DOES NITROGEN AND SULFUR DEPOSITION AFFECT FOREST PRODUCTIVITY?

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Abstract.—We studied the effects of atmospheric nitrogen and sulfur deposition on forest productivity in a 10-year-old, aggrading forest stand at the Fernow Experimental Forest in Tucker County, WV. Forest productivity was expressed as total aboveground wood biomass, which included stem and branch weight of standing live trees. Ten years after stand regeneration and treatment initiation, total aboveground wood biomass was compared among three treatments: whole tree harvest (WT), whole tree harvest plus annual nitrogen (N) and sulfur (S) additions at two times ambient deposition rates (WT+NS), and whole tree harvest plus N, S (two times ambient), and dolomitic lime (WT+NS+CA) additions. Furthermore, future stand productivity was estimated for a subsequent 70 years using growth projection simulator SILVAH. Total aboveground wood biomass at 10 years was not significantly different among treatments (ANOVA: $F = 1.20$, $p = 0.33$, $n = 9$). Mean total aboveground wood biomass values for the WT, WT+NS, and WT+NS+CA treatments were 47.5 (± 15.3) Mg ha^{-1}, 53.0 (± 14.3) Mg ha^{-1}, and 51.0 (± 15.5) Mg ha^{-1}, respectively. The dominant tree species was pin cherry (average aboveground dry weight of the three treatments was 38.2 Mg ha^{-1}). Lack of significant differences in the aboveground wood component at the stand level suggests that 10 years of three times ambient rates of nitrogen and sulfur deposition and mitigation did not impact the ability of this site to produce woody biomass. At the species level, however, yellow-poplar had significantly higher diameter at breast height and aboveground wood biomass in the WT+NS+CA stands, indicating the potential for N, S, and Ca additions to impact individual species' growth over forest succession. Projected aboveground wood biomass at stand age 80 was 230.3 Mg ha^{-1}, 229.9 Mg ha^{-1}, and 349.7 Mg ha^{-1} for the respective treatments WT, WT+NS, and WT+NS+CA. Our results suggest that although N and S additions alone do not increase stand growth, N, S, and dolomite additions increase growth of individual species within the first 10 years of stand development. Based on this early biomass increase, long-term growth in the WT+NS+CA treatment may increase 34 percent by forest age 80.

INTRODUCTION

Total global production of anthropogenic nitrogen (N) is currently 10 times greater than late 19th-century production rates (Galloway et al. 2004). During the last few decades, atmospheric N deposition to forest ecosystems has increased, especially in the northeastern United States, as a result of an increase in factory and automobile fossil fuel burning and emissions from agricultural fertilizer inputs. The increase in N deposition has led to N saturation, defined as a condition in which atmospheric inputs of N exceed the biological demand of an ecosystem (Aber et al. 1989). Nitrogen saturation can lead to nitrate leaching to stream waters, a change in species composition, decreased soil carbon (C) to N ratio, lower foliar and fine root biomass, and a potential decrease in net primary productivity (Aber et al. 1989). Increased N deposition to a forest also may result in increased losses of base elements such as calcium (Ca), magnesium (Mg), and potassium, and others such as sulfur (S) and phosphorus (Johnson 1992). Depletion of these essential nutrients may impact the productivity and health of a forest community (Yanai et al. 1999, Hamburg et al. 2003, Sullivan et al. 2006, Bigelow

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and Canham 2007). For example, Wallace et al. (2007) attributed overall decline in live basal area to an N saturation effect caused by fertilizer additions in a northern New York mixed-oak forest; tree mortality in the fertilized plots was higher even though basal area of live trees increased significantly in the fertilized plots as compared to the control plots.

Stands that receive high ambient rates of N deposition, but that have not reached N saturation, may experience an increase in productivity as N limitations are relieved. Nitrogen enrichment at the Harvard Forest in Massachusetts (Aber et al. 1993, Magill et al. 2004) resulted in increased annual net primary productivity, while an N deposition gradient in the southern Appalachians (Boggs et al. 2005) demonstrated increased basal area growth in sugar maple trees (see Appendix for list of common and scientific names for trees). Further, hardwood trees respond differently from conifers to N additions. The conifer sites at the Harvard Forest exhibited 56-percent mortality after 15 years of N additions and complete mortality was predicted for the near future; hardwood stands experienced 17 percent mortality (Magill et al. 2004). Red spruce stands in Vermont also experienced a decline (40 percent) in live basal area after 14 years and researchers suggested that high-elevation spruce forests could be converted into stands of birch and maple under continued elevated N deposition (McNulty et al. 2005).

