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Stand Dynamics of Reference Plots in the West Virginia Long-Term Soil Productivity Studies

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Abstract

Tree death is a natural part of forest dynamics, yet is not often studied over long periods, particularly in temperate mixed-species hardwood stands. In this study, we evaluated stand dynamics of four reference plots on each of the West Virginia Long-term Soil Productivity (LTSP) Studies. The Fork Mountain LTSP Study was initiated in 1996 and the Middle Mountain LTSP Study in 1997. The two locations represent distinct stand types (mixed mesophytic and cherry-maple) and site conditions (elevation, parent material, aspect). We found that after 20 years, there were differences in patterns of mortality and ingrowth between the two sites. Mortality rates ranged from 1.5 to almost 5 percent for a 5-year period on Fork Mountain to 1 to 1.5 percent on Middle Mountain. Generally, ingrowth exceeded mortality on Fork Mountain, while the reverse was observed on Middle Mountain. Possible reasons for differences in mortality and ingrowth between the two sites include differences in species composition related to soil and site characteristics and differences in past disturbance that have created different stages of stand development.

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Cover Photos

Fork Mountain Long-term Soil Productivity Study plot and sign over two decades, looking southeast toward McGowan Mountain. Clockwise from top left: winter 1997, summer 1998, winter 2009, and winter 2020. Photos by Mary Beth Adams, USDA Forest Service.

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INTRODUCTION

Tree death is a natural part of forest dynamics. It is generally accepted that much of the historic mortality in forest stands results from self-thinning (Johnson et al. 2002). As trees grow larger, they require more resources and growing space to survive, with the result that some individuals are periodically crowded out and die. However, disturbances such as wildfire, drought, extreme weather, and insect and disease epidemics also result in pulses of tree mortality (Johnson et al. 2002). As extreme weather events, wildfires, and infestations are expected to increase across most of the globe due to climate change (Easterling et al. 2000), tree mortality may be expected to increase and become more widespread as well (Allen et al. 2010, Anderegg et al. 2013). For example, widespread tree mortality has recently been documented in ponderosa pine (*Pinus ponderosa*) forests in western United States (Fettig et al. 2019), correlated with drought and interactions with other stressors, such as insects. Background (non-event) mortality rates also have increased in recent decades (Peng et al. 2011, van Mantgem et al. 2009). These changes and the likelihood for increased tree mortality are important because increases in mortality have the potential to change forest structure, species composition, and productivity, and because healthy forests with live trees are a carbon sink. In addition, live trees provide a variety of ecosystem services that can be impaired or lost with increased tree mortality (Allen et al. 2010).

Stand development of hardwood forests has been studied extensively, yet mortality of these important forest types over long periods of time is rarely quantified because it is highly variable and difficult to predict (Monserud 1976). Elliott and Swank (1994) reported mortality rates resulting from a severe multiyear drought ranging from about 12 percent (1.7 percent yr^{-1}) for oak-pine communities within the Coweeta Basin, North Carolina, USA, to 20 percent (2.8 percent yr^{-1}) for cove hardwoods, and 23 percent (3.4 percent yr^{-1}) for mixed-oak communities. Others have reported typical background mortality rates for temperate forests from 1-2 percent per year (Brown and Schroeder 1999). Kabrick et al. (2004) reported mortality among oak-dominated forests in Missouri, USA, to be 13.9 percent per decade, or 1.5 percent per year.

A major concern related to forest productivity and soil processes in the central Appalachians and globally is the issue of acidic deposition (particularly elevated deposition of nitrogen [N] and sulfur [S]), with resulting soil acidification, base cation depletion, N saturation and leaching, and implications for the productivity, diversity, and sustainability of central Appalachian hardwood forests (Adams 1999).

In these studies, we evaluate the stand dynamics, including the mortality rate, of two distinct hardwood forest types in the central Appalachians of West Virginia: mixed mesophytic and cherry-maple forests. These stands are part of experiments evaluating effects of acidic deposition on forests in the central Appalachians; this report uses only the information from the untreated reference plots. In particular, information will be used to document baseline "natural" mortality rates over a 20-year period and will also be used to inform growth and succession models being developed to forecast forest dynamics in a changing climate.

OBJECTIVES

1) Describe 20 years of stand dynamics (mortality, ingrowth, and species composition) on the reference plots of two Long-term Soil Productivity (LTSP) Studies located in West Virginia.
2) Compare and contrast mortality rates over time between the two forest types.

SITE DESCRIPTIONS AND METHODS

This study utilizes the uncut, untreated reference plots for the West Virginia Long-Term Soil Productivity Studies (Fig. 1), initiated in West Virginia (Adams et al. 2004) as an affiliate of the North American Long-Term Soil Productivity (LTSP) Study (Powers 2005). The first LTSP Study site in West Virginia, known as the Fork Mountain LTSP, is situated in a mesic mixed hardwood forest (Fig. 1). A second site is located on the Loop Road Research Area of the Monongahela National Forest in a cherry-maple stand (Fig. 1) (for scientific names of trees, see appendix 1). The research design, objectives, and hypotheses are the same for both LTSP West Virginia locations. The treatments include whole-tree harvesting and application of fertilizer and lime alone and in combinations; there are also unharvested, untreated reference plots. At both locations, there are four replicate blocks, designed to account for spatial variation and gradients across the site. For a detailed description of the study design, objectives, and pretreatment conditions, along with plot and treatment maps, see Adams et al. (2004) and Adams (2018). (See appendix 2 for aerial images of both sites obtained after the whole-tree harvests had been implemented. The reference plots are indicated on the photos). The reference plots are located randomly among the treatment plots with one reference plot per block. Both sites lie within the area classified as the Allegheny Mountain Section of the Central Appalachian Broadleaf Forest Province (McNab and Avers 1994). More detailed site descriptions are provided below.

