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Effects of 21 Years of Simulated Acidic Deposition on Tree Growth and Species Composition in an Aggrading Appalachian Hardwood Forest

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Abstract

The long-term effects of soil acidification on the development of a young aggrading Appalachian forest were examined after 21 years of continuous treatment. Beginning with a clearcut harvest in 1997, annual ammonium sulfate (N+S) and ammonium sulfate with lime (N+S+LIME) treatments were aerially applied to a developing forest. The lime treatment was designed to counteract the acidification of the nitrogen and sulfur amendments. After 21 years, the N+S and N+S+LIME treatments had little impact on total woody biomass accumulation relative to the control. There were significant differences among species and treatment responses with respect to woody biomass accumulation, however. Biomass of *Prunus pensylvanica* was about twice as much as any other species in N+S and N+S+LIME treatments but was similar to *Liriodendron tulipifera* and *Betula lenta* on control areas. Treatment effects were not significant for average tree diameter or stem density, although both varied among the six tree species with the highest importance values. The importance value of *P. pensylvanica* decreased by almost half in the last 6 years due to mortality, but this was not associated with either the N+S or N+S+LIME treatments. The dynamic nature of this short-lived tree species is potentially masking any effects of the N+S or N+S+LIME treatments to date.

Study Implications

We examined the long-term impact of nitrogen and sulfur additions with and without lime on forest stand development. After 21 years, the forest showed little change in aboveground woody biomass, although the distribution of biomass among species was affected by the treatments. *Prunus pensylvanica* (pin cherry) accumulated the greatest biomass on N+S and N+S+LIME treatments relative to the untreated areas. However, *P. pensylvanica* is a short-lived species, and our data show it is declining. It is unclear whether the treatments are having minimal impacts or they are being masked by the early dominance and subsequent mortality of *P. pensylvanica*.

Keywords: pin cherry, nitrogen, sulfur, lime, fertilization, LTSP, stand development

The role of nitrogen (N) cycling in forest productivity and development has been studied globally (LeBauer and Treseder 2008). For many temperate forest ecosystems, soil N availability is less than biological demand (Aber et al. 1989, Vitousek and Howarth 1991), especially in aggrading forests. There are, however, areas that receive chronically high levels of nitrogen from atmospheric deposition (Zhang et al. 2012), potentially leading to excess levels in the ecosystem (Peterjohn et al. 1996) and N saturation (Aber et al. 1989).

Although the Clean Air Act of 1970 and its 1990 amendments resulted in a significant decline in N deposition in the United States, there are still areas in the eastern United States, western Canada, and throughout Europe and Asia that experience elevated deposition rates (Kanakidou et al. 2016). Research on the impacts of chronic nitrogen deposition tends to focus on soil acidification and biogeochemical processes, soil carbon and nitrogen cycling, soil microbial communities, stream chemistry, and understory plant biodiversity (Gilliam et al. 2019), whereas the effects on the tree community are not as well documented.

Several regional studies have demonstrated tree species-specific responses to nitrogen deposition (Thomas et al. 2010, Horn et al. 2018, Van Houtven et al. 2019). Experiments that manipulate nitrogen inputs using annual fertilizer applications to simulate chronic deposition have shown varied responses, ranging from positive to neutral to negative. Positive responses were reported in *Acer saccharum* stands for aboveground net primary productivity in Michigan (Pregitzer et al. 2008) and for basal area and hardwood biomass in Maine (Elvir et al. 2005, Patel et al. 2019). Depending on the fertilization rate, the mixed hardwood stands in the Harvard Forest's chronic nitrogen experiment showed either increased or similar productivity compared to nonfertilized trees (Magill et al. 2004). At a companion study site on the Harvard Forest, nitrogen applications resulted in substantial mortality of *Pinus resinosa*. Similarly, low and high rates of

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nitrogen applied annually over a 14-year period ultimately increased mortality and reduced basal area for a *Picea rubens* stand in Vermont (McNulty et al. 2005, McNulty et al. 2017). However, the same species showed no change in basal area following nitrogen additions in Maine (Elvir et al. 2005).

