Growth Fluctuation of Loblolly Pine Due to Periodic Air Pollution Levels: Interaction of Rainfall and Age

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ABSTRACT

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The effect of a periodic source of a NO_x-SO_2 air pollution regime on the growth of loblolly pine was investigated. Radial increment growth studies were conducted to determine if correlations existed between emission levels (predictions of production levels were used as a surrogate) of a source and radial increment growth of loblolly pine. Three stands of loblolly pine proximal to the emission source were sampled by obtaining breast-height (1.37 m above the base of the tree) increment cores from 50 trees in the dominant or codominant crown classes of each stand. Multiple linear regression analyses utilizing annual radial increment growth as the dependent variable and the independent variables of annual production levels, total annual rainfall, annual seasonal rainfall, and age were used to evaluate radial growth of sample trees within all stands. An inverse relationship significant at $P = 0.01$ was demonstrated between growth and production levels in two of the loblolly pine stands. Additional analyses of these stands indicated theoretical reductions in diameter growth within both stands without the presence of visible injury. Growth and production levels were not significantly correlated in the remaining loblolly pine stand.

Additional key words: tree growth loss, sulphur dioxide, nitrogen oxides, *Pinus taeda*.

The inhibition of growth in forest trees due to the presence of several different air pollutants has been demonstrated (2, 5, 7, 8, 9, 12). Several researchers have demonstrated that growth losses can occur without the presence of "visible symptoms" (5, 9, 12). The "hidden injury" theory of plant damage due to air pollution as developed by Stoklasa (10) in 1923 considered two points important to the analysis of growth loss: a reduction in the photosynthetic activity of the plants, and reduced growth and/or yield without symptom development.

Treshow et al. (12) conducted annual radial growth studies with Douglas fir (*Pseudotsuga menziesii* Mirb.) surrounding a source of atmospheric fluorides. They found a reduction of up to 50% in the annual radial growth of trees subjected to the ambient fluoride pollution. This reduction in growth was present irrespective of foliar (or visible) injury. Pollanshutz (9), working with the impact of SO_2, hydrogen fluoride, and magnesite dust on the growth of several forest tree species, found a reduction in annual radial growth without the appearance of visible symptoms. Horntvedt (7) presented the work of Stein and Dassler who conducted radial increment growth studies with spruce subjected to ambient SO_2. They found 45%, 27%, and 18% reduction in diameter growth over a 9-yr period which corresponded directly to mean yearly ambient SO_2 levels of 543.4, 143.0, and 114.4 $\mu g/m^3$, respectively.

Linzon (8) studied white pines (*Pinus strobus* L.) subjected to ambient SO_2 fumigations in the forest surrounding the Sudbury Smelter district of Ontario, Canada, to obtain an estimate of the economic impact of ambient pollution levels. He found that there was an annual stumpage loss of $14,000 and that the market value loss per year was $117,000. The estimates involved only white pine which comprised 7.6% of the forests in the 84.569954×10^6 m^2 (23 mi^2) of affected area. Carlson and Hammer (2) utilized annual radial growth to predict the growth impact of a fluoride air pollution-insect interaction on lodgepole pine (*Pinus contorta* Engelm.). They determined a loss of 3.7 m^3/hectare/yr (57 board feet/acre/year) based upon radial growth. Extrapolation to the entire affected area resulted in a loss estimate of approximately 38,505 m^3 (8.5 million board feet) per year.