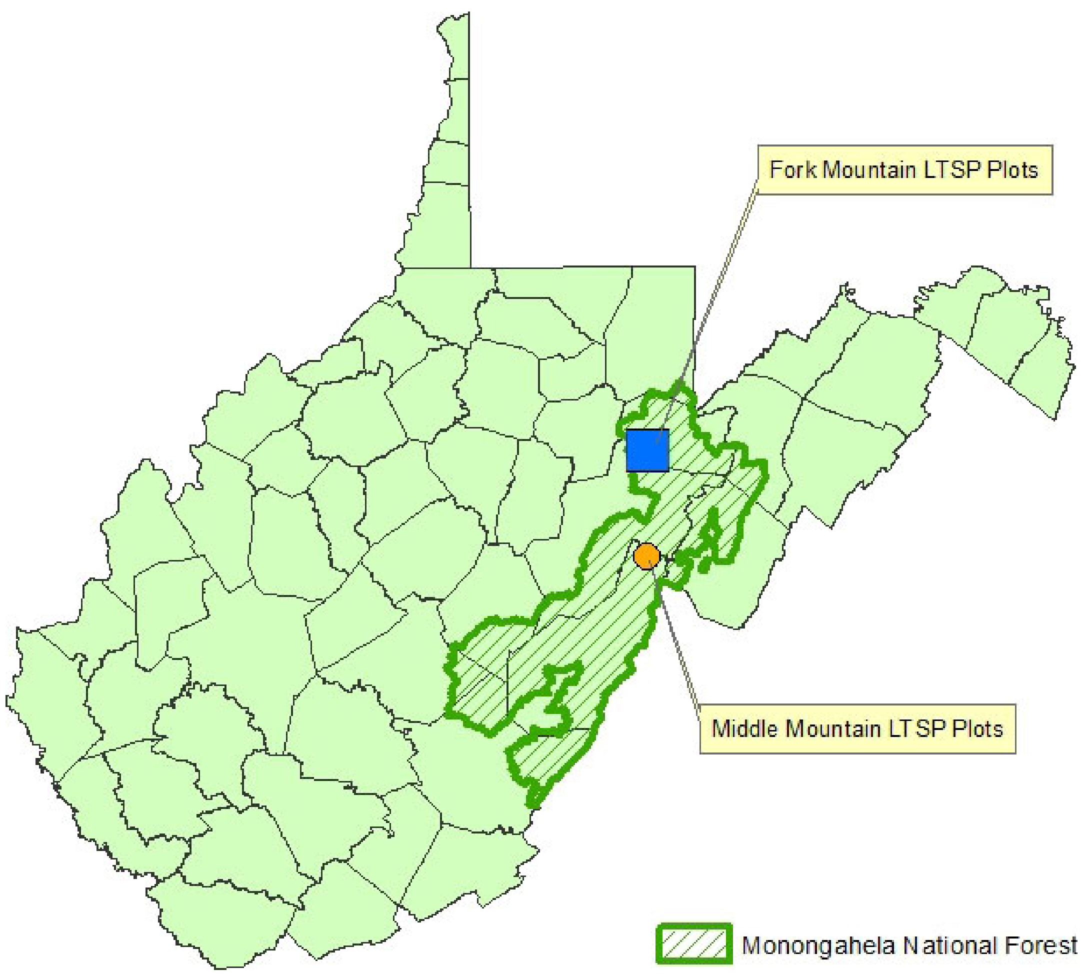

Figure 1.—Location of the Fork Mountain and Middle Mountain Long–term Soil Productivity Studies in West Virginia.

Fork Mountain

These plots (reference plots 4, 8, 11, 16) are located on the Fernow Experimental Forest in Tucker County, West Virginia (latitude 39º 04′ N, longitude 79º 41′ W) on Fork Mountain and were established in 1996 (Adams et al. 2004). The site has a southeast aspect, with slopes ranging from 15 to 31 percent. Elevation ranges from 798 m to 847 m, and dominant parent materials include the sandstones and shales of the Hampshire Formation (Adams et al. 2012). Soils are mapped as Calvin/DeKalb channery silt loam (loamy-skeletal, mixed, active, mesic Typic Dystrudepts). Annual average precipitation is 146 cm and is relatively evenly distributed between the growing and dormant seasons (Adams et al. 2012). Mean annual air temperature is 9.3 °C. At the initiation of this study, trees were approximately 85 years old and were typical of a relatively high-productivity central Appalachian mixed-hardwood forest (red oak site index = 24 m at age 50). With the exception of a small part of the most easterly plots (including reference plot 8), which was included in a strip clearcut in July 1977, this site was last harvested around 1910.

Middle Mountain

These plots (reference plots 17, 24, 28, 35) are located on the Loop Road Research Area on Middle Mountain, in Pocahontas County, West Virginia (38°38′15′N, 79°42′30″ W) (Fig. 1) and were established in the summer and autumn of 1997. The Loop Road Research Area was initially set aside for research use in 1980. Elevations range from 1072 to 1129 m. Landforms include mostly convex ridgetops and side slopes. Aspect is generally southern, although most of the plots are located on or near the ridge tops, and slopes are generally less than 20 percent. The dominant parent material is the hard sandstone of the Pocono formation (Adams 2018). Soils are mapped as the Mandy series (loamy-skeletal, mixed, active, frigid, Spodic Dystrudepts). Average annual precipitation is 138 cm, distributed evenly throughout the year, with 241 cm average annual snowfall. Mean annual air temperature was 7.55 °C (U.S. Climate Data). At the initiation of the study, trees were approximately 75 years old. These stands originated following heavy timber cutting around 1920 (Miller 1997) and were typical of a black cherry-maple forest type (Society of American Foresters forest cover type 28; Eyre 1980). The overstory includes black cherry, American beech, red maple, sugar maple, and striped maple. Site index for black cherry in the study area is 23 m at base age 50 years, typical of a moderately productive site in the region.

Methods

Within the twenty 0.4047-ha measurement plots, all trees $\geq$2.54 cm in diameter were identified to species and tagged with metal tags in spring 1996 (Fork Mountain) and spring 1997 (Middle Mountain). The diameter at breast height (d.b.h.; 1.37 m above ground) was measured to the nearest 0.25 cm. All trees within the plots were remeasured every 5 years during the dormant season, and their status (live, dead) was recorded. As new trees reached 2.54 cm diameter, they were tagged and added to the tree list, representing ingrowth.[1] There were 657 tagged trees on the Fork Mountain reference plots, and 1250 tagged trees on the Middle Mountain reference plots at the start of the studies. Over the intervening 20 years, almost 1200 additional trees were tagged as ingrowth and monitored.

[1] Ingrowth is defined as trees that during a specified time period have grown to an arbitrary minimum diameter or height.

Tree inventory data were used to calculate basal area and stand density. To evaluate changes in species composition, relative density (RD) and relative basal area (RBA) were used to calculate a relative importance value (RIV) for each tree species, where

$$RIV = \frac{(RD + \text{RBA})}{2}$$

(Jenkins and Parker 1997). Ingrowth was calculated as the number of new trees $\geq$ 2.5 cm recorded in each 5-year period. Mortality was defined as the "newly dead" trees in each 5-year period (trees that died during that 5-year period only). The percentage mortality was calculated as

$$\frac{(\textit{density of newly dead trees})}{\textit{total density}} \times 100$$

for each 5-year period. The total density of trees was the sum of the ingrowth for that 5-year period, the number of newly dead trees in that 5-year period, and the number of live trees. Data were summarized for the whole site and by plot, and by measurement date. Where appropriate, means and standard errors were calculated across the four plots at each site.

Fork Mountain LTSP reference plot 4, January 2020, showing large down trees from storms. Photos by Mary Beth Adams, USDA Forest Service.

RESULTS

Fork Mountain

At study initiation, these plots represented a diverse stand of mature trees (Table 1). Average basal area was 36.9 m^2 ha^{-1} (std. error=1.6) and there were 811 stems ha^{-1} (std. error=85) . The pretreatment stand was dominated by sugar maple, red maple, northern red oak, and yellow-poplar. Black cherry and striped maple also were present in substantial proportions. The largest tree was a northern red oak measuring 102 cm d.b.h. Twenty-four species were recorded during the 20-year period but two species (white oak and pin cherry) were no longer present in the stand by the 2017 measurement period. Pin cherry was not a component of the pretreatment stand in 1996, but it was measured in 2007 and 2012, before disappearing again in the 2017 measurement. In addition, sourwood was not present in 1996, and first appeared in the 2002 census. American hornbeam was only recorded in 2012 and 2017.

Over 20 years, sugar maple importance decreased from 33.7 to 22.2 percent, and black cherry decreased from 7.6 to 3.4 percent (Fig. 2). Sweet birch increased from 1.4 to 18.9 percent, (increasing from 10 trees ha^{-1} to 233 tree ha^{-1}) between the 2002 and 2007 censuses (Table 1), reflecting a large number of ingrowth trees (Table 2).

Both basal area and stem density increased over time (Table 1). The number of ingrowth trees peaked in 2007 and decreased only slightly in 2012, before returning to approximately pretreatment rates in 2017 (Table 2). Ingrowth on the Fork Mountain reference plots was dominated by sweet birch, striped maple, and yellow-poplar, with sugar maple showing the largest increase during the first 5 years of the study. Mean diameter for sweet birch and yellow-poplar decreased as the number of trees increased (Table 1).

The highest average mortality rates were observed between 1996 and 2002 and between 2012 and 2017 (3.09 and 4.95 percent, respectively) (Table 3). Mortality rates of several species, particularly black locust and white oak, were notably high during these time periods, although these were represented by few, relatively large trees (Table 1). Most of the dead stems were in the 2.5 cm to 9.9 cm diameter class (Fig. 3).

Left: Middle Mountain, LTSP reference plot 35, October 2018. Right: Middle Mountain LTSP reference plot 17, October 2018. Photos by Mary Beth Adams, USDA Forest Service.

