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Acid deposition effects on forest composition and growth on the Monongahela National Forest, West Virginia

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ABSTRACT

The northern and central Appalachian forests are subject to high levels of atmospheric acid deposition (AD), which has been shown in some forests to negatively impact forest growth as well as predispose the forest system to damage from secondary stresses. The purpose of this study was to evaluate the possible contribution of AD to changes in composition and productivity of the Monongahela National Forest, and to evaluate soil-based indicators of acidification that might be useful for detecting AD-related forest changes. Soils adjacent to 30 Forest Inventory and Analysis (FIA) sites were sampled and analyzed for a suite of acidity indicators. These indicators were correlated with the periodic mean annual volume increment (PMAVI) of the forest stands on FIA plots for the 10-yr period 1989–2000. PMAVI ranged from -9.5 to 11.8 $m^3\ ha^{-1}\ yr^{-1}$, with lower-than-expected growth ($<3\ m^3\ ha^{-1}\ yr^{-1}$) on two-thirds of the sites. In the surface horizon, effective base saturation, Ca^{2+} concentration, base saturation, K^+ concentration, Ca/Al molar ratio, and Mg/Al molar ratio, were positively correlated with PMAVI and Fe concentration was negatively correlated with PMAVI ($p \leq 0.1$). In the subsurface horizon $pH_{(w)}$ and effective base saturation were positively correlated and Al^{3-} concentration and K^+ concentration were negatively correlated with PMAVI. We hypothesized that NO_3-N/NH_4-N ratio would also be correlated with PMAVI, but it was not. Correlations between soil chemical indicators and PMAVI suggest that AD may contribute, in part, to the lower-than-expected forest growth on the Monongahela National Forest.
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1. Introduction

Located in eastern West Virginia, the Monongahela National Forest (MNF) encompasses over 360,000 ha of land. The forest is second and third growth, and maintains a high level of biological diversity, supporting 13% of the rare plant and animal species in West Virginia (USDA Forest Service, 2006). Situated only a few hours from large urban centers and containing over 1200 km of hiking trails, the MNF is a popular recreation destination, while still producing about 0.2 million m^3 of timber annually (Widmann and Griffith, 2004).

The MNF lies at the confluence of the mixed mesophytic and oak-chestnut forest regions, with remnants of northern hardwoods at high elevations (Braun, 1950). Since the loss of the *Castanea dentata* Marsh. (American chestnut) and removal of virgin timber at the turn of the 19th and 20th centuries, this forest has been dominated by *Quercus alba* L. (white oak), *Liriodendron tulipifera* L. (tulip-poplar), *Quercus velutina* Lam. (black oak), *Quercus prinus* L. (chestnut oak), *Carya* spp. (hickories), *Nyssa sylvatia* Marsh. (blackgum), *Quercus rubra* L. (northern red oak) and *Robinia pseudoacacia* L. (black locust) (Braun, 1950). The species composition above 1000 m is dominated by *Picea rubens* Sarg. (red spruce), *Acer saccharum* Marsh. (sugar maple), *Fagus grandifolia* Ehrh. (American beech), *Tilia americana* L. (American basswood), and *Betula alleghaniensis* Britton (yellow birch).

Historically, the average annual productivity of these second and third growth forests was around 2 $m^3\ ha^{-1}$ on poor sites, and over 7 $m^3\ ha^{-1}$ on excellent sites and where management improves growth rate (Hicks, 1998). Some of the earliest growth data for oaks were gathered in upland even-aged stands in West Virginia before the widespread effects of chestnut blight and industrial pollutants influenced forest composition and growth. These measurements were taken mostly in the 1920s and 1930s on second-growth sprout stands across a wide range of site qualities in fully stocked stands (Schnur, 1937). Periodic mean annual volume increment (PMAVI) ranged from 1.8 to 2.4 $m^3\ ha^{-1}\ yr^{-1}$on poor and fair sites, 3.0 to 3.6 $m^3\ ha^{-1}\ yr^{-1}$ on average to good sites, and over 4.3 $m^3\ ha^{-1}\ yr^{-1}$ on rich sites (Schnur, 1937). These growth rates were expected to plateau at age 50 and then remain constant up to age 100. Stand disturbances, such as management practices, can influence and increase average annual growth rate. For example, growth rates 5 yrs after thinning of 65-yr-old

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hardwood plots in West Virginia were greater than 5 $m^3\ ha^{-1}\ yr^{-1}$ (Smith et al., 1994). Such documented growth rates provide a baseline against which current measurements can be compared.

The MNF is situated down-wind from sources of sulfate and nitrate pollutants. In 2007 measurements from various weather stations across the forest averaged wet SO_4^{2-}-S deposition around 8 kg ha^{-1}, wet NO_3-N deposition around 3 kg ha^{-1}, and deposition pH around 4.4 (National Atmospheric Deposition Program (NRSP-3), 2007). Therefore, when the Forest Management Plan was revised in 2006, the Forest Service set objectives to evaluate management actions "that have the potential to contribute to soil nutrient depletion," specifically evaluating "for the potential effects of depletion in relation to on-site AD conditions" (USDA Forest Service, 2006). Evidence for forest decline due, in part, to AD has been established for some species in some areas. Red spruce suffers from both direct effects of AD, such as nutrient leaching from needles, as well as indirect effects such as elevated Al levels in soils (Godbold et al., 1988; Schaberg et al., 1997). Similarly, sugar maple decline, most often cited in the non-glaciated regions of the Allegheny Plateau of Pennsylvania, is reportedly related to soil acidification as well as other site factors (Horsley et al., 2000; Bailey et al., 2005). Northern red oak decline in western Pennsylvania has been associated with more acidic sites, suggesting that nutrient deficiency and Al toxicity may be stressing this species as well (Demchik and Sharpe, 2000). Furthermore, harvesting practices can have varying effects on site acidification (Adams et al., 2000). Calcium removed through harvesting can range from around 200 kg ha^{-1} in a clearcut to almost 1000 kg ha^{-1} in multi-entry selective harvesting (Adams et al., 2000).