The U.S. Army's Radford Army Ammunition Plant (RAAP) is an industrial source of nitrogen oxides (NO_x) and SO_2. Stone and Skelly (11) have conducted annual radial increment growth studies at the RAAP with white pine and yellow poplar (*Liriodendron tulipifera* L.). The unique history of the RAAP, having three distinct periods of production (World War II, the Korean conflict, and the Vietnam conflict), and the relationship of this periodicity to air pollution studies was presented by Stone and Skelly (11). A simple linear regression analysis was used by the researchers to evaluate the relationship of annual radial increment growth to production levels (an indicator of air pollution levels). They demonstrated a significant inverse relationship between annual growth and annual pollution levels for both yellow poplar and white pine. This work incorporating a more refined statistical analysis was the basis for studies at the RAAP involving several stands of loblolly pine (*Pinus taeda* L.). Loblolly pine also was examined owing to its importance to the forest industry of Virginia and the southeastern United States (6). There were three distinct objectives of these investigations: (i) to determine what correlations, if any, existed between historic production levels of the RAAP and the annual radial growth of loblolly pine; (ii) to evaluate what effect tree age and rainfall had upon correlations of growth and production levels; and (iii) to obtain an estimate of the growth impact of the SO_2-NO_x air pollution regime on loblolly pine within the RAAP.

MATERIALS AND METHODS

Radial increment studies were conducted in three planted stands of loblolly pine to determine if a correlation existed between past pollution levels at the RAAP and the annual radial growth rates of trees subjected to these levels. All of the sampled stands were growing in a level area on a 1.8-m spacing in a sandy clay soil. Loblolly pine stand No. 1 was located 2.6 km northeast of the RAAP's main power facility and was 15 yr old at the time of sampling. Loblolly pine stand No. 2 was 18 yr old at the time of sampling and was located in the same general area as the site of loblolly pine stand No. 1 – 2.7 km northeast of the main power facility. Loblolly pine stand No. 3 was also 15 yr old and was located 1.4 km northwest of the main power facility. No silvicultural treatments had been conducted in these stands.

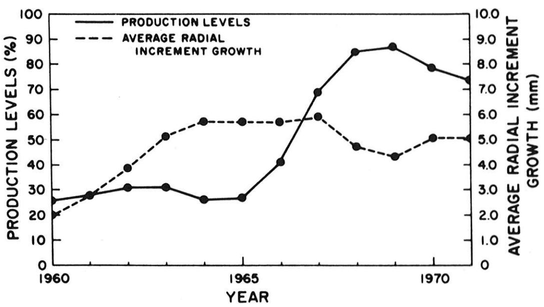
The stands were sampled by the method of Stone and Skelly (11). This sampling provided the variables of annual radial increment growth and age of the tree at the time of sampling. The annual radial increments of the sampled trees were determined to the nearest 0.01 mm for the period of 1960-1971.

Multiple linear regression analyses were conducted utilizing annual radial increment growth as the dependent variable and age, total annual rainfall, annual seasonal rainfall, and percent average annual production levels of the RAAP as independent variables; the latter as derived by Stone and Skelly (11). Tree ages were obtained as previously mentioned. Rainfall data obtained from the Blacksburg, Virginia Meterological Station (3) provided the remaining independent variables of total annual rainfall and annual seasonal (from 1 April through 30 September of the year) rainfall.

Four simple linear regression (SLR) analyses and four multiple linear regression (MLR) analyses were conducted with data from the individual stands. The four SLR analyses were computed with annual radial increment growth as the dependent variable and annual production levels, annual seasonal rainfall, total annual rainfall, and age separately as the independent variable. The four MLR analyses utilized 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. These eight linear regression analyses were conducted for all three sample stands.

A stand analysis also was conducted to obtain an estimate of the effect of past pollution levels at the RAAP on growth of the sample stands. This analysis was conducted with those stands which exhibited a significant inverse relationship between growth and production levels after removing the effect of age and two rainfall variables. The estimate was obtained by predicting the growth rates of trees within the RAAP and trees grown in an hypothesized pollution-free condition.