Table 1.—Stand data for Fork Mountain LTSP Study reference plots pretreatment and at 5-year measurement intervals. Values are averages of four plots.

Fork Mountain	1996				2002				2007				2012				2017			
Species	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV
Bitternut hickory	0.4	6	25.9	0.9	0.4	6	26.8	0.9	0.4	6	27.6	0.8	0.5	6	28.3	0.8	0.5	5	34.0	0.7
American hornbeam													0.001	1	3.6	0.0	0.002	1	4.3	0.0
Eastern hophornbeam	0.1	16	6.3	1.1	0.1	19	6.9	1.2	0.1	17	7.9	0.8	0.1	11	10.7	0.5	0.1	9	11.4	0.4
Sweet birch	0.4	14	17.9	1.4	0.4	10	21.6	1.2	0.5	233	3.8	9.6	0.8	472	4.2	15.5	1.3	494	4.9	18.9
American beech	0.045	12	5.8	0.8	0.1	14	7.5	0.9	0.1	16	8.2	0.8	0.1	19	8.7	0.7	0.2	17	10.6	0.8
White oak	0.1	1	34.5	0.2																
Chestnut oak	1.1	7	43.4	2.0	1.2	7	45.3	2.2	1.4	7	47.5	2.1	1.5	7	49.5	2.1	1.7	7	52.2	2.2
Northern red oak	7.5	28	54.5	11.9	7.9	27	57.6	12.9	8.8	27	60.8	12.7	9.2	26	63.7	12.4	10.1	26	66.6	13.0
Cucumbertree	0.6	10	25.4	1.4	0.7	10	27.7	1.5	0.8	12	24.2	1.5	0.8	15	20.3	1.4	0.9	16	20.6	1.6
Fraser magnolia	1.3	35	17.9	3.9	1.2	41	14.1	4.0	1.2	59	10.9	3.8	1.3	59	12.1	3.4	1.4	62	12.6	3.8
Yellow-poplar	6.5	43	41.0	11.5	7.2	41	44.9	12.5	7.3	90	22.4	13.0	8.0	172	14.3	15.3	8.0	154	16.0	15.1
Downy serviceberry	0.044	4	11.4	0.3	0.1	4	12.7	0.3	0.1	4	13.5	0.2	0.026	2	11.6	0.1	0.028	2	12.1	0.1
Pin cherry									0.005	2	4.8	0.1	0.006	2	5.3	0.1				
Black cherry	4.3	30	36.4	7.6	2.8	20	37.1	5.1	3.0	21	36.1	4.7	2.3	19	31.1	3.5	2.4	16	36.4	3.4
Black locust	0.2	2	33.7	0.4	0.001	1	2.8	0.1	0.026	14	4.8	0.6	0.039	15	5.5	0.5	0.002	2	3.4	0.1
Sugar maple	7.5	383	10.7	33.7	6.4	409	9.9	32.7	7.2	406	10.8	25.1	7.8	398	11.4	22.0	8.3	346	13.0	22.2
Striped maple	0.1	85	3.9	5.4	0.2	128	4.1	7.7	0.3	238	3.9	9.6	0.3	244	4.0	7.9	0.2	120	4.2	4.4
Red maple	4.5	99	20.9	12.1	4.6	90	22.3	11.8	5.1	105	20.7	10.8	5.0	115	18.6	9.8	4.8	101	20.0	9.3
American basswood	0.7	15	20.5	1.8	0.8	17	19.6	2.1	0.8	15	22.7	1.6	0.8	14	24.9	1.5	0.9	12	27.9	1.5
Blackgum	0.2	1	41.9	0.3	0.2	1	42.4	0.3	0.2	1	42.2	0.3	0.2	1	41.9	0.3	0.2	1	42.9	0.3
Sourwood					0.001	2	2.5	0.1	0.003	4	3.1	0.1	0.004	2	4.3	0.1	0.008	2	6.6	0.1
White ash	1.5	10	39.8	2.6	1.0	9	35.6	1.9	0.8	7	30.1	1.3	0.8	14	17.0	1.4	0.8	11	18.9	1.3
Spicebush	0.003	4	3.0	0.2	0.003	2	3.9	0.1	0.005	2	4.8	0.1	0.006	2	5.5	0.1	0.006	2	5.5	0.1
Witch hazel	0.007	6	3.8	0.4	0.009	9	3.5	0.5	0.015	14	3.7	0.5	0.022	20	3.7	0.6	0.015	11	4.1	0.4
Total	36.9	811			35.2	867			37.9	1302			39.7	1636			41.7	1420		
Std. error	1.6	85			3.0	120			3.4	230			3.7	248			4.0	228		

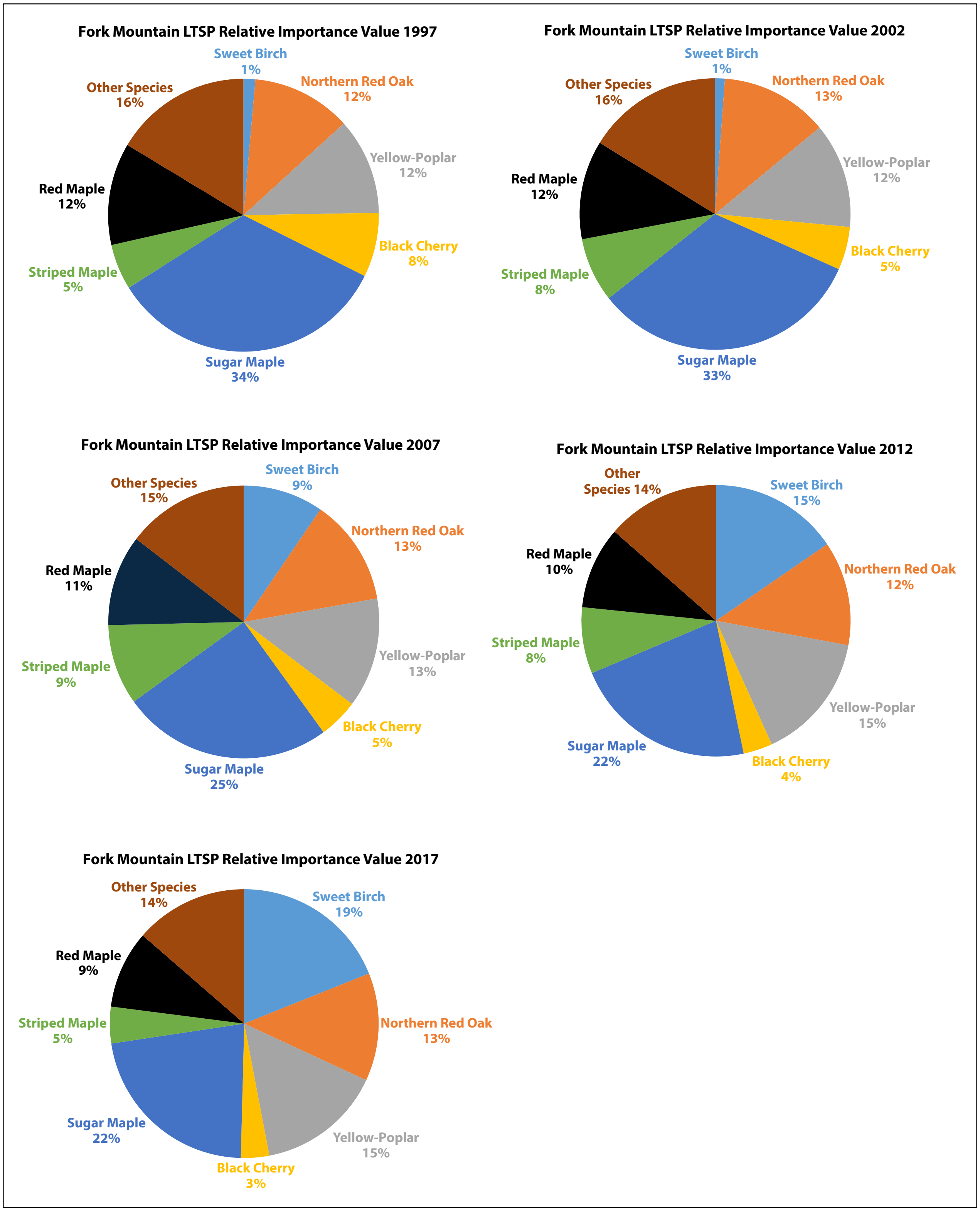

Figure 2.—Average tree species composition on the Fork Mountain LTSP Study reference plots, expressed as relative importance (percent), at five measurement dates.