The mixed mesophytic forests of the central Appalachians also vary in response to chronic N additions depending on the metric used, the age of the forests, and species encountered. Species such as *Prunus serotina* and *Liriodendron tulipifera* responded positively in terms of biomass production in the early years of stand development to ammonium sulfate fertilizer (Adams et al. 2007), whereas *Acer rubrum* and *Betula lenta* showed no response. However, relative growth rates from tree core data indicated decreases in radial growth rates for all three species after approximately 9 years of annual N additions (DeWalle et al. 2006).

Aboveground biomass of *L. tulipifera* in West Virginia was stimulated following 13 years of annual N fertilization in a separate study (Fowler et al. 2015), whereas May et al. (2005) observed reduced stem diameter growth rates for *L. tulipifera, P. serotina, and A. rubrum* trees exposed to 10 years of chronic N additions. The differences in response between the two growth metrics (i.e., biomass accumulation and individual incremental growth rates) highlight the possibility of delays in detecting negative effects associated with nitrogen additions.

Although most of these studies have focused on the impacts of elevated N, many areas that experienced high nitrogen deposition are also exposed to elevated levels of sulfur (S) deposition. Combined, N and S deposition decreases soil pH, increases available soil aluminum levels, and increases cation exports (Adams et al. 2007), which affect soil biological processes (Bowden et al. 2019). Elevated rates of N and S have been correlated with health and vigor concerns for many forest species (Houston 1999, Magill et al. 2004, Wallace et al. 2007). Increases in available Al^{3+} and concurrent decreases of available Ca^{2+}, Mg^{2+}, and K^{+} are linked to stress in susceptible tree species (Shortle and Smith 1988, Schaberg et al. 2006). Additions of Ca (i.e., liming treatments) can increase the amount of exchangeable Ca and Mg in soils affected by acidic deposition, resulting in increases in vigor and tree size of some hardwood species (Long et al. 1997, Huggett et al. 2007, Fowler et al. 2015).

The Fork Mountain Long-Term Soil Productivity site (LTSP) was established on the Fernow Experimental Forest in 1996 as a part of a nation-wide effort to quantify anthropogenic influences on forest soil long-term productivity. The Fork Mountain LTSP was established to evaluate the effects of elevated N and S and remedial dolomitic lime treatments on nutrient cycling and ecosystem health. Our particular objective with this study was to examine the impact of 21 years of these treatments on the growth and species composition of these Appalachian hardwood stands. One unique aspect of this study is that fertilizer treatments began shortly after the site was completely harvested, and not in older, established forests like most other studies. The second unusual feature of this experiment was the addition of a liming treatment intended to alleviate the loss of base cations from soil acidification. Our objectives were to document changes in biomass accumulation, species composition, and the overall impact from 21 years of elevated inputs of N, S, and remedial dolomitic lime treatments.

Methods

This study was conducted at the Fork Mountain LTSP site on the Fernow Experimental Forest in Tucker County, West Virginia, USA (latitude 39°04'' N, longitude 79°41'' W). The Fork Mountain LTSP site is approximately 5 ha with a predominant southeast aspect and slopes between 15% and 30%. Elevations range from approximately 800 to 850 m. The site was whole-tree harvested in 1996. The original stand was an 85-year-old mixed Appalachian hardwood forest dominated by *Quercus rubra*, *Acer saccharum*, *Prunus serotina,* and *L. tulipifera* representing 21%, 20%, 17%, and 15% of the 23.6 m^2/ha of total basal area (see Adams et al. 2004 for more detailed site descriptions). The site quality was very good (site index 24 m, base age 50 yr) for *Q. rubra*. Soil was classified as Dekalb soil series (Soil Survey Staff 2022).