Given the concern of forest managers over the potential deleterious effects of AD, our objectives were to: (1) determine if there was any correlative connection between less-than-expected growth rates and AD on the MNF and (2) if growth was less than expected, determine the relationships with key soil indicators related to acidification. We hypothesized that mortality of acid-sensitive species would be higher and that PMAVI would be less than expected during the interval 1989–2000 due to chronic input of AD. We predicted that pH, Ca/Al molar ratio, effective base saturation, NO_3-N/NH_4-N, and sum of bases could serve as indicators of forest change and less-than-expected growth.

2. Methods

2.1. Site description

We used Forest Inventory and Analysis (FIA) plots to gather data along the range of site conditions of the MNF. The FIA program is a national monitoring network, with plots located across the country on all land usages (i.e. public, non-governmental, corporate, individual, Native American) (USDA Forest Service, 2007). Each plot is re-sampled every 5 yrs, so that within each state 20% of the plots are measured each year. Ground-plot measurements are taken over three 0.017 ha plots arranged around another 0.017 ha center-plot. Data collected include tree diameter at breast height, total height, bole height, species, tree class, and any visible damage.

2.2. Stand inventory

FIA data for West Virginia cycles 4 and 5 were downloaded from the Forest Service FIA DataMart webpage (available online at http://fiatools.fs.fed.us/fiadb-downloads/fiadb3.html [verified May 21, 2008]). The "TREE" data table was used for stand composition and productivity inventories. The FIA plot locations listed in the public data are only accurate to 1.6 km. Therefore, actual plot locations were obtained from FIA National Spatial Data Services of the Northern Research Station.

Stand measurements were grouped by species to compare changes in composition between 1989 and 2000. Basal area, PMAVI, and number of individuals were allocated among northern red oak, sugar maple, *Acer rubra* L. (red maple), hickories, *Betula* spp. (birches), American beech, tulip-poplar, red spruce, other oaks, other hardwoods and other conifers categories. These species groups were chosen in particular because of their hypothesized sensitivity to AD and their value as wildlife and timber species (Hicks, 1998). Mortality was calculated using total number of dead individuals on each plot summed across all the FIA plots on the MNF. For sites where the species did not exist no value was assigned. Dead trees of a given species as a proportion of all dead trees across all species was calculated as follows using northern red oak as an example:

$$\frac{\sum \text{dead Northen red oak individuals}}{\sum \text{dead individuals on the FIA plots}} \times 100 \qquad (1)$$

Dead trees as a proportion of all live and dead trees of a given species was calculated as follows using northern red oak as an example:

$$\frac{\sum \text{dead Northen red oak individuals}}{\sum \text{Northen red oak individuals on the FIA plots}} \times 100 \qquad (2)$$

Species turnover rate (ST) was calculated as a metric of compositional changes between two measurement periods. Values closer to 100% indicate more changes and values closer to 0% indicate smaller or no changes in species composition at each location. ST was calculated using the following equation (Holland, 1978):

$$\text{ST} = 100 \times \frac{\text{Sum of number of species unique to the first} + \text{unique to second samples}}{\text{Total number of species found in first} + \text{second samples}} \qquad (3)$$

For each species, percent dead of species was calculated as the number of trees of each species that were standing dead divided by the total number of standing trees of that species. Across all the FIA sites on the MNF, PMAVI from 1989 to 2000 was determined using average annual growth values calculated in cubic meters per hectare per year ($m^3\ ha^{-1}\ yr^{-1}$) by FIA for each individual tree.

In West Virginia, FIA growth is calculated using the following equations (Scott, 1981):

$$\text{volume} = b_n + b_n D^{bn} + b_n D^{bn} H^{bn} \qquad (4)$$

where b (n = 1–5) is a value estimated for each species, D is the diameter at breast height and H is bole length.

$$\text{average annual growth} = \frac{V_2 - V_1}{t_2 - t_1} \qquad (5)$$

where V is the volume (Scott, 1981) and t is the time (yr).

Due to changes in FIA plot-arrangement between 1989 and 2000, subplot 1 contained the only re-measured trees between the two sampling periods. Therefore, average annual growth for each tree in subplot 1 was summed to calculate plot PMAVI. Estimates of stand basal area were calculated using individual tree basal area and summing all trees on the plot. Stands were considered adequately stocked if basal area was greater than 16 $m^2\ ha^{-1}$ and less than 46 $m^2\ ha^{-1}$ (Roach and Gingrich, 1968).

Outlying trees were removed from the FIA data set. Outliers had diameters above 45.7 cm, which was larger than the third quartile of the diameter data by over 1.5 times the interquartile range. These trees (95 of 1498) were anomalously large (remnant "wolf" trees from the previous cutting cycle) and did not represent the population of the average stands on the MNF.

2.3. Field procedures

Stand data and soil samples were collected for 30 representative FIA plots across the MNF. Average stand age and site index were calculated using cores from three dominant or codominant trees adjacent to FIA plots. Height was sampled to the nearest 0.33 m using a reloscope. Increment cores were taken at 0.3 m above ground level. A total of 90 trees were sampled, of which 46% were northern red oak, 37% were *Prunus serotina* Ehrh. (black cherry), 9% were *Quercus coccinea* Muenchh. (scarlet oak), 5% were chestnut oak, and 3% were white oak. Site index was calculated for each oak species and converted to Northern red oak SI using equations from Hicks (1998). For black cherry stands, Northern red oak SI was estimated using height and diameter at breast height (Lamson, 1987). Average stand age was calculated by counting the number of early-wood rings on each core. Average ages ranged from 31 yrs old to 94 yrs old. Stands in the central hardwoods region are expected to aggrade until age 170 (Hicks, 1998). All stand data were collected in November and December of 2007.