Table 2.—Ingrowth of trees during 5-year measurement period, by species, across Fork Mountain LTSP Study reference plots

	Number of ingrowth trees across four plots			
Species	2002	2007	2012	2017
American hornbeam	0	0	1	0
Eastern hophornbeam	2	0	0	0
Sweet birch	0	185	210	69
American beech	1	2	2	0
Cucumber magnolia	0	2	3	2
Fraser magnolia	12	18	4	3
Yellow-poplar	0	41	67	11
Pin cherry	0	2	0	0
Black cherry	0	1	3	0
Black locust	1	10	2	1
Sugar maple	61	19	13	4
Striped maple	58	122	62	17
Red maple	1	12	16	1
American basswood	2	0	0	0
Sourwood	2	1	0	0
White ash	0	1	7	0
Witch hazel	3	4	8	1
Total number of ingrowth trees	143	420	398	109
Average number of ingrowth trees per hectare	88.4	259.4	245.9	67.3

Table 3.—Average percentage mortality by species and measurement period, for four Fork Mountain LTSP Study reference plots, based on number of trees per hectare

	Percent mortality			
Species	2002	2007	2012	2017
Bitternut hickory				5.00
Eastern hophornbeam		1.67	8.93	5.56
Sweet birch	6.82	0.52	1.07	2.83
American beech				1.67
White oak	25.00			
Northern red oak	1.09		1.14	
Cucumber magnolia			1.92	1.79
Fraser magnolia	4.38	1.47	1.92	0.49
Yellow-poplar	1.43	0.34	0.18	4.17
Downy serviceberry			8.33	
Pin cherry				25.00
Black cherry	8.33		6.25	3.33
Black locust	16.67		1.92	21.15
Sugar maple	2.76	1.50	1.46	3.53
Striped maple	4.53	3.65	5.59	13.72
Red maple	2.47		1.98	3.19
American basswood		3.57	2.08	2.27
Sourwood			8.33	
White ash	3.13	6.25	3.85	4.55
Spicebush	8.33			
Witch hazel	3.13		3.95	11.76
Average percent mortality across all species	3.09	1.49	2.20	4.95
Std. error	3.83	0.93	1.63	3.29

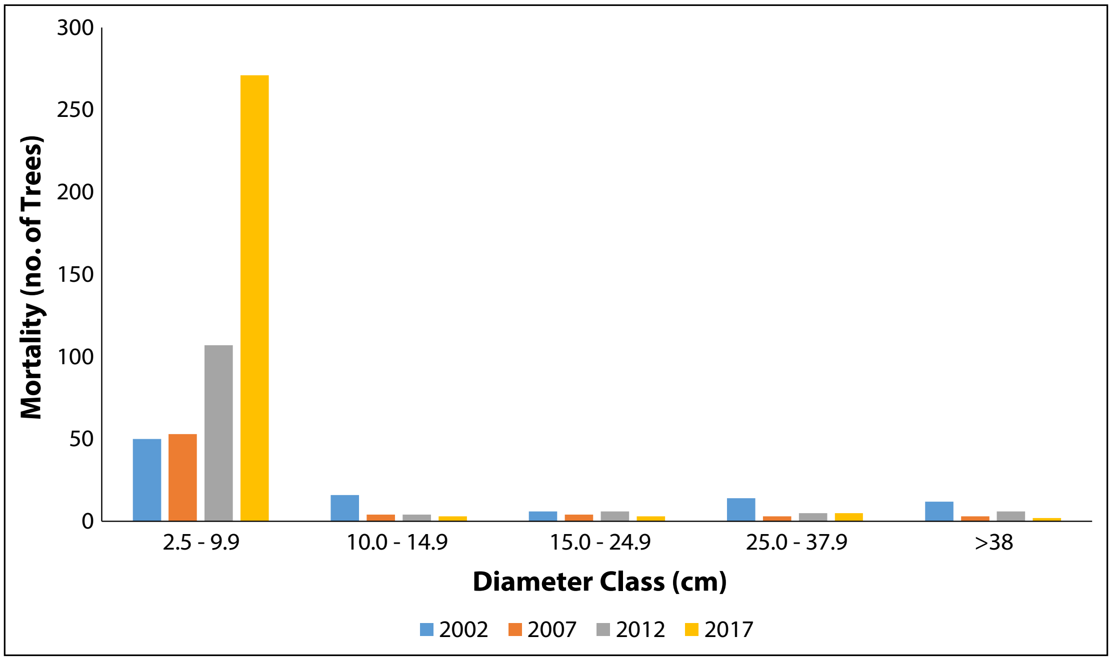

Figure 3.—Total number of newly dead trees, across four reference plots, by measurement date and diameter class, Fork Mountain LTSP reference plots.

Middle Mountain

At the beginning of the study, the Middle Mountain stand had high stem density (1543 stems ha^{-1}, std. error=270.2), with almost twice the number of trees as Fork Mountain. The Middle Mountain stand also had lower species richness, with 12 tree species, and just four species made up 90 percent of the species richness (Table 4). The reference plots were dominated by red maple (approx. 40 percent RIV), black cherry (29 percent), American beech (19 percent), and about 7 percent red spruce. Basal area was 43.1 m^2 ha^{-1} (std. error=2.3) and the trees were generally smaller in diameter than at Fork Mountain. The largest tree on Middle Mountain was a black cherry measuring 53.6 cm d.b.h. The relative proportions of species did not change over time (Fig. 4), nor were any species added or lost from the stand during the 20 years. One plot (plot 35) had almost twice the number of live trees per hectare than the other three reference plots (Fig. 5); otherwise the four plots were similar.

Although Middle Mountain stem density was originally higher than Fork Mountain (1543 trees ha^{-1}compared to 811 trees ha^{-1}on Fork Mountain), density declined slightly over time, and after 20 years was approximately the same as Fork Mountain (~1400 trees ha^{-1}). Black cherry, sweet birch, and red maple density decreased over time and average diameter increased, while American beech density increased over time with a slight increase in average diameter. Basal area increased over the 20 years (Table 4). Ingrowth was limited to a few species and was dominated by American beech (Table 5), occurring mostly by sprout origin (M.B. Adams, unpublished data). The number of ingrowth stems was considerably fewer than on Fork Mountain. There were no large changes in mortality either among plots or overall on Middle Mountain, and mortality was generally slightly above 1 percent over each 5-year period (Table 6). The number of dead trees was more evenly distributed across the size classes on Middle Mountain reference plots than on Fork Mountain reference plots, but the total number of dead trees was low (data not shown).

Table 4.—Stand data for Middle Mountain LTSP Study reference plots, pre-treatment and at 5- year measurement intervals. Values are averaged across four plots.