To determine the long-term effects of elevated rates of acidic deposition on forest productivity of young stands, three treatments were initiated following the harvest. Each treatment plot was made up of a 0.2 ha growth plot plus a 7.6 m buffer (Adams et al. 2004). The treatments were nontreated control (Control), ammonium sulfate fertilization (N+S), and ammonium sulfate fertilization plus dolomitic lime (N+S+LIME) arranged in a complete randomized block design with four blocks (replicates). The dolomitic lime addition was designed to mitigate the negative effects of soil acidification to better understand the effect of continual fertilizer addition to the ecosystem. The ambient rates of N and S for the area, as measured in throughfall from 1980 to1981, were 15 kg N/ha/yr and 17 kg S/ha/yr (Helvey and Kunkle 1986). Stream water export of Ca and Mg measured from a nearby watershed study was 11.2 kg Ca/ha/yr and 5.8 Mg/ha/yr (Adams et al. 2007). The ammonium sulfate and liming treatments were added at rates equivalent to twice these ambient input/export rates. Fertilizer treatments began in 1997 and were applied as split applications three times per year to simulate natural deposition patterns. Lysimeters installed to a 45 cm depth do not show evidence of nutrient movement among blocks or treatments (unpublished data, M.B. Adams, USDA Forest Service).

We measured the overstory trees (≥ 2.5 cm dbh) in the summer of 2017 (stand age 21). Trees between 2.5 and 12.7 cm dbh were measured on five 3.6 m radius plots, whereas trees greater than 12.7 cm diameter at breast height (DBH) were measured on five 11.3 m plots in each treatment plot. This type of inventory allowed us to characterize not only the species composition and density of smaller trees but also provide a more representative sample of the dominant trees on the site. Species and DBH were recorded for each tree.

We used regeneration data from 1997, the year after the stand was harvested, to compare initial species composition across all treatment areas. Twenty permanent subplots within each treatment plot were selected, and seedlings were counted by species, height class, and origin (Adams et al. 2004).

Generalized allometric biomass equations (Chojnacky et al. 2014) were used to calculate the aboveground biomass (trees > 2.5 cm). Some species present on the site were not included in the Chojnacky's taxa groupings for the generalized equations. *Magnolia acuminata* was included with the other Magnoliaceae species. *Carpinus caroliniana* was placed in the Betulaceae ≥ 0.60 specific gravity group (based on Miles and Smith 2009). The equation from the Cornaceae/

Ericaceae/Lauraceae/Platanaceae/Rosaceae/Ulmaceae taxa grouping was used to estimate aboveground biomass for *Ilex montana* and *Aralia spinosa*, based on similar specific gravity values of the species (Briand et al. 1999, Miles and Smith 2009).

Importance values (IV) were calculated for each tree species on the LTSP site to describe the composition of the stand (Cottam and Curtis 1956). Relative importance value was determined based on the sum of the average of relative density, relative frequency, and relative dominance for each species converted to a percentage of the total.

Data were analyzed using two-way ANOVA with SAS JMP, version 13.0 statistical software. Blocks were used as a random effect in the mixed model. Biomass and tree density data were transformed using a square root transformation to meet the normality assumptions of ANOVA. *P*-values are reported from transformed data, whereas reported means and figure data use back-transformed means. The Tukey Kramer HSD posteriori test was used to determine differences for significant model effects ($P < 0.05$). We used the slicing technique in the two-way ANOVA to interpret the within-species effect of the treatments.

Results

After 21 years, N+S and N+S+Lime treatments had no effect on importance values (IV) of the species in this stand. *P. pensylvanica*, *L. tulipifera, B. lenta*, and *P. serotina* had the greatest IV across all treatments. Compared to inventories conducted in 2009 at age 13 (Fowler et al. 2014), the species composition of the site has changed little, but the importance of several species did vary (Table 1). Most notably, the IV of *P. pensylvanica* decreased greatly, whereas increases were noted for *L. tulipifera* (8.2%), *B. lenta* (4.5%), *M. acuminata* (3.6%), *P. serotina* (2.5%), and *M. fraseri* (2.6%). Three species (*Carpinus caroliniana*, *Tilia americana*, *Quercus montana*) that combined for < 1% IV value in the 2009 inventory were not encountered at age 21. The ingrowth of one eastern hemlock (*Tsuga canadensis*) tree was the only new species encountered.

Basal area changed little over the 9-year period (Table 1). Across all treatments, basal area increased only 1.3 m^2/ha. A major factor responsible for the small change was the large decline in *P. pensylvanica*, which dropped more than 50%. Much of the decline was offset by increases in *L. tulipifera* and *B. lenta*.