Soils were sampled by digging one narrow soil pit (to 1 m or bedrock) adjacent to each FIA site to determine depth of the master horizons. Representative samples from the A and B master horizons (hereafter referred to as surface and subsurface soils) from each pit as well as from sub-samples at azimuths of 60°, 180°, and 300° from the center FIA plot were sampled between July 2006 and August 2007. For all soil samples an effort was made to avoid areas that appeared disturbed or too close to trees. Soil bulk density was also sampled at these locations using a soil core sampler (approximately 100 cm^3) where possible; however, when rock fragment content impeded the core sampler, density was estimated by excavation (Page-Dumroese et al., 1999). All samples used for soil chemical analysis were air-dried, sieved through 2-mm mesh and stored at room temperature until analysis.

2.4. Laboratory procedures

Criteria for judging soil chemical change due to AD were soil acidity, soil fertility, potential toxicity level, N-saturation, and acid neutralization potential. We analyzed for hypothesized indicators within each of these criteria: pH and exchangeable acidity are indicators of soil acidity, effective base saturation (EBS) is an indicator of soil fertility, Ca/Al molar ratio is an indicator of soil toxicity level, NO_3-N/NH_4-N ratio and C/N ratio are indicators of N-saturation, and sum of bases is an indicator of soil neutralization potential related to cation exchange. Soil $pH_{(w)}$, total cations, effective cation exchange capacity, extractable nutrients, inorganic nitrate and ammonium were determined using standard methods (Bray and Kurtz, 1945; Amacher et al., 1990; Mulvaney, 1996; Sims, 1996; Thomas, 1996). Soil exchangeable cations were measured using 1N NH_4Cl. Strontium chloride (0.01 M $SrCl_2$) was used to determine Ca/Al molar ratio (Joslin and Wolfe, 1989). The Sr-method has been used in the past because soil minerals have a greater selectivity for Sr than for monovalent cations, it is a quick one-step process, and it is considered to be an analytical surrogate for soil solution Ca/Al ratio (Edmeades and Clinton, 1981). For each of these procedures, filtrate was refrigerated at 4 °C until elemental concentrations were determined using an inductively coupled plasma spectrometer (ICP) (Vista-MIX CCD Simultaneous ICP, Varian, Walnut Creek, CA).

Total carbon and nitrogen values were determined using a C/N analyzer (Vario MAX CNS analyzer, Elementar, Hanau, Germany). Exchangeable acidity was determined by extraction with 1N KCl (Bertsch and Bloom, 1996). Filtrate was then titrated with 0.01N NaOH on a Radiometer Copenhagen auto-titrator using an ABU901 Autoburette, TIM900 Titration Manager.

All soil values were averaged for the three sub-samples for each master horizon. Total profile values were calculated using horizon depths and bulk densities.

2.5. Data analysis

Stand and soil properties were correlated with PMAVI and considered significant at $p \leq 0.1$. Data were evaluated to confirm the use of parametric methods, and non-linear relationships with PMAVI were investigated and transformed for use in linear regression. All stand and soil factors that were significantly correlated with PMAVI, as well as those hypothesized to influence growth were included as potential variables in the model. The variable screening process identified multicolinearity and redundancy and retained the independent and significant correlations. From the remaining soil factors, only those significant enough to enter or remain during selection processes (forwards, backwards, stepwise, max R^2) were included in the model. Using the filtered data set, a model was chosen based on maximizing adjusted R^2, significance of the model, and biological significance.

2.6. Other factors influencing stand volume

To evaluate potential effects of AD on forest growth other sources of forest change were considered and ruled out as the predominant influencing factors. There are forest pathogens on the MNF; however, occasional defoliation would not significantly affect average growth rate over a decade. Also, most stands have coped with many of these factors for thousands of years and overall growth would still be around average historical levels (Johnson et al., 1992). Wind and ice damage, which is common across the Appalachian mountains, and which occur randomly across the forest, could be detected by large decreases in basal area between measurements. Only 6 FIA plots lost more than 2 $m^2\ ha^{-1}$ between the measurements, and none of these were used for the intensive soil-site study.

3. Results

3.1. Stand inventory

On FIA plots, elevation ranged from 473 to 1386 m, slope ranged from 1 to 80%, and the plots covered all aspects. FIA plots were located in the Ridge and Valley and Allegheny Mountain provinces, where they received between 76 and 152 cm of pH 4.4 precipitation per year (USDA Forest Service, 2006; National Atmospheric Deposition Program (NRSP-3), 2007). The plots used for soil analysis were representative of all FIA plots on the MNF, covering the entire range of elevations, slopes, aspects, and geographic provinces. Stocking estimates show that 29% of all plots and 10% of the soil-sampling plots were under stocked, 66% of all plots and 83% of soil-sampling plots were adequately stocked, and 5% of all plots and 7% of soil-sampling plots were over stocked. PMAVI ranged from −9.5 to 11.8 $m^3\ ha^{-1}\ yr^{-1}$ on all FIA plots, and −9.5 to 6.2 $m^3\ ha^{-1}\ yr^{-1}$ on the soil-sampling plots.

3.2. Species composition

Across all FIA plots on the MNF in 1989 basal area of oaks (27%), birches (12%), red maple (11%) and other hardwoods (15%) dominated the stands (Table 1). In 2000 basal area of oaks (23%), red maple (14%), birches (12%), and other hardwoods (17%) predominantly occupied FIA sites. In 2000 across all species, the birch (20%) and other hardwoods (17%) and tulip-poplar (14%)

Table 1
Average stocking, diameter and composition in 1989 across all Forest Inventory and Analysis plots in the Monongahela and the difference from 1989 to 2000.