Middle Mountain	1997				2003				2007				2013				2018			
Species	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV	Average BA (m^2/ha)	Average Trees/ha	Average d.b.h. (cm)	RIV
Red spruce	0.8	178	7.0	6.7	1.0	179	7.9	7.1	1.2	181	8.8	7.5	1.5	188	9.5	8.1	1.7	183	10.3	8.3
Sweet birch	1.2	33	19.5	2.4	0.9	22	20.7	1.7	0.6	15	21.0	1.1	0.5	11	22.8	0.9	0.5	10	23.1	0.9
Yellow birch	0.1	2	24.6	0.2	0.1	2	25.5	0.2	0.2	2	26.3	0.2	0.1	1	37.1	0.2	0.1	1	37.6	0.2
American beech	2.0	516	6.2	19.0	2.2	516	6.5	19.7	2.5	530	6.8	20.9	2.8	551	7.0	22.1	3.0	562	7.2	23.4
Cucumbertree	0.3	4	27.5	0.5	0.3	4	29.0	0.5	0.4	4	30.1	0.5	0.4	2	42.3	0.4	0.4	2	44.3	0.5
Downy serviceberry	0.3	23	11.2	1.1	0.3	23	11.1	1.1	0.2	20	11.4	0.9	0.2	19	11.2	0.9	0.2	17	11.7	0.9
Black cherry	19.2	209	33.5	29.0	20.2	201	35.1	28.5	20.3	186	36.6	27.6	20.1	174	37.7	26.5	19.4	154	39.1	25.0
Sugar maple	0.3	16	13.3	0.9	0.3	14	13.9	0.8	0.3	11	15.4	0.7	0.3	11	15.5	0.7	0.3	11	15.9	0.7
Striped maple	0.006	6	3.5	0.2	0.009	6	4.2	0.2	0.010	6	4.4	0.2	0.010	5	5.1	0.2	0.011	5	5.4	0.2
Red maple	18.9	544	19.2	39.6	21.0	511	20.9	39.8	22.2	480	22.2	39.8	23.4	456	23.4	39.7	24.2	422	24.8	39.5
Spicebush	0.008	10	3.2	0.3	0.009	11	3.2	0.4	0.011	12	3.3	0.4	0.011	11	3.4	0.4	0.012	11	3.6	0.4
Witch hazel	0.001	1	3.6	0.0	0.001	1	3.8	0.0	0.002	1	4.1	0.0	0.002	1	4.1	0.0	0.002	1	4.6	0.0
Total	43.1	1543			46.4	1491			47.9	1449			49.3	1430			50.0	1380		
Std. error	2.3	270.2			7.6	275.4			2.4	266.1			2.3	273.0			2.4	257		

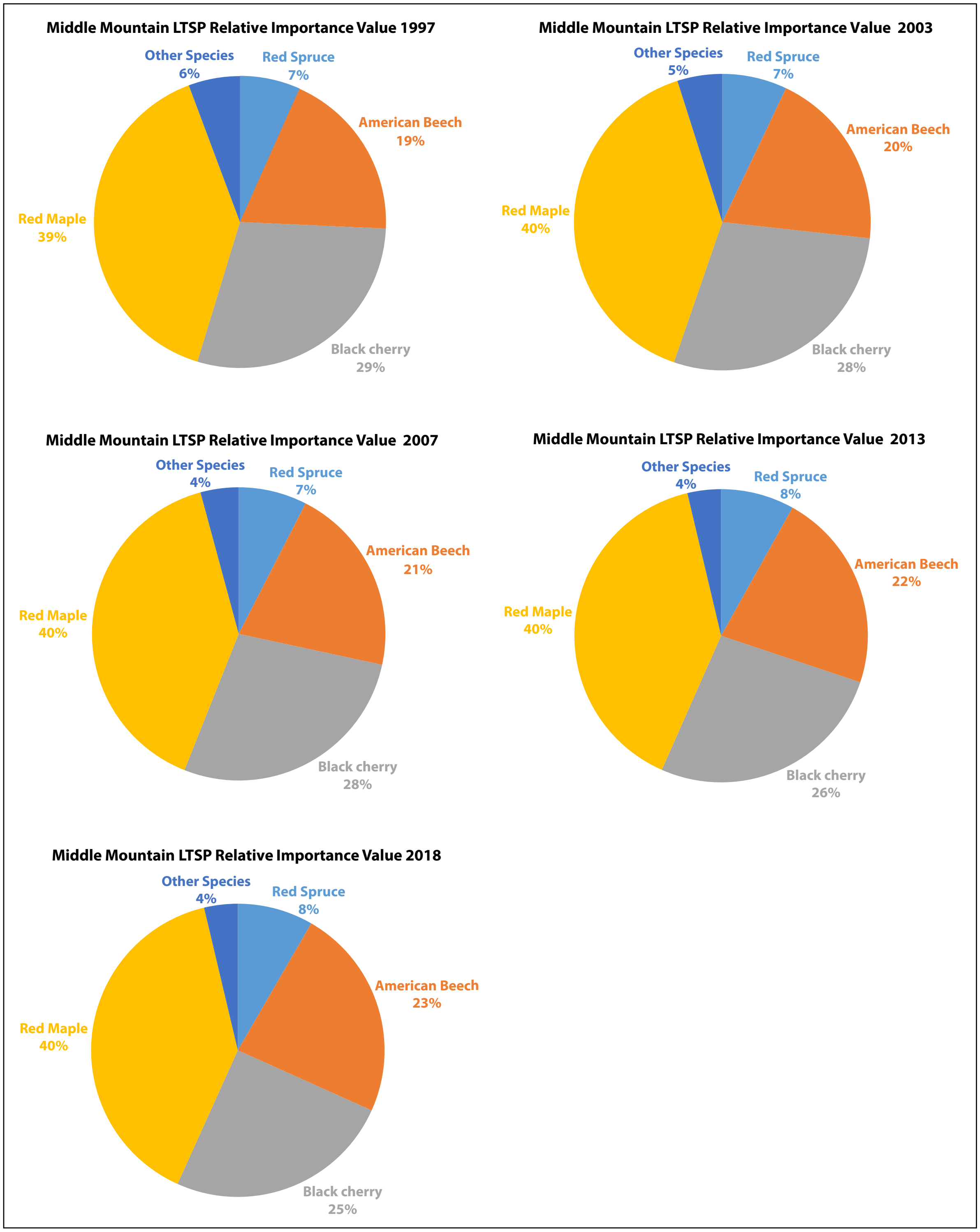

Figure 4.—Average tree species composition on the Middle Mountain LTSP Study reference plots, expressed as relative importance value (percent), at five measurement dates.

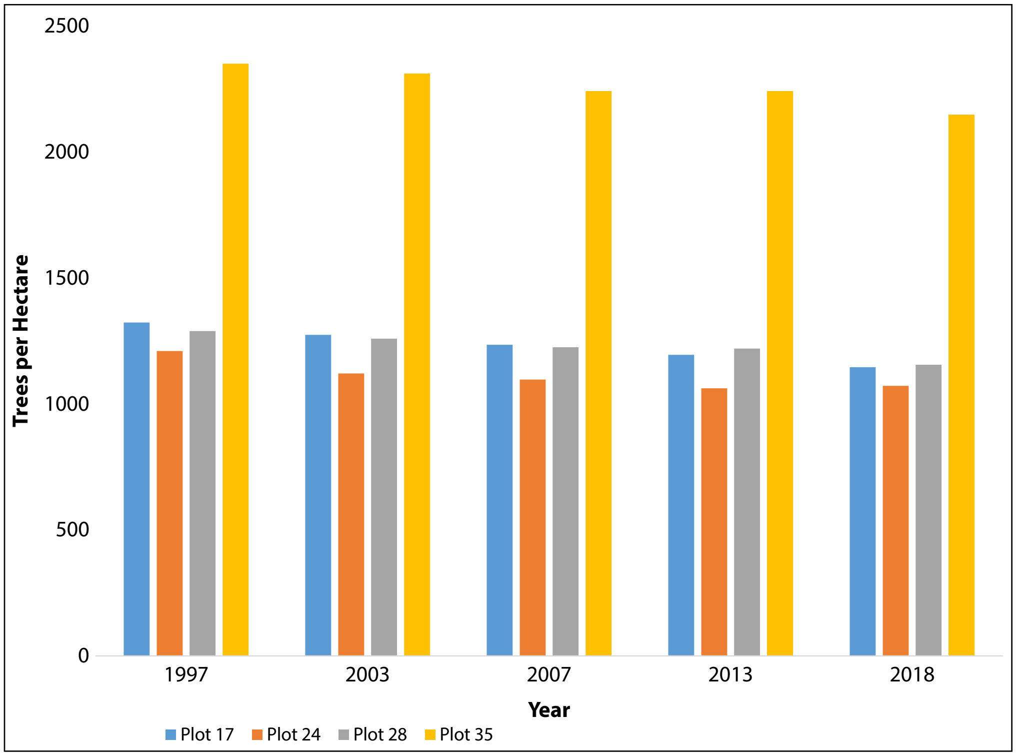

Figure 5.—Total number of live trees per hectare on the Middle Mountain LTSP Study reference plots, at five measurement dates.