Nineteen species were encountered across the entire study site. The number of species recorded on Control, N+S, and N+S+LIME plots were sixteen, sixteen, and twelve, respectively. Species richness varied among treatments at age 21 ($P = 0.0448$). The treatment areas receiving the N+S+LIME treatment averaged 5.8 species per measurement subplots compared to 5.0 and 4.9 species on Control and N+S treatments. These differences resulted from a general increase in diversity across N+S+LIME treatments, but also the presence of *Tsuga canadensis* (single occurrence) and *A. saccharum*, which only occurred within plots receiving the liming treatment.

Total aboveground biomass at age 21 was unaffected by N+S or N+S+LIME treatments for all stems combined ($P = 0.472$) or for the top six species combined ($P = 0.657$). The top six species (out of nineteen total) on average made up between 90% and 96% of the total biomass (Figure 1). The total aboveground biomass response to fertilization treatments varied among the six species (trmt × spp interaction, $P = 0.017$) (Figure 2). *Prunus pensylvanica* accumulated the greatest total biomass relative to all other species. In fact, *P. pensylvanica* accounted for 25.1%, 41.1%, and 37.7% of the total aboveground biomass for control, N+S, and N+S+LIME treatments, respectively. Most species achieved their greatest biomass associated with N+S and N+S+LIME treatments; however, *B. lenta* and *L. tulipifera* were notable exceptions, where the control plots had greater total biomass.

Stem density was somewhat variable among species and treatment combinations. No interaction ($P = 0.464$) or treatment effect ($P = 0.403$) was noted. However, stem density did vary among the six top species ($P < 0.001$), with *L. tulipifera* the most abundant (Figure 3) but not statistically different from most of the other dominant species. For half the species, stem density was lower when associated with N+S or N+S+LIME treatments, but again, not enough to suggest species varied by treatment.

Current trends for *L. tulipifera* and *P. serotina* densities generally reflect their high stem densities estimated from the first growing season inventory (Table 2). Although not significantly different, *L. tulipifera* had higher stem densities in the Control treatments over time, whereas *P. serotina* was

Table 1. Percent importance and basal area (m^2/ha) of tree species sampled across all treatment areas at age 21 (in 2017) and age 13 (in 2009).

Species	Code	Age 13[a] IV	Age 21IV	IV change	Age 13 basal area[b]	Age 21 basal area	Basal area change
Prunus pensylvanica	PRPE	51.9	28.9	–23.0	13.9	7.6	–6.3
Liriodendron tulipifera	LITU	12.8	21.0	8.2	1.9	4.9	3.0
Beula lenta	BELE	12.4	16.9	4.5	1.0	3.6	2.6
Prunus serotina	PRSE	7.5	10.0	2.5	1.2	2.0	0.8
Acer rubrum	ACRU	4.2	4.7	0.5	0.6	0.8	0.2
Magnolia acuminata	MAAC	1.0	4.6	3.6	0.2	0.8	0.6
Magnolia fraseri	MAFR	0.9	3.5	2.6	0.1	0.6	0.5
Acer pensylvanicum	ACPE	2.3	2.7	0.4	0.2	0.2	0.0
Quercus rubra	QURU	1.6	2.1	0.5	0.2	0.2	0.0
All other species	—	5.2	5.7	0.5	0.7	0.6	–0.1

[a]Importance values for 2009 are from Fowler et al. (2014).
[b]Basal areas for 2009 are from Fowler (unpublished data).