The estimate of these growth differences was obtained by means of the MLR equation which predicted radial increment growth from the independent variables of age, total annual rainfall, annual seasonal rainfall, and annual production levels at the RAAP. Estimates of annual growth differences within individual stands were



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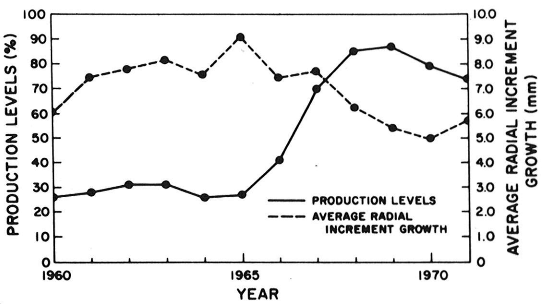

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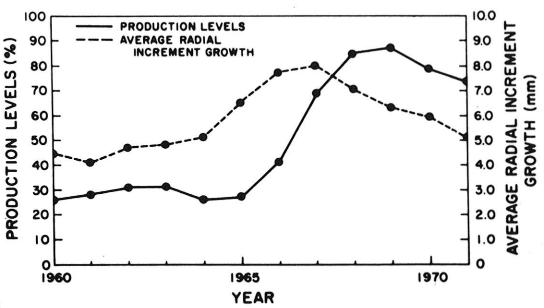

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Fig. 1-3. Average annual radial increment growth of 50 loblolly pine trees located in each of three stands [Fig. **1**), **2**), and 3) represent data for tree stands 1, 2, and 3, respectively] at the U. S. Army's Radford Army Ammunition Plant (RAAP) and the production levels of the RAAP from 1960-1971.

obtained from the yearly data of rainfall (annual and seasonal), age, and production which were substituted in the equation simultaneously to predict a mean annual radial increment for trees subjected to pollution. This prediction of growth was accomplished for all years which were included in the regression analysis. A pollution-free growth was hypothesized by interjecting the yearly data of age, annual seasonal rainfall and total annual rainfall in the equation. However, instead of inserting the corresponding production level for that year, a zero level of pollution was assumed to predict mean annual radial increment growth of the sample trees under a pollution-free condition. The mean annual radial increment growth predicted for both the pollution and pollution-free conditions within an individual stand were summed over all years and compared by means of percentages of growth reduction.

RESULTS

The annual radial increment growth of the sample trees within loblolly pine stand No. 1 did not demonstrate a significant linear relationship with annual production levels of the RAAP (Fig. 1, Table 1). A significant positive linear relationship existed between annual radial increment growth and the age of the sample trees of this stand. The two rainfall variables were not significantly correlated with radial increment growth in a SLR analysis. The MLR analyses then were utilized to compare annual radial growth to annual production levels of the RAAP after first removing the effect of other variables independently or in combination. When the effect of age was removed, annual radial increment growth demonstrated a significant inverse correlation to annual production levels. A significant linear relationship was not demonstrated between growth and production after removing either of the rainfall variables. A significant inverse linear relationship was demonstrated between increment growth and production levels when age and the two rainfall variables were removed first. This relationship had a higher F-value and partial correlation coefficient than any of the previous regression analyses.

In loblolly pine stand No. 2, all of the independent and MLR variables demonstrated a significant inverse linear relationship between annual radial increment growth and production levels (Fig. 2, Table 1). The higher F-values and correlation coefficients were demonstrated by the regressions of production on growth. The regression analysis in which age was removed and production regressed on growth also yielded high F-values as did growth regressed on production after all other variables were removed. This last analysis maintained the greatest degree of correlation and the largest F-value.

The annual radial increment growth of sample trees in loblolly pine stand No. 3 had a significant positive linear relationship to annual production levels (Fig. 3, Table 1). Age also had a significant positive correlation with increment growth. A significant inverse relationship between total annual rainfall and increment growth was found also, but no significant relationship was exhibited between increment growth and annual seasonal rainfall. When either of the two rainfall variables were removed first and production in the MLR analysis was compared to radial growth, an increase in positive correlation and significance was exhibited. However, when all other variables were removed or age alone was removed, the relationship between growth and production was nonsignificant.