	Basal area (%)		Avg. dia (cm)		Percent of individuals		Dead trees (% across all species)[a]		Dead trees (% within species)[a]	
	1989	2000	1989	2000	1989	2000	1989	2000	1989	2000
Northern red oak	10.4	9.5	30.5	28.8	8.2	4.7	6.9	3.4	4.8	10.4
Other oaks	16.8	13.5	25.1	22.2	15.7	11.2	7.4	9.7	4.4	12.2
Sugar maple	6.8	6.5	20.8	18.9	7.1	7.5	6.9	3.4	5.6	6.3
Red maple	10.7	14.0	22.7	21.3	12.8	15.4	6.4	6.3	3.1	5.7
Hickories	2.5	1.4	25.4	21.2	2.8	1.9	4.5	4.4	9.1	33.3
Birches	11.5	11.5	21.2	20.8	13.4	14.3	24.3	20.0	11.8	19.2
Am. beech	8.5	6.9	24.8	18.8	8.7	8.9	5.0	9.2	3.6	14.4
Tulip-poplar	5.6	5.6	32.8	32.4	4.3	2.2	6.9	14.6	9.3	9.1
Other hardwoods	14.5	17.4	25.2	21.0	15	19.2	13.9	17.4	–	–
Red spruce	5.2	6.6	28.3	21.2	4.7	5.7	9.4	6.3	11.9	15.5
Other conifers	7.5	7.1	26.0	26.2	7.3	9.0	8.4	5.3	–	–

[a] Dead trees (% across all species): percent of total dead trees (number dead of a given species divided by total number dead of all species times 100); dead trees (% within species): percent dead (number dead of a given species divided by the total number of live and dead trees of that species times 100). See Section 2 for equations.

categories had the highest amount of dead individual trees. Within species over 9% of the birches, red spruce, hickories and tulip-poplar were standing-dead. Across all species the birch and other hardwoods categories had the highest percentage of dead trees. The percentage of dead trees within species generally increased from 1989 to 2000.

From 1989 to 2000 the percent of basal area of red maple increased by 3.3% across FIA sites and basal area of Northern red oak, other oaks, sugar maple, hickories, American beech, and other conifers decreased. The percentage of individual red oak, other oaks, hickories, and tulip-poplar also decreased. In 2000 over 20% of standing oaks were dead, over 30% of standing hickories were dead, over 15% of standing red spruce and almost 20% of standing birches were dead.

Due to variability across the 30 sites where soils were sampled, sample sizes for species comparisons were small ($n = 10$ plots with red oak, $n = 13$ plots with sugar maple, $n = 19$ plots with red maple, and $n = 4$ plots with hickories); however, these data allowed us to examine general trends between growth of some species and soil characteristics. When comparing species composition with soil values we found that hickories were the only species to significantly decrease on sites with surface base saturation below 20% and surface effective base saturation below 2.5%. Percent dead Northern red oak were highest on sites with surface Al concentrations above 43 $\text{cmol}_{(+)}\,\text{kg}^{-1}$ soil. ST was not statistically related to soil factors; however, there were more unique species in 2000 on sites with subsurface base saturation above 10%.

To further investigate trends in the relationship between species and stand changes with key indicators of soil acidity we grouped sites into classes that showed no net growth (less than 0 $m^3\,ha^{-1}\,yr^{-1}$of growth), grew at less-than-expected rates (0–3 $m^3\,ha^{-1}\,yr^{-1}$) and grew at historically average rates (over 3 $m^3\,ha^{-1}\,yr^{-1}$). Average ST and mortality were highest on stands with no net growth and were lowest on stands growing at historically average rates (Table 2). There was a slight trend in soil pH, an indicator of acidity, which was lowest on stands with higher ST and highest on stands with lower values. Calcium/aluminum ratio and sum of bases in the subsurface horizon were highest on stands with lower ST values. Surface horizon EBS was similar across all three growth-groups.

3.3. Periodic mean annual volume increment 1989–2000

PMAVI for all FIA plots between 1989 and 2000 ranged from −9.5 to 11.8 $m^3\,ha^{-1}\,yr^{-1}$. On 30 sampled plots, PMAVI was negatively correlated with basal area in 2000 ($p \leq 0.1$) (Fig. 1a), was non-linearly and negatively correlated with age ($p \leq 0.05$) (Fig. 1b) and was not correlated with site index (Fig. 1c). Basal area,

Table 2
Forest stand and soil properties arranged in PMAVI classes for intensively-sampled FIA plots.

	Less than 0 $m^3\,ha^{-1}\,yr^{-1}$	Between 0 and 3 $m^3\,ha^{-1}\,yr^{-1}$	Over 3 $m^3\,ha^{-1}\,yr^{-1}$
Volume increment range ($m^3\,ha^{-1}\,yr^{-1}$)	−9.5 to −0.04	0.03 to 2.9	3.0 to 6.2
Mortality (% of individuals that are dead)	10–30 Average: 18.5	0–50 Average: 17	0–35.7 Average: 10.7
Species turnover values (%)	9–56 Average: 35	7–55 Average: 29	0–45 Average: 22
Basal area in 2000 ($m^2\,ha^{-1}$)	16.7–57.0 Average: 31.8	12.6–37.3 Average: 23.8	12.4–43.2 Average: 27.0
Surface soil			
Average pH	3.7	3.8	3.9
Average Ca/Al	1.4	2.3	3.6
Average EBS (%)	26	27	26
Average sum of bases ($\text{mol}_{(+)}\,ha^{-1}$)	14,732	8051	19,099
Average NO_3-N/NH_4-N	0.86	0.95	0.68
Subsurface soil			
Average pH	4.1	4.3	4.3
Average Ca/Al	0.31	0.35	0.55
Average EBS (%)	13	10	10
Average sum of bases ($\text{mol}_{(+)}\,ha^{-1}$)	31,999	36,661	43,322
Average NO_3-N/NH_4-N	0.56	0.38	0.55