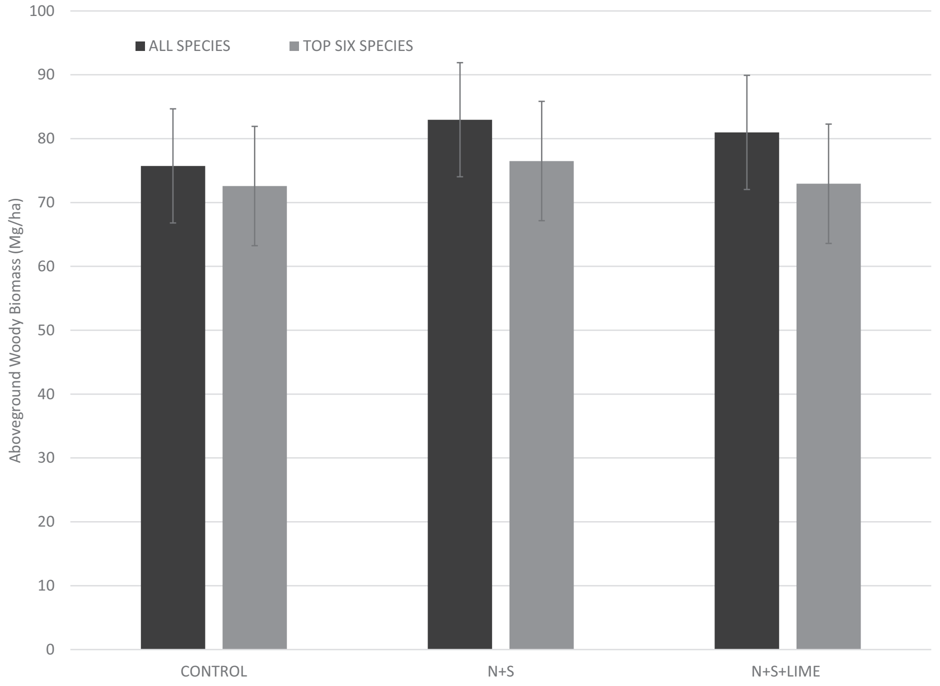

Figure 1. Total aboveground woody biomass at age 21 by treatment for all trees and for the six species with highest IV. Error bars represent upper and lower 95% confidence intervals. N+S, annual ammonium sulfate; N+S+LIME, ammonium sulfate with lime.

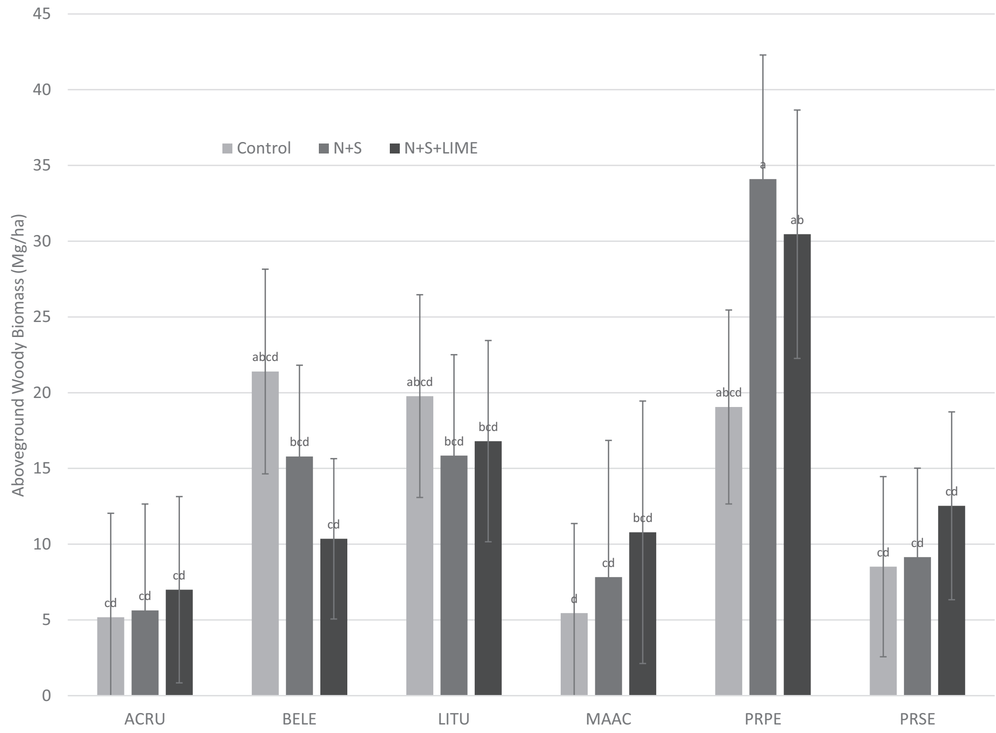

Figure 2. Aboveground woody biomass (>2.5 cm dbh) per hectare for the six species with highest IV at age 21. Error bars represent upper and lower 95% confidence intervals. Columns with different letters are statistically different at $P = 0.05$. ACRU, *Acer rubrum*; BELE, *Beula lenta*; LITU, *Liriodendron tulipifera*; MAAC, *Magnolia acuminata*; N+S, annual ammonium sulfate; N+S+LIME, ammonium sulfate with lime; PRPE, *Prunus pensylvanica*; PRSE, *Prunus serotina*.