The Fernow Experimental Forest (FEF) in Tucker County, WV, experiences some of the highest rates of N deposition in the United States, and forest stands display symptoms of N saturation (Peterjohn et al. 1996, 1999). The objective of this study was to better understand the impact of atmospheric N and S deposition on the production of total aboveground wood biomass and individual tree species' biomass response in a young, aggrading deciduous forest at this location. Further, we were interested in whether the effects can be mitigated with dolomitic lime additions. Our final objective was to estimate, by using a growth simulation model, whether early fertilization in this forest type stimulates biomass accretion during the life of a forest.

STUDY AREA

We conducted the study at the Long-Term Soil Productivity (LTSP) sites on Fork Mountain in the FEF near Parsons, WV (39°03′ N, 79°29′ W). Annual temperatures range from an average of -2 °C in January to an average of 20 °C in July (Adams et al. 2004). Precipitation averages 146 cm annually (Wallenstein et al. 2006). Dominant soil type is a Calvin channery silt loam derived from acidic sandstone and shale of the Upper Devonian Hampshire formation (Kochenderfer 2006).

In 1996, four blocks were established along a slope gradient ranging from 798 m to 847 m in elevation. Four treatments were imposed in a complete randomized block design: an unharvested and unfertilized control, unfertilized whole-tree harvested control (WT), whole-tree harvested ammonium sulfate additions (WT+NS), and whole-tree harvested ammonium sulfate additions plus dolomitic lime (WT+NS+CA). Individual treatment plots measure 0.2 hectares including treated buffer areas; plots are adjacent to each other within a block. The rate of addition for the WT+NS treatment was two times the ambient N and S throughfall deposition. Ambient deposition in early 1980 contained ~15 kg N $ha^{-1} \cdot yr^{-1}$ and 17 kg S $ha^{-1} \cdot yr^{-1}$ (Helvey and Kunkle 1986); therefore, 36 kg N $ha^{-1} \cdot yr^{-1}$ and 40 kg S $ha^{-1} \cdot yr^{-1}$ are added in fertilizer. The WT+NS+CA plots received two times ambient N and S fertilizer as well as 22.5 kg Ca $ha^{-1} \cdot yr^{-1}$ plus 11.6 kg Mg $ha^{-1} \cdot yr^{-1}$, which is equivalent to two times the rate of export of Ca and Mg to stream water (Wallenstein et al. 2006). Pre-treatment mean soil pH was 4.24 (Adams et al. 2004). Five years after treatment, soil pH was 2.96, 3.22, and 3.41 in the WT+NS, WT, and WT+NS+CA treatments, respectively (Wallenstein et al. 2006).

METHODS

Data for three of the four blocks were available for use in this study. Trees were inventoried in 2006 using either four or five 0.004 ha vegetative growth subplots in each plot. Diameter at breast height (d.b.h.) was measured for all trees greater than 2.54 cm and recorded by species. Total wood dry weight was estimated with regression equations based on d.b.h. For trees with d.b.h. 5.1 to 12.7 cm, equations were developed at the FEF (M.B. Adams, unpublished data); for trees with d.b.h. 12.8 to 50.8 cm, equations of Brenneman et al. (1978) were used (Table 1). Several tree species did not have their own equation; therefore, we used wood specific gravity to match species without an equation to species with a known equation to calculate total aboveground wood dry weight.

Analysis of variance in SAS (SAS Institute Inc., Cary, NC) was used to test for significant differences between treatments in biomass estimates for individual tree species and plot totals. Alpha level of ≤ 0.1 was used.

A growth model for the Allegheny Hardwoods (Marquis and Ernst 1992) was used to project stand growth to 80 years. Of the available growth simulation computer programs for the Allegheny hardwoods, SILVAH exhibits the least error associated with the projections (J.R. Brooks, unpublished). Data for SILVAH were plot size, tree species, and d.b.h.; growth in SILVAH is estimated by using species-specific basal area growth and mortality equations. Tree per acre (TPA) and basal area values are generated at the stand level for every 5-year period.