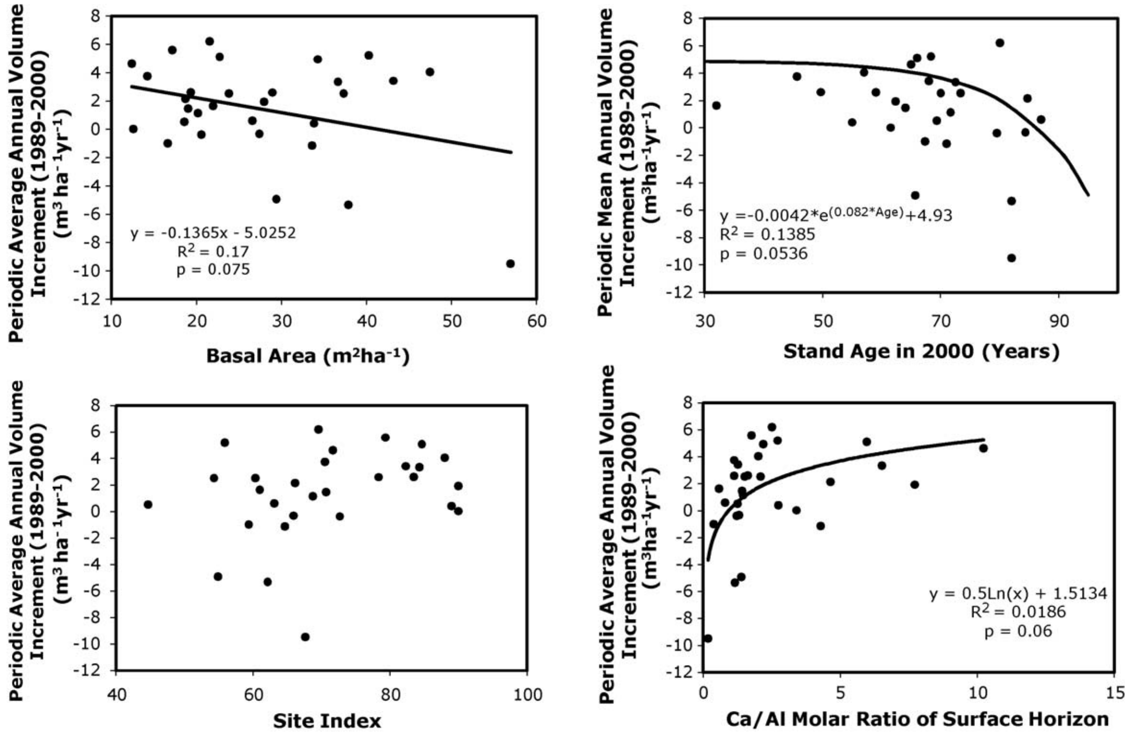

Fig. 1. Periodic mean annual volume increment as a function of (a) stand basal area in 2000, (b) stand age in 2000, (c) site index and (d) Ca/Al molar ratio, a key indicator of soil acidification, on FIA plots.

site index, and stand age were not correlated among one another. On the FIA sites, 29% of the plots had a negative PMAVI, 40% had PMAVI from 0 to 2.9 $m^3\,ha^{-1}\,yr^{-1}$, and 31% had PMAVI over 3 $m^3\,ha^{-1}\,yr^{-1}$. Based on historical data an average PMAVI of 3 $m^3\,ha^{-1}\,yr^{-1}$ can be expected on sites of average to excellent quality in West Virginia (Schnur, 1937).

3.4. Soil indicators

PMAVI was correlated with soil chemical properties considered to be potential acidity indicators (Table 3). Effective base saturation ranged from 5 to 77% and 2 to 28% in the surface and subsurface horizons respectively, and was positively correlated ($p \leq 0.1$) with PMAVI in the surface horizon. In the surface horizon, Ca concentration was also positively correlated ($p \leq 0.05$) with PMAVI. Mehlich I Fe concentration was negatively correlated ($p \leq 0.1$) with PMAVI. Calcium/aluminum molar ratios ranged from 0.17 to 10.2 in the surface horizon, and were positively correlated ($p \leq 0.01$) with PMAVI (Table 3). In the subsurface horizon Ca/Al ratio ranged from 0.09 to 2.2, but was not significantly correlated with PMAVI.

The C/N values ranged from 7.3 to 28.9 for the surface horizon and 6.2 to 34.7 for the subsurface horizon. These values were not significantly correlated with PMAVI. The C/N ratios on 77 and 87% of plots were below 20 in the surface horizon and subsurface horizons, respectively. Values for surface and subsurface soil pH ranged from 3.3 to 4.9 and 3.7 to 4.7, respectively. These pH values were positively correlated ($p \leq 0.05$) with PMAVI for the subsurface horizon. Exchangeable acidity was not significantly correlated with PMAVI. The ratio of KCl-extractable NO_3-N/NH_4-N was not correlated with PMAVI for either the surface or subsurface horizons.