Table 5.—Ingrowth of trees during 5-year measurement period, by species, across four Middle Mountain LTSP reference plots

	Number of trees across four plots			
Species	2003	2007	2013	2018
Red spruce	3	2	5	1
American beech	16	26	31	29
Downy serviceberry	1	0	0	0
Red maple	1	1	1	1
Spicebush	1	3		1
Total	22	32	37	32
Average number of ingrowth trees per hectare	13.6	19.8	22.9	19.8

Table 6.—Average percent mortality by species and measurement period, for four Middle Mountain LTSP Study reference plots

Species	2003	2007	2013	2018
Red spruce	0.34			0.82
Sweet birch	8.33	8.33	6.25	2.78
Yellow birch			12.50	
American beech	0.92	0.84	0.71	1.05
Cucumber magnolia			8.33	
Downy serviceberry	1.25	3.95	1.56	1.67
Black cherry	0.89	1.84	1.66	2.84
Sugar maple	3.85	4.55		
Striped maple			5.00	
Red maple	1.58	1.57	1.35	1.83
Spicebush		4.17	2.50	2.50
Average percent mortality across all species	1.26	1.33	1.07	1.49
Std. error	1.18	0.64	0.32	0.61

DISCUSSION

These reference plots align well with the pretreatment measurements of the entire study areas, as described in Adams et al. (2004) and Adams (2018), which suggests they are representative of the entire study areas. The differences observed between the two sites are also the same as described at study initiation (Adams et al. 2004, Adams 2018). These stands are similar in age, but differ in structure, diversity, and productivity. Generally, Middle Mountain had greater stem density and basal area, but smaller diameter trees, than the Fork Mountain site. The Fork Mountain site also had a greater number of tree species.

The stand dynamics also differed between the two sites during the 20 years. Mortality was generally greater at the Fork Mountain site (Table 3) than at Middle Mountain (Table 6) and was more variable among the measurement periods. Likewise, ingrowth was less on Middle Mountain (15 to 20 trees ha^{-1}), and more consistent over the 20 years. Also, the number of ingrowth stems at Middle Mountain represented 35 to 70 percent of the newly dead trees during a 5-year period, indicating a decline in stem density with time. By contrast, ingrowth on Fork Mountain exceeded the number of newly dead trees, except in 2017, and was 10 times greater or more than Middle Mountain (Fig. 6).

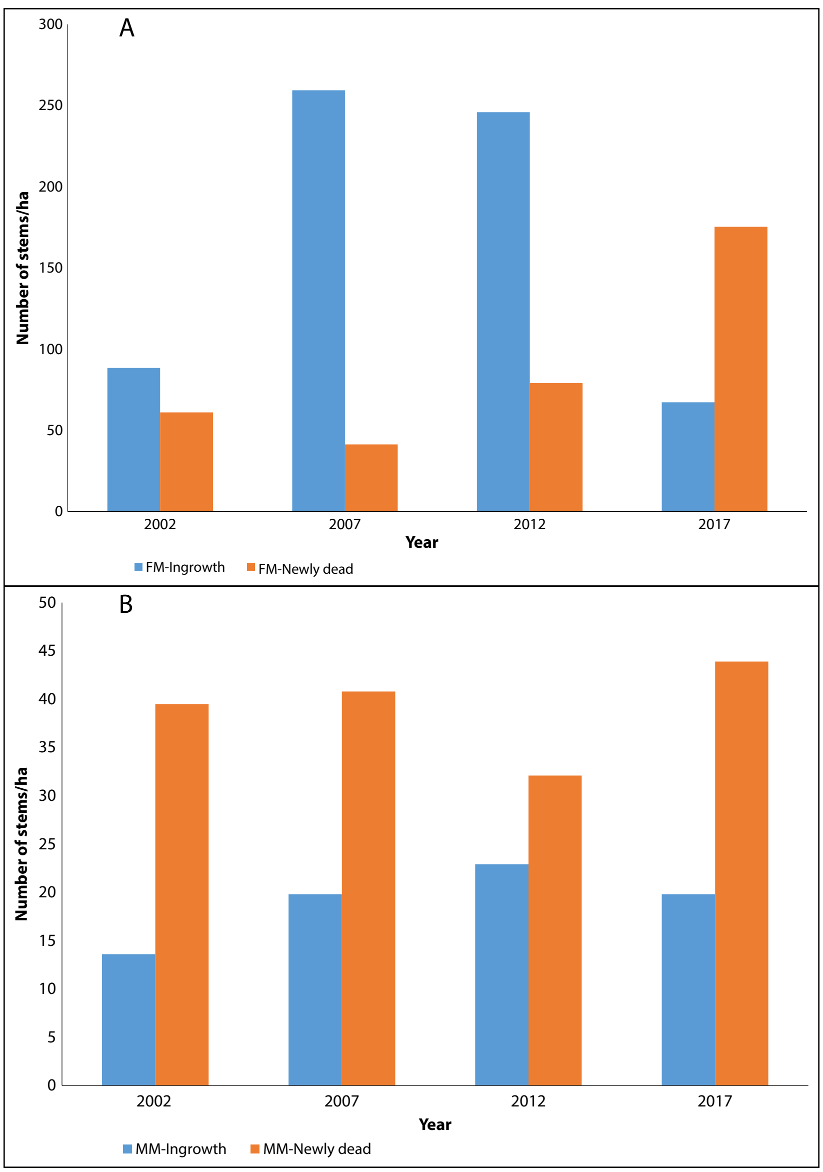

Figure 6.—Number of ingrowth trees and newly dead trees per hectare over each 5-year measurement period for Fork Mountain (A) and Middle Mountain (B) LTSP Study reference plots. Note the difference in scales for the y axes. Measurements started in 1996 at Fork Mountain and 1997 at Middle Mountain.

There are several possible reasons for the differences in mortality and ingrowth between the two sites, including differences in: 1) species composition, reflective of different site conditions; and 2) disturbance history, including experimental layout.

The species composition between the two sites is influenced particularly by climatic and soil parameters. While the soils are similar—relatively young soils with high coarse fragment content, low base saturation, and relatively low available water holding capacity—the soil processes have clearly been affected by climate. The presence of spodic characteristics at the higher elevation Middle Mountain site reflect the cooler annual temperature, as well as perhaps the influence of conifer vegetation historically. The less diverse stands at Middle Mountain reflect a cooler climate, and likely shallower, more acidic soils resulting from the influence of the more resistant hard sandstone parent material. In contrast, the Fork Mountain site is warmer, receives slightly more precipitation, and has deeper, less acidic soil, likely allowing for greater forest stand diversity. While there are species common to both sites, differences in species undoubtedly affected mortality rates, as has been reported elsewhere (Fien et al. 2019).