The differences between predicted mean annual radial increment growth of trees subjected to past air pollution levels of the RAAP and trees in a hypothesized pollution-free condition provided a relative estimate for the amount of growth reduction in the sample stands. Only loblolly pine stands No. 1 and No. 2 demonstrated the necessary significant inverse relationship of radial increment growth to annual production levels of the RAAP needed to provide an estimate of growth reduction. The predictive model for mean annual radial increment growth in loblolly pine stand No. 1 was $Y = 7.26356 - 0.07698\ X_1 + 0.75930\ X_2 - 0.02541\ X_3 - 0.16941\ X_4$; where: Y = mean annual radial increment; X_1 = annual production levels of the RAAP; X_2 = age; X_3 = total annual rainfall; and X_4 = annual seasonal rainfall. This equation provided an estimated diameter-inside-bark (d. i. b.) growth of 56.7 mm for trees subjected to the RAAP's ambient air pollution levels and 103.2 mm for the same

TABLE 1. Multiple linear regression analysis results for three loblolly pine stands at the Radford Army Ammunition Plant, Radford, Virginia. Dependent variable considered was annual radial increment growth from 1960-1971

Regression number	Independent variable	Loblolly stand #1 values for		Loblolly stand #2 values for		Loblolly stand #3 values for	
		F	r	F	r	F	r
1	Average annual production	0.37	+0.026	43.76**	−0.265	10.66*	+0.151
2	Age	18.60**[e]	+0.180	9.44*	−0.126	6.97	+0.123
3	Total annual rainfall	2.21	−0.063	12.78**	−0.147	8.76	−0.137
4	Total seasonal rainfall	3.16	+0.075	28.75**	−0.217	1.96	−0.066
5	Average annual production[a]	44.60**	−0.273	63.55**	−0.314	3.72	+0.090
6	Average annual production[b]	0.66	+0.034	39.78**	−0.253	14.58**	+0.176
7	Average annual production[c]	0.01	−0.004	24.69**	−0.202	15.77**	+0.183
8	Average annual production[d]	57.88**	−0.308	105.81**	−0.393	0.36	−0.028

[a]Correlated to annual radial increment holding age constant.
[b]Correlated to annual radial increment holding total annual rainfall constant.
[c]Correlated to annual radial increment holding annual seasonal rainfall constant.
[d]Correlated to annual radial increment holding all other variables constant.
[e]Asterisks indicate: (*) significant F-value at P=0.05 and (**) significant F-value at P=0.01.

trees in an hypothesized pollution-free condition over a 12-yr period. Thus, the estimated diameter growth inhibition is 46.5 mm or a 45% reduction in d. i. b. due to the RAAP's ambient air pollution levels.

The regression equation provided for predicting mean annual radial increment growth in loblolly pine stand No. 2 was: $Y = 9.17036 - 0.10275\ X_1 + 0.71510\ X_2 + 0.16040\ X_3 - 0.53127\ X_4$. The estimated d. i. b. growth over a 12-yr period for sample trees in this stand subjected to the RAAP's air pollution levels was 78.7 mm; that for pollution-free growth was estimated at 142.5 mm. The predicted growth inhibition was 63.8 mm or a 45% reduction in d. i. b.

DISCUSSION

The effect of air pollution on the growth of loblolly pine has not been evaluated prior to this study. The SLR analysis with annual radial increment as the dependent variable and annual production levels as the independent variable as previously used (11) demonstrated the relationship between air pollution levels and growth of the sample trees without considering variations in tree age and rainfall. The MLR analysis in which annual radial increment was regressed on annual production levels after removing rainfall and age effects was considered the most valid appraisal of the effects of air pollutants upon the growth of the sample trees. The remaining three MLR analyses that were conducted allowed the two rainfall variables and the age variable to be removed independently before evaluating the relationship of air pollution on growth.