3.5. Modeling growth

We modeled PMAVI as a function of stand and soil factors, to further understand their combined effects on forest growth. After the variable screening process, the remaining potential soil factors were C/N ratio, pH, exchangeable acidity, and NO_3-N/NH_4-N ratio of both horizons, Fe, P, Ca concentration and Ca/Al ratio of the surface horizon, and Al, EBS and effective cation exchange capacity of the subsurface horizon. Due to the significant positive relationship between site index and the Ca/Al molar ratio of the surface horizon (Fig. 2), and the fact that PMAVI was not correlated with site index, the only stand factors used in the regression model were basal area and age. The first model iteration using all independent stand and soil factors was

$$\mathrm{PMAVI} = 1.2 - 1.8\left(\ln\frac{\mathrm{Ca}}{\mathrm{Al}_{\mathrm{surface}}}\right) + 0.14(-0.004\mathrm{e}^{0.09(\mathrm{Age})} + 4.9) + 0.007\mathrm{Ca}_{\mathrm{surface}} - 0.06\mathrm{Ex.\,Acidity}_{\mathrm{surface}} + 0.3\mathrm{C/N}_{\mathrm{subsurface}} - 0.07BA \quad (6)$$

The total R^2 for this model was 0.42, the adjusted R^2 was 0.26 and the p-value was 0.044. To further improve model significance and simplicity we created a second iteration model:

$$\mathrm{PMAVI} = 0.6 + 2.2\left(\ln\frac{\mathrm{Ca}}{\mathrm{Al}_{\mathrm{surface}}}\right) + 0.18(-0.004\mathrm{e}^{0.09(\mathrm{Age})} + 4.9) - 0.73(\mathrm{NO_3\text{-}N/NH_4\text{-}N}_{\mathrm{subsurface}}) \quad (7)$$

The factors in the final model were Ca/Al ratio of the surface horizon, stand age, and NO_3-N/NH_4-N ratio of the subsurface horizon. The model R^2 was 0.41, adjusted R^2 was 0.33 and the p-value was 0.005. The coefficients and partial R^2 values for the soil variables are shown in Table 4. After using several regression analysis techniques including stepwise, forward, backward, max R^2, this model consistently provided the highest level of significance and the highest R^2 values. The Ca/Al molar ratio of the surface horizon alone accounted for over 30% of the variation in PMAVI (Table 4). The single factor functional relationship between PMAVI and Ca/Al molar ratio is shown in Fig. 1d. Other soil factors not included in the model were individually correlated

Table 3
Mean, min–max, and standard error of soil sampling from 30 FIA study plots.

Soil factor, level of significance	Surface horizon	Subsurface horizon
Acidity		
pH**	3.8 (3.3–4.9, 0.07)	4.2 (3.7–4.7, 0.05)
Exchangeable acidity (cmol$_{(+)}$ kg soil^{-1})	6.4 (1.2–19.5, 0.8)	5.5 (1.3–12.3, 0.5)
Toxicity		
Ca/Al ratio***	2.6 (0.2–10.2, 0.4)	0.4 (0.09–2.2, 0.08)
Ca_{SrCl_2} (cmol$_{(+)}$ kg soil^{-1})**	0.6 (0.1–2.2, 0.08)	0.1 (0.02–1.2, 0.04)
Al_{SrCl_2} (cmol$_{(+)}$ kg soil^{-1})	0.3 (0.09–0.8, 0.04)	0.3 (0.05–0.7, 0.03)
Fertility		
Effective base saturation$_{NH_4Cl}$ (%)*	26 (4.8–77, 2.7)	10.9 (2.2–28.5, 1.2)
$ECEC_{NH_4Cl}$ (cmol$_{(+)}$ kg soil^{-1})	8.4 (2.3–22, 0.8)	6.1 (1.5–12.9, 0.53)
Al_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})**	46.2 (11.8–103, 3.9)	43.1 (15.2–85.7, 3.4)
Mn_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})	0.5 (0.0–1.4, 0.08)	0.1 (0.0–1.1, 0.04)
Ca_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})**	1.5 (0.1–3.6, 0.2)	0.3 (0.05–2.2, 0.07)
K_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})	0.3 (0.08–0.5, 0.02)	0.1 (0.05–0.2, 0.008)
Mg_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})	0.04 (0.008–0.08, 0.003)	0.01 (0.004–0.09, 0.003)
Na_{NH_4Cl} (cmol$_{(+)}$ kg soil^{-1})	0.2 (0.07–0.4, 0.02)	0.2 (0.06–0.4, 0.01)
$Fe_{Mehlich}$ (mg kg soil^{-1})*	103 (22.3–251, 10.5)	72.8 (26.4–284, 10.8)
$P_{Mehlich}$ (mg kg soil^{-1})	6.4 (2–18, 0.8)	2.4 (2–14, 0.4)
N-saturation		
C/N ratio	17.4 (7.3–29.0, 1.0)	17.6 (6.2–34.7, 1.0)
Carbon (%)	3.7 (0.5–17.0, 0.6)	4.4 (0.6–19.1, 0.6)
Nitrogen (%)	0.2 (0.03–1.0, 0.04)	0.3 (0.03–1.0, 0.03)
NO_3-N/NH_4-N ratio	0.8 (0.008–3.5, 0.2)	0.5 (0.001–1.7, 0.1)
NO_3-N (mg kg soil^{-1})	12.7 (0.1–62.4, 2.7)	26.9 (0.02–112.3, 6.3)
NH_4-N (mg kg soil^{-1})	21.7 (4.9–122.7, 4.5)	55.9 (4.5–170.4, 8.9)
Neutralization		
Base saturation NH_4OAc (%)*	27.4 (8.3–73.1, 2.8)	15.0 (4.3–39.6, 1.8)
Sum of bases NH_4OAc (mol$_{(+)}$ ha^{-1})	13,219 (2603–41811, 2073)	37,636 (7763–98526, 3936)

There is no significant relationship for values without asterisk.
* $p \le 0.1$ (significance with periodic mean annual volume increment).
** $p \le 0.05$ (significance with periodic mean annual volume increment).
*** $p \le 0.01$ (significance with periodic mean annual volume increment).

with PMAVI and they could serve as acidity indicators; however, they did not account for additional independent variation in PMAVI in the multiple regression models, or they were covariate with other factors in the model. For example, EBS was highly correlated with Ca/Al ratio and C/N ratio was correlated with NO_3-N/NH_4-N.