The SILVAH-generated values for basal area per acre and TPA for each 5-year increment were used to calculate quadratic mean diameter with Equation 1 for each of the three treatments.

$$QMD = \sqrt{\left(\frac{\frac{BA/AC}{TPA}}{k}\right)} \qquad (1)$$

Where:

QMD = quadratic mean diameter
BA/AC = basal area per acre
TPA = trees per acre
k = -0.0054542

The quadratic mean diameter for each 5-year period was then used in the species-specific biomass equations (Table 1). The biomass for each species in each treatment was multiplied by that individual species' relative density at year 10 and then by the total-stand TPA (Table 2). The sum of

Table 1.—Individual tree species dry weight equations based on d.b.h.. ($Y=ax^b$). The Fernow equations are in kilograms while Brenneman et al. (1978) equations are in pounds. Results of this study are reported in kilograms.

	Tree species	a	b	R-square
Fernow	Black birch	1.1064	2.4877	0.98
	Yellow-poplar	0.7037	2.4806	0.99
	Black cherry	0.8833	2.6047	0.98
	Red maple	0.9305	2.5922	0.99
	Pin cherry	0.8833	2.6047	0.98
	Striped maple	0.8833	2.6047	0.98
	Hercules club	0.8833	2.6047	0.98
	Sourwood	0.9305	2.5922	0.99
	Sassafras	0.8833	2.6047	0.98
	Fraser magnolia	0.8833	2.6047	0.98
Brenneman	White ash	2.3626	2.4798	0.99
	Black locust	1.5647	2.6887	0.95
	Cucumbertree	1.4359	2.5622	0.98
	Northern red oak	2.4601	2.4572	0.95
	Yellow birch	3.1042	2.3753	0.97
	Sugar maple	2.4439	2.5735	0.98
	E. hophornbeam	2.0340	2.6349	0.99

Table 2.—Species trees per hectare (TPH) used to calculate percent relative density (RD) for the dominant tree species ≥2.54 cm d.b.h. by treatment. The "other species" include striped maple, eastern hophornbeam, yellow birch, sassafras, white ash, sugar maple, black locust, northern red oak, and sourwood. The last row represents total values by treatment. Treatments are unfertilized whole tree harvest (WT), whole tree harvest plus annual nitrogen and sulfur additions (WT+NS), and whole tree harvest plus nitrogen, sulfur, and dolomitic lime (WT+NS+CA).

	WT		WT+NS		WT+NS+CA	
Tree species	TPH	RD (%)	TPH	RD (%)	TPH	RD (%)
Pin cherry	2,947	46.3	2,964	51.0	2,806	48.0
Black cherry	776	12.2	889	15.0	689	12.0
Sweet birch	1,023	16.1	477	8.0	494	9.0
Yellow-poplar	689	10.8	215	4.0	529	9.0
Red maple	247	3.9	477	8.0	566	10.0
Fraser magnolia	195	3.1	180	3.0	0	0.0
Cucumbertree	35	0.5	99	2.0	247	4.0
Other species	458	7.3	479	8.0	477	8.3
Total	6,370	100	5,780	100	5,807	100

weights for all species was used to estimate total aboveground wood biomass over the 80-year period. For the purpose of this paper, values are reported in metric units.

SILVAH does not include growth or mortality functions specific to nutrient addition treatments, such as N, S, or liming, in growth projections. Therefore, to ensure a level of validity for SILVAH estimates, basal area values from SILVAH at age 35 were compared to mean stand basal area values of 35-year-old forested watersheds at the FEF, which include a control and N and S amendments at the same levels as the LTSP treatments (Kochenderfer 2006). The treated watershed had a basal area of 36.0 m^2 ha^{-1} while the control watershed contained 28.0 m^2 ha^{-1} (DeWalle et al. 2006). Mean predicted basal area values for the LTSP sites from SILVAH at 35 years were 27.3, 28.0, and 29.1 m^2 ha^{-1}, for the WT, WT+NS, and WT+NS+CA treatments, respectively, at 35 years.

RESULTS

10-Year-Old Stands

Total Aboveground Wood Biomass and d.b.h.

Total aboveground wood biomass did not differ significantly between treatments at age 10 ($p = 0.33$); the highest value was 53.0 (± 14.3) Mg ha^{-1} in the WT+NS treatment, followed by the WT+NS+CA and WT treatments with 51.0 (± 15.5) and 47.5 (± 15.3) Mg ha^{-1}, respectively. Total aboveground wood biomass in each plot by block and treatment are displayed in Figure 1. The WT, WT+NS, and WT+NS+CA treatments had an average d.b.h. of 4.44 (± 1.75) cm, 4.62 (± 1.98) cm, and 4.65 (± 1.98) cm, respectively.

