves. The relatively slow sawtimber growth of the species group, and decline in poletimber volume (Luppold and Bumgardner 2018), supports concerns over future supplies as evidenced by efforts such as the White Oak Initiative in 2018 (American Forest Foundation 2019) and recent silvicultural research specifically addressing white oak (*e.g.*, Schweitzer *et al*. 2019).

Walnut had the largest percentage increase in removals. The increase in removals of walnut likely is related to the near 100% increase in exports between 2011 and 2018 (USDA FAS 2020). Walnut mortality was not reported because of too few observations (but walnut was included in the analysis given its economic importance in recent years). Walnut mortality appears to have been minimal during the study period, although walnut volume increased 17.4% between 2011 and 2018; this increase was significant at the 0.01 level (USDA FS 2020). The total Central region removals decreased 7.6% during the study period but this decrease was not significant.

Table 4. Volumetric and Percentage Changes in Annual Growth, Mortality, and Removals of Hardwood Sawtimber between the Base and Current Periods[a] for Species with Statistically Significant Increases in at Least One of the Volume Measures in the Central Region

Central Region	Change in Growth		Change in Mortality		Change in Removals	
	Million CF	Percent	Million CF	Percent	Million CF	Percent
Total	127.7**	6.8	175.3**	27.4	-85.3	-7.6
Select red oaks	15.7**	10.1	5.6	10.1	0.1	0.1
Hickory	24.3**	16.4	-4.2	-8.8	7.2	10.0
Soft maple	12.1*	9.6	12.5**	41.5	4.8	9.4
Walnut	10.2**	25.5			12.9**	75.9
Select white oaks	11.9	4.8	33.7**	67.1	-24.0	-13.2
Other red oaks	9.3	3.5	39.0**	28.4	-51.9**	-25.0
Ash	0.6	0.8	76.5**	195.2	21.5**	67.4
Cherry	-0.7	-1.6	7.7**	90.1	-4.4	-12.3

[a] See Appendix Table A1 for applicable years in each period;
* Significant at the 0.05 level. Growth: Soft maple (p=0.015);
** Significant at the 0.01 level Growth: Total (p<0.001), Select red oaks (p=0.002), Hickory (p<0.001), Walnut (p<0.001); Mortality: Total (p<0.001), Soft maple (p=0.002), Select white oaks (p<0.001), Other red oaks (p<0.001), Ash (p<0.001), Cherry (p<0.001); Removals: Walnut (p<0.001), Other red oaks (p=0.001), Ash (p<0.001)

Ash, other red oak, and select white oak had relatively high annual mortality relative to growth in the Central region, suggesting declining sawtimber volume. However, additional factors, such as ingrowth, affect changes in actual volume. An analysis of sawtimber volume between the current and base periods revealed a highly significant 9.1% decrease in ash volume, virtually no change in other red oak volume, and a highly significant 4.2% increase in select white oak volume (USDA FS 2020). While the change in select white oak volume was below the 6.7% increase for all hardwoods in the Central region, it still increased. However, the small (1.4%) and insignificant increase in other red oak volume suggests a plateau in total volume of this species group.

Mid-Atlantic Region

The Mid-Atlantic region (Table 5) had a change in growth of 10.1%, a relatively high annual mortality of 30.5%, and the greatest decline in removals, -20.3%, of all regions. All these changes were significant. Still, select white oak, hickory, yellow-poplar, and sweetgum were the only species groups in this region found to have a significant increase in growth.

All species groups with more than a trace sawtimber volume in the Mid-Atlantic region (Table 1) had increased mortality, even though only hickory and soft maple were statistically significant and listed in Table 5. Similarly, all species groups shown in Table 1 had negative changes in removals in the Mid-Atlantic region even though only sweetgum was statistically significant. These consistent increases in mortality and declines in removals are reflected in the total regional estimates of these measures.

Table 5. Volumetric and Percentage Changes in Annual Growth, Mortality, and Removals of Hardwood Sawtimber Between the Base and Current Periods[a] for Species with Statistically Significant Increases in at Least One of the Volume Measures in the Mid-Atlantic Region

Mid-Atlantic Region	Change in Growth		Change in Mortality		Change in Removals	
	Million CF	Percent	Million CF	Percent	Million CF	Percent
Total	92.4**	10.1	59.4**	30.5	-108.2*	-20.3
Select white oaks	15.5*	14.1	6.6	39.5	-8.6	-12.7
Hickory	12.1**	36.0	4.9*	55.6	-6.6	-33.4
Sweetgum	9.1*	17.2	1.3	9.4	-19.1*	-39.3
Yellow-poplar	32.1**	12.5	0.5	2.5	-15.8	-10.0
Soft maple	-6.0	-9.2	8.7**	58.1	-3.9	-12.3