most frequently encountered in the N+S+LIME treatment. Incidentally, *P. serotina* was the only species for which the initial stem density varied significantly among treatments ($P = 0.026$; Table 2).

Mean tree diameter differed among species ($P < 0.001$) but not by treatment or their interaction. *Prunus pensylvanica* stems had a quadratic mean diameter of 14.4 cm, which was > 75% larger than all other species (Figure 4). *Betula*

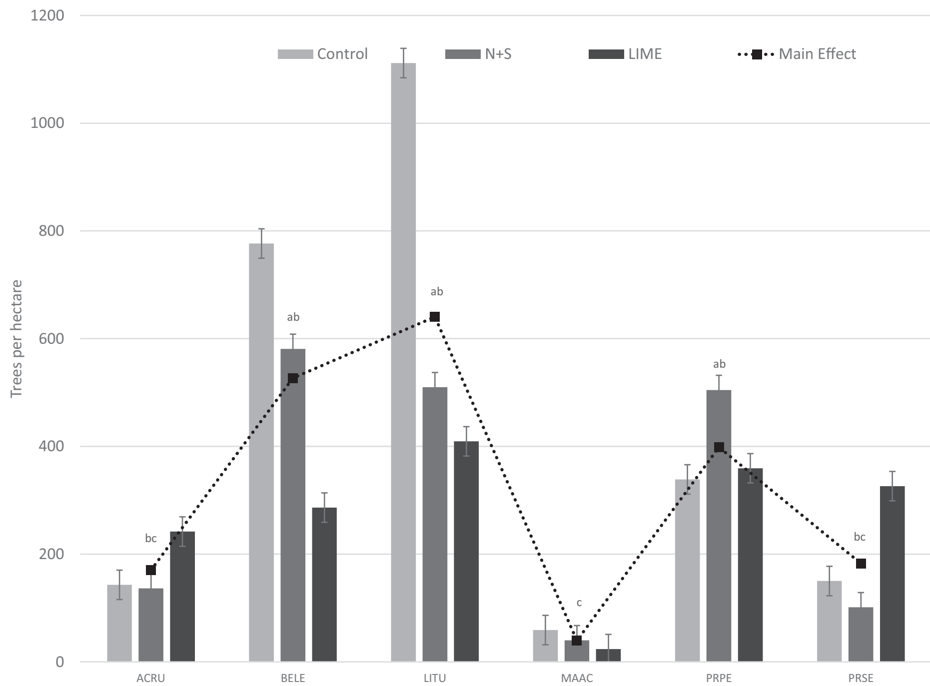

Figure 3. Trees per hectare for the six species with highest IV. Error bars represent upper and lower 95% confidence intervals. Different letters associated with the main effect are statistically different at $P = 0.05$. N+S, annual ammonium sulfate; N+S+LIME, ammonium sulfate with lime; ACRU, *Acer rubrum*; BELE, *Beula lenta*; LITU, *Liriodendron tulipifera*; MAAC, *Magnolia acuminata*; PRPE, *Prunus pensylvanica*; PRSE, *Prunus serotina*.

Table 2. Seedlings per hectare (for the six species with the highest IV) measured in the first growing season regeneration survey.

Species	Control	N+S	N+S+LIME
Acer rubrum	14,680	14,912	12,622
Betula lenta	3,667	3,442	6,439
Liriodendron tulipifera	101,034	68,214	79,569
Magnolia acuminata	4,482	3,089	4,129
Prunus pensylvanica	21,473	17,099	25,498
Prunus serotina	54,591a	72,370a	139,581b
All other species	12,839	22,689	20,366

For *Prunus serotina*, treatment means with different letters are statistically different at $P = 0.05$. All other were not significant ($P > 0.05$).

lenta, *L. tulipifera*, *P. serotina*, *and M. acuminata* all had similar quadratic mean diameters that ranged from 5.2 to 8.7 cm. *Acer rubrum* stems were the smallest, averaging just over 2.5 cm DBH.