Individual Tree Species

Pin cherry (Fig. 2) was the most abundant species in these 10-year-old stands regardless of treatment, followed by black cherry and sweet birch, yellow-poplar, red maple, Fraser magnolia, and cucumbertree.

Yellow-poplar and cucumbertree exhibited significantly higher total aboveground wood biomass in the WT+NS+CA treatment ($p = 0.09$ and 0.10, respectively). Aboveground wood biomass of yellow-poplar in the WT+NS+CA treatment was 90 percent higher than in the WT+NS treatment and 79 percent higher than in the WT treatment. Cucumbertree followed a very similar trend in the WT+NS+CA treatment with an 84 percent and 88 percent higher aboveground wood biomass than in the WT+NS and WT treatments, respectively. Yellow-poplar did not have the highest relative density, but its average d.b.h. was significantly higher in the WT+NS+CA treatment compared to the WT and WT+NS treatments ($p = 0.03$). The average d.b.h. for yellow-poplar in the WT+NS+CA treatment was 5.74 (± 1.19) cm compared

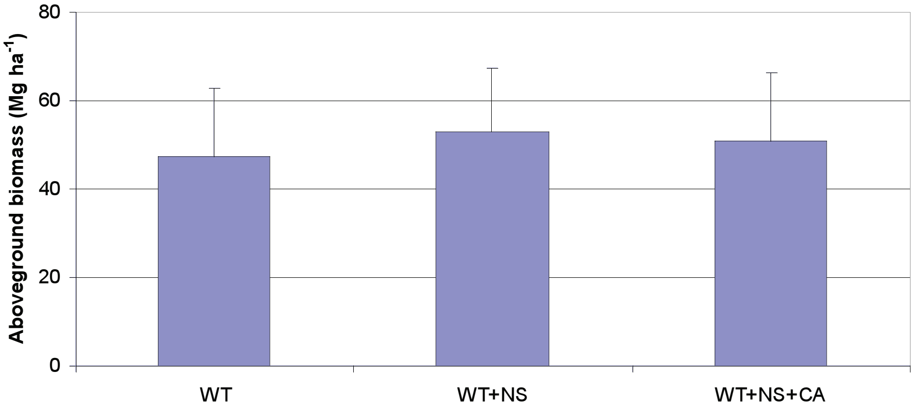

Figure 1.—Total aboveground wood biomass values by treatment for the 10-year-old Long-Term Soil Productivity site. Treatments are unfertilized whole tree harvest (WT), whole tree harvest plus annual nitrogen and sulfur additions (WT+NS), and whole tree harvest plus nitrogen, sulfur, and dolomitic lime (WT+NS+CA).

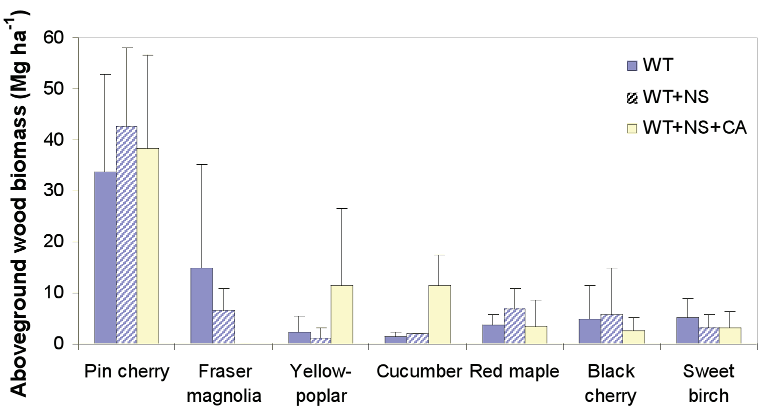

Figure 2.—Comparison of the dominant species' wood biomass component on the Fernow Long-Term Soil Productivity site between treatments. Treatments are unfertilized whole tree harvest (WT), whole tree harvest plus annual nitrogen and sulfur additions (WT+NS), and whole tree harvest plus nitrogen, sulfur, and dolomitic lime (WT+NS+CA).

to 3.38 (± 0.21) cm and 3.40 (± 0.26) cm in the WT+NS and WT treatments, respectively. Fraser magnolia was the only species that was not present within all treatments; it was absent in the WT+NS+CA treatment plots even though it had a large wood biomass component (14.9 Mg ha^{-1}) in the WT treatment. Aboveground wood biomass for red maple was not statistically different between treatments even though average d.b.h. was significantly greater (4.55 ± 0.20 cm) in the WT+NS treatment than in the WT+NS+CA treatment (3.02 ± 0.55 cm; $p < 0.05$). No other abundant species (pin cherry, black cherry, and sweet birch) showed large variations in diameter or aboveground wood biomass among treatments (Table 2).

