The Growth of Two Forest Tree Species Adjacent to a Periodic Source of Air Pollution

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ABSTRACT

The effects of an isolated, periodically varied source of nitrogen oxides and sulfur dioxide air pollutants on the growth of two forest timber species was investigated. The annual production levels from 1941 through 1971 of the Radford Army Ammunition Plant (Arsenal), Radford, Virginia, were used as indicators of relative pollution emissions. The annual increment growth of 43 eastern white pine and 50 yellow poplar was determined to the nearest 0.05 mm with a dendrochronograph from 3.2 mm diam increment cores taken 1.37 m up from the base of each tree. An inverse relationship, significant at the 99.5% confidence level, was found by linear regression analyses to exist between the fluctuating production levels of the Arsenal and the annual increment growth of white pine and yellow poplar. Correlations significant at the 97.5% confidence level were found to exist between the annual increment growth of white pine and yellow poplar and the amount of seasonal and annual rainfall, respectively.

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The adverse effects of air pollutants on plant life have been known for many years. Controlled experiments conducted by researchers during the past thirty years have identified many natural and man-made gases as being phytotoxic, and the list continues to lengthen as our knowledge increases.

An industrial source of air pollutants, mainly nitrogen oxides, the Radford Army Ammunition Plant (Arsenal), is located in southwest Virginia. This industrial complex is uniquely suited to source-ecosystem studies, as it is located in a forested geographic bowl, and is isolated from other major pollution sources.

Production of nitrocotton, nitrated propellants, nitroglycerine, nitric acid, and sulfuric acid was begun at the Arsenal in 1941, and has continued through 1972. Continuous trinitrotoluene (TNT) production was begun in 1969, and some nitrated fuels and fertilizers have been produced during periods of low munition demand. Two coal-burning power houses, located within the facility, supply all electrical and steam requirements for the installation.

The levels of operation at the arsenal are dependent upon military need and are therefore highest during periods of national emergency. This point is of special interest, as it provides the researcher with three extended periods (World War II, Korean Conflict, Vietnam Conflict) of high operation levels separated by periods of zero or low operation levels (Table 1). As a result of this varying production level history, any living tree established in the area prior to 1936 has continued to grow through three cycles of low pollution-high pollution intervals over the 35-yr period from 1936 to 1971. This situation was ideal since any tree selected for investigation has thus acted as its own control during the periods of low pollution, and pollution sensitive trees should therefore exhibit growth inhibition during the three fumigation periods with the three periods of low pollution levels providing the control or reference levels of growth.

Two oxides of nitrogen, nitric oxide (NO) and nitrogen dioxide (NO_2), are gases whose importance as phytotoxicants are currently being ascertained. These oxides are by-products of all combustion processes including the internal combustion engine, and of many industrial processes, and are extremely difficult to control at the source (18, 33). As a result of our present inability to effectively control oxides of nitrogen, the increase in the ambient levels of these two gases is expected to continue (33).

Nitric oxide is rapidly converted to NO_2 in the atmosphere by reaction with an oxygen molecule (O_2) or oxygen atom (O). Nitrogen dioxide is therefore the nitrogen oxide normally most abundant in the atmosphere (13, 18, 21).

The type of plant damage resulting from NO_2 exposure is dependent upon the dosage the plant receives. Tissue collapse with subsequent development of necrotic areas,

TABLE 1. Production history of the Radford Army Ammunition Plant, Radford, Virginia

Production period	Duration (years)	Arsenal production levels[a]
1936 - 1940[b]	5	0%
1941 - 1945	5	89%
1946 - 1949	4	0%
1950 - 1956	7	47%
1957 - 1965	9	27%
1966 - 1971	6	76%

[a]Average annual production levels based on an assumed maximum production of 98% of capacity during 1942 through 1945, using the annual coal consumption of Power House I as the production level indicator.

[b]The years 1936 - 1940 represent years when growth was measured prior to production years.

is the typical acute foliar symptom expressed. The necrotic areas developing on the leaves of broadleaf plants are generally irregular, white to tan, interveinal, and scattered over the leaf surfaces. Occasionally marginal necrosis occurs (5, 16, 21, 22, 23). Acute damage on coniferous plants appears as reddish-brown tip necrosis, or tipburn, of the needles and occasionally scattered necrotic areas develop along the needles. The tipburn progresses toward the base of the needles if acute exposure levels are maintained. Usually a sharply defined band separates the necrotic tip from the green tissue (5, 15, 16, 23). Early abscission of deciduous leaves and of conifer needles is typical of both acute and chronic NO and/or NO_2 exposure.

Chronic injury from the oxides of nitrogen occurs as chlorosis, reduced metabolic function, and overall reduced growth rate on both broadleaf and coniferous plants (5, 15, 16, 23, 24). Heck (14) notes that little is known of the roles of NO in chronic injry.

Acute damage from sulfur dioxide (SO_2) exposures in broadleaf and coniferous plants is similar to, and often indistinguishable from NO_2 injury. However, continued SO_2 exposures at subacute levels will result in accumulation of sulfate in the leaf tips and margins with eventual characteristic necrosis of these areas (1, 6, 7, 16, 32). Chronic injury from SO_2 exposures typically appears as a chlorotic banding or mottlings of needles and as overall chlorosis on broadleaf plants. Early abscission of needles or leaves occur with both acute and chronic SO_2 exposures (1, 16, 32).

In the most definitive work on the synergistic effects of air pollutants on plants to date, Tingey et al. (25) and Dunning et al. (12) worked with mixed atmospheres of NO_2 and SO_2. They found that atmospheres of NO_2 below 200 pphm (parts per hundred million) or atmospheres containing less than 50 pphm of SO_2, did not cause leaf injury.

Sulfur dioxide is known to interact synergistically with other air pollutants in causing severe plant damage. In addition to the NO_2-SO_2 synergistic effects cited above, Menser and Heggestad (17) found that 3 pphm of O_3 and 24 pphm of SO_2 did not individually cause injury to *Nicotiana tabacum* L. 'Bel W-3' tobacco, but that combinations of the gases at or below these levels did.

Dochinger et al. (9) found that 10 pphm of either O_3 or SO_2 produced little acute damage on eastern white pine (*Pinus strobus* L.), but that a mixture of 10 pphm of each gas caused needle mottling and needle abscission. Jaeger and Banfield (15) repeated this work, using levels of SO_2 and O_3 at 5 pphm each. Exposures to the individual gases for 10 days or more resulted in no damage or minor change, while the combination of gases produced acute damage on some trees and chronic injury on all trees.

Berry (2, 3), Costonis (6) and others (4) have noted that susceptibility to air pollutants varies considerably within *P. strobus*. Berry has established distinct clonal lines of *P. strobus* that are resistant to air pollutants, and susceptible to mixtures of air pollutants, and has proposed that scion wood from these clonal lines be used in air pollution detection and monitoring work (2).

A well-known and much-reported response of *P. strobus* to atmospheric pollutants has been called the "chlorotic dwarf condition." Photochemical oxidants and SO_2 have all been implicated in the stunted chlorotic appearance typical of this condition (8, 9, 10). Less susceptible white pines typically respond to ambient pollution with increased needle abscission, needle tipburn, and needle mottle or banding resulting in an overall chlorotic appearance.

Investigations begun in 1970 of the vegetation in and around the Arsenal, indicated that atmospheric pollution levels were sufficent to be phytotoxic to eastern white pine. On a 1.2-hectare (ha) plot located adjacent to the TNT sources and planted in white pine in 1968, it was determined that 95% mortality had occurred by 1971. The surviving five percent had a burned, tufted appearance and had not produced new growth (19).

A stand of 13-yr-old white pine, located 300 m northeast of the TNT sources, was investigated in 1972. A randomly located stake within the stand was the center for a circular sample plot that contained 50 white pines. Pines within this plot ranged from 1-m tall saplings in the "chlorotic dwarf condition" to vigorous 10-m tall individuals. Measurements of the 50 trees indicated that those pines not dwarfed, but exhibiting foliar symptoms of air pollution susceptibility, averaged one-third less height growth than those trees with no overt pollution symptom expressions. Diameter-breast-height (D.B.H., 1.4 m above ground level) of the shorter of the affected trees were also correspondingly less (20).

The purpose of our investigations were to determine what correlation exists between forest tree growth and Arsenal production levels, and to determine to what extent the Arsenal pollutant emissions have affected susceptible tree species.

MATERIALS AND METHODS.—In order to determine what effects the past pollutant levels might have had on the established timber species proximal to the Arsenal, two forested areas were chosen in the prevailing downwind directions for sampling. Fifty pine (*Pinus strobus*) and 50 yellow poplar (*Liriodendron tulipifera*) were selected within these areas, respectively. Trees in the dominant or codominant crown classes were selected for sampling. A diameter measurement and a 3.2-mm diam increment core was taken at DBH from each tree. Increment cores were transported to the laboratory in soda straws and immediately placed in a refrigerator to prevent desiccation and shrinkage. Within 48 h of the time they were taken from the tree the cores were placed on a DeRouen dendrochronograph (Forestry Supplier, Jackson, Mississippi) equipped with ×25 magnification. The annual increments of the sampled trees from 1935 to 1971 were determined to the nearest 0.05 mm.

A linear regression analysis was chosen to establish a statistical model in order to test the hypothesis that an inverse relationship existed between the rate of annual growth of the sampled trees and the annual levels of production at the Arsenal. The regression equation was $Y = \alpha + \beta X$, where Y is regressed on X according to the population regression parameters α and β. The average annual increment growth (Y) of the white pine and the yellow poplar was represented as y_1 and y_2, respectively. The percent annual average production level of the Arsenal was used as an indicator of the relative amounts of pollution emitted, and was represented as x_1. The regression equation relating the growth of white pine with

TABLE 2. Regression analysis results comparing growth rate of white pine with annual production levels of the Radford Army Ammunition Arsenal and rainfall levels

White Pine	X-variable	Time span	F	Signif. level (P)	Correl. coeff. (r)
Y_1[a]	X_1[b] (annual production level)	1936 to 1971	11.2	99.5	−0.50
Y_1	X_1 (annual production level)	1941 to 1971	1.5	ns[d]	−0.23
Y_1	X_2 (annual rainfall)	1936 to 1971	2.2	ns	0.25
Y_1	X_2 (annual rainfall)	1941 to 1971	2.5	ns	0.28
Y_1	X_3[c] (seasonal rainfall)	1936 to 1971	5.7	97.5	0.37
Y_1	X_3 (seasonal rainfall)	1941 to 1971	4.6	ns	0.37

[a]Average annual growth increment of 43 white pines.
[b]Based on an assumed maximum of 98% of capacity during 1942 through 1945, and calculated using the annual coal consumption of Power House I. [c]1 April through 30 September. [d]ns = not significant.

Arsenal production levels was therefore as follows: $y_1 = a + bx_1$, where a and b are the sample regression coefficients used as estimators of the population parameters α and β, respectively.

The production level values used were based on the assumption that production levels during the 1942 through 1945 periods were at 98% of the maximum production capacity of the facility. These values were then correlated with the amount of coal consumed by the power house during the same time period, and the annual coal consumption of the power house was thereafter used to establish relative annual production levels for all succeeding years. Actual data on levels of pollution were obtained from four surveys conducted in 1967 and 1969 (26, 27, 28, 29).

Two other variables, annual rainfall and seasonal (1 April through 30 September) rainfall, were incorporated in the regression program as variables x_2 and x_3, respectively. Rainfall data were obtained from the records for the Blacksburg, Va. Meterological Station (30, 31).

To insure that any effects of rainfall and/or pollution on tree growth appeared concurrent with, and not subsequent to, the respective yearly increment growth; regression analyses were also run lagging the rainfall and pollution levels one year behind annual growth.

Several multiple regression analyses, both lagged and non-lagged, were included to determine the cumulative effects of production and rainfall levels.

RESULTS.—Eastern white pine increment core samples were taken from trees in a mixed, uneven-aged stand. The size and age of these trees varied widely, and the diam of sampled trees ranged from 13.0 cm to 57.8 cm with an average of 36.8 cm. Seven of the white pine increment cores proved unfit for increment measurements and were discarded, leaving a useable sample of 43 white pine.

A correlation coefficient (r) of −0.50, with a significant F value of 11.2 was determined. Various regression analyses are presented in Table 2. The annual increment growth of white pine was inversely related to Arsenal production levels.

White pine increment growth correlated well with seasonal rainfall (Table 2) and was significant at the 97.5% confidence level, with an F value of 5.7 and an r of 0.37. Increment growth did not correlate significantly with annual rainfall (Table 2).

Yellow poplar increment core samples were removed from trees in a relatively even-aged stand. The diam of trees sampled ranged from 22.9 cm to 45.1 cm with an average of 34.0 cm. The yellow poplar were relatively young trees; the stand was established about 1935. This necessitated the elimination of the 1936 through 1941 preproduction period for this species. Thus, two sets of regression analyses were necessary, one using the 1936 through 1971 period for white pine, and one using the 1941 through 1971 period for yellow poplar.

The annual increment growth of yellow poplar was inversely related to Arsenal production levels. Results of the regression analysis are presented in Table 3. The annual increment growth of yellow poplar was inversely related to annual production levels at the Arsenal for the years 1941 through 1971. An r value of 0.52, with a significant F value of 10.9 at the 99.5% confidence level were found. Yellow poplar increment growth correlated with annual rainfall (Table 3).

Annual increment growth increased from 4 mm/year during the 1941 through 1945 World War II period to 7 mm/year during the 1946 through 1949 interval period (Fig. 2). Annual increment growth decreased steadily to a rate of 4 mm/year during the Korean Conflict 1950 through 1956 period. During the 1957 through 1965 interval, Arsenal production was continuous but at low levels, and the increment growth rate remained at 4

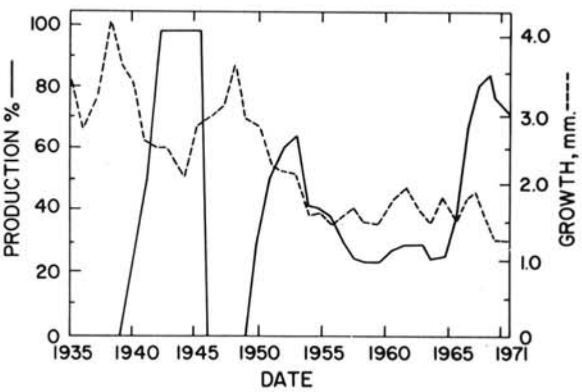

Fig. 1. Influence of the periodic production levels of the Radford Army Ammunition Plant (Arsenal), Radford, Virginia, on the average annual increment growth of 43 white pine trees. Legend: Growth– – –; % Production ———.

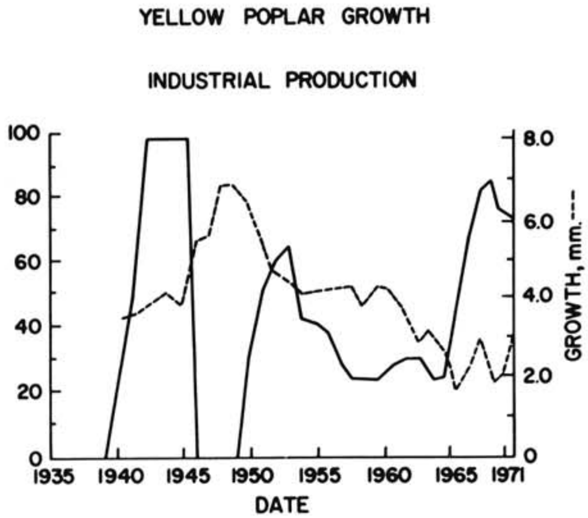

Fig. 2. Influence of the periodic production levels of the Radford Army Ammunition Plant (Arsenal), Radford, Virginia, on the average annual increment growth of 50 yellow poplar trees. Legend: Growth ———; % Production ———.

mm/year until it declined further in 1961. The lowest increment growth rate for yellow poplar, 1.7 mm/year, occurred during the 1966 through 1971 Vietnam Conflict period. The failure of the increment growth rate of yellow poplar to increase above 4 mm/year subsequent to 1957 indicate a continued suppression of growth at low relative pollution levels.

The direct correlation was significant at the 97.5% confidence level, with an F value of 6.4 and an r of 0.43. Increment growth did not correlate significantly with seasonal rainfall (Table 3).

Atmospheric monitoring and sampling data were obtained from the Arsenal. These data included: (i) two atmospheric sampling surveys, one conducted in 1967 (31) and one conducted in 1969 (28); and (ii) two source-emission sampling surveys, one conducted in 1967 (30) and one conducted in 1969 (29). Maximum 1-h atmospheric levels of NO_2 and SO_2 detected in 1969 were 58 pphm and 67 pphm, respectively, at a sampling station located adjacent to the two forested research areas (28, 31). The average daily NO_2 and SO_2 1-h concns at the station were 6.1 pphm and 1.8 pphm, respectively. All 1969 atmospheric levels were substantially higher than the 1967 levels, an indication of the increased production rates (Fig. 1 and 2). Maximum 1-h levels in 1967 for NO_2 and SO_2 were 12 pphm and 4 pphm, respectively. Estimated total emission rates of pollutants from the Arsenal were 1062 kg/h of NO_2 and 1969 as compared to 584 kg/h in 1967, and 960 kg/h of SO_2 in 1969 as compared to 685 kg/h in 1967 (28, 31).

DISCUSSION.—The susceptibility of *P. strobus* to air pollutants has been well documented, and several investigators have reported growth losses in conjunction with air pollution damage. Berry (2) has shown that growth losses occur with susceptible white pine clonal lines due to chamber exposures to air pollutants. Dochinger (9, 10) has reported extensively on the "chlorotic dwarf condition" of white pines, and has shown that individual trees in this condition will recover and grow at greatly accelerated rates when they are grown in pollution-free atmospheres. Drummond and Wood (11) observed the growth of a stand of white pines following the removal of the emissions from a power generating facility in the area. They reported accelerated growth rates two years following removal of the atmospheric pollution sources.

The inverse relationship found by this investigation between the annual increment growth of eastern white pine and the annual production levels of the Arsenal is in agreement with current literature. The high degree of significance demonstrated by the 99.5% confidence level of the regression analysis indicated that levels of atmospheric pollution were of major importance to the growth rate of this stand of white pine. This observation was further substantiated by the relatively lower degree of significance shown (97.5% confidence level) between increment growth rates and seasonal rainfall. The sampled trees therefore responded more strongly to Arsenal production levels than to levels of available moisture. Skelly et al. (19) have shown that atmospheric pollution levels adjacent to the TNT sources at the Arsenal are high enough to cause mortality of newly established white pine seedlings.

TABLE 3. Regression analysis results comparing growth rate of yellow poplar with annual production levels of the Radford Army Ammunition Arsenal and rainfall levels

Yellow poplar	X-variable	Time span	F	Signif. level (P)	Correl. coeff. (r)
Y_2^a	X_1^b (annual production level)	1936 to 1971	3.5	ns[d]	−0.31
Y_2	X_1 (annual production level)	1941 to 1971	10.5	99.5	−0.52
Y_2	X_2 (annual rainfall)	1936 to 1971	3.2	ns	−0.30
Y_2	X_2 (annual rainfall)	1941 to 1971	6.5	97.5	0.43
Y_2	X_3 (seasonal rainfall)	1936 to 1971	2.4	ns	0.26
Y_2	X_3^c (seasonal rainfall	1941 to 1971	4.0	ns	0.35

[a]Average annual growth of 50 yellow poplar.

[b]Based on an assumed maximum of 98% of capacity during 1942 through 1945, and calculated using the annual coal consumption of Power House I.

[c]1 April through 30 September.

[d]ns = not significant.

Other work by Skelly et al. (20) in a 13-yr-old stand of white pine at the Arsenal indicated that a wide range of foliar symptom expression occurs. They noted that extremely susceptible trees appear yellow due to chlorosis and tipburn of the needles, and that extremely resistant trees appear dark green with no foliar symptoms. Needle mottling, banding, and early needle abscission were other symptoms noted. These symptoms have also been extensively reported by other investigators (2, 3, 5, 6, 9, 15). These color changes indicate that the white pine sampled for this investigation included trees in all ranges of pollution susceptibility, as the crowns of sampled trees ranged in color from yellow and light green to dark green when viewed from a distance.

The sharp reductions in growth during the 1941 through 1945 World War II high production period and the 1950 through 1956 Korean Conflict high production period can be seen in Fig. 1. The slight increase in annual increment growth during the 1957 through 1965 low production interval period was of special interest, as the growth rate clearly did not return to the same level as during the two previous zero production interval periods. This growth suppression indicated that a linear-type relationship may exist between levels of atmospheric pollution and rates of growth of *P. strobus*.

Except for a single reference by Wood (34), who noted acute damage to yellow poplar seedlings following exposures to 25 pphm of O_3 for 8 h, the pollution sensitivity of *L. tulipifera* was unknown. Yellow poplar showed the same strong inverse relationship to Arsenal production levels as did white pine, with significance at the 99.5% confidence level.

Variations in growth were approximately twice those of white pine, and the response of the yellow poplar to the 1941 through 1945, the 1950 through 1956, and the 1965 through 1971 high production periods were more pronounced than for white pine (Fig. 2). Yellow poplar also responded less strongly to rainfall than to pollution levels, with a correlation significant at the 97.5% confidence level between annual increment growth and annual rainfall.

The failure of yellow poplar to regain its previous high

TABLE 4. Regression analysis results for 1 year lagging of growth rate and annual rainfall data with production levels of the Radford Army Ammunition Arsenal

Y-variable	X-variable	Time span	F	Signif. level (*P*)	Correl. coeff. (r)
Y_1[a] (white pine)	X_1[b] (annual production level)	1941 to 1971	1.0	ns[d]	−0.19
Y_1 (white pine)	X_2 (annual rainfall)	1936 to 1971	6.7	97.5	0.40
Y_1 (white pine)	X_2 (annual rainfall)	1941 to 1971	5.1	97.5	0.39
Y_2[c] (yellow poplar)	X_2 (annual rainfall)	1936 to 1971	5.6	97.5	0.38

[a]Average annual growth increment of 43 white pines.
[b]Based on an assumed maximum of 98% of capacity during 1942 through 1945, and calculated using the annual coal consumption of Power House I.
[c]Average annual growth increment of 50 yellow poplar.
[d]ns = not significant.

TABLE 5. Multiple regression results when annual production level and rainfall were compared together against growth rate of tree species listed

Y-variable	X-variable	Lagged one year	Time span	F	Signif. level (*P*)	Correl. coeff. (r)
Y_1[a] (white pine)	X_1[b] and X_2 (annual production levels and annual rainfall)	no	1941 to 1971	2.7	ns[d]	0.41
Y_2[c] (yellow poplar)	X_1 and X_2 (annual production levels and annual rainfall)	no	1941 to 1971	9.1	99.5	0.63
Y_1 (white pine)	X_1 and X_2 (annual production levels and annual rainfall)	yes	1941 to 1971	1.8	ns	0.34

[a]Average annual growth increment of 43 white pines.
[b]Based on an assumed maximum of 98% of capacity during 1942 through 1945, and calculated using the annual coal consumption of Power House I at the Radford Army Ammuniton Arsenal.
[c]Average annual growth increment of 50 yellow poplar.
[d]ns = not significant.

growth rate following the 1950 through 1956 production period suggests that a continued suppression of growth resulted from the low production levels of the 1956 through 1965 interval period. A linear-type relationship between levels of atmospheric pollution and annual growth rate is therefore indicated.

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