Discussion

The tree community in the Fork Mountain LTSP is at an important stage in its development. Although no treatment effects for IV have been noted thus far, some trends may prove important into the future. The importance of *P. pensylvanica* has declined to nearly half of its 2009 value (Table 1). *Liriodendron tulipifera*, the species with the largest IV increase across treatments between 2009 and 2017, showed a trend towards fewer but larger trees in the N+S and LIME treatments (Figures 3 and 4). The reduced stem densities with N+S and N+S+LIME treatments are consistent with other fertilization studies in mixed hardwood stands (e.g., Fahey et al. 1998, Schuler and Robison 2006). *P. serotina* also had larger stems associated with N+S and N+S+LIME treatments, but the number of stems under the N+S+LIME treatment were much higher, which was undoubtedly confounded by the substantially higher initial densities encountered during the initial inventory conducted when the stand was harvested 21 years ago. If the trend in replacement of *P. pensylvanica* continues, then it is likely that the future species composition of the N+S and N+S+LIME treatment areas will differ from the control areas.

The greater tree species richness on the plots receiving dolomitic lime suggests that the acidification effect of the N+S treatment may have affected the ability of certain species to develop or persist. Gilliam et al. (2016) reported that elevated N deposition caused a decline in species richness of understory plants and homogenized soil N resources. Interestingly, although there was not much focus on *A. saccharum* in this study due to its low abundance on the current LTSP plots, the only occurrences of *A. saccharum* stems were on plots that received the N+S+LIME treatment. In the pretreatment

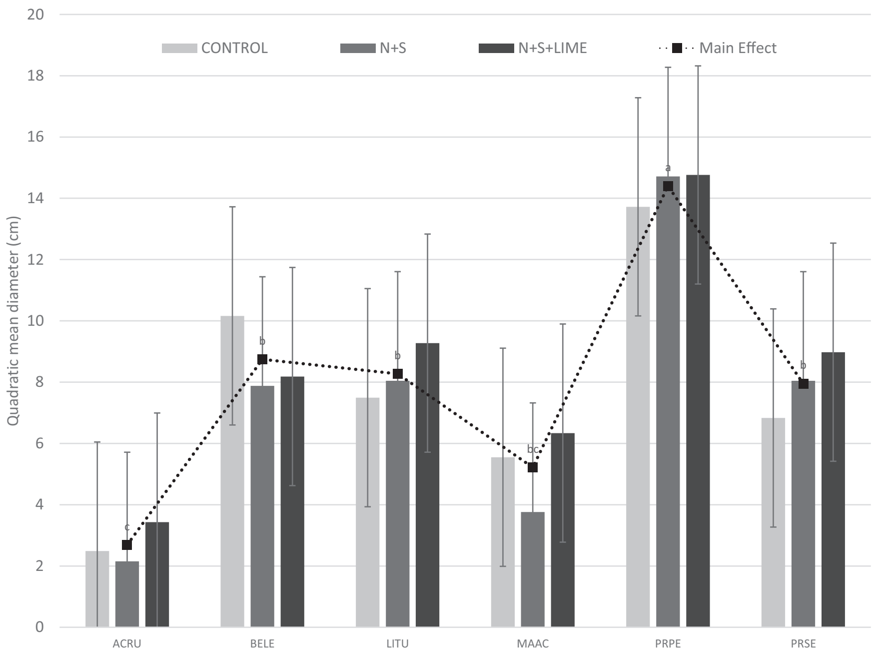

Figure 4. Quadratic mean diameter for the six tree species with the highest IV. Error bars represent upper and lower 95% confidence intervals. Different letters associated with the main effect are statistically different at $P = 0.05$. N+S, annual ammonium sulfate; N+S+LIME, ammonium sulfate with lime; ACRU, *Acer rubrum*; BELE, *Beula lenta*; LITU, *Liriodendron tulipifera*; MAAC, *Magnolia acuminata*; PRPE, *Prunus pensylvanica*; PRSE, *Prunus serotina.*

regeneration survey (Adams et al. 2004), *A. saccharum* was found on all treatment plots on this site. Thus, there may be a link between the acidification treatments and the presence of sugar maple, which may be related to its reported sensitivity to soil acidification and low Ca and Mg levels (Houston 1999, Drohan et al. 2002, Duchesne et al. 2002).

