A Regional-Scale Survey and Analysis of Forest Growth and Mortality as Affected by Site and Stand Factors and Acidic Deposition

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ABSTRACT. Regression analyses were used to identify factors most closely related to species growth and mortality on continuous forest survey plots in Pennsylvania. In 1985, 200 plots with two prior measurements (in the 1960s and 1970s) were selected and measured for a third time to determine periodic forest growth and mortality rates. Growth and mortality were analyzed for temporal change and for relationship to site, stand, defoliation, and climatic factors and to wet atmospheric deposition. While basal area growth increased over the two intersurvey periods, growth rates declined and mortality rates increased from the first to the second intersurvey period. Growth and mortality patterns were most frequently related to stocking, defoliation by insects, and drought. Neither sulfate nor nitrate deposition for the years 1982–1985 was determined to be a major influence on tree growth or mortality. FOR. SCI. 40(3):543–557.

ADDITIONAL KEY WORDS. Forest survey, sulfate and nitrate deposition, basal area increment.

ATMOSPHERIC DEPOSITION HAS BEEN WIDELY SUGGESTED to be associated with forest decline and mortality, especially in the popular press (see comments in Skelly 1992). While the final report of the National Acid Precipitation Assessment Program concluded that ". . . there is no evidence of a general decline of forests due to acidic deposition" (Barnard et al. 1990), concerns about local episodes of forest decline continue.

Based on data from one of the most spatially dense atmospheric monitoring networks in the United States, Pennsylvania receives the most acidic precipitation, containing some of the highest concentrations of sulfate and nitrate ions, in the United States and Canada (Lynch 1990). The precipitation is most acidic in western Pennsylvania and becomes less acidic west-to-east. Wet sulfate deposition follows the same pattern, with highest rates in the western part of the state ($\geq$37.5 kg/ha/yr) and decreasing rates to the east and north. If dry deposition is considered, total sulfate deposition may approach 50 kg/ha/yr (Lynch and Corbett 1989). Nitrate deposition exhibits less spatial variability than sulfate deposition, with only minor decreases from west to east (Lynch 1990). Dry NO_x deposition varies considerably but has been estimated to be equivalent to wet nitrate deposition (Fisher and Oppenheimer 1991).

The objective of the study was to identify major temporal or spatial changes in growth or mortality that may be attributed to the high levels of atmospheric deposition occurring in western and central Pennsylvania. A preliminary summary of this study was reported previously (Brooks 1989). This work was completed prior to the publication by Schreuder and Thomas (1991) discussing the use of extensive forest survey data for establishing cause-effect. It was not an objective of this study to assess cause-effect, but rather to explore relationships between growth or mortality and deposition estimates over a large area with a significant "acid rain" problem. This paper reports tests of the hypotheses that there were no significant relationships between sulfate or nitrate deposition and tree growth or mortality, after accounting for the effects of site, stand, defoliation, and climatic influences.

METHODS

Permanent forest-survey plots of the USDA Forest Service Forest Inventory and Analysis (FIA) and Allegheny National Forest and of the Pennsylvania Bureau of Forestry in central and western Pennsylvania were screened to identify those plots constituting a cohort: (1) with two prior survey measurements, (2) free from catastrophic fire, windthrow, or human-caused disturbance at each survey, and (3) classified as either oak-hickory or northern hardwoods forest-type groups. Candidate plots were mapped, and 200 were systematically selected using map-grid cells.

The forest survey plots were established in the 1960s and remeasured in the 1970s. The plots were mostly (n = 143) fixed-radius, 0.08 ha samples, with the balance (n = 57) being 10 point clusters of variable-radius points. In 1985, each plot was measured a third time. The average period between the first and second survey was 12.9 yr, and 8.7 yr between the second and third survey.

At each plot, the diameter and condition of all sample trees 5.0 in. (12.7 cm) and larger in diameter at breast height were measured. Copies of tally records from the prior survey of the plot were checked in the field to ensure all previously measured trees were remeasured or otherwise accounted for. Data were collected on topographic and physiographic location of the plot and on soil structure. Soil horizons 0, A, and B were sampled and later analyzed for pH, exchangeable acidity, aluminum, and base cations, total carbon and sulfur, and double-acid extractable elements by methods recommended by Robarge and Fernandez (1986). The data were collected according to Northeastern FIA standards and definitions, and crews were trained and evaluated by FIA permanent staff. A subsample of plots were remeasured to check for adherence to data quality standards.

Secondary, off-plot data were compiled to characterize plot-level climatic, defoliation, and atmospheric deposition histories. Monthly climate data, described using Palmer's Hydrological Drought Index, were obtained from the National Climatic Data Center (Karl et al. 1983). The authors state that the Index more closely reflects soil moisture than Palmer's Drought Severity Index and that it responds more slowly to weather changes because it is more closely tied to water storage. Continuous monthly Index values were placed into one of 11 discrete drought classes, from extreme moisture to extreme drought (Karl et al. 1983). For each climate division in Pennsylvania, a two-period climate history was developed, defined as the number of months in each drought class over the periods

1963–1972 and 1973–1982. Each forest survey plot located in a climate division was assigned the climate history of the division.

An insect defoliation history of each plot from the mid-1960s to 1985 was obtained using pest survey data from the Pennsylvania Bureau of Forestry. The Bureau conducts annual aerial surveys, recording defoliation occurrence and intensity class (i.e., light, moderate, heavy) on topographic base maps. Each survey plot location was identified on the appropriate map, and the annual occurrence and intensity class of defoliation of the plot was recorded. No data existed for quantifying the effects of nondefoliating insect and pathogen factors.

Atmospheric deposition data were provided by the Institute for Research on Land and Water Resources, The Pennsylvania State University. Annual reports describe the deposition collection and analysis procedures (e.g., Lynch et al. 1986). For the years 1982 to 1985, quarterly estimates of sulfate, nitrate, and hydrogen ion deposition were made for each plot using a multiquadratic equations algorithm (Grimm and Lynch 1991). No data exist to make deposition estimates prior to 1982.

The various primary and second sources of information were integrated into tree- and plot-level data files. Analyses were at the plot-level of resolution, as the plots were the independent samples. Analyses were completed for all tree species combined and for the 12 individual species for which more than 100 trees were sampled at each occasion. In all analyses, growth and mortality were expressed as average annual increments in basal area over the periods between surveys. Schreuder and Thomas (1991) suggest that volume may be a better gauge of growth than basal area, as it also accounts for changes in height growth. I elected to use basal area increment, because the remeasurement of height of full-foliage deciduous trees over long time intervals (10+ yr) is susceptible to considerable measurement error.

For all procedures, significance is defined as having the probability of the test statistic ≤ 0.05. Temporal changes in growth or mortality were tested using a paired t-test. Growth (or mortality) over the first period, from the initial plot survey (1960s) to the first remeasurement (1970s), was compared to growth (or mortality) over the period from the first remeasurement to the second (1985).

Growth (or mortality) patterns were analyzed for relationships to sulfate and nitrate deposition after removing variation associated with a standard set of site, stand, defoliation, and climate variables. Multicollinearity among all independent variables was first checked by exploring correlation-coefficient matrices. One of each significantly correlated variable pair was deleted based on the strength of correlations to the dependent variables. The standard suite of independent variables was selected from those remaining after correcting for multicollinearity by (1) examining correlations between dependent and independent variables and selecting those independent variables that were most consistently correlated with growth or mortality and (2) considering the generally accepted factors influencing growth and mortality (e.g., Spurr and Barnes 1980). The final set of independent variables (defined in Table 1) contains measures or indicators of stocking, defoliation, drought, soil factors, and atmospheric deposition.

A two-step regression process was used to analyze the influence of deposition on growth or mortality. First, growth (or mortality) was regressed on the standard suite of independent variables. A simple linear model was used, rather than a more complex model (e.g., Schreuder and Thomas 1991, p. 1508), because

TABLE 1.

Definitions of variables used in regression analyses of periodic growth and mortality.

Variable	Definition/explanation
Species BA	Species basal area at the beginning of the growth period
Competing BA	Basal area of all other species at the beginning of the growth period (surrogate for stand density)
Diameter	Quadratic mean stand diameter at the beginning of the growth period
Drought	Number of drought months during growth period
Defoliation	Dummy variable; 0 if no record of defoliation during growth period, 1 if otherwise
A base cations	Total base cations in the A-horizon, in meq/100g
Soil depth	Dummy variable; 0 if soil deeper than 50 cm, 1 if otherwise
Mottles	Dummy variable; 0 if no mottling recorded, 1 if otherwise
Terrain position	Combination of terrain position, slope, and aspect; 0 if flat, otherwise (percent slope * (aspect − 225))
Sulfate deposition	Average annual sulfate deposition, estimated for the survey plot, in kg/ha/yr, 1982–1985
Nitrate deposition	Average annual nitrate deposition, estimated for the survey plot, in kg/ha/yr, 1982–1985

several of the independent variables were coarse plot-level estimates. Models containing complex mathematics were considered inappropriate given the resolution of the independent variables.

Positive residuals from the first regression models were interpreted to mean that growth (or mortality) was underestimated by the standard variable set, while negative residuals meant that growth (or mortality) was overestimated. Underestimation implies the existence of an unaccounted growth- or mortality-stimulating influence, while overestimation implies the existence of an unaccounted growth- or mortality-suppressing influence.

Residuals from the first regressions were, in turn, regressed on average annual sulfate and nitrate deposition estimates to determine the relationship between deposition and that portion of growth (or mortality) not explained by site, stand, defoliation, and climatic influences. In the analysis of residual growth, a positive regression coefficient implies that deposition had a stimulatory effect; a negative coefficient implies a suppressive effect. In the analysis of residual mortality, a positive regression coefficient implies greater mortality with increasing deposition and a negative coefficient implies decreasing mortality with increasing deposition.

RESULTS

The 200 forest survey plots were characterized by a wide range of physiographic and edaphic conditions (Brooks 1989). Insect-caused defoliation incidents in Pennsylvania were more common and of greater severity during 1976–1984 than 1963–1975, with average annual gypsy-moth (*Lymantria dispar*)-caused defoliation of 432,000 ha and 83,000 ha respectively (USDA Forest Service 1985).

Across all climate divisions, months of drought, characterized by the Palmer Hydrological Drought Index, were 2.3 times more common than months of moist conditions during the first intersurvey period. The situation was reversed during the second intersurvey period, when months of moist conditions were 6.6 times more common than months of drought. This pattern occurred in all climate divisions.

Tree species composition closely paralleled that reported in the third survey of Pennsylvania's forest resources (Considine and Powell 1980). Using standards for upland oaks, the plots were, on average, fully stocked (Gingrich 1971). While average live-tree basal area increased at each survey (Table 2), the rate of increase in growth declined from the first to the second intersurvey period for all species combined and for 9 of the 12 major species (Figure 1). The decrease in growth rate was significant for all species combined and for white oak (*Quercus alba* L.), chestnut oak (*Q. prinus* L.), and sweet birch (*Betula lenta* L.) individually. Changes in growth rates of the remaining species were nonsignificant.

Growth was regressed on the standard suite of site, stand, defoliation, and climatic influences (Table 1). Significant growth models were found for all species combined and for sugar maple (*Acer saccharum* Marsh.), red maple (*A. rubrum* L.), white ash (*Fraxinus americana* L.), sweet birch, black cherry (*Prunus serotina* Ehrh.), northern red oak (*Q. rubra* L.), and eastern hemlock (*Tsuga canadensis* L.) individually (Table 3). The goodness of fit or coefficient of multiple determination, adjusted for degrees of freedom, ranged from −3 to 36%.

For all species combined, quadratic-stand diameter, drought, and defoliation were significant explanatory variables of growth (Table 3). For individual species, initial species stocking, competing stocking, and quadratic-stand diameter were the most common, significant independent variables. The occurrence of drought was significant for sweet birch, black cherry, and northern red oak. Soil variables (i.e., A-horizon base cations, depth, and mottling) and topographic location were infrequently retained as significant independent variables.

Neither sulfate nor nitrate deposition for the years 1982–1985 was significant in the analysis of residual growth (Table 3). For all species combined and for red maple separately, the probability associated with the model was less than 0.1 for

TABLE 2.

Average basal area and density at three successive forests surveys by tree history class for 200 forest survey plots, Pennsylvania.

Tree history class	First survey (1960s) Basal area (m^2/ha)	First survey (1960s) Density (#/ha)	Second survey (1970s) Basal area (m^2/ha)	Second survey (1970s) Density (#/ha)	Third survey (1985) Basal area (m^2/ha)	Third survey (1985) Density (#/ha)
Survivor[1]	15.7	390.4	17.5	314.8	21.1	358.3
Ingrowth[2]	Not applicable		3.1	120.6	1.8	62.5
Other	Not applicable		0.2	2.5	0.1	1.5
total, all live trees	15.7	390.4	20.8	437.9	23.0	422.3
Removed/dead and down	Not applicable		0.1	5.7	0.3	8.4
Mortality	Not applicable		1.4	41.3	2.1	49.7

[1] Survivors are the initial sample at the time of first measurement, trees of the initial sample found alive at the first remeasurement, and trees of the initial sample plus ingrowth from the first remeasurement found alive at the second remeasurement

[2] Ingrowth are the trees attaining 5.0-in. dbh or larger during the period between measurement occasions

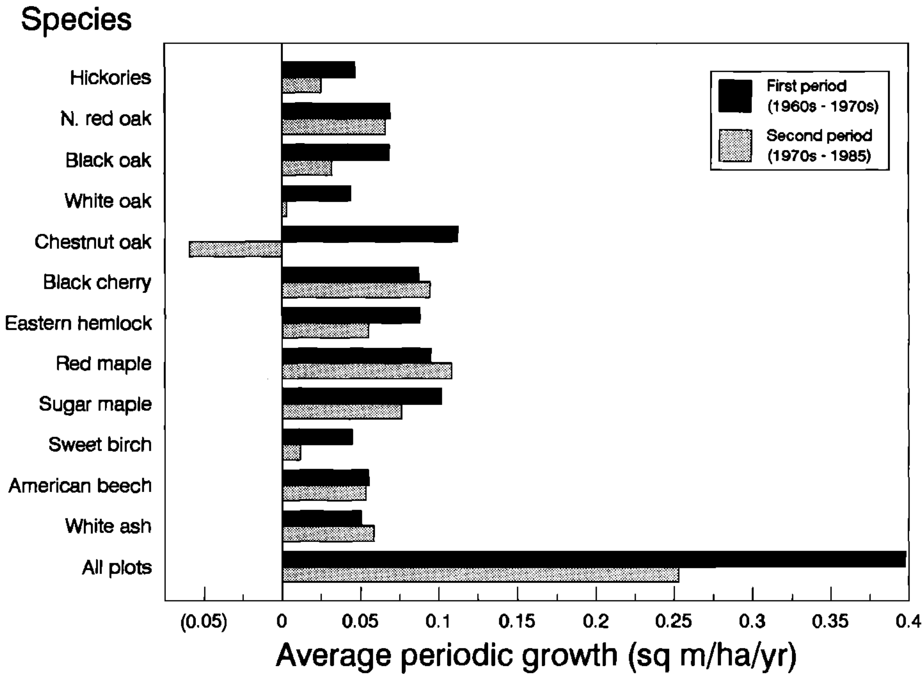

FIGURE 1. Average annual periodic basal area growth by species and for all plots on 200 forest survey plots in western and central Pennsylvania for the intersurvey periods 1960s–70s and 1970s–85.

nitrate deposition ($P = 0.056$ and 0.099 respectively). In both cases the regression coefficients were negative ($b = -0.136$ and -0.132 respectively), which can be interpreted to mean that growth was increasingly overestimated (i.e., less than "expected") by site, stand, defoliation, and climatic influences, in the presence of increasing nitrate deposition.

Basal area of standing-dead trees increased from the second to third survey (Table 2). Mortality rates increased significantly for all species combined, and for white, chestnut, and black oaks and for sweet birch individually (Figure 2). Mortality rates increased nonsignificantly for seven other common species and decreased, nonsignificantly, for white ash.

Mortality of all species combined was best predicted by initial stocking, quadratic-stand diameter, and defoliation (Table 4). Nine individual species models were significant, and initial species stocking was the most important independent variable. Adjusted goodness-of-fit statistics ranged between -4.2 and 47.8%.

Sulfate deposition was significantly related to residual mortality for northern red oak (Table 4). The model accounted for 2.9% of the variation in residual mortality. The positive standardized beta ($b = 0.193$) can be interpreted as meaning that as sulfate deposition increased, mortality rates were increasingly underestimated by the first regression model. That is, mortality was greater than that accounted for by site, stand, defoliation, and climate variables.

Three additional regressions of residual mortality on deposition had associated probabilities between 0.05 and 0.1. Residual mortality of white ash, sweet birch, and all species combined was positively related to estimated sulfate deposition. Residual mortality of white ash and all species combined was related to nitrate

Table 3.

Number of plots (n) where species was sampled and standardized regression coefficients and their probability (in parentheses) for analyses of periodic annual increment in basal area of living trees, by species, Pennsylvania, 1970s–1985.

Independent variables	Sugar maple (n = 76)	Red maple (n = 159)	White ash (n = 55)	Sweet birch (n = 76)	Black cherry (n = 96)
Species BA	0.258 (0.084)	0.331 (0.0)	0.606 (0.0)	−0.114 (0.301)	0.17 (0.106)
Competing BA	−0.055 (0.699)	−0.204 (0.02)	−0.204 (0.161)	0.048 (0.708)	−0.112 (0.362)
Diameter	−0.368 (0.006)	−0.114 (0.17)	−0.078 (0.579)	−0.234 (0.068)	−0.268 (0.025)
Drought	−0.036 (0.753)	0.001 (0.992)	0.042 (0.733)	0.346 (0.004)	−0.248 (0.022)
Defoliation	−0.170 (0.17)	−0.06 (0.477)	0.0 (0.999)	0.012 (0.913)	0.065 (0.538)
A base cations	0.147 (0.218)	−0.096 (0.213)	−0.01 (0.94)	−0.114 (0.327)	−0.133 (0.186)
Soil depth	−0.278 (0.017)	−0.039 (0.6)	−0.001 (0.995)	−0.112 (0.299)	−0.03 (0.76)
Mottles	−0.007 (0.953)	0.017 (0.83)	0.076 (0.577)	0.058 (0.61)	−0.18 (0.086)
Terrain position	0.207 (0.091)	0.001 (0.988)	0.081 (0.563)	0.222 (0.079)	−0.077 (0.469)
F-statistic	2.62 (0.012)	5.76 (0.0)	4.32 (0.001)	2.88 (0.006)	3.22 (0.002)
Adjusted R^2	0.163	0.215	0.36	0.186	0.177
Sulfate deposition	−0.013 (0.913)	−0.044 (0.583)	−0.125 (0.369)	−0.079 (0.501)	0.065 (0.537)
F-statistic	0.01 (0.913)	0.3 (0.583)	0.82 (0.369)	0.46 (0.501)	0.38 (0.537)
Adjusted R^2	−0.013	−0.004	−0.003	−0.007	−0.007
Nitrate deposition	−0.043 (0.71)	−0.132 (0.099)	−0.143 (0.302)	0.014 (0.907)	0.057 (0.587)
F-statistic	0.14 (0.71)	2.75 (0.099)	1.09 (0.302)	0.01 (0.907)	0.3 (0.587)
Adjusted R^2	−0.012	0.011	0.002	−0.014	−0.008

Independent variables	Hickories (all species) (n = 53)	White oak (n = 75)	Chestnut oak (n = 76)	Northern red oak (n = 125)	Black oak (n = 63)
Species BA	0.276 (0.091)	−0.157 (0.236)	−0.291 (0.103)	0.206 (0.048)	0.092 (0.548)
Competing BA	−0.193 (0.279)	−0.336 (0.021)	−0.081 (0.678)	−0.274 (0.008)	−0.108 (0.509)
Diameter	−0.065 (0.648)	0.084 (0.556)	−0.073 (0.607)	−0.024 (0.812)	0.156 (0.34)
Drought	0.017 (0.906)	0.14 (0.306)	0.166 (0.2)	−0.302 (0.002)	−0.25 (0.09)
Defoliation	−0.22 (0.172)	−0.097 (0.486)	−0.085 (0.502)	−0.087 (0.353)	0.016 (0.919)
A base cations	−0.389 (0.012)	−0.056 (0.66)	0.038 (0.766)	0.007 (0.934)	−0.028 (0.85)
Soil depth	−0.129 (0.369)	0.086 (0.484)	0.135 (0.27)	0.048 (0.568)	0.068 (0.637)
Mottles	0.046 (0.76)	−0.104 (0.426)	−0.048 (0.707)	−0.125 (0.165)	−0.072 (0.629)
Terrain position	0.072 (0.652)	−0.144 (0.29)	−0.168 (0.214)	−0.072 (0.434)	0.076 (0.601)
F-statistic	2. (0.063)	1.17 (0.331)	1.52 (0.159)	4.14 (0.0)	0.8 (0.617)
Adjusted R^2	0.147	0.02	0.06	0.187	−0.03
Sulfate deposition	0.082 (0.561)	−0.002 (0.983)	−0.176 (0.131)	−0.119 (0.189)	0.022 (0.864)
F-statistic	0.34 (0.561)	0.0 (0.983)	2.34 (0.131)	1.74 (0.189)	0.03 (0.864)
Adjusted R^2	−0.013	−0.014	0.018	0.006	−0.016
Nitrate deposition	0.033 (0.816)	−0.09 (0.444)	−0.106 (0.367)	−0.067 (0.461)	0.166 (0.194)
F-statistic	0.05 (0.816)	0.59 (0.444)	0.82 (0.367)	0.55 (0.461)	1.73 (0.194)
Adjusted R^2	−0.019	−0.006	−0.002	−0.004	0.012

Independent variables	American beech (n = 55)	Eastern hemlock (n = 45)	All species (n = 198)
Species BA	0.192 (0.282)	−0.066 (0.66)	−0.114 (0.145)
Competing BA	−0.077 (0.662)	0.219 (0.145)	n/a
Diameter	−0.425 (0.013)	−0.507 (0.002)	−0.3 (0.0)
Drought	−0.081 (0.566)	0.063 (0.687)	−0.184 (0.012)
Defoliation	−0.124 (0.388)	0.052 (0.717)	−0.233 (0.002)
A base cations	−0.253 (0.081)	−0.076 (0.587)	−0.023 (0.735)
Soil depth	0.097 (0.483)	−0.303 (0.033)	−0.019 (0.779)
Mottles	0.044 (0.761)	0.269 (0.089)	0.036 (0.614)
Terrain position	0.090 (0.551)	0.082 (0.599)	0.036 (0.61)
F-statistic	1.42 (0.209)	3.02 (0.009)	6.33 (0.0)
Adjusted R^2	0.067	0.292	0.178
Sulfate deposition	−0.096 (0.488)	−0.168 (0.27)	−0.088 (0.216)
F-statistic	0.49 (0.488)	1.25 (0.27)	1.54 (0.216)
Adjusted R^2	−0.01	0.006	0.003
Nitrate deposition	−0.194 (0.161)	−0.066 (0.668)	−0.136 (0.056)
F-statistic	2.03 (0.161)	0.19 (0.668)	3.71 (0.056)
Adjusted R^2	0.019	−0.019	0.014

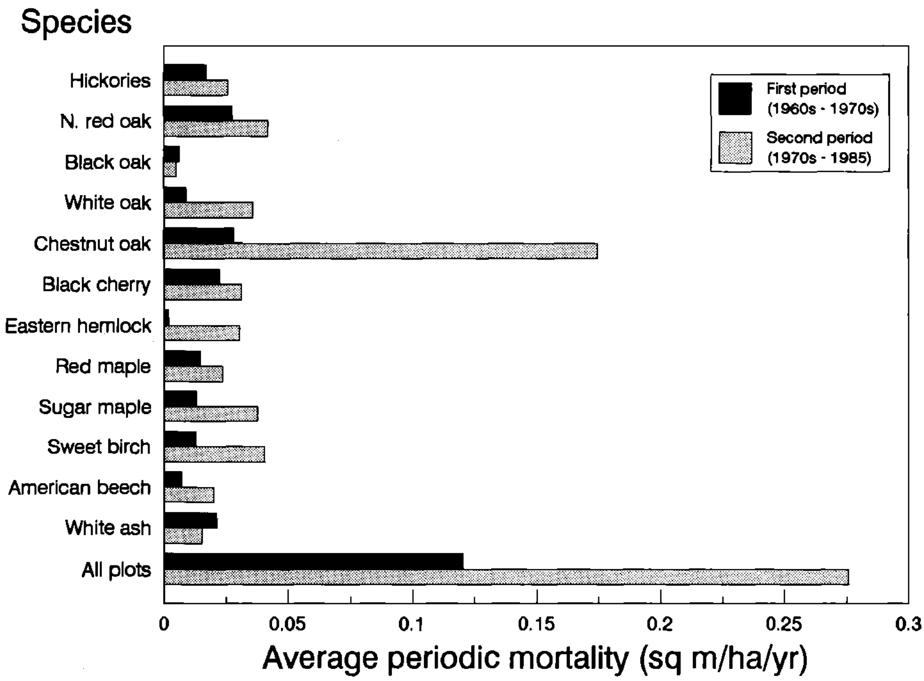

FIGURE 2. Average annual periodic basal area mortality by species and for all plots on 200 forest survey plots in western and central Pennsylvania for the intersurvey periods 1960s–70s and 1970s–85.

deposition (Table 4). In each case, the interpretation is that mortality was increasingly underestimated by standard site, stand, defoliation, and climate variables with increasing nitrate deposition.

DISCUSSION

Average periodic basal area growth declined significantly from the first to the second intersurvey period for all species combined and for white and chestnut oaks and sweet birch individually (Figure 1). All other species showed no significant change, whether increasing or decreasing, in growth rates between intersurvey periods. Changes in rates of mortality were similar compositionally to changes in growth rates. Mortality rates of all species combined, and of black, white, and chestnut oaks and sweet birch individually increased significantly from the first to the second intersurvey period (Figure 2). Mortality rates of all other species, except white ash, increased nonsignificantly. Regression analyses explained a significant but small portion of plot-level variation in growth (adjusted r^2 = 0.178) and mortality (adjusted r^2 = 0.156) for all species combined over the intersurvey period from the mid-1970s to 1985 in western and central Pennsylvania.

A decline in volume growth rates over the period 1964–1977 of Pennsylvania's forests was noted in the state's third forest survey and was partially ascribed to mortality in oak due to insects and disease, in particular the gypsy moth (Powell

Table 4.

Standard regression coefficients and their probability (in parentheses) for analyses of periodic annual increment in basal area of dead trees, by species, Pennsylvania, 1970s–1985.

Independent variables	Sugar maple	Red maple	White ash	Sweet birch	Black cherry
Species BA	0.327 (0.02)	0.462 (0.0)	0.19 (0.2)	0.391 (0.0)	0.673 (0.0)
Competing BA	0.045 (0.74)	0.047 (0.588)	0.146 (0.375)	−0.173 (0.145)	−0.085 (0.365)
Diameter	0.226 (0.079)	0.123 (0.136)	0.013 (0.937)	0.237 (0.047)	0.268 (0.004)
Drought	0.006 (0.958)	−0.02 (0.8)	−0.059 (0.689)	−0.219 (0.044)	0.17 (0.039)
Defoliation	0.054 (0.646)	0.111 (0.172)	−0.143 (0.338)	−0.073 (0.487)	−0.055 (0.499)
F-statistic	3.27 (0.01)	8.79 (0.0)	0.8 (0.552)	6.68 (0.0)	18.4 (0.0)
Adjusted R^2	0.131	0.198	−0.018	0.275	0.478
Sulfate deposition	−0.052 (0.656)	−0.041 (0.608)	0.223 (0.099)	0.19 (0.1)	−0.08 (0.438)
F-statistic	0.2 (0.656)	0.26 (0.608)	2.82 (0.099)	2.78 (0.1)	0.61 (0.438)
Adjusted R^2	−0.011	−0.005	0.032	0.023	−0.004
Nitrate deposition	−0.025 (0.828)	0.034 (0.671)	0.228 (0.091)	0.159 (0.17)	−0.081 (0.428)
F-statistic	0.05 (0.828)	0.18 (0.671)	2.97 (0.091)	1.92 (0.17)	0.63 (0.428)
Adjusted R^2	−0.013	−0.005	0.035	0.012	−0.004
Independent variables	**Hickories (all species)**	**White oak**	**Chestnut oak**	**Northern red oak**	**Black oak**
Species BA	0.222 (0.193)	0.664 (0.0)	0.493 (0.001)	0.5 (0.0)	0.247 (0.088)
Competing BA	−0.055 (0.765)	0.153 (0.17)	0.017 (0.92)	−0.003 (0.979)	0.078 (0.61)
Diameter	0.053 (0.737)	−0.095 (0.412)	0.032 (0.802)	−0.023 (0.81)	−0.064 (0.68)
Drought	0.011 (0.945)	0.025 (0.813)	−0.1 (0.389)	0.137 (0.119)	0.231 (0.097)
Defoliation	0.075 (0.633)	0.04 (0.719)	0.073 (0.509)	0.139 (0.103)	−0.098 (0.478)
F-statistic	0.58 (0.713)	9.28 (0.0)	4.72 (0.001)	9.65 (0.0)	1.19 (0.325)
Adjusted R^2	−0.042	0.359	0.199	0.259	0.015
Sulfate deposition	−0.012 (0.932)	0.048 (0.68)	0.145 (0.21)	0.193 (0.031)	0.05 (0.699)
F-statistic	0.01 (0.932)	0.17 (0.68)	1.6 (0.21)	4.76 (0.031)	0.15 (0.699)
Adjusted R^2	−0.019	−0.011	0.008	0.029	−0.014
Nitrate deposition	−0.126 (0.37)	0.103 (0.381)	0.08 (0.492)	0.142 (0.114)	−0.065 (0.613)
F-statistic	0.82 (0.37)	0.78 (0.381)	0.48 (0.492)	2.54 (0.114)	0.26 (0.613)
Adjusted R^2	−0.019	−0.003	−0.007	0.012	−0.012
Independent variables	**American beech**		**Eastern hemlock**		**All species**
Species BA	0.753 (0.0)		0.448 (0.001)		0.237 (0.003)
Competing BA	0.071 (0.573)		−0.033 (0.793)		n/a
Diameter	0.039 (0.746)		0.484 (0.001)		0.198 (0.011)
Drought	0.122 (0.242)		0.105 (0.384)		0.132 (0.069)
Defoliation	0.046 (0.659)		0.023 (0.845)		0.162 (0.025)
F-statistic	10.52 (0.0)		8.69 (0.0)		10.2 (0.0)
Adjusted R^2	0.467		0.455		0.156
Sulfate deposition	0.133 (0.332)		0.092 (0.537)		0.119 (0.094)
F-statistic	0.96 (0.332)		0.39 (0.537)		2.84 (0.094)
Adjusted R^2	−0.001		−0.014		0.009
Nitrate deposition	0.214 (0.116)		0.105 (0.483)		0.128 (0.071)
F-statistic	2.55 (0.116)		0.5 (0.483)		3.31 (0.071)
Adjusted R^2	0.028		−0.011		0.011

and Considine 1982). Mortality was estimated to be equivalent to 32% of net volume growth for all growing-stock oaks and 43% of net growth in white oaks in 1977 (Considine and Powell 1980). This was an increase from a mortality rate estimated to be equivalent to 9% of net growth for all growing-stock oaks in 1964

(Ferguson 1968). The most recent forest survey, which occurred subsequent to this study but is inclusive (1977–88) of the study's second intersurvey period, found mortality of all oaks was 74% of net growth and 149% of net growth for white, including chestnut, oaks (Alerich 1993). No cause for this increase in mortality was suggested, as this was a statistical report, but gypsy moth defoliation is an obvious consideration (Gansner et al. 1993).

The Pennsylvania Bureau of Forestry indicated that insect defoliation was more common and severe during the second intersurvey period. Gypsy moth was a frequently cited defoliator. White and chestnut oaks, two species with significant growth declines and mortality increases, are especially favored by this pest (Gansner et al. 1983, Skelly et al. 1988).

Defoliation was commonly a significant variable in the regression analysis of growth of all species combined, but was not a significant variable in any single-species regression (Table 3), despite prior knowledge that white oaks in particular have declined due to gypsy moth defoliation (Gansner et al. 1983). Similarly, defoliation was a significant independent variable in the analysis of mortality increment for all species combined but not for any single species (Table 4).

Stocking was a second major factor influencing growth. In 1977, 77% of Pennsylvania's forests were greater than 100% stocked, as calculated using all-live trees (Powell and Considine 1982). In 1988, the area of timberland in Pennsylvania at or more than 100% stocked was statistically the same as in 1977, but the proportion of stands overstocked (≥130%) increased from 29 to 35% of total timberland (Alerich 1993). Average stocking of the 200 plots in this study increased from approximately 62% in the 1960s to 85% in 1985, based on standards developed by Gingrich (1971). Maximum net basal-area growth is reported to occur at 60% stocking, and above that growth rates can be expected to decline (Gingrich 1971).

Stocking, quantified as the basal area of competing species on the plot at the beginning of the intersurvey period, was a significant variable in the regression analysis of periodic growth of northern red and white oaks and red maple (Table 3). In each of these models, competing species basal area had a negative influence on dependent species growth. Competing stocking was a nonsignificant independent variable in all analyses of mortality (Table 4). This analysis suggests that competition was sufficient to suppress growth but insufficient to result in mortality.

A third major influence on growth since the 1960s has been periodic drought. Drought was a significant, negative variable in the analysis of growth for all species combined (Table 3). Drought was more prevalent during the years of the first intersurvey period, but months of incipient to moderate drought were also common in 1977–1978 and 1981–1982 (Karl et al. 1983). The influence of drought was probably retained into the early years of the second intersurvey period.

Growth of sweet birch was positively related to drought during the second intersurvey period, while growth rates of black cherry and northern red oak growth were negatively related to drought (Table 3). Drought was positively related to black cherry mortality and negatively related to sweet birch mortality (Table 4). The seemingly anomalous response of sweet birch to drought (increased growth, reduced mortality), might be explained by a reduction in competition if other species on the birch plots were more drought sensitive.

Two additional stand variables were frequently significant in the analysis of periodic growth. Basal area of the species at the beginning of an intersurvey period was significant in explaining growth of northern red oak, red maple, and white ash (Table 3). A plot with greater initial basal area of a species will generally have greater accretion of the species than a plot with less initial basal area. However, the basal area of a species is also a measure of intraspecific competition and would be expected to be related to reduced growth or mortality when stocking is above a critical level.

Initial species basal area was the principal explanatory variable for the analysis of mortality increment (Table 4). In all instances when the relationship was significant, it was positive. These results suggest that intraspecific competition was a more important determinant of mortality than growth. Another interpretation is that mortality of a species would be greatest on plots with the greatest initial stocking of the species when mortality is species related (e.g., gypsy moth defoliation of white oaks).

The stand age of sample plots was classified as mixed by FIA for 164 of the 200 plots. In lieu of age, the quadratic mean stand diameter (i.e., diameter of the tree of average basal area) was used as a surrogate of the age of the trees on the plot. Basal area growth was expected to decrease with increasing diameter (Gingrich 1971). When significant, stand diameter had a negative influence on periodic growth (Table 3) and a positive influence on species mortality (Table 4).

Neither estimated sulfate nor nitrate deposition for the years 1982–1985 was significant in the analysis of residual periodic basal-area growth over the second intersurvey period. Sulfate deposition was significantly ($P = 0.031$) related to residual northern red oak mortality increment over the second intersurvey period but the regression model accounted for less than 3% of the variability in mortality. This regression result, and those of the seven growth or mortality models with probabilities of F between 0.05 and 0.1, support the interpretation that with increasing levels of deposition, periodic basal-area growth is less than expected when estimated by a suite of standard site, stand, defoliation, and climatic influences and that mortality rates are greater than expected.

The paucity of significant relationships between deposition and residual growth or mortality leads to a conclusion that atmospheric deposition was not a major forest influence over the early 1980s compared to the influences of defoliation, drought, and overstocking. However, to the extent that deposition is related to growth or mortality, the direction of the relationship implied a negative effect, either as reduced growth or increased mortality.

Other studies of forest growth and atmospheric deposition in Pennsylvania have led to similar conclusions. Changes in growth patterns in, and chemical composition of, wood cores from two oak forests in eastern Pennsylvania were related to air pollution or acid rain, but no unambiguous evidence of forest health effects were found (Mujumdar et al. 1991). In an intensive deposition-gradient study within the area covered by this study, no general relationship between overall tree health and atmospheric deposition was identified (Nash et al. 1992).

From these and my results, it can be concluded that the forests of Pennsylvania are not suffering a growth decline due to atmospheric deposition. Measured declines in growth are consistent with increased stocking, endemic insect defoliation, and periodic drought. White oak, and especially chestnut oak, which exhibited significant growth declines and mortality increases, are the species most affected by gypsy moth defoliations. Additionally, chestnut oak is commonly found on dry upland sites with shallow and sandy or rocky soils with low moisture-holding capacity (McQuilkin 1990), which make it particularly susceptible to drought.

The predominance of stand variables (i.e., stocking, diameter) over site, defoliation, and climate variables as significant variables in the regression analyses of growth and mortality is not surprising, given the precision of plot-level data and the imprecision of forest environment data estimated from secondary, off-plot sources of information. The point estimates of off-plot data for each plot were of unknown accuracy.

The failure of defoliation data to be a significant variable in explaining variation in growth or mortality of individual species is probably due to the resolution of the defoliation data. The data were generated by sketch mapping from a small airplane with a specified minimum mapping resolution of 5 ac (2 ha) (Pennsylvania Division of Forest Pest Management 1985), an area considerably larger than the area of the survey plots. This process and resolution offer considerable opportunity for error in estimation of plot-level defoliation occurrence and intensity. The acquisition of defoliation data from FIA plots is unlikely due to the long periodicity (typically 10+ yr) of remeasurement. The Forest Health Monitoring (FHM) program will resolve this problem of incompatible sampling scales by collecting and reporting both tree-level stress (defoliation, injury) and response (growth, mortality, dieback) data on a 1–4 yr schedule (Brooks et al. 1992a, Eagar et al. 1992, Gillespie et al. 1993).

Climate data were averages of weather station data across climate divisions which were applied to all survey plots within the division. Neither climate nor deposition data will likely be collected on either FIA or FHM plots due to instrumentation costs. Techniques for making point-estimates of climatic variables from weather station data using spatial statistics are being developed but were unavailable for this study (M.R. Holdaway, unpubl. rep., USFS, North Central Forest Experiment Station, St. Paul, MN, 1991).

Deposition data for each plot were point-estimates obtained from deposition monitoring data for the years 1982–1985 using multiquadratic equations, a surface-fitting algorithm (Grimm and Lynch 1991). In a test of the accuracy of this procedure, average percent error was 12.8% for nitrate and 12.3% for sulfate deposition. Maximum percent errors were 34.2% for nitrate and 26.1% for sulfate. While deposition data for this study were probably some of the best estimates available, because of the density of monitoring sites in Pennsylvania, an even higher density of sites would be required to reliably estimate local (i.e., plot) deposition patterns (Grimm and Lynch 1991). It is essential that the existing deposition monitoring network, in Pennsylvania and nationally, be maintained at its present intensity if regional assessments of deposition effects are to be made.

Dry deposition and ozone were additional but unquantified stress factors on Pennsylvania's forests over the period of this study. In other studies, dry deposition has been estimated to be 30 to 50% of wet deposition (Lynch and Corbett 1989, Fisher and Oppenheimer 1991). Dry deposition was not considered in this study due to the lack of recognition about its magnitude and potential effects. Its consideration in future studies is limited by the lack of consensus on the proper monitoring technique from among the many methodologies being currently used (Davidson and Wu 1990).

Ozone is now considered the pollutant of greatest concern with regard to regional-scale influences on forest health and productivity in the United States (Barnard et al. 1990, Cowling et al. 1990). It was not considered in this study due to the legislatively limited focus of the funding program to effects due to concerns about "acid rain." The future consideration of ozone effects over regional scales and in forested locales is limited by the sparse network of ozone monitoring sites in rural locations.

Limitations to this study, other than the accuracy of off-plot data, are related to its design as an assessment based on extensive survey data rather than being implemented as a controlled study of treatment effects. The detection or assessment of significant but minor or of more complex deposition effects (i.e., interactions with site, stand, defoliation, and climate factors) is beyond the limits of the data or the design of the study. Such analysis would require that all data to be measured at the same plot-level resolution (Schreuder and Thomas 1991) and that plots be rigorously selected to be able to consider all treatment and interaction effects.

Integrated monitoring of forest responses to atmospheric deposition, pollution, and other biological and anthropogenic stresses by the FHM program is critical to the continued assessment of the health and productivity of forests (Brooks et al. 1992a, 1992b). As standardized, integrated, and more precise and accurate data are collected and reported by this new program, the objectives of this study can be more vigorously pursued, and its findings can be more rigorously tested.

SUMMARY AND CONCLUSIONS

This study evaluated the use of extensive forest survey data, and associated off-plot data, for assessing the potential affect of atmospheric deposition on forest growth and mortality in western and central Pennsylvania. While significant declines in growth and increases in mortality were identified from the first to second intersurvey periods for many species, these changes could be explained by the occurrence of drought, overstocking, and gypsy moth defoliation. Wet atmospheric deposition was not a major influence on forest growth or mortality over the early 1980s.

This study identified or affirmed limits to the use of extensive forest survey data for investigating complex natural phenomena. Nevertheless, national and regional forest surveys are an important source of information for many unintended purposes because of their unique and extensive temporal and spatial coverage. Off-plot data are frequently a component of any study that uses remeasured survey data, due to the cost of obtaining such data at each plot and due to the often retrospective nature of the studies. Consequently, it is critical that techniques be developed to improve point estimates of off-plot data.

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Manuscript received July 1, 1993

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Robert T. Brooks is Research Wildlife Biologist, USDA Forest Service, Northeastern Forest Experiment Station, University of Massachusetts, Amherst, MA 01003. J. Barnard, D. Davis, G. Hertel, J. Skelly, J. McClenahen, and anonymous individuals reviewed the manuscript and offered many constructive comments. At different times, S. Fitzgerald, R. Boone, and L. Bozzuto assisted with data compilation. R. Damon offered advice with statistical analysis. The author appreciates their advice and assistance.