[a] See Appendix Table A1 for applicable years in each period;
* Significant at the 0.05 level. Growth: Select white oaks (p=0.013), Sweetgum (p=0.035); Mortality: Hickory (p=0.021); Removals: Total (p=0.010), Sweetgum (p=0.036);
** Significant at the 0.01 level. Growth: Total (p<0.001), Hickory (p<0.001), Yellow-poplar (p=0.004); Mortality: Total (p<0.001), Soft maple (p=0.001)

Southern Region

The Southern region had no significant changes in growth or mortality but did have significantly decreased removals second only to the Mid-Atlantic region in relative size between the base and current periods (Table 6).

Table 6. Volumetric and Percentage Changes in Annual Growth, Mortality, and Removals of Hardwood Sawtimber Between the Base and Current Periods[a] for Species with Statistically Significant Increases in at Least One of the Volume Measures in the Southern Region

Southern Region	Change in Growth		Change in Mortality		Change in Removals	
	Million CF	Percent	Million CF	Percent	Million CF	Percent
Total	20.5	1.4	-31.1	-4.8	-174.9**	-17.6
Select red oaks	19.6*	21.5	1.6	3.7	-1.7	-3.8
Other red oaks	-13.1	-2.9	-17.8	-8.2	-71.2*	-22.4
Hickory	3.6	4.5	1.0	2.8	-24.5*	-34.7
Sweetgum	23.7	14.2	1.3	2.0	-45.8**	-23.9

[a] See Appendix Table A1 for applicable years in each period;
* Significant at the 0.05 level. Growth: Select red oaks (p=0.024); Removals: Other red oaks (p=0.018), Hickory (p=0.017);
** Significant at the 0.01 level. Removals: Total (p=0.003), Sweetgum (p=0.006)

Other red oaks, hickory, and sweetgum all realized significant declines in removals. The only species group to have significant change in growth was select red oaks, which increased 21.5%. No species group had a significant change in mortality in the Southern region.

CONCLUSIONS

1. Changes in sawtimber growth ranged from a statistically insignificant 1% in the Southern region to nearly 17% in the Lake States. The Northeast and Central regions had similar annual growth—approximately 7%—while the Mid-Atlantic region had a 10% increase. Sawtimber mortality increased in all but the Southern region, and removals declined in all but the Lake States and Central regions.
2. With the exception of ash, there are no indications of immediate declines in eastern sawtimber volume. However, continued increases in mortality, a resurgence of removals, and slowing annual growth could cause sawtimber volume to plateau in the coming decades. It will require further research to project when these changes will occur because of an ever-changing domestic market for hardwood production and insufficient knowledge of the factors causing observed mortality.
3. Many of the regional changes in hardwood growth, mortality, and removals are associated with changes for major species groups. The Central region, which contains over 40% of the select white oak volume, saw relatively constant growth of this species group while mortality increased 67%.
4. Select red oak growth increased in the Northeast and Lake State regions. This species group also had large decreases in removals in these regions but no significant changes in mortality. The apparent lack of demand for high quality red oak seemingly has resulted in such trees not being harvested at past levels.
5. In contrast to select red oaks, removals of other red oak species increased in the Lake States region but decreased in the Central region. Similarly, growth of other red oaks has increased in the Lake States region but was not significant in the Central region.
6. Ash mortality increased greatly in the Northeast, Lake States, and Central regions. EAB has devastated all species of ash in the northern portion of the eastern United States and has contributed to the growing proportion of mortality in these regions.
7. Walnut and cherry historically are high value species. Walnut growth and removals increased in the Central region. In contrast, cherry growth and removals did not change in the Central region but growth did increase in the Northeast region. Cherry has experienced considerable increases in mortality in both the Northeast and Central regions. These proportional increases were exceeded only by ash.
8. Soft maple had significant increases in growth and mortality in the Northeast, Lakes States, and Central regions, and increased mortality in the Mid-Atlantic regions. Soft maple removals also increased significantly in the Lake States region.

REFERENCES CITED

Ambrose, M. J. (2018). "Chapter 5–Tree mortality," in: *Forest Health Monitoring: National Status, Trends, and Analysis 2017* (General Technical Report SRS-233), K. M. Potter, and B. L. Conkling (eds), U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, USA, pp. 85-98.