While these plots are uncut, untreated reference stands, some of the differences we see in stand processes could reflect the disturbance history of the experimental areas. For example, the position of the reference plots relative to the treated plots on the landscape. On Fork Mountain, the reference plots had whole-tree harvested plots on at least two sides (appendix 2, Fig. 9), and two of the reference plots (plots 8 and 11) had cut plots on three and four sides, respectively. Although there was a buffer (7.6 m wide) along each edge, given the taller trees on Fork Mountain (29.3 m on average, compared with 22.6 m for Middle Mountain) (Adams et. al. 2004, Adams 2018), it may be that the removal of surrounding trees from the treated plots increased the amount of light reaching the forest floor within the reference plots. The greater light incidence may have caused a pulse of ingrowth in the early measuring periods. Ingrowth was higher on plots 8 and 11, the more exposed plots, than on plots 4 and 8, providing some support for that hypothesis (Fig. 7). Reference plots on Middle Mountain, however, had "open" edges on, at most, two sides (appendix 2, Fig. 10), and the trees were generally shorter and smaller in diameter on Middle Mountain. Thus, the influence of harvesting adjacent plots on resulting light incidence was likely less substantial. This could explain the larger ingrowth at Fork Mountain.

However, the patterns of newly dead trees were not the same for the two sites (Fig. 6). On Fork Mountain, the number of newly dead trees per hectare decreased during the first 10 years, then increased during the second decade, with the greatest number of newly dead trees in the measurement period ending in 2017. This is also reflected in the mortality rate, which reached almost 5 percent on Fork Mountain in 2017. The mortality rate on the Middle Mountain site showed no trends and consistently remained between 1 and 1.5 percent.

We hypothesize that the patterns of mortality, and to a lesser extent ingrowth, observed on Fork Mountain may be mostly attributed to storm damage. There was a large pulse of newly dead trees in 2002, which corresponded with a decrease in live basal area between 1997 and 2002 (Fig. 8). On January 2, 1999, a severe wind event directly impacted the Fork Mountain LTSP. Estimates at the time suggested that 50 percent of the basal area had blown down on plot 4 (M.B. Adams, personal communication). Later assessment documented that 34 trees had been blown over or severely damaged on plot 4, with an additional eight trees on plot 8. Notably, the live basal area declined for plot 4 during the 5-year period from 1997–2002 (from 40 m^2 ha^{-1} to approximately 28 m^2 ha^{-1}) (Fig. 8) and the newly dead basal area also was greater on plot 4 in 2002 (15 m^2 ha^{-1}). The other reference plots were relatively less damaged by this storm. The large increase in ingrowth after 10 years (measurement date 2007) (Figure

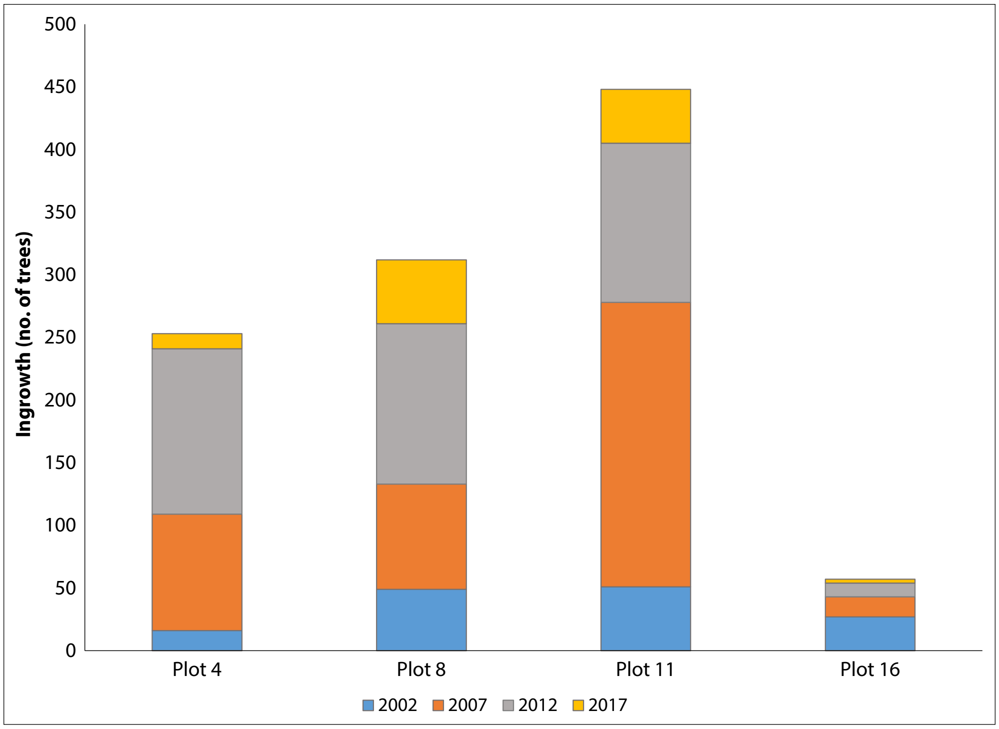

Figure 7.—Ingrowth of trees by plot and measurement date for Fork Mountain LTSP Study.

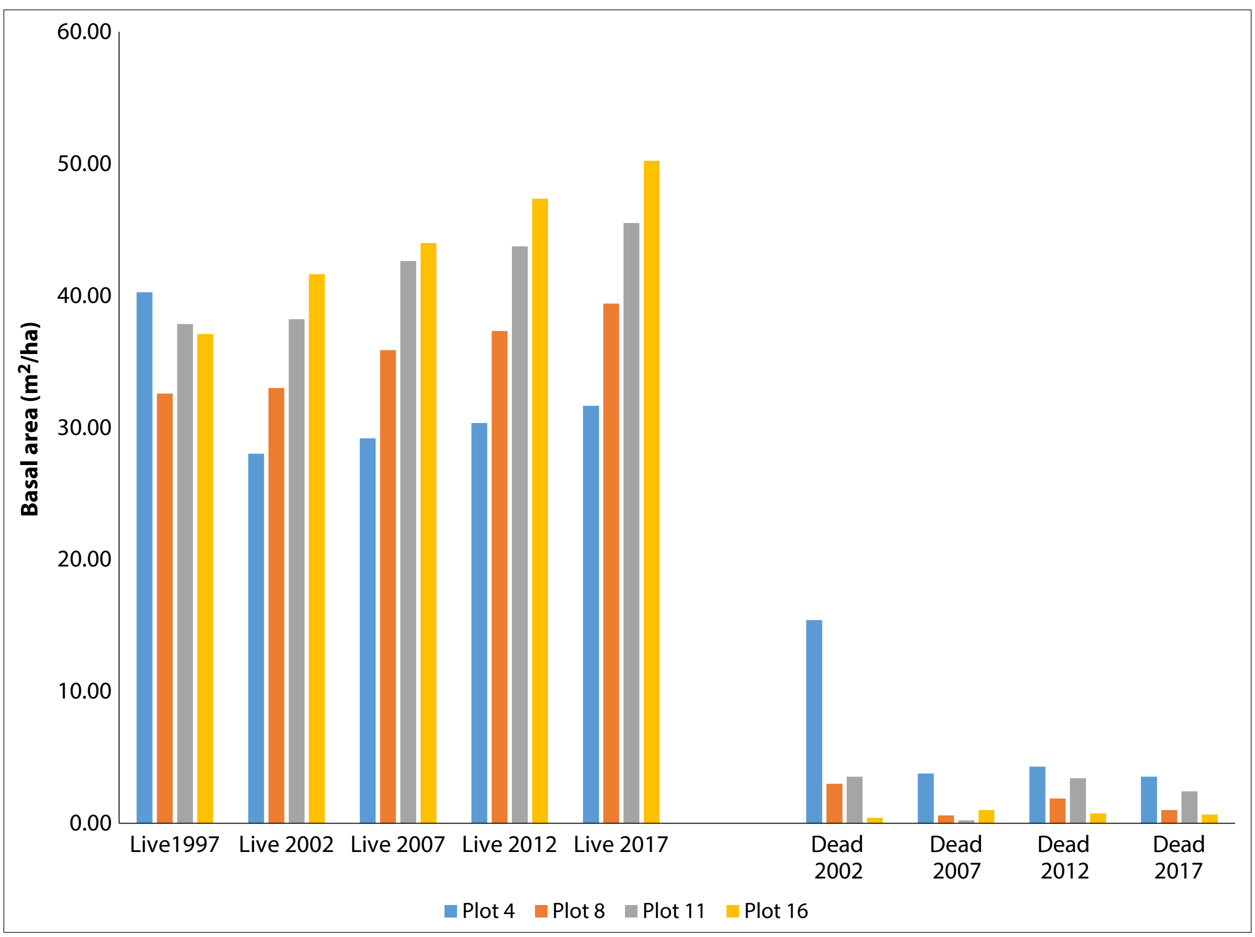

Figure 8.—Basal area per hectare for live and dead trees for four reference plots on the Fork Mountain LTSP Study.