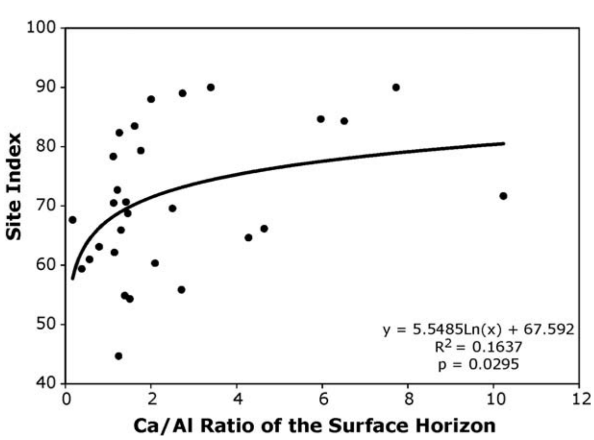

Fig. 2. Site Index as a function of surface Ca/Al molar ratio on FIA plots.

3.6. Acid neutralization potential

Soil acid neutralization and buffering mechanisms vary with soil properties such as base saturation, mineralogy, and texture as well as with pH (Bache, 1980). A generally accepted scheme for soil buffering begins with carbonate buffering, then moves to silicate buffering, followed by cation buffering, Al buffering, and ending with Fe buffering (Ulrich, 1980). The current soil pH across our plots on the MNF indicates that cation and Al buffering are the dominant acid neutralization processes. We estimated the acid neutralization potential (ANP_{CEC}) produced by base cation buffering. To do so, we multiplied the effective cation exchange capacity times effective base saturation of the total soil depth to a root-limiting layer.

Although this calculation does not include changes in CEC due to weathering, or the possibility of buffering from fragments larger than 2 mm, these calculations provide a comparative range of neutralization potential on the MNF. ANP_{CEC} ranged from 22 to 314 kmol charge ha^{-1}. Assuming 18 kg ha^{-1} yr^{-1} of SO_4^{2-} deposi-

Table 4
Site and soil factors in regression model predicting periodic mean annual volume increment on FIA plots.

Model: $0.60119 + 2.20299\ln(Ca/Al) + 0.17949(-0.00416e^{0.09(A)} + 4.9274) - 0.72899N$

Factor	Coefficient value	Standardized coefficient	Partial R^2	Total R^2
Ca/Al: Ca/Al molar ratio of the surface horizon	2.20299	0.53968	0.3270	0.3270
A: stand age	0.17949	0.27339	0.0703	0.3973
N: NO_3-N/NH_4-N ratio of the subsurface horizon	−0.72899	−0.09947	0.0096	0.4070

Model $p = 0.0051$; Adj-$R^2 = 0.3328$

tion, 12 kg ha^{-1} yr^{-1} of NO_3^- deposition, 2.5 kg ha^{-1} yr^{-1} of NH_4^+ deposition, 100% nitrification, 50% S retention, and 50% N retention (Adams et al., 1997; Aber et al., 2003) about 0.3 kmol of negative charge per hectare will leach through the forest soil each year. Therefore, based on this calculation, the least buffered sites will be depleted of ANP_{CEC} within 75 yrs.

4. Discussion

Significant changes in the forest occurred between 1989 and 2000. Basal area of Northern red oak, other oaks, sugar maple, beech, and hickories decreased from 1989 to 2000. Some of this decrease in basal area could be due to pathogens and diseases such as beech bark disease, which does occur on the MNF (Juergens, 2008, personal communication); however, AD may have contributed to site susceptibility to insect damage (Driscoll et al., 2001). The increase in dead hickories from 9.1 to 33.3% was especially striking. The dominance of oak individuals also decreased from 23.9 to 15.9%, indicating that these species may be negatively impacted by similar stress factors.

Our study of species changes among growth classes (less than 0 m^3 ha^{-1} yr^{-1}, 0–3 m^3 ha^{-1} yr^{-1}, and over 3 m^3 ha^{-1} yr^{-1}) showed general trends in relation to soil factors. Stands with no net growth (less than 0 m^3 ha^{-1} yr^{-1}) had the highest average percent of dead individuals, lowest average soil pH values in the surface and subsurface horizons, and the highest average species turnover rates. However, to better describe the statistical importance of the relationship between species changes and soil acidity a larger data set would be needed.

We did not predict the negative relationship between PMAVI and stand age, given the relatively young age of the stands. Yield of upland oaks has been positively correlated with age at least through 100 yrs (Schnur, 1937); our results indicate that tree growth is slowing prematurely. At these largely intermediate ages, stand dynamics such as stem exclusion may influence individual stem growth, but if stand dynamics were the main factor driving PMAVI on these fully stocked stands, then the overall average plot PMAVI would be both positive across the whole forest, and would be closer to average historical values of over 3 m^3 ha^{-1} yr^{-1}.