Projected Stands

Although the 10-year-old treated and control stands did not differ in the total aboveground biomass, growth projections (Fig. 3) suggest that around age 30, growth in the WT+NS+CA treatment may exceed the growth in the WT and WT+NS treatments by 16 and 12 percent, respectively. SILVAH's final projection at 80 years yielded a 34 percent higher aboveground wood biomass at 349.7 Mg ha^{-1} than both the WT and WT+NS treatments (230.3 and 229.9 Mg ha^{-1}, respectively). Greater biomass in the WT+NS+CA treatment can be attributed to differences in quadratic mean diameter between the treatments at 80 years of age. The WT+NS+CA treatment had a 7 percent projected higher quadratic mean diameter (28.7 cm) than the 26.5 cm and 26.7 cm values for the WT and WT+NS treatments, respectively.

DISCUSSION

Total Aboveground Wood Biomass Production of 10-Year-Old Stands

After 10 years of regeneration following whole-tree harvest and elemental additions, which delivered a total of 350 kg N ha^{-1} and 400 kg S ha^{-1}, total aboveground wood biomass in our study was not significantly affected by either increased N and S inputs or liming. In contrast, 23-year-old trees in a

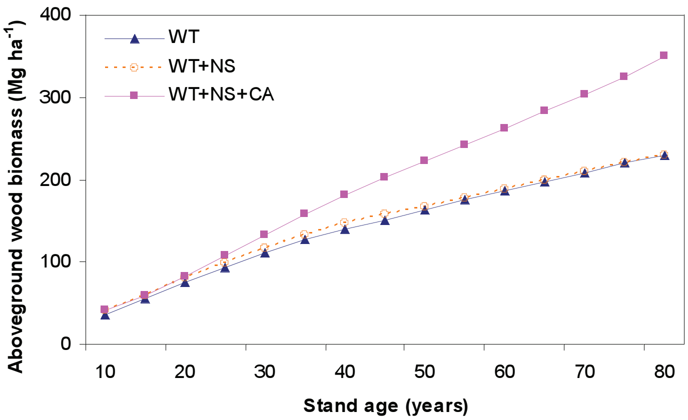

Figure 3.—Projected growth in aboveground wood biomass over 80 years by treatment. Treatments are unfertilized whole tree harvest (WT), whole tree harvest plus annual nitrogen and sulfur additions (WT+NS), and whole tree harvest plus nitrogen, sulfur, and dolomitic lime (WT+NS+CA).

watershed-level N and S addition study also conducted at the FEF exhibited significantly higher annual net growth than control trees 4 years after treatment had begun (DeWalle et al. 2006). Other acidification studies have also shown an increase in wood biomass production due to increased N availability for biomass growth with N and S additions (Nelleman and Thomsen 2001, Magill et al. 2004, Wallace et al. 2007).

The lack of differences in biomass between treatments in our study may be attributed to factors associated with the young age of these stands. Full site occupancy (observed as canopy closure) has been reached only recently in these stands, and light and nutrient limitations may not have affected overall stand productivity. Therefore, trees did not yet respond to nutrient additions. Trees that receive N, S (WT+NS), and liming (WT+NS+CA) amendments do not yet show a response compared to the WT trees because there appear to be sufficient nutrient resources to support this level of biomass, allowing all sites to be productive. This conclusion is supported by soil N chemistry assessments (Wallenstein et al. 2006) at the LTSP site 5 years into treatment, which demonstrated no difference in soil percent-N, net N mineralization, and nitrification among all treatments. However, soil pH was significantly greater in the WT+NS+CA treatment compared to the WT and WT+NS treatments, which may further increase site productivity in this treatment. Already at stand age 10, dolomitic lime additions seem to be able to reverse some effects of N and S additions. For example, Piatek et al. (2009) found that 10 years of N and S additions (WT+NS) lowered the capacity of foliar litter for N immobilization and that dolomitic lime reversed the effect.