Our results demonstrate the complexities between increased N and S deposition to a forested system and the growth response of the overstory community. Through 21 years, the total aboveground woody biomass remained similar among treatments despite the annual additions of N, S, and lime (Figure 1). This is different from the positive effects that were reported at age 13 (Fowler et al. 2015). Perhaps the effects of the chronic N+S additions are beginning to negatively influence productivity, which has been hypothesized for other hardwood forest systems (Aber et al. 1998).

Alternatively, the developmental patterns of *P. pensylvanica* could be confounding the observed trends. First, *P. pensylvanica* is the dominant species, but is a relatively short-lived species on our site. *Prunus pensylvanica* accumulated about 11 Mg/ha more aboveground woody biomass on the N+S+LIME and N+S treatments compared to other species, which supports the designation of *P. pensylvanica* as an exploitive species (Bormann and Likens 1979). However, *P. pensylvanica* stems commonly experience heavy mortality starting around the second decade after establishment (Ristau and Horsley 2006). This mortality temporarily decreases aboveground biomass until the residual stems reoccupy the growing space. However, given the dominance of *P. pensylvanica* in the overstory, the development of other species was likely inhibited (Heitzman and Nyland 1994, Ristau and Horsley 2006), especially on the N+S and N+S+LIME treatment plots, thereby reducing biomass growth and giving the impression of acidification effects.

The dominance of early successional species across the study site likely contributes to the limited treatment effects. Past studies have shown that the species most sensitive to acid deposition tend to be late successional ones, having reduced growth and declining vigor (e.g., Duchesne et al. 2002). The complete harvest across all of the treatments favored the shade-intolerant species, which represented the top four biomass producers across the entire study.

Higher levels of soil N can favor *P. pensylvanica*'s persistence in the overstory but may not allow it to compete as effectively for nutrients with species that have invested more energy into root growth (Fahey et al. 1998). This may have resulted in higher mortality and lower yields of biomass on a per acre basis for the control plots in comparison to the N+S and N+S+LIME treatments.

Liriodendron tulipifera has been identified as a species that responds positively to more traditional high rate, one-time fertilizer applications in both mature (Auchmoody and Smith 1977) and immature stands (Broadfoot and Ike 1968, Jacobs et al. 2005, Schuler and Robison 2006). However, *L. tulipifera* (and *B. lenta*) was largely unresponsive to the N+S and N+S+LIME treatments after 21 years. This is different from results in years 10 and 13, which suggested that dolomitic lime appeared to mitigate and even reverse the negative effects of chronic additions of ammonium sulfate (Johnson et al. 2010, Fowler et al. 2015). However, in our study, after 21 years, the lack of difference in aboveground biomass (Figure 1) between N+S and N+S+LIME treatment suggests the lime mitigation of the negative effects of nitrogen and sulfur may be short-lived or insufficient over time. In fact, 13 years of lysimeter data since the initiation of the study show soil pH on control plots ranging from about 5.3 to 5.5, whereas soil pH on N+S- and N+S+LIME-treated areas have steadily declined to about 4.5 (unpublished data, William Peterjohn, West Virginia University, 2013) suggesting too little calcium has been added.

Conclusion

Twenty-one years of ammonium sulfate and lime treatments to a young aggrading central Appalachian forest has not changed aboveground biomass accumulation. The complexity of the mixed species forests has afforded some degree of stability to the system. However, we expect that longer-lived species such as *L. tulipifera*, *P. serotina*, and *B. lenta* will continue to increase in importance as the *P. pensylvanica* continues to decline. A decrease in species richness was recorded on the control and N+S treatments, suggesting that background as well as elevated levels of acidic deposition may lead to decreased presence of sensitive species in the region.

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