Basal area ranged from 12.4 to 57 m^2 ha^{-1}, and was weakly correlated with PMAVI. Several fully or overstocked stands decreased in volume by more than -4 m^3 ha^{-1} yr^{-1}. An unexpected finding was no relationship between PMAVI and site index. Normally one would expect aggrading stands to grow faster on better sites. A partial explanation is that two-thirds of the stands over age 65 were growing at rates less than expected (3 m^3 ha^{-1} yr^{-1}) regardless of site quality. Site index was positively correlated with Ca/Al molar ratio suggesting that site quality may be influenced by Ca depletion or Al toxicity. The significant positive correlation between PMAVI and the Ca/Al molar ratio, and the fact that the Ca/Al ratio is correlated with many other soil acidity indicators, supports this contention. Based on our analysis, the Ca/Al molar ratio of the surface horizon was the soil indicator most related to volume growth and was correlated with other stand and soil factors including: site index (+), Ca concentration (+), Mg/Al molar ratio (+), subsurface Ca/Al molar ratio (+), Fe concentration (−), C/N ratio of the surface horizon (−), and EBS of both horizons (+). The Ca/Al ratio accounted for the most variation in PMAVI in our multivariate modeling indicating that it is probably a good indicator for monitoring potential AD effects.

Effective base saturation below 20% indicates that Al will dominate soil exchange complexes and soil solution (Reuss, 1983). EBS of the surface horizon ranged from 5 to 77% and from 2 to 28% in the subsurface soil, suggesting that Al dominates the exchange sites on the soils of many FIA plots. In previous work MNF managers have considered sites where surface horizon base saturation was below 20% and Ca/Al ratio was below 1.0 to be at the highest risk for less-than-expected growth rates (Connolly et al., 2007). Of our 30 plots, four fit this risk criterion while 40% of the plots had base saturation values below 20% in the surface horizon but Ca/Al ratio values > 1.0.

By itself, NO_3-N/NH_4-N ratio was not significantly correlated with PMAVI; however, this factor was included in the final multivariate model of growth. High NO_3^--N levels are probably due to greater nitrification on sites receiving N input exceeding biological demand. The negative relationship between NO_3-N/NH_4-N ratio and PMAVI shows that stands with the highest NO_3^--N levels are growing at slower rates or not at all, meaning that N-saturation may be negatively influencing stand growth on the MNF. Furthermore, soil C/N ratio values below 20 can indicate N-saturation (Fenn et al., 1998). Carbon/nitrogen values ranged from 7.3 to 28.9 for the surface horizon and 6.2 to 34.7 for the subsurface horizon, with mean values of 17.4 and 17.6, respectively. The C/N ratio was below the N-saturation criterion for surface soils on 77% of plots and on 87% of plots for subsurface horizons. These data suggest that some, but not all, of these plots may be moving from stage 2 (fertilized) towards stage 3 of N-saturation, where excess N may become polluting and cause growth to be lower than expected (Aber et al., 1989).

There are some symptoms of N-fertilization on the MNF including sites where base saturation is above 20% and sites where productivity is at or above historical levels of PMAVI (Schnur, 1937). However, less-than-expected growth, changes in tree species composition, low base saturation and C/N ratios, and high Al concentrations are consistent with N-saturation and may suggest a problem on the forest. Phosphorus concentration by Mehlich I and Bray I extractions was not correlated with PMAVI. These stands have not reached the *P* limitations hypothesized to occur after Ca limitations have been exceeded as a result of base depletion and N-saturation (Adams, 1999).

Cation exchange-acid neutralization potential values and Fe concentration were positively correlated with PMAVI. Cation exchange is clearly an important buffering component, but these correlations suggest that Al buffering is also contributing to acid neutralization, and, on the most acidic sites, Fe buffering is occurring.

We hypothesized that surface and subsurface soil chemistry values would be equally indicative of productivity. While more soil factors of the surface horizon were correlated with PMAVI, our final productivity model included Ca/Al of the surface horizon, NO_3-N/NH_4-N ratio of the subsurface horizon, as well as stand age. Final model selection was based on maximizing adjusted R^2, significance of the model, and biological significance. The final model included a factor from both the surface and subsurface horizons, which supports the hypothesis that sampling both horizons is important in understanding soil chemical status and its relationship with forest growth. We also hypothesized that soil profile elemental content would add to our interpretations of soil effects on growth. However, relationships between PMAVI and site nutrient levels based on content (kg ha^{-1}) were no different from those based on concentration. Nonetheless, nutrient content on a whole-soil basis varies widely across the forest largely as a function of mineralogy and soil depth, which may have management implications relative to practices affecting nutrient extraction.

Despite the significant correlations between PMAVI and soil acidity indicators, direct cause and effect attribution to AD of less-than-expected growth, species turnover rate, and mortality cannot be made due to the lack of an unaffected control forest and our incomplete knowledge of other causative mechanisms. In studies concerning red spruce decline with similar experimental limitations Johnson et al. (1992) concluded, that AD increased red spruce sensitivity to winter injury, Al mobilization, and cation loss. They came to this conclusion by showing (1) temporal and spatial consistency of symptoms and suspected agents, (2) a plausible mechanism for the symptoms, or plausible linked processes leading to the symptoms, and (3) that the symptoms could be replicated in controlled environments. Our correlations between PMAVI and AD indicators are compelling, but this study did not meet the third criterion of this epidemiological approach, which requires a replicated response under controlled conditions in order to definitively associate forest productivity and AD-induced acidity gradients. Using a replicated experiment to fertilize slow-growing stands on acidic soils with Ca and other base cation nutrients to test for a growth response would be a next step to further test the AD hypothesis in the MNF.

5. Conclusions

Low PMAVI values from 1989 to 2000 on some FIA plots relative to historical average growth rates raise concern about sustainable growth on some parts of the MNF. Less than historical average growth, altered species composition, and trends in key indicators of soil acidity support the hypothesis that productivity measurements may be useful for AD-related monitoring across the MNF. Additionally, AD may be playing a role within the context of other environmental factors in affecting forest productivity and sustainability. The relationships between growth data and soil chemistry show that precautionary monitoring of soil acidity indicators is warranted, and that forest management that mitigates or decreases further acidification may be needed.

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