American Forest Foundation (2019). "Working to enhance America's white oak forest," (https://www.forestfoundation.org/enhancing-white-oak), Accessed 15 June 2020.

Bechtold, W. A., and Scott, C. T. (2005). "The forest inventory and analysis sampling frame," in: *The enhanced Forest Inventory and Analysis Program—National Sampling Design and Estimation Procedures*, W. A. Bechtold and P. L. Patterson (eds.), Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Pages 27-42.

Brooks, R. T. (1994). "A regional-scale survey and analysis of forest growth and mortality as affected by site and stand factors and acidic deposition," *Forest Science* 40(3), 543-557.

Clinton, B. D., Yeakley, J. A., and Apsley, D. K. (2003). "Tree growth and mortality in a Southern Appalachian deciduous forest following extended wet and dry periods," *Castanea* 68(3), 189-200.

Elliott, K. J., and Swank, W. T. (1994). "Impacts of drought on tree mortality and growth in a mixed hardwood forest," *Journal of Vegetation Science* 5, 229-236.

Gillespie, A. J. R. (1999). "Rationale for a national annual forest inventory program," *Journal of Forestry* 97(12), 16-20.

Hanks, L. F., Gammon, G. L., Brisbin, R. L., and Rast, E. D. (1980). *Hardwood Log Grades and Lumber Grade Yields for Factor Lumber* (Research Paper NE-468), U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station, Broomall, PA, USA.

Howard, J. L., and Liang, S. (2019). *U.S. Timber Production, Trade, Consumption, and Price Statistics, 1965–2017* (Research Paper FPL-701), U.S. Department of Agriculture, Forest Service Forest Products Laboratory, Madison, WI, USA.

Long, R. P., Wiemann, M. C., and Kuster, T. A. (2019). "The frequency and anatomical characteristics of anomalous dark rings in black cherry, and their relation to cherry scallop shell moth defoliations," *Forest Science* 65(3), 324-335. DOI: 10.1093/forsci/fxy057

Luppold, W. G., and Bumgardner, M. S. (2013). "Factors influencing changes in U.S. hardwood log and lumber exports from 1990 to 2011," *BioResources* 8(2), 1615-1624. DOI: 10.15376/biores.8.2.1615-1624

Luppold, W. G., and Bumgardner, M. S. (2018). "Structural changes in the growing stock of important tree species groups in the Central Hardwood Region," *Journal of Forestry* 116(5), 405-411. DOI: 10.1093/jofore/fvy028

Morin, R. S., Liebhold, A. M., Pugh, S. A., and Crocker, S. J. (2017). "Regional assessment of emerald ash borer, *Agrilus planipennis*, impacts in forests of the Eastern United States," *Biological Invasions* 19, 703-711. DOI: 10.1007/s10530-016-1296-x

Oswalt, S. N., Smith, W. B., Miles, P. D., and Pugh, S. A. (2019). *Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment* (General Technical Report WO-97), U.S. Department of Agriculture Forest Service, Washington, DC, USA.

Rast, E. D. (1974). *Log and Tree Sawing Times for Hardwood Mills* (Research Paper NE-304), U.S. Department of Agriculture Forest Service, Upper Darby, PA, USA.

Reams, G. A., Smith, W. D., Hansen, M. H., Bechtold, W. A., Roesch, F. A., and Moisen, G. G. (2005). "The forest inventory and analysis sampling frame," in: *The Enhanced Forest Inventory and Analysis program—National Sampling Design and Estimation Procedures*, W. A. Bechtold and P. L. Patterson (eds.), Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Pages 11-26.

Schweitzer, C. J., Dey, D. C., and Wang, Y. (2019). "White oak (*Quercus alba*) response to thinning and prescribed fire in northcentral Alabama mixed pine-hardwood forests," *Forest Science* 65(6), 758-766. DOI: 10.1093/forsci/fxz031

Shifley, S. R., Fan, Z., Kabrick, J. M., and Jensen, R. G. (2006). "Oak mortality risk factors and mortality estimation," *Forest Ecology and Management* 229(1-3), 16-26. DOI: 10.1016/j.foreco.2006.03.033

Social Science Statistics (2020). "P value from T score calculator," (https://www.socscistatistics.com/pvalues/tdistribution.aspx), Accessed 20 August 2020.