The variability of a plant's reaction to air pollution often is related to age. This variation in sensitivity has been demonstrated with loblolly (1) and Virginia pine (4) seedlings subjected to fumigations with ozone. The effect of age as it affects pollution sensitivity was apparent in loblolly pine stands No. 1 and No. 2 at the RAAP. In loblolly pine stand No. 1 when annual radial increment growth and annual production levels were compared in SLR analysis the relationship was not significant. When the variability in growth due to the influence of age was removed, a significant inverse relationship was demonstrated between growth and production levels. The effect of age on this relationship had completely disguised the significant effect of air pollutants on the growth of the sample trees. Similar results were found with the sample trees of loblolly pine stand No. 2. In this stand, both production levels and age independently were demonstrated to have a highly significant effect upon the growth of the sample trees. The removal of variation associated with age within this stand demonstrated that a higher inverse correlation of radial growth to production levels was present than had been obtained with a SLR analysis. The effect of age on air pollution-growth relationship in this situation had not completely disguised this significant relationship as in loblolly pine stand No. 1, but the failure to consider this variable reduced the negative correlation between air pollutants and growth.

Environmental factors considered in the analyses of stands at the RAAP consisted of rainfall variables: total annual rainfall and annual seasonal rainfall. Unlike age, the two rainfall variables did not greatly affect the correlation between production levels and growth when their effect was removed first; i.e., the inverse correlation of production to increment growth became stronger in loblolly pine stands No. 1 and No. 2. After removing the effect due to the two rainfall variables and age, the negative partial correlation coefficient between growth in loblolly pine stand No. 3 and annual production level was not significant. Similar results concerning the variability in sensitivity of trees to air pollutants due to environmental factors were presented by Wilhour (13).

The sample trees within loblolly pine stands No. 1 and No. 2 failed to exhibit foliar symptoms which were characteristic of air pollution injury in spite of the significant effect of air pollutants on growth within the stands. Treshow et al. (12) had demonstrated this phenomenon with Douglas fir subjected to atmospheric fluorides.

Loblolly pine stand No. 3 exhibited air pollution injury symptoms on the majority of the sample trees and was located 1.4 km from the main emission sources. Loblolly pine stands No. 1 and No. 2 were located 2.6 and 2.7 km, respectively, from the main emission areas. Therefore, loblolly pine stand No. 3 was probably subjected to higher pollution concentrations than stands No. 1 and No. 2 owing to the greater diffusion of the pollutants by the time they had reached the more distant stands. Loblolly pine stand No. 3 was situated proximal to a source of highly concentrated sulfuric acid mist. However, the SLR analysis regressing increment growth on production levels indicated a significant positive influence of air pollution. The effect of age on growth also was positive and highly significant. When the influence of age was held constant the relationship between air pollution and growth became insignificant. The correlation between age and growth during the period of 1960-1971 was very high. Therefore, the positive influence of air pollution on growth in the SLR analysis was a result of failing to consider tree age as a growth variable. Production levels were not correlated significantly with the growth of sample trees within this stand even after removing the effect of age and rainfall. This phenomenon could be due to a tolerance of the sampled trees within the stand to air pollution injury. The sensitivity expressed by the other two stands which were more distant from the sources of air pollution and without visible injury compared to the foliar injury within stand No. 3 preclude this conclusion. A more reasonable explanation of these differences may be that air pollution levels near and within stand No. 3 may have been sufficiently high to inhibit growth to a maximum point where no further response to the known fluctuations in the pollution densities above this critical level was detected. The fact that sample trees within loblolly pine stand No. 3 demonstrated foliar symptoms of air pollution indicated the presence of consistently higher levels of air pollution than were present in stands No. 1 and No. 2. The statistical analysis under such conditions would not detect this static influence of air pollution on growth.

These results indicate that loblolly pine trees planted within the RAAP may be undergoing an inhibition of growth which is proportional to the RAAP's production levels and which is influenced by tree age and rainfall. These results, therefore, conform to Stoklasa's (10) concept of invisible injury. It also is probable that some loblolly pine trees may exhibit a tolerance to the NO_x-SO_2 air pollution regime at the RAAP. The conclusion that symptom expression is not a prerequisite for growth loss places severe restrictions upon growth loss estimates utilizing symptoms for damage estimates. It, therefore, is highly possible that growth loss in forests subjected to low-level and long-term exposure to air pollutants may be occurring unnoticed and/or unevaluated.

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