Treatment Effects at Species Level

Even though our study shows no stand-level differences in aboveground wood biomass between treatments, yellow-poplar and cucumbertree have demonstrated significantly more wood biomass accumulation in the WT+NS+CA treatment at 10 years. Yellow-poplar has also shown a positive response in basal area growth to N and N+P fertilization as higher foliar N concentrations boost photosynthesis rates (Auchmoody and Smith 1977). Similar species results were observed in the FEF watershed study. Growth plots dominated by yellow-poplar and black cherry on the amended watershed yielded higher relative radial growth rates and basal area increment for 7 years since the start of N and S additions; plots with mainly sweet birch and red maple also demonstrated greater cubic volume growth for this time period (DeWalle et al. 2006). The greater wood biomass that we observed in some species in the WT+NS+CA treatment compared to the WT and WT+NS treatments is suggestive of differential species responses to soil pH caused by dolomitic lime additions. These differences may also be evidence of beginning competition for nutrient resources in these stands.

Pin cherry had the highest basal area, relative density, and aboveground wood biomass in all treatments (WT, WT+NS, and WT+NS+CA) in our study. The prevalence of pin cherry results from its vigorous early successional behavior after a clearcut and from high N soil conditions (Nyland et al. 2007) in the LTSP sites. For example, pin cherry has demonstrated greater germination rates with the addition of N fertilizer (Auchmoody 1979) and with more N available in soil solution (Bjorkbom and Walters 1986, Nyland et al. 2007). As an early successional species, however, pin cherry is expected to be lost from these stands approximately 35 years after stand regeneration due to natural mortality (Marquis 1967, Marks 1974, Heitzman and Nyland 1994, Nyland et al. 2007). Therefore, individual species' responses to the expected change in species composition in addition to excess N deposition are inevitable yet unclear at this point.

Potential Future Stand Productivity

Growth projections with SILVAH suggest that the WT+NS+CA treatment will be most productive by 80 years of age, producing 34 percent more aboveground wood biomass than the WT and WT+NS treatments. SILVAH is not sensitive to treatment in that it does not use treatment-specific equations for biomass growth. Therefore, differences in projected growth among treatments are likely driven by increased diameters of yellow-poplar and cucumbertree at age 10. There are no replicates of the liming amendments at the watershed scale at the FEF to compare with these results, but estimates from SILVAH provide insight as to how the WT+NS+CA treatment may result in greater tree productivity of a hardwood stand over a complete rotation. Alternatively, these results may indicate the potential of a lower soil pH, as seen in the WT and WT+NS treatments (Wallenstein et al. 2006), to reduce forest productivity compared to the WT+NS+CA treated plots. The reportedly lower soil pH may have altered cation availability, most notably Ca, which can explain the observed species' responses to a decade of dolomitic lime additions. The way in which acidification ultimately impacts species composition and stand productivity at the LTSP site has important implications for C-sequestration and financial returns for landowners.

CONCLUSIONS

The results from this study suggest that stand-level total aboveground wood biomass, therefore apparent productivity, has not been affected by increased acidic deposition or liming additions after 10 years. SILVAH results and comparisons of individual species' diameters between treatments indicate the WT+N+CA sites may have higher productivity over the next several decades. The increase in diameter growth in yellow-poplar and cucumbertree alongside the changes that have resulted in higher soil pH in the WT+NS+CA treatment suggest that liming may be effective at ameliorating acidified soil conditions. These results also imply that forested sites that receive high rates of ambient N deposition may experience reduced productivity compared to sites that receive dolomitic lime amendments. Therefore, applying lime to forests that experience elevated levels of N deposition, have acidic soils, and have a stand composition similar to the LTSP sites could increase aboveground wood biomass, likely resulting in a greater financial return for the landowner.

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APPENDIX

List of common and scientific names of the tree species present on the Fernow Long-Term Soil Productivity site.

Common Species Name	Scientific Species Name
Pin cherry	*Prunus pensylvanica* L.f.
Fraser magnolia	*Magnolia fraseri* Walt.
Yellow-poplar	*Liriodendron tulipifera* L.
Cucumbertree	*Magnolia acuminata* L.
Red maple	*Acer rubrum* L.
Black cherry	*Prunus serotina* Ehrh.
Sweet birch	*Betula lenta* L.
Striped maple	*Acer pensylvanicum* L.
E. hophornbeam	*Ostrya virginiana* (Mill.) K. Koch
Yellow birch	*Betula alleghaniensis* Britton
Sassafras	*Sassafras albidum* (Nutt.) Nees
White ash	*Fraxinus americana* L.
Sugar maple	*Acer saccharum* Marsh.
Black locust	*Robinia pseudoacacia* L.
Northern red oak	*Quercus rubra* L.
Sourwood	*Oxydendron arboreum* (L.) DC.

The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.