6) may reflect the flush of growth following the canopy-opening event of 1999, perhaps in combination with the differential impacts of implementing the experimental treatments. Other wind events in 2009 and Superstorm Sandy in 2012 (Walter 2016) also likely impacted the Fork Mountain LTSP. While these events do not appear to affect the total live basal area (Fig. 8), they may have contributed to the slight increase in dead basal area in 2012 (plots 8 and 11) (Fig. 8). Also, as the large number of ingrowth stems became competitive on the Fork Mountain plots over time, density-dependent mortality likely increased among these trees. Despite its higher elevation and greater snowfall, the plots on Middle Mountain were not exposed to these severe events.

We suggest that the two stands are at different stages of stand development due to both site differences and the disturbances described above. Fork Mountain was likely "reset" to the stand initiation stage while Middle Mountain has progressed to the stem exclusion stage. The differences in stage of stand development, along with the patterns of light availability and differences in species composition and shade tolerance, help elucidate the differences between mortality and ingrowth patterns documented between the two sites.

Finally, the mortality rates reflect severe disturbance on Fork Mountain (1.5 percent to almost 5 percent over a 5-year period), which are comparable to those reported by Elliott and Swank (1994) in response to a severe multiyear drought. Mortality rates at the Middle Mountain site are lower, and represent the lower end of the spectrum for background mortality rates relative to other published values in the literature (Brown and Shroeder 1999, Kabrick et al 2004).

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APPENDIX 1

Table 7.—Common and scientific names of trees found on Fork Mountain and Middle Mountain LTSP Studies reference plots

Common Name	Scientific Name
Red spruce	*Picea rubens*
Sweet birch	*Betula lenta*
Yellow birch	*Betula alleghaniensis*
American beech	*Fagus grandifolia*
Cucumber magnolia	*Magnolia acuminata*
Downy serviceberry	*Amelanchier arborea*
Black cherry	*Prunus serotina*
Sugar maple	*Acer saccharum*
Striped maple	*Acer pensylvanicum*
Red maple	*Acer rubrum*
Spicebush	*Lindera benzoin*
Witch hazel	*Hamamelis virginiana*
Bitternut hickory	*Carya cordiformis*
American hornbeam	*Carpinus caroliniana*
Eastern hophornbeam	*Ostrya virginiana*
White oak	*Quercus alba*
Chestnut oak	*Quercus montana*
Northern red oak	*Quercus rubra*
Frasier magnolia	*Magnolia fraseri*
Yellow-poplar	*Liriodendron tulipifera*
Downy serviceberry	*Amelanchier arborea*
Pin cherry	*Prunus pensylvanica*
Black locust	*Robinia pseudoacacia*
American basswood	*Tilia americana*
Blackgum	*Nyssa sylvatica*
Sourwood	*Oxydendrum arboreum*
White ash	*Fraxinus americana*

APPENDIX 2

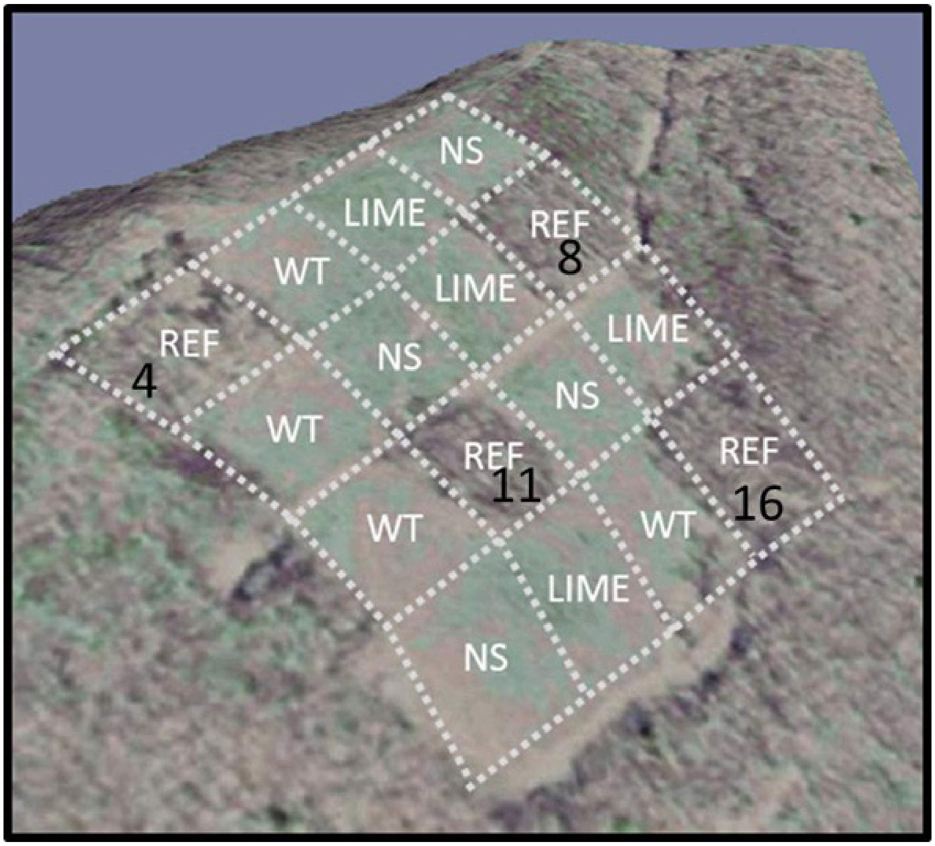

Figure 9.—Aerial photo of Fork Mountain LTSP Study plots, showing the location of reference (REF) plots; all other plots were whole-tree harvested. For details of study, see Adams et al. 2004.

Figure 10.—Aerial photo of the Middle Mountain LTSP Study plots, with the reference plots shown by black box outlines, adjacent to plots that had been whole-tree harvested. See Adams 2018 for details of treatment assignments.

Adams, Mary Beth; Simpson, Brian; Kelly, Charlene; Schuler, Jamie L.; Juracko, John. 2020. **Stand dynamics of reference plots in the West Virginia long-term soil productivity studies.** Gen. Tech. Rep. NRS-192. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 20 p. https://doi.org/10.2737/NRS-GTR-192.

Tree death is a natural part of forest dynamics, yet is not often studied over long periods, particularly in temperate mixed-species hardwood stands. In this study, we evaluated stand dynamics of four reference plots on each of the West Virginia Long-term Soil Productivity (LTSP) Studies. The Fork Mountain LTSP Study was initiated in 1996 and the Middle Mountain LTSP Study in 1997. The two locations represent distinct stand types (mixed mesophytic and cherry-maple) and site conditions (elevation, parent material, aspect). We found that after 20 years, there were differences in patterns of mortality and ingrowth between the two sites. Mortality rates ranged from 1.5 to almost 5 percent for a 5-year period on Fork Mountain to 1 to 1.5 percent on Middle Mountain. Generally, ingrowth exceeded mortality on Fork Mountain, while the reverse was observed on Middle Mountain. Possible reasons for differences in mortality and ingrowth between the two sites include differences in species composition related to soil and site characteristics and differences in past disturbance that have created different stages of stand development.

KEY WORDS: tree mortality, forest stand dynamics, mixed hardwood forests, LTSP

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