GROWTH LOSS OF LOBLOLLY PINE (*Pinus taeda* L.), WHITE PINE (*P. strobus* L.) AND SYCAMORE (*Platanus occidentalis* L.) PROXIMAL TO A PERIODIC SOURCE OF AIR POLLUTION

by

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INTRODUCTION

The population growth-rate of the United States and the world has placed greater demands on world resources today than at any other time in history. The increased industrialization and urbanization which have resulted from trying to meet the world's demands for food and fiber has resulted in deleterious changes in the environment. Air pollution is one of the increasing and everchanging deleterious environmental factors to which plant life is being exposed. Increasing air pollution levels in the United States are indicative of increases in the three major emission sources: transportation, manufacturing industry, and the generation of electrical power.

Chronic air pollution levels have become a common, rather than an abnormal situation. Urbanization has introduced various sources of change in the environment of rural America through the increased levels of transportation and industry along with increased demands for electrical power. These changes have resulted in the spread of air pollution, once a problem of cities, into most areas of the nation. The increased introduction of hydrocarbons into the atmosphere mainly by the internal combustion engine has increased oxidant air pollution levels by interfering with their normal degradation. This interference with normal cycles allows sources of oxidant air pollutants to affect larger and larger areas of plant life with low-level, long-term exposures to air pollutants.

The forests of this country are one of its most important renewable natural resources. Forests comprise one-third of the land area of North America, 1.8 billion acres. These forests are a source of wood, water, forage, recreation, and aesthetic qualities, all of which play a part in the survival of the American people. Trees, because they are a perennial crop, are exposed to the environmental changes that occur over several years. Several tree species have served as bioindicators for air pollution and some species have exhibited differential responses for different pollutants and even for different levels of pollutants. Studies dealing with the evaluation of growth losses and associated economic impact of air pollution on plants, however, have dealt primarily with annual crops. Research evaluating the growth-impact of low-level, long-term (chronic) air pollution exposures to forest trees is an important and necessary concern.

Little is known about the effect of ambient air pollution levels upon the growth of forest trees. Air pollution injury to trees is becoming a more common occurrence and has been linked by investigators working with trees and other crops to reductions in growth of the plants. It has also been suggested that growth loss is possible without the presence of visible injury. A determination of growth loss is needed which is not based solely upon symptoms so that all losses due to the effect of air pollutants on the forests may be realized. The effect of air pollutants on the total forest ecosystem is an important area of research which is only recently being investigated. This research is necessary to evaluate the effect of ambient air pollutants on growth because a plant's reaction to air pollutants is complicated by the influence of other parts of its environment. The evaluation of the effect of air pollution upon these other factors is required to gain a true evaluation of the effect of air pollutants on tree growth.

The U. S. Radford Army Ammunition Plant (Arsenal) is an industrial source of nitrogen oxides (NO_X) and sulphur dioxide (SO_2) located near Radford, Virginia. The Arsenal, one of the largest industrial complexes in southwestern Virginia, is situated in a forested geographic bowl isolated from other major pollution sources. The Arsenal's production of nitrogenous ammunitions is the main source of nitrogen oxides emitted. Two coal burning powerhouses located within the Arsenal provide all heat and power requirements for the installation and are also an emission source of SO_2.

The Arsenal, established in 1940, and its production levels have been directly linked to the military and security efforts of the United States. The periods of greatest military effort (World War II, Korean conflict, and Vietnam conflict) have represented peaks in the production levels at the Arsenal which are separated by periods of little or no production during peacetime (Table 1). As a result of these periodic fluctuations in production levels, any trees planted in the Arsenal prior to the increase in production during the Vietnam conflict (1966) have experienced both high and low levels of pollution corresponding to the production levels at the Arsenal.

The U. S. Radord Army Ammunition Plant is an exceptional area for determining the growth-impact of air pollution on forest trees.

Table 1. Production history of the Arsenal.

Production period	Duration (years)	Arsenal production levels[a]	Associated historical periods
Prior to 1941	-	0%	Preproduction periods
1941 through 1945	5	100%	World War II
1946 through 1949	4	0%	Plant shutdown
1950 through 1956	7	47%	Reactivation of plant during Korean conflict
1957 through 1965	9	27%	Production of nitrogenous fertilizers
1966 through 1971	6	76%	Vietnam conflict

[a] Average annual production levels predicted by the method of Stone (39) and Stone and Skelly (40) utilizing annual coal consumption of the main power facility.

It is a geographically isolated emission source located in an area second only to the Los Angeles basin in the frequency of occurrence of atmospheric inversions. The fluctuating production levels of the Arsenal incorporate a control condition upon the growth of trees exposed to these air pollution levels. Surrounded by natural and planted stands of various forest tree species, the Arsenal area allows the comparison of susceptibility among and within individual species.

The intent of this investigation was to determine the growth-impact of the air pollution levels at the Arsenal upon the surrounding forests. The alternating air pollution levels may have produced significant differences in the annual radial increment growth of pollution-sensitive trees. It was felt that the growth of the trees at low or zero levels of production could be utilized as checks upon the growth demonstrated during high pollution levels. The results of this analysis of the growth-impact of air pollutants could possibly give an indication of the impact of chronic air pollution levels upon the forests of Virginia.

LITERATURE REVIEW

The available literature on the symptomatic effect of air pollutants on vegetation is substantial. Such literature deals with all types of plant life, pollutants, and environmental conditions. The underlying effects of air pollutants on plant life (i.e., aberrant physiology, growth, yield, reproduction, ecology, etc.) are not as well substantiated and have in most cases only been suggested. The scope of growth-impact of air pollution on plants is linked to most, if not all, of the previously mentioned underlying effects to plants caused by air pollutants. This literature review will attempt to cover the extent of growth loss and/or reduced yield associated with economic losses due to air pollutants with special emphasis on forest trees. The need for further work will be demonstrated.

The effect of air pollutants on plants is divided by the "Air Quality Criteria for Sulphur Oxides" (48) into three general categories: 1) acute injury - severe foliar injury usually a result of a single exposure to relatively high levels of pollutants; 2) chronic injury - light foliar injury usually as a result of several exposures to relatively low levels of pollutants; 3) physiological effects - including alterations in growth, photosynthesis, respiration, and reproduction. These classes are not entirely independent of each other but suggest stages or levels of plant injury and are important considerations in estimating the growth-impact of air pollutants.

