Eastern White Pine Exhibits Growth Retardation by Fluctuating Air Pollutant Levels: Interaction of Rainfall, Age, and Symptom Expression

S. O. Phillips, J. M. Skelly, and H. E. Burkhart

Former Graduate Research Assistant, and Associate Professor in the Department of Plant Pathology and Physiology, and Associate Professor in the School of Forestry and Wildlife, respectively, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

Senior author is currently Special Projects Forester, Missouri Department of Conservation, Columbia, MO 65201.

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ABSTRACT

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Growth inhibition of asymptomatic white pines subjected to three peaks in pollution levels during a 35-yr period was investigated. Four levels of symptom expression that developed in eastern white pine exposed to SO_2 and NO_x were used to categorize the sample trees for computer analysis of their respective growth rates. Analysis of regression correlations revealed no significant growth rate differences between symptom classes during pollution peaks; i.e., growth of asymptomatic trees was reduced as much as that of injured trees during peak pollution periods.

Additional key words: *Pinus strobus* L., SO_2, NO_x, growth loss.

Eastern white pine (*Pinus strobus* L.) has been used in several field and laboratory experiments to study the effects of air pollutants. Emergence tipburn of white pine was one of the first diseases shown to be incited by O_3 (3, 18); and chlorotic dwarf disease of white pine has been attributed to the action of O_3, oxides of nitrogen (NO_x), SO_2, and various photochemical oxidants (14).

Many researchers have noted that white pine varies in its sensitivity to air pollutants (1, 2, 3, 4, 5, 6, 7, 8, 11). Berry and Ripperton (3) studied emergence tipburn and developed clonal lines of *P. strobus* distinctly tolerant or sensitive to air pollutants and suggested the use of sensitive clonal lines as bioindicators of air pollution. Houston (11) showed that exposure of *P. strobus* seedlings to O_3 alone did not produce a consistent response among tolerant and sensitive clones but that consistent and more severe injury resulted from exposure to SO_2 alone and SO_2 plus O_3 in combination.

Berry (1) developed sensitive clones of white pine that demonstrated growth reduction when subjected to O_3 and SO_2 in controlled atmosphere chambers. Drummond and Wood (10) measured the growth retardation of eastern white pine in the vicinity of a coal-burning electric generating plant after shutdown of short stacks and use of a tall stack. Increased growth rates occurred after termination of the power plant's "in close" emissions.

Various economic assessment studies of reduced growth in forest trees resulting from air pollution were reviewed in the previous paper by Phillips et al. (13).

Stoklasa (16) introduced the hypothesis of "invisible injury" in 1923 when he suggested that air pollutants could reduce plant growth without inducing visible symptoms. He showed that respiration of spruce (*Picea* spp.) was inhibited by SO_2 even though no foliar symptoms developed. Phillips et al. (13) also reviewed work in support of Stoklasa's hypothesis.

Several natural and planted white pine stands occur within the confines of the U. S. Army's Radford Army Ammunition Plant (RAAP). The RAAP is a source of nitrogen oxides (NO_x) and SO_2, and it is one of the largest industrial complexes in southwestern Virginia. Previous work at the RAAP by Skelly et al. (15), Stone and Skelly (17), and Phillips et al. (13) have presented the history of this point source for NO_x and SO_2 and its usefulness for forest tree growth loss studies.

Skelly et al. (15) conducted height studies in a 13-yr-old stand of white pine at the RAAP. Asymptomatic trees as well as chlorotic dwarf trees were observed; severely affected trees (excluding the chlorotic dwarfs) averaged 66% of the height of asymptomatic trees. Previously, Stone and Skelly (17) also extensively studied the annual radial increment growth in the same white pine stand used in this current study and in a yellow poplar (*Liriodendron tulipifera* L.) stand. They used a simple linear regression analysis to evaluate the relationship of annual radial increment growth to annual production levels (an indicator of air pollution levels). A significant inverse relationship between growth and air pollution was demonstrated in both white pine and yellow poplar and their results were the basis for continued studies. The objectives of our study were: (i) to determine the impact of fluctuating levels of air pollution on growth rates of white pine, (ii) to determine if trees with varying degrees of symptom expression suffered corresponding growth losses, and (iii) to account for the variables of tree age, annual rainfall, and seasonal rainfall as they affected tree growth rates.

TABLE 1. Multiple linear regression analysis results for white pine stand No. 2 at the U.S. Army's Radford Army Ammunition Plant, Radford, Virginia. Dependent variable was annual radial increment growth from 1935-1974. Data expressed for all symptom rating classes combined and for each of the four separate classes

Regression number	Independent variable	All classes combined		Symptom class 1[a]		Symptom class 2[b]		Symptom class 3[c]		Symptom class 4[d]	
		F	r	F	r	F	r	F	r	F	r
1	Average annual production	110.55**[i]	−0.225	23.41**	−0.324	11.37**	−0.176	56.51**	−0.278	36.75**	−0.205
2	Age	410.55**	−0.406	27.55**	−0.349	6.11*	−0.130	205.47**	−0.483	225.00**	−0.459
3	Total annual rainfall	2.11	+0.032	1.38	+0.083	0.47	−0.036	0.77*	+0.034	2.14	+0.050
4	Annual seasonal rainfall	21.09**	+0.100	1.23	+0.078	1.14	+0.057	7.84**	+0.107	13.58**	+0.126
5	Average annual production[e]	75.39**	−0.187	17.10**	−0.282	9.81*	−0.164	34.73**	−0.221	24.62**	−0.169
6	Average annual production[f]	108.58**	−0.222	22.61**	−0.320	11.85**	−0.179	55.70**	−0.276	35.26**	−0.201
7	Average annual production[g]	105.85**	−0.220	22.83**	−0.322	10.98**	−0.173	54.65**	−0.274	34.43**	−0.198
8	Average annual production[h]	74.14**	−0.186	15.81**	−0.273	10.70*	−0.171	33.92**	−0.219	23.91**	−0.166

[a]Symptom class 1 = tree crowns with more than 25% of the needles tipburned.
[b]Symptom class 2 = tree crowns with not more than 25% of the needles tipburned.
[c]Symptom class 3 = tree crowns with chlorotic needles, but showing no tipburn.
[d]Symptom class 4 = tree crowns asymptomatic.
[e]Average annual production is correlated to annual radial increment after removing the effect of age.
[f]Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.
[g]Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.
[h]Average annual production is correlated to annual radial increment after removing the effect of all other variables.
[i]Asterisks indicate difference between means significant (*) at $P = 0.05$ and (**) at $P = 0.01$.

MATERIALS AND METHODS

Radial increment studies were conducted to determine the correlation between pollution levels at RAAP and annual radial growth rates of white pines. One natural stand of eastern white pine was sampled within RAAP. This stand was located on a sharply sloping northwest exposure 1.6 km east and downwind of the closest emission source for NO_x. The trees within the stand ranged in age from 35 to 135+ yr old. Individual trees within the stand exhibited foliage symptoms which varied in expression of air pollution damage from severely affected to unaffected. No silvicultural operations were conducted within the stand prior to sampling.

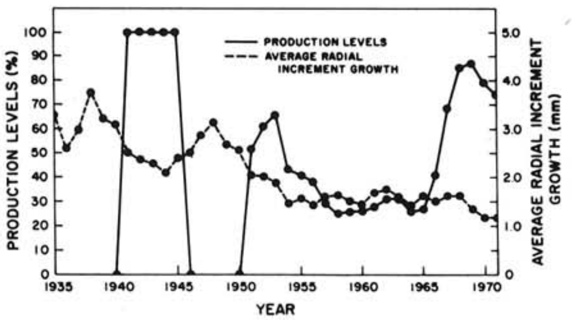

Fig. 1. Average annual radial increment growth of 52 white pines in all symptom rating levels combined located at the U.S. Army's Radford Army Ammunition Plant at Radford, Virginia (RAAP) and the production levels of the RAAP from 1935-1971.

Sample trees consisted of those previously sampled by Stone and Skelly (17) in their study and nine other trees which had not been utilized previously that were chosen within the study area. Measurements of annual radial growth to the nearest 0.01-mm were obtained from increment cores removed at 1.37 m (d.b.h.; diameter breast height) above the ground and measured according to the methods of Stone and Skelly (17). The constant inward measurement of the increment core from the cambium allowed the dating of growth with the first increment corresponding to the year of sampling. By counting the number of annual increments present on the increment core and obtaining a chronological age at d. b. h., an age variable was associated with the annual increment growth for each year measured. Measurements of annual radial growth to the nearest 0.01 mm and age were obtained for the period of 1935-1971 for the sample trees.

The method of Stone and Skelly (17) which was based upon annual coal consumption of the RAAP's power facilities was used to determine the percent average annual production levels. The independent variables of total annual rainfall and annual seasonal rainfall (from 1 April to 1 October were obtained from a climatological summary (6) of data collected at the Blacksburg Meteorological Station operated by the U.S. Department of Agriculture's Agricultural Research Service.

Four simple linear regression (SLR) analyses and four multiple linear regression (MLR) analyses were

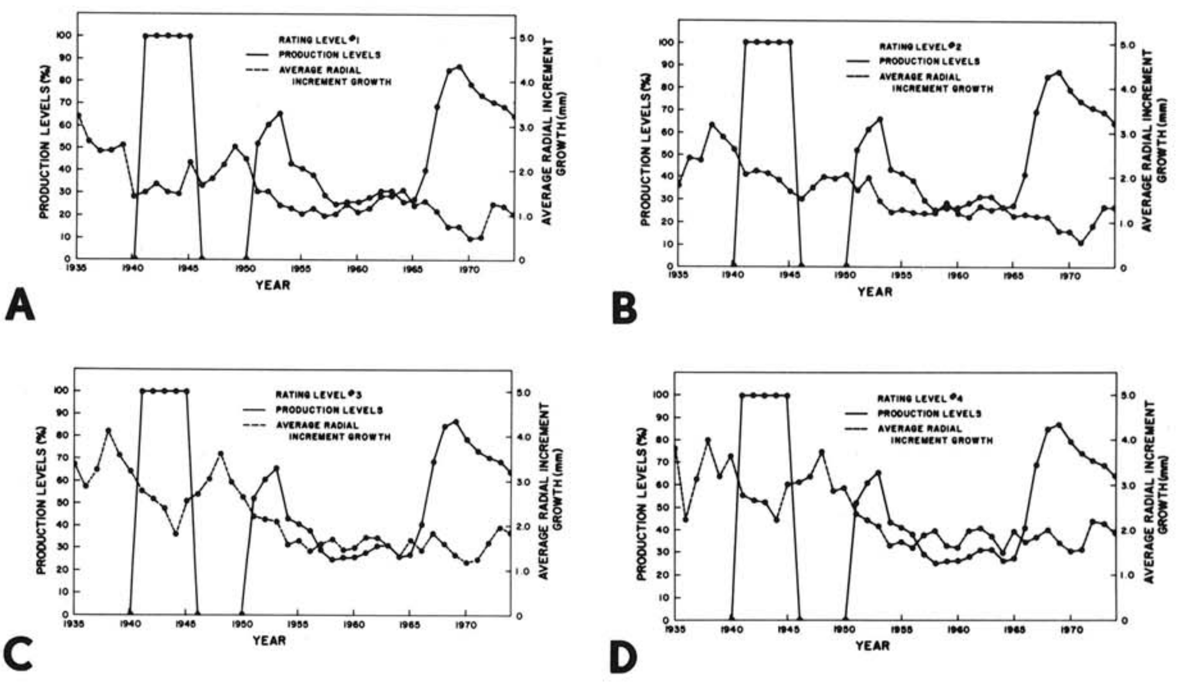

Fig. 2-(A to D). Average annual radial increment growth of white pines in four symptom classes at the U.S. Army's Radford Army Ammunition Plant (RAAP) and the production levels of the RAAP from 1936-1971: **A)** rating level 1, >25% needles tip burned, five trees; **B)** rating level 2, < 25% needles tip burned, nine trees; **C)** rating level 3, chlorotic needles, 17 trees; and **D)** rating level 4, asymptomatic, 21 trees.

conducted. The four SLR analyses were conducted with annual radial increment growth as the dependent variable and annual production levels, total annual rainfall, annual seasonal rainfall, and tree age separately as independent variables. The four MLR analyses also used annual radial increment growth as the dependent variable with the following combinations of independent variables: age and production levels; total annual rainfall and production levels; annual seasonal rainfall and production levels; and age, total annual rainfall, annual seasonal rainfall, and production levels.

To determine if foliage injury was directly linked to the correlations of growth to RAAP production levels, the sampled trees within the stand were visually rated for foliage injury. The rating levels were: 1 = tree crowns with more than 25% of the needles showing tipburn; 2 = tree crowns with not more than 25% of the needles showing tipburn; 3 = tree crowns with chlorotic needles and no tipburn; and 4 = tree crowns were asymptomatic.

The previously mentioned eight regression analyses were then conducted for the undifferentiated stand (all ratings included). Data for the trees were segregated by crown injury symptom classes and subjected to the same eight regression analyses as individual data groups. All five sets of the regression analyses were compared to determine whether the presence and severity of visible injury affected the relationship of annual radial growth to production levels of the RAAP.

RESULTS

The SLR analysis of the undifferentiated stand demonstrated significant relationships with all variables except total annual rainfall (Table 1, Fig. 1). The correlation of production levels and annual radial increment growth was negative whereas that of annual seasonal rainfall was positive. The MLR analyses compared annual radial increment growth to annual production after removing the effect of the other variables. All four of the MLR analyses of annual radial increment regressed on production were highly significant negative relationships (P = 0.01). The comparison of growth with age had the highest F-value and correlation coefficient. The regressions of annual radial increment on production levels produced higher correlation coefficients and F-values than the regression of growth on the rainfall variables. No large change in the correlation of growth to production levels was found after removing the effect of the age and rainfall variables simultaneously or independently in the MLR analysis.

Data for the sample trees were segregated under the four crown injury classes. The number of trees within each rating class were: rating level 1, 5; level 2, 9; level 3, 17; and level 4, 21. The sample trees within level 1, when subjected to the regression analyses, demonstrated the same significant linear relationship as the analysis of the complete stand except the SLR analysis of increment growth and annual seasonal rainfall became insignificant (Table 1, Fig. 2-A). The analyses involving production levels within this rating demonstrated increases in their associated negative correlation coefficients over those exhibited in the undifferentiated stand analysis. The correlation coefficient associated with the regression involving age, however, was reduced. The major difference exhibited between the analyses of sample trees within rating level 2 and that of the undifferentiated stand was that annual seasonal rainfall as in rating level 2 was not significantly related to annual radial increment growth (Table 1, Fig. 2-B). A reduction in the magnitude of the correlation coefficients and F-values of all regressions was found when the analysis of sample trees in rating level 2 was compared to that of the undifferentiated stand. All relationships except those with rainfall singly were significant at not less than $P = 0.025$. Sample trees within rating level 3 did not differ in significant relationships from the undifferentiated stands (Table 1, Fig. 2-C). There was an increase in the associated correlation coefficients of all eight of the regression relationships in this rating category. The MLR analysis of sample trees within rating level 4 was not different from the complete stand except in the size of the correlation coefficients (Table 1, Fig. 2-D). The correlation coefficients associated with the regression of growth on production levels were smaller and the correlation coefficients associated with growth when regressed on age and the two rainfall variables were larger.

The inverse relationship between annual radial increment growth of the sample trees in this stand of white pine and annual production levels of the RAAP remained highly significant irrespective of the occurrence of foliar symptoms. No differences were found in the nature (inverse or direct) of the correlation of any significant variable within the five analysis groups. Within the five groups of MLR analyses, the highest correlation coefficient was in the regression of annual increment growth on age except in rating level 3 when the regression of growth on production levels had the highest correlation coefficient. The MLR analysis in which annual radial increment was regressed on production levels after removing variation due to rainfall and age was considered the most valid appraisal of the effect of air pollutants on the growth of the sample trees.

DISCUSSION

The sample trees of white pine demonstrated a significant inhibition of growth which was proportional to the RAAP's fluctuating NO_x-SO_2 air pollution levels. These results correspond to those of Stone and Skelly (17) and Linzon (12) in which the annual radial increment growth of white pine was significantly affected by air pollutants. These investigators failed to consider any environmental or physiological variables other than air pollution within their studies. The significant inhibition of growth within the investigated stand of white pine was also present after removing variation associated with age and rainfall.

The analysis of the stand according to sensitivity classes of white pine based on severity of air pollution symptoms provided further evidence of "hidden injury" in that asymptomatic trees also suffered significant growth loss. The data also indicate that the fluctuating pollution levels within the RAAP had a significant effect on growth of the sample trees in all categories. These results agree with those of Stoklasa (16) with spruce, Treshow et al. (18) with Douglas fir, Pollanshutz (14) with white pine and several other species, and Donobauer (9) with various European species of pines and hardwoods.

The conclusion that symptom expression is not a prerequisite for growth loss places severe restrictions upon economic loss estimates such as those in the Pennsylvania state survey (19) which are based upon symptom expression alone. It is, therefore, highly probable that growth loss in forests subjected to low-level and long-term exposures to air pollutants may be occurring unnoticed and/or unevaluated.

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