Turcotte, R. M., Larcenaire, C., Long, R., Martin, D. K. H., and Barringer, L. (2018). "The spotted wing drosophila, *Drosophila suzukii* (Diptera: Drosophilidae): A new pest of concern for black cherry, *Prunus serotina*, on the High Allegheny Plateau in Pennsylvania," *Entomological News* 127(4), 390-399. DOI: 10.3157/021.127.0412

U.S. Department of Agriculture, Foreign Agricultural Service (USDA FAS) (2019). "Global agricultural trade system," (https://apps.fas.usda.gov/Gats/Default.aspx), Accessed 7 Nov 2019.

U.S. Department of Agriculture, Forest Service (USDA FS) (2017). *Forest Inventory and Analysis National Core Field Guide. Volume 1: Field Data Collection Procedures for Phase 2 Plots, version 7.2*, USDA FS, Washington D.C., USA.

USDA FS (2020). "Forest inventory EVALIDator web-application version 1.8.0.01," USDA, (https://apps.fs.usda.gov/Evalidator/evalidator.jsp), Accessed 12 June 2020.

Yaussy, D. A., Iverson, L. R., and Matthews, S. N. (2013). "Competition and climate affects US hardwood-forest tree mortality," *Forest Science* 59(4), 416-30. DOI: 10.5849/forsci.11-047

Article submitted: July 1, 2020; Peer review completed: October 10, 2020; Revisions accepted: October 29, 2020. Published: November: 9, 2020.
DOI: 10.15376/biores.16.1.62-76

APPENDIX

Sample Plot Selection and Design

Per personal correspondence with Jim Westfall of the Northern Forest Inventory and Analysis unit: "When the annual FIA program was implemented in 1999, spatial balance of the sample was obtained *via* a grid composed of 5,937 acre (2,403 ha) hexagons superimposed over the area using a random starting location. When one or more existing inventory plots were found within a hexagon, one of those points was chosen based on a predefined set of rules (Reams *et al.* 2005). Sample plot locations were chosen *via* random selection of a point for hexagons having no pre-existing plots. *(continued on next page)*

Table A1. Re-measured Survey Years Used to Develop Base Period and Current Period Estimates of Growing Stock Growth, Mortality, and Removal by State

Region/State	Base Period	Current Period
Northeast		
Connecticut	2008 to 2011	2012 to 2018
Maine	2007 to 2011	2014 to 2018
Massachusetts	2008 to 2011	2012 to 2018
New Hampshire	2008 to 2011	2012 to 2018
New Jersey	2009 to 2011	2013 to 2018
New York	2008 to 2011	2012 to 2018
Pennsylvania	2007 to 2011	2012 to 2018
Rhode Island	2008 to 2011	2012 to 2018
Vermont	2008 to 2011	2012 to 2018
Lake States		
Michigan	2007 to 2011	2012 to 2018
Minnesota	2007 to 2011	2014 to 2018
Wisconsin	2007 to 2011	2012 to 2018
Central		
Illinois	2007 to 2011	2012 to 2018
Indiana	2007 to 2011	2012 to 2018
Iowa	2007 to 2011	2012 to 2018
Kentucky	2005 to 2011	2012 to 2017
Missouri	2007 to 2011	2012 to 2018
Ohio	2007 to 2011	2012 to 2018
Tennessee	2005 to 2011	2012 to 2017
West Virginia	2009 to 2011	2012 to 2018
Mid-Atlantic		
Delaware	2009 to 2011	2012 to 2018
Maryland	2009 to 2011	2012 to 2018
North Carolina	2003 to 2011	2009 to 2018
Virginia	2008 to 2011	2014 to 2018
Southern		
Alabama	2001 to 2011	2011 to 2018
Arkansas	2006 to 2011	2013 to 2018
Florida	2009 to 2011	2012 to 2017
Georgia	2005 to 2011	2014 to 2018
Louisiana	2009 to 2011	2009 to 2017
Mississippi	2009 to 2011	2013 to 2018
South Carolina	2007 to 2011	2014 to 2018

Each plot consists of a 4-point cluster where the central point corresponds with the location chosen within each hexagon and the remaining 3 peripheral points are dispersed at a distance of 120 ft (36.6 m) on azimuths of 120, 240, and 360 degrees (Bechtold and Scott 2005). Centered at each point are subplots having a 24 ft (7.3 m) radius. Subplot-based measurements include trees having diameter at breast-height (dbh) ≥ 5.0 in. (12.7 cm) and various other site attributes such as forest type and stand size. Each subplot contains a 6.8 ft (2.1 m) radius microplot with center offset 12 ft (3.7 m) at 90 degrees azimuth. Trees having 1.0 in. (2.5 cm) ≤ dbh ≤ 4.9 in (12.4 cm) are recorded within the microplot."