The use of foliar injury (i.e., the acute or chronic class of injury) as a means of assessing air pollution damage is widespread among researchers working with many crop types. The alternate method of assessing the growth-impact of air pollutants, that of measuring reduced volume or growth, would include all three classes of the previously mentioned effects of air pollutants. The area of damage assessment divides the literature into two major types. The first type includes experiments which depend solely on visible damage (i.e., necrosis, chlorosis, etc.) to determine volume or growth loss. The second type differs in that the idea of "invisible injury" or damage without foliar symptoms is included as a possibility by measuring more directly the reduced volume or growth of a plant due to pollutants.

Invisible Injury

The "invisible injury" theory of plant damage was first developed by J. Stoklasa (43) in 1923, yet the literature indicates that it was and still is a controversial subject in air pollution research. Stoklasa associated "invisible injury" with two points which were important for the consideration of the growth-impact of air pollutants: a reduction of the photosynthetic activity of plants and reduced growth or yield. Even though not a direct measurement of reduced growth, a reduction in photosynthetic activity was accepted as a method in which a reduction of growth could occur in plants (25, 41). In defense of his theory, Stoklasa presented his work with spruce (*Picea* A. Dietr.) in which he showed an inhibition of respiration after being subjected to SO_2 fumigations. This inhibition of respiration of these trees without visible injury was related by Stoklasa to a concurrent inhibition of photosynthesis.

Stoklasa's theory has been substantiated by subsequent works such as that of Bleasdale (7) with rye grass (Lolium perene L.) in 1952. This study dealt with a long-term exposure of rye grass to ambient levels of SO_2 under field conditions. A control plot was established by passing the ambient air through a filter and water scrubber set up to remove the SO_2. The concentrations of pollutant varied in the number of parts-per-million (ppm) of pollutant between less than 0.01 ppm to 0.2 ppm due to the ambient nature of the fumigation. This concentration range was not high enough to cause visible injury (i.e., foliar injury) on the plants, yet it did cause significant reductions in dry weight yields of the fumigated plants (at the 0.05 level). This difference was found in all stages of the plant's growth. At the Second International Congress of Plant Pathology in September 1973, a paper was presented by Bell and Clough (3) of the United Kingdom who duplicated the experiments of Bleasdale with rye grass. This second study on rye grass was also a long-term low-level fumigation procedure in which SO_2 was again the air pollutant used. The results in the study by Bell and Clough substantiated those found by Bleasdale. Significant differences in yield of the plants on a dry weight basis was found without visible injury occurring.

Flower production has also been shown by Feder and Campbell in 1968 (20) to be affected by "invisible injury" due to air pollutants. This study entailed the fumigation of carnations (Dianthus caryophyllus L.) with low level concentrations (5-10 parts-per-hundred-million (pphm)) of ozone over a three month period. This experiment was conducted under controlled greenhouse conditions with artificial fumigation and a non-fumigated control. The data resulting from this study revealed a reduction in number of stems, average stem length, and a reduction in flower production of the fumigated carnations without foliar injury. There was also an indication of a reduction in quality of the flowers which were produced by the fumigated plants.

Treshow *et al*. (46) working with Douglas fir (*Pseudotsuga menziesii* Mirb.) surrounding a phosphate reduction industry presented an account of the "invisible injury" of air pollutants affecting trees. The air pollutant in this case was hydrogen fluoride. Treshow measured the annual radial increment growth of the trees around the industry and correlated the growth of the trees to two controls. The first control was the comparison of radial increment before and during the presence of the industry. Another check was developed by measuring a group of trees five miles away from the phosphate industry. In the analysis of their data, they found a reduction in radial growth of the fumigated trees. This reduction was evident both in the comparison of the growth during the period of pollution to growth prior to the installation of the phosphate industry and also in comparison of the check plot to the fumigated plots. Reduction in growth was present even in plots where there was no foliar or visible injury.

Growth and/or Yield Effects

Reduction in growth and/or yield of plants has been shown in numerous cases to occur in the presence of visible injury to plants.

One such work is that of Bisley and Jones (10) with wheat. In this study, wheat plants were planted in the field in spatially separated plots and alternating plots were designated as control and fumigation areas. The fumigation plots were then covered with vinyl plastic-covered cabinets by which the wheat plants were fumigated with SO_2 at various times during the growing season. The results of this study indicated that SO_2 caused a reduction in the yield of wheat which was directly correlated to the amount of leaf injury produced by the fumigations. A subsequent work under similar methods by Brisley *et al*. (9) supported the conclusions of the previous study by Brisley and Jones. This second study dealt with the fumigation in the field of cotton with SO_2 and also resulted in a direct correlation between amount of visible damage and the reduction in yield of the fumigated plants.

The studies of Thompson *et al*. (44) and Thompson and Taylor (45) working with citrus crops in ambient air pollution studies found that growth and yield were greater in charcoal-filtered chambers than in the presence of SO_2 or fluorine at ambient levels. A work conducted by Heagle *et al*. (24) in North Carolina working with sweet corn (*Zea mays* L.) (grown in a sandy clay-loam soil) which was subjected to field exposures of ozone for 6 hours/day found reductions of fresh weight of ears, number of kernels, and dry weight of kernels on plants receiving 10 pphm of ozone. These reductions were significant at the 95% level with the variety 'Golden Midget.' Other researchers have shown the depressed growth and/or yield of spinach, beets, endive, oats, and alfalfa (22); pinto beans and tomato seedlings (42); sweetgum and larch (37); and tobacco (*Nicotiana tabacum* L.) (31), along with numerous other crops, which indicates the widespread growth-impact of air pollutants. The works which dealt with aberrant photosynthetic processes due to air pollution are also numerous. One example is the work of Botkin *et al*. (8) who found reductions in net photosynthesis of white pine (*Pinus strobus* L.) after exposure to ozone. Nitrogen oxides have been shown to inhibit apparent photosynthesis of oats (*Avena sativa* L. var. Park) and alfalfa (*Medicago sativa* L. var. Ranger) (25). These works again are only a sample of what has been done.

Air Pollution and Forests

The previous studies presented substantiated the fact that growth and/or yield of plants (both agricultural and forest) can be reduced when symptoms are present or when symptoms are lacking. The effect on forest trees due to their life span and culture cannot always consider only the effect of pollutants to the visibly injured, but instead must consider the effects upon entire biosphere. William Smith (38) in his paper on the effects of air pollution on the quality and resilience of the forest ecosystem, gives insight to the effect of air pollutants in this situation. In this paper Smith divided the effect of air pollutants on the forest ecosystem into three classes which were based on pollution levels --

> "The Class I relationship which exists under conditions of low dosage results in the vegetation and soils of the ecosystem functioning as a very important sink for air pollutants. Depending on the nature of the pollutant, the ecosystem impact of this transfer (of pollutants) could be undetectable (innocuous effect) or stimulatory

> (fertilizer effect). The Class II relationship existing at intermediate dosages causes individual tree species or individual members of a given species to be adversely and subtly affected by nutrient stress, reduced photosynthetic or reproductive rate, predisposition to entomological or microbial stress, or direct disease induction. The ecosystem impact in this instance could include reduced productivity or biomass, shifts in species composition, increased secondary effects such as insect outbreaks or disease epidemics, or increased morbidity and reduced vigor. Exposure to high dosage, Class III relationship, alters the structure of the ecosystem by gross simplification and/or basic changes in hydrology, nutrient cycling, erosion, microclimate and overall stability."

Smith presented in his paper several points which he felt needed correction or were lacking in the assessment of the effects of air pollutants on forest ecosystems. These drawbacks were:

1. Numerous tree species have not been evaluated in their response to air pollutants;
2. Most studies do not deal with exposure of plants to more than a single pollutant;
3. Too much research has dealt with pollutant levels in excess of ambient concentration levels;
4. Most of the experiments involved artificial conditions.

Few recent studies consider or contain all of these drawbacks. The following studies which measure the effect of air pollutants on forest trees overcome most of these.

The previously mentioned work of Treshow *et al*. (46) met most of the standards. The study dealt with Douglas fir trees subjected to ambient pollutants in varying dosages (with distance from the emission area). The study had a sampling technique incorporating five sets of sample points in varied distances from the source of fluorides (1/2, 1, 2-1/2, 3-1/2, and 5 miles). At all of these sample points, radial increment cores were taken from the trees and the radial growth of the individual years were measured. The results of these measurements showed:

1. Average annual radial growth decreased with higher fluoride concentrations (as they were closer to the industrial source);
2. Calculations of the correlation between fluoride levels and growth during the years of operation revealed a significant (at the 0.01 level) negative correlation coefficient of 0.9538;
3. Growth in the sample area nearest the source was significantly less (at the 0.01 level) during operations of the source than before operations;
4. No significant increment differences appeared among sites or groups in years preceeding operations;
5. Increment differences between central groups and fumigated trees averaged nearly 50%.

Treshow's data showed a serious effect of air pollutants on tree growth.

Katz and McCallum (28) conducted research in 1929-36 to evaluate the effect of SO_2 emissions from a smelter upon Douglas fir, Lodgepole pine (Pinus contorta Dougl.), and yellow pine trees in Trail. British Columbia. The study consisted of obtaining increment cores from over 10,000 trees from which measurements of annual increment growth were obtained. These measurements of annual increment growth were used to establish growth curves for the three tree types. The trees (of all three types) affected by SO_2 in the smoke zone failed to respond to favorable periods of annual precipitation by increased radial increment growth; instead, the growth rate of these trees showed a declining curve while the curve for the control trees was ascending. However, following installation of recovery units for SO_2 at the smelter, the exposed trees showed growth increases which were greater than the controls. No evidence was found to support the "invisible injury" theory of plant damage as only trees exhibiting foliar injury expressed the growth retardation.

Pollanschultz (33) working in Europe with the effect of SO_2, hydrogen fluoride (HF), and magnesite dust upon the growth of larch, white pine, spruce, fir, aspen, ash, beech, and maple found that growth loss can occur without the appearance of macroscopic symptoms. He also found that chronic damage caused by SO_2 can result in the continuous yearly depression of radial growth in conifers which may lead to death. This depression of growth was statistically significant in all of the species except larch. The hardwood species were not as severely affected by the air pollutants due to their annual foliage. Horntvedt (26) also working in Europe with the effect of SO_2 on forests found deciduous trees to be more resistant to air pollution injury than conifers. Horntvedt presented the work of Stein and Dassler in which they evaluated the growth of spruce surrounding a coal burning power plant. Stein and Dassler found a 45%, 27%, and 18% reduction in diameter increment from 1956-65 of trees subjected to mean yearly levels of 0.19, 0.05, and 0.04 ppm of SO_2, respectively, compared to growth prior to installation of the plant (1946-55).

Stone (39) in 1970-71 studied the forest ecosystem surrounding the Radford Army Ammunition Plant in Radford, Virginia. This munitions plant which began production in 1941 served as an isolated point source whose production levels varied with our nation's military and defense efforts. One part of Stone's work was the analysis of 43 increment core samples from white pine (P. strobus), 50 from yellow poplar (Liriodendron tulipifera L.), and 15 from red oak (Quercus rubra L.). The average annual increment growth (in mm) obtained from these cores for the individual species was then correlated to relative production levels at the Arsenal (based on coal consumption) by the use of a linear regression analysis. An inverse relationship, significant at the 0.005 level, was found to exist with white pine and yellow poplar while no significant relationship existed with red oak. The periodic fluctuations of production at the Arsenal provided checks (or controls) for the analysis along with the growth of white pine and red oak prior to production at the Arsenal. The effect of retardation of white pine growth was also found in the work of Drummond and Wood (18) who observed the growth of white pines surrounding a power generating facility following its removal. In their study they found increased growth rates in the white pines following the removal of the power facility. The relative pollution sensitivity of yellow poplar and red oak was demonstrated in the work of Wood (51) with ozone. Wood found that acute injury occurred on yellow poplar following exposures to 25 pphm of O_3 for 8 hours while red oak was uninjured at this same concentration for the same amount of time. The previously mentioned works, along with those of Linzon (29) and Donobauer (17), substantiate Stone's findings.

The work of Donobauer (17) as presented at the Second International Congress of Plant Pathology used methods similar to that of Treshow *et al*. (46) and Stone (39). Donobauer, working in the forests of Austria, measured thousands of radial increment cores and found significant reductions in the growth of a variety of trees subjected to a variety of ambient air pollutants. In this study, Donobauer found growth losses on trees which varied from no visible injury to trees which were totally defoliated.

The documentation on the growth-impact of air pollutants on forest trees is sufficient for this effect of air pollution to be accepted. The work of Cobb and Stark (11) relating the synergistic effect of air pollution and bark beetles (*Dendroctonus* spp.) on ponderosa pine (*Pinus ponderosa* Laws.) illustrates the reduction in vigor or occasional death of trees due to air pollution. Other studies such as those describing the "chlorotic dwarf" condition of eastern white pine (6, 16, 36) demonstrated a reduced growth condition that can be considered a loss whether the tree is used as an ornamental, a Christmas tree, or for fiber production. These types of effects were illustrated in a Class II condition which was described in the previously mentioned work by Smith (38). This type of work illustrates that losses linked to air pollution cannot always be traced to the individual action of pollutants and thus go unnoticed when estimations of losses due to air pollution are made.

Economic Aspects

Losses due to air pollution are measured on varying standards (i.e., dry weight, annual increment, bushels, etc.). To achieve cohesion they must be converted to a standard measure (i.e., monetary losses). Difficulties arise in this transformation due to the fact that the scope of the growth-impact of air pollution on plants is an area of extensive allegations with few factual accounts. Linzon (29), in his assessment of economic losses due to air pollution affecting trees, presents the point that "an annual loss of 11 billion dollars (for damage due to air pollution) has often been cited, and this figure was derived by multiplying $60 by the U. S. population in 1958. It must be noted that many of the allegations concerning the economic impact of air pollutants are far from scientific." Kneese (29) has stated that "current estimates of national costs of air pollution are indefensible and should be abandoned;" this is due to the unscientific methods which have been employed in most cases. The area of the economic impact due to air pollution effects on plants is one which needs more extensive research and substantiation of estimates.

The attainment of an economic assessment of reduced growth of a forest trees species was accomplished in the work of Linzon (29) in the Sudbury Smelter district of Ontario, Canada with eastern white pines. Linzon estimated the reduced growth of the white pines in and surrounding the smelter area over a ten year period by measuring heights of the trees, annual radial increment growth, and mortality (due to unknown causes) which occurred during the period of study.

> "The measurements of heights and diameters of white pine trees were used to make a local volume table for each plot. The total volume in cubic feet was computed from the volume tables for white pine trees in the 7"-12" D.B.H. class which were living in 1953, and was compiled again for those trees which were still living in 1963 on each sample plot. The 7-12 inch D.B.H. class was selected for a standard of comparison...It is apparent from the volume growth tables that in the areas contiguous to the sources of the sulphur fumes white pine trees exhibited a net average annual loss of 0.10 cu. ft. per white pine tree in the 7-12 inch D.B.H. class due to the combination of trees dying from unknown causes and reduced growth of surviving trees. In the non-fume zone each tree added 0.30 cu. ft. in total volume per year. Together this represented a loss of 0.40 cu. ft. in total volume per tree per year in the Inner Fume Zone."

Using the figure of 50% net merchantable volume of the gross total volume for sawlogs, the acreage of productive forest land affected (244,916 acres or 23 sq. mi.), and the fact that only 7.6% of the total land was occupied by white pine, along with the assumption of 50 white pines per acre, Linzon found an annual stumpage loss of $14,008 while $117,100 was lost per year as the producer's value. Though the figure of losses is small, it must be remembered that this is an area of only 23 sq. mi. and the only loss measured is that of only white pine which comprised less than 10% of the entire forest.

The work of Middleton _et al_. (30) was one of the first attempts to measure the conomic impact of air pollutants to agricultural crops. The damage in Los Angeles County, California, was assessed during 1949. Using the "1949 Annual Crop Report of the Los Angeles Agricultural Commissioner" to set the average per acre yields, or normal yields for the area during 1949, the affected areas were compared to normal growth present and losses due to air pollution were obtained as the difference. The volume loss found was converted to a monetary loss by the use of established market prices for that year. This produced a direct (to crops) annual loss of $479,495 in Los Angeles County. This corresponds well with the later work of Linzon (29) as previously mentioned) in that large annual losses are found corresponding to localized or specific effects of pollutants which give an indirect estimation of the enormous losses capable of occurring nationally due to air pollution. Weidensaul and Lacasse (49), dealing with the effect of air pollution on crops (agricultural, forest, and ornamental) in the state of Pennsylvania, presented a direct economic loss to crops in excess of $3.5 million annually. They also found an indirect loss (which included losses due to crop substitution, grower relocation costs, and profit losses) in excess of $8 million annually.

In 1971 a survey and assessment of air pollution damage to vegetation in New Jersey was conducted by Feliciano (21) and the state extension service. They estimated the economic loss to crops due to air pollution at $1.2 million for 1971. Indirect losses to growers along with economic losses to forest trees and ornamental plants were not included in the estimate. Field observations provided the main source of data for the analysis of crop loss. The field observations were provided by growers and the extension service. Both the work in New Jersey and Pennsylvania (49) along with that of Middleton *et al*. (30) relied on visual perception of air pollution injury and a subsequent estimate of damage. In the case of Middleton *et al*., damage estimates came from expressing the volume loss calculations in a monetary form while the study of damage in Pennsylvania relied upon trained observers (a post doctoral scholar in plant pathology and staff of the Center for Air Environmental Studies) for estimates of damage. In the New Jersey study, methods of assessing loss varied. The work in these experiments is commendable but they fail to consider the possibility of reduced yield without visible symptoms.

In 1969 and 1970 the Stanford Research Institute (1) conducted a detailed survey in which estimates of the effect of air pollutants on plants were presented for the entire United States. The basis for this estimate was the evaluation of previous data presented in literature and the conversion of these independent data types mathematically through a formula into loss estimates. The loss estimates were found by consideration of air pollutant emission data, plant sensitivity data, meteorological data, crop yield data, and experience in the area of the effect of air pollutants on growth. The mathematical formula developed for estimating the approximate dollar loss of a particular crop due to a particular pollutant was

$$C = XY \frac{(Z - Y)}{Z}$$

where

C = approximate dollar loss;

X = price per unit produced under polluted conditions;

Y = number of units produced under polluted conditions;

Z = potential units produced under clean conditions.

This essentially says that the dollar loss is equal to the value of the crop times the percentage reduction in yield ascribable to the pollution. This formula produced estimates in 1969 of losses due to commercial crops only. These losses were:

$65,000,000 due to oxidants (ozone, PAN, and nitrogen oxides)

$ 3,500,000 due to SO_2

$ 3,000,000 due to fluorides.

These estimates were considered by the Stanford Research Institute to be deficient in three major ways:

1. Estimates of severity of pollution in various countries were based on emission data only, and the effects of meteorological and other factors in consideration.
2. In estimating the loss of individual crops, it was assumed that crops considered sensitive to a given pollutant were equally sensitive and those resistant were equally resistant.
3. Losses to ornamental plantings were not considered due to a lack of time in acquisition of data.

These drawbacks were alleviated in the second year.

The second year's study assigned a pollution potential to the different geographic areas individually and found independent values for each pollutant. These ratings were based on area, emission data, and meteorological data. This pollution potential was then combined with crop value and a crop sensitivity rating to give a dollar loss estimate. When the results of the study were concluded, the economic loss to agricultural and ornamental crops was found to be approximately $85.5 million annually in the U. S. The annual loss to forest and nursery crops was found to be in excess of $19 million. This study, though it is more of a scientific or computer model of air pollution in the U. S., is the most complete study on the economic-impact of air pollutants on plants to this date.

The aforementioned literature has demonstrated that air pollutants can and do reduce growth and/or yield of agricultural and forest crops. Also, a lack of in-depth studies in this area is clearly recognizable and air pollution, long considered a menace to plants, should be recognized for its far-reaching effects. Growth and/or yield loss in this time of short supplies should be researched and studied so as to alleviate or terminate its occurrence.

MATERIALS AND METHODS

Field Chamber Studies: Location

Seven forest tree species were subjected to ambient pollution levels by the use of exposure chambers and ambient field plots to determine the impact of air pollution on seedling height growth and senescence (1973). These seedlings were yellow poplar (*Liriodendron tulipifera* L.), sycamore (*Platanus occidentalis* L.), red oak (*Quercus rubra* L.), green ash (*Fraxinus pennsylvanica* Marsh.), white ash (*F. americana* L.), sweetgum (*Liquidambar styraciflua* L.), and Virginia pine (*Pinus virginiana* Mill.). Three stations were established for this experiment. Stations I and II were located in areas where relatively high ambient pollution levels were known to occur by prior monitoring of the U. S. Army Environmental Hygiene Agency in 1967 (47). Station I was located within the boundaries on the prevailing downwind (southeast) side. This station was situation 0.5 km from the Arsenal's closest emission source of nitrogen oxides (the TNT facility) (Figure 1). Station II was located in the downwind area 4.8 km east of the Arsenal on land leased by VPI & SU. Station III which was to act as a control on the two downwind stations was located 7.8 km upwind from the Arsenal's production area on land utilized for storage by the Arsenal in Dublin, Virginia.

Experimental Apparatus

The seedlings were placed in three semi-controlled exposure situations previously established by Stone (39) and Skelly and

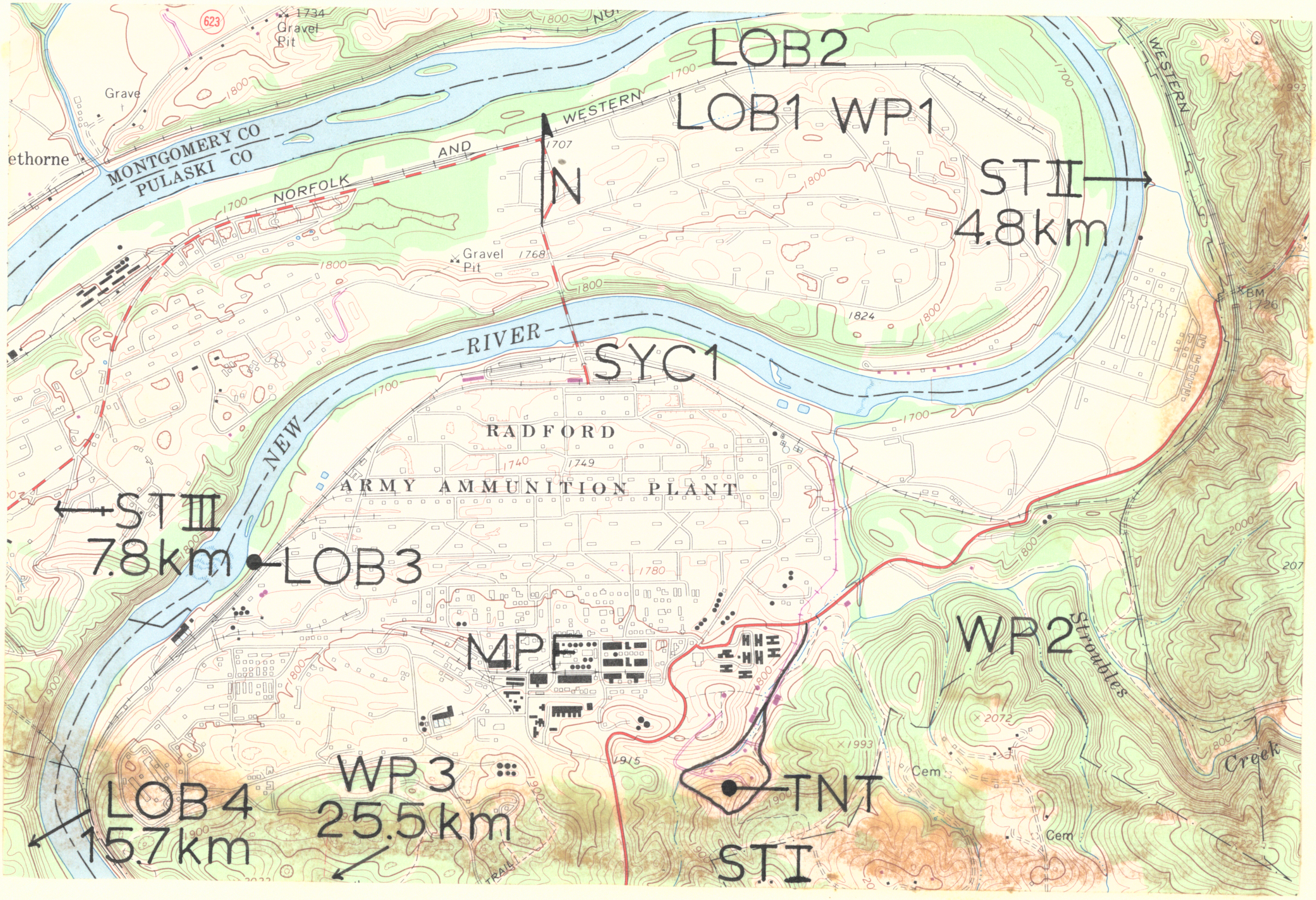
Figure 1. Topographic map of the U. S. Radford Army Ammunition Plant, or Arsenal, in Radford, Virginia, and the surrounding area, depicting field research stations, forested sampling areas, and the Arsenal's main power facility.

Map Legend:

ST I	-	Virginia Polytechnic Institute and State University (VPI & SU) Field Research Station I
ST II	-	VPI & SU Field Research Station II
ST III	-	VPI & SU Field Research Station III
LOB 1	-	Loblolly Pine Stand #1: A Stand of 16-Year Old Loblolly Pine
LOB 2	-	Loblolly Pine Stand #2: A Stand of 19-Year Old Loblolly Pine
LOB 3	-	Loblolly Pine Stand #3: A Stand of 16-Year Old Loblolly Pine
LOB 4	-	Loblolly Pine Stand #4: A Stand of 18-Year Old Loblolly Pine
WP 1	-	White Pine Stand #1: A Stand of 16-Year Old White Pine
WP 2	-	White Pine Stand #2: A Stand of 35-140-Year Old White Pine
WP 3	-	White Pine Stand #3: A Stand of 30-70-Year Old White Pine
SYC 1	-	Sycamore Stand: A Stand of 30-200+-Year Old Sycamore
MPF	-	Main Power Facility of the Arsenal
TNT	-	Trinitrotoluene (TNT) Production Area

Scale: 1: 24,000

Contour Interval: 6.1 m (20 feet)


LOB2
LOB1 WP1
N
ST II
4.8 km
SYC1
ST III
7.8 km
LOB3
MPF
WP2
WP3
25.5 km
LOB 4
15.7 km
TNT
ST I
MONTGOMERY CO
PULASKI CO
NORFOLK AND WESTERN
NEW RIVER
RADFORD
ARMY AMMUNITION PLANT
Gravel Pit
Grave
ethorne
Stroubles Creek
Cem
Cem
WESTERN

Stone (37). One chamber at each station was designated as the filtered-air chamber. This chamber received air flow by means of an activated charcoal filtration system. The activated charcoal filters used in this experiment were 46 cm by 46 cm by 2.5 cm thick obtained from Barneby-Chaney Incorporation (Columbus, Ohio). A flexible four mil polyethylene ductwork replaced the previous sheet-metal ductwork used by Stone (39) and Skelly and Stone (37) for better air delivery. The ductwork channeled the filtered air through evenly distributed 5 cm diameter holes. A weighted louver was again utilized to maintain a constant positive pressure within the chambers which eliminated the entrance of unfiltered air. The second chamber at each station was designated the non-filtered chamber. Ventilation was improved by placing wire screening, instead of the vents previously used, 10 cm in height along the bottom of both sides of the chambers. The open plots received ambient air flow. To stabilize moisture availability, an automatic watering system was added in the chambers at each plot.

Instrumentation

A Belford Hygrothermograph® (Belfort Instrument Company, Baltimore, Maryland) was located at all three exposure situations in each station. A Mast NO_2 meter (Mast Development Company, Davenport, Iowa) was located within the instrument shed at each station along with a Mast Strip-chart Recorder. The Mast NO_2 meters sampling probes were connected by means of teflon tubing to the open-air and filtered-air conditions at each plot. The meters continuously monitored total oxidant levels of the ambient air pollution at each station except for periodic checks on the activated charcoal filtration systems of the filtered air chambers. The detected levels were recorded as parts-per-million (volume:volume) on the Mast Strip-chart Recorder.

Seedling Growth and Measurement

Seedlings of six hardwood and one coniferous species were established at each station. These were yellow poplar, sycamore, red oak, green ash, white ash, sweetgum, and Virginia pine, as previously listed. The seedlings, 1-0 (outplanted for one year) nursery stock obtained from Virginia Division of Forestry Nursery, Waynesboro, Virginia, were maintained in cold storage until planting in May 1973. The seedlings were planted 3 per 11.35 liter pot containing a 1:1:1 potting mixture of Weblite® (an expanded shale product of Webster Brick Company, Roanoke, Virginia), sawdust, and clay-loam soil. The pots were placed in rows of five with a distance of 30 cm inbetween them. Two pots of each species were placed in all exposure situations at the individual stations. The seedlings remained at the research stations from June until October during the time periodic checks of foliar symptoms were taken. In October of 1973 the seedlings were removed to a cold storage bin at the air pollution research center on Glade Road in Blacksburg where measurements on annual terminal elongation and foliar senescence were obtained. Senescence ratings were based on leaf coloration and leaf fall where 1 = 0-10%, 2 = 11-50%, 3 = 51-90%, and 4 = 91-100%.

Statistical Analysis

Each station was developed to expose replicates of each tree species to filtered-air, non-filtered air, and open conditions. An Aposterior test was utilized to determine if any significant differences in terminal elongation occurred between the filtered-air, non-filtered air, and open-grown seedlings. The growth of plants in the filtered-air chambers acted as a control for the plants exposed to air pollutants in the open and non-filtered air situations. The open plots functioned as a control for the greenhouse conditions experienced in the chambers.

The research stations which utilized semi-controlled conditions eliminated a large part of variation due to the influence of the environment upon growth. Environmental influences on growth were one of the largest problems in determining the growth-impact of air pollutants in field experiments. The results from the chamber study, therefore, functioned as a control upon the natural conditions of the increment core studies. The chamber data simulated an absolute in growth response which was compared to the results from the variable environmental conditions of the increment core studies.

Annual Radial Growth Studies: Location

Radial increment studies were conducted to determine if a correlation existed between past pollution levels at the Arsenal and the annual radial growth rates of the forest trees subjected to these levels. Loblolly pine (*Pinus taeda* L.), white pine (*P. strobus* L.), and sycamore (*Platanus occidentalis* L.) were sampled in several stands within the Arsenal. One stand of loblolly pine and one stand of white pine were sampled outside the Arsenal to act as controls.

All of the loblolly pine stands which were sampled were growing in a level area on a sandy-clay soil. These stands had been artificially generated and were planted on a 6 feet (1.8 m) by 6 feet (1.8 m) spacing. Loblolly pine #1 was located within the confines of the Arsenal 2.6 km northeast of the main power facility (Figure 1). This stand had been planted in 1959. Loblolly pine #2 which was planted in 1956 was located in the same general area as loblolly pine #1 -- 2.7 km northeast of the main power facility. This was the oldest stand of loblolly pine within the Arsenal. Loblolly pine #3 was located 1.4 km northwest of the main power facility. This stand was planted in 1959. Loblolly pine #4 which was planted in 1957 functioned as the control plot and was located outside the confines of the Arsenal 15.7 km southwest and upwind of the main power facility at Claytor Lake State Park. No sivicultural treatments other than those associated with normal planting procedures had been conducted in these stands.

Three stands of white pine were also sampled. White pine #1 was located 2.6 km northeast of the main power facility of the Arsenal in the same general area as loblolly pine #1 and #2. This stand was artificially generated in a 6' (1.8 m) X 6' (1.8 m) spacing on slightly northerly sloping topography. The stand which was planted in 1959 had undergone lower limb pruning to a height of approximately five feet in 1970. White pine #2 was located in a natural, uneven-aged, mixed stand of white pine and hardwoods on a sharply sloping northwest exposure 1.6 km east of the main power facility. White pine #3 which was to act as a control was located 25.5 km southwest of the Arsenal's main power facility at the intersections of state routes 738 and 640 near Pulaski, Virginia. This stand was similar to white pine #2 as it was located on a sharp and northerly sloping terrain.

The one stand of sycamore which was sampled was located 1.4 km north of the Arsenal's main power facility. This stand was adjacent to the section of New River which flows through the Arsenal. The stand had been naturally generated and was uneven-aged and interspersed with other wet site hardwoods.

Sampling Procedure

Fifty trees from the dominant or codominant crown class of each stand were sampled. In the naturally generated stands, trees were chosen at random within the dominant or codominant class. The artificially regenerated stands were sampled by randomly selecting trees from the dominant or codominant crown classes which were located around the outside edges of the stands. This was done to remove the influence of stand closure upon the growth rate of the sampled trees due to their close spacing. Loblolly pine #3, however, was randomly sampled by the method used in the natural stands due to the lack of a definable edge in its location.

Sampling was accomplished by using an increment borer to obtain a 3.2 millimeter (mm) in diameter increment core from each tree. The increment cores were taken at d.b.h. (1.37 m from the base of the tree) and on the same aspect of the stand whenever possible. Once obtained, the cores were placed into ordinary soda straws with masking tape placed over both ends for protection during transfer to the laboratory. The increment cores and the corresponding trees were both labelled to keep a constant relationship between the tree and any data resulting from it. At the laboratory, the cores were placed in a refrigerator to prevent dessication until radial increment measurements were taken.

Increment cores were measured and dated by means of a DeRouen dendrochronograph utilizing a variable power (7-30X) binocular scope. The instrument was adjusted to zero at the beginning of each core; then, proceeding from the cambial layer inward, the annual increments differentiated by density changes between early and late wood were measured. The constant inward measurement allowed the dating of growth by the first increment corresponding to the year of sampling and each year thereafter was dated with reference to that first radial increment. This dating allowed the age of the artificially generated trees in a certain year to be associated with the annual radial increment growth that each tree demonstrated that year. This chronological age variable was not obtainable in the natural uneven-aged stands by this manner. An age variable was associated with the growth increment of these trees by counting the number of annual increments present on the increment core and obtaining a chronological age at d.b.h. for these trees. Utilizing this age at d.b.h. and the previously mentioned dating procedure, an age variable was associated to the annual increment growth of the individual trees for each year measured. Measurements of annual radial growth from 1960-1971 were obtained for the sampled trees in the loblolly pine stands and also for the sampled trees in the white pine #1 stand. The measurements of annual radial growth of the older uneven-aged stands of white pine and sycamore were obtained from 1935-1971. The age variable was not obtainable in the sycamore stand due to the size of the sample trees surpassing the capabilities of the increment borer.

Statistical Analysis

The growth increment data was analyzed by means of a multiple linear regression analysis. This analysis was used to establish a statistical model to test the null hypothesis that there was no relationship between Arsenal production levels and annual increment growth rate of the trees. The annual radial increment growth of the individual trees of each species acted as the dependent variable Y. The multiple regression model used was:

$$Y = \alpha + \beta_1 X_1 + \ldots + \beta_Q X_Q$$

where the dependent variable Y is regressed on the independent variables $X_1 - X_Q$ according to the regression parameters $\beta_1 - \beta_Q$. Estimates of the population parameters α and $\beta_1 - \beta_4$ were solved with the sample data.

Independent Variables

The percent average annual production level of the Arsenal was obtained by the method of Stone (39) and Stone and Skelly (40) which was derived from the past annual coal consumption of the powerhouses. Coal consumption and all other levels were standardized accordingly. Production levels were represented by the independent variable X_1.

The age of the trees at the time the corresponding radial growth occurred (found by the previously mentioned method) was used as the independent variable X_2. Rainfall data obtained from the Blacksburg, Virginia Meteorological Station (12) provided the remaining two independent variables of total annual rainfall and seasonal (April 1 through September 30) rainfall, which were represented by the variables X_3 and X_4, respectively.

Hidden Injury Studies

The trees in the stand of white pine designated white pine stand #2 showed typical varying foliar responses to the surrounding ambient air pollutants. To determine if foliar injury was directly linked to the correlations of growth to production levels at the Arsenal, the sampled trees within this stand were subjected to a multiple linear regression analysis containing a visible injury variable. The trees when sampled were visually rated for foliar injury present in the crown. These ratings were:

1 = the crowns of trees within this class demonstrated tipburn of more than 25% of the needles;

2 = the crowns of trees within this class demonstrated tipburn of not more than 25% of the needles;

3 = the crowns of trees within this class exhibited chlorosis but not tipburn of the needles and thin crowns due to stunted short needles or defoliation;

4 = the crowns of trees within this class were symptomless.

The regular multiple linear regression analysis as previously discussed was conducted for this stand. Once this had been accomplished, the trees were separated into their individual crown rating classes and the regression analysis was again conducted with the individual classes in order to demonstrate whether the severity or presence of visible injury affected the correlations of annual radial growth to production levels of the Arsenal.

Growth Loss Studies

A stand analysis was conducted to obtain an estimate of the effect of past pollution levels at the Arsenal on growth of the sample stands. This analysis was conducted by predicting growth rates of trees within the Arsenal and trees grown in an hypothesized pollution-free condition.

A relative estimate of growth differences was obtained by means of the statistical models created in the previously mentioned multiple linear regression analysis. It was necessary to establish a growth estimate for both non-polluted trees and trees subjected to the historical production levels of the Arsenal. The statistical model utilized was the multiple linear regression analysis in which mm of radial increment growth was predicted by the independent variables of age, total annual rainfall, annual seasonal rainfall, and average annual production levels of the Arsenal. To determine what differences in growth within individual stands would have been present, the yearly data of rainfall (annual and seasonal), age, and production were placed into the equation simultaneously and a measurement of mean annual radial increment was obtained 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 then hypothesized by interjecting the yearly data of age, annual seasonal rainfall, and total annual rainfall into the equation. However, instead of inserting the corresponding production level for that year, a zero level of pollution was inserted 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

Field Chamber Studies

The instrumentation present at each of the three sites provided several qualitative as well as quantitative points of information. The periodic checks of the filtered-air chambers demonstrated the reliability of a near pollution-free condition within these chambers at all three plots. The hygrothermograph readings at all three sites indicated the absence of large variations in temperature between the filtered and non-filtered chambers. The comparison of maximum and minimum temperatures between the two chambers demonstrated that differences in these two temperature variables were generally from 0.5-3.0 C and never greater than 5.0 C. Differences in maximum and minimum temperatures between the filtered-air chamber and the open plot, however, were generally greater than 3.0 C and in some cases as large as 9.0 C. The comparison of these two temperature variables between the non-filtered air chamber and open plot indicated a less differentiated situation with temperature differences generally less than 3.0 C. Quantitatively, the continuous air pollution monitoring system at each plot provided readings of total oxidant levels which were utilized to derive monthly maximum and minimum 24 hour mean concentrations in pphm (Table 2).

The periodic visual checks on the foliage of the sample trees indicated that acute symptoms of air pollution injury were found

Table 2. Maximum and minimum 24 hour mean monthly total oxidant concentrations for the field chamber studies in parts per hundred million (pphm).

Month	Station I*		Station II**		Station III***	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
May	8.7 pphm	35.7 pphm	2.0 pphm	37.0 pphm	2.7 pphm	50.8 pphm
June	8.0 pphm	32.6 pphm	14.3 pphm	32.2 pphm	5.7 pphm	13.7 pphm
July	3.3 pphm	12.1 pphm	12.7 pphm	36.0 pphm	6.3 pphm	14.1 pphm
August	3.2 pphm	12.5 pphm	16.2 pphm	36.7 pphm	5.3 pphm	12.7 pphm
September	5.0 pphm	11.1 pphm	11.8 pphm	36.6 pphm	6.0 pphm	13.5 pphm

* Station I was located 0.5 km southeast of the main power facility of the Arsenal.

** Station II was located 4.8 km east of the main power facility of the Arsenal.

*** Station III was located 7.8 km southwest of the main power facility of the Arsenal.

consistently on sweetgum in the non-filtered chambers and open plots at all three locations. Yellow poplar and sycamore were probably the second most severely affected species at the three locations and chronic symptoms (purple stippling and glazing of the leaves) were located on the majority of seedlings in the open plot and on a few seedlings in the non-filtered chambers. Seedlings of green ash exhibited chronic symptoms on five of the 18 seedlings in the open plots while seedlings in the filtered and non-filtered chambers failed to exhibit symptoms. Less than one-third of the seedlings of white ash and red oak in the open plots exhibited the purple stippling indicative of chronic air pollution injury; however, all other seedlings in the open plot and non-filtered chamber failed to demonstrate symptoms of air pollution injury. The seedlings of Virginia pine failed to exhibit visually detectable air pollution symptoms in the non-filtered chamber or open plots at any of the three stations. The seedlings within the filtered-air chambers consistently failed to demonstrate symptoms attributable to air pollution injury.

Measurements of terminal elongation of the seedlings were divided into individual species among all three stations and utilized to derive an average terminal elongation value for each species within each exposure situation (Table 3). The seedlings maintained in the filtered-air chambers, except those of sycamore, consistently demonstrated increases in terminal elongation compared to the seedlings grown in the non-filtered chambers and the open plots. Seedlings grown in the non-filtered air chambers also demonstrated increases in terminal elongation over seedlings grown in the open plots except for seedlings of

Table 3. The average terminal elongation of seedlings of seven forest tree species established in field chambers and open plots at three locations associated with relatively high ambient air pollution levels.

Species	Chamber type		Open
	Filtered	Non-filtered	
Sycamore	29.6 cm	36.1 cm	25.3 cm
Yellow poplar	21.1 cm	18.3 cm	14.3 cm
Sweetgum	21.4 cm	20.4 cm	18.3 cm
White ash	12.3 cm	9.2 cm	11.8 cm
Green ash	30.3 cm*	26.1 cm	22.4 cm
Red oak	10.8 cm* †	7.0 cm	6.5 cm
Virginia pine	16.5 cm** †	13.5 cm	11.7 cm

* Significant difference between filtered and open at 0.05 level.

** Significant difference between filtered and open at 0.01 level.

† Significant difference between filtered and non-filtered at 0.05 level.

white ash. These differences in terminal elongation were significant in only three of the seven species. Green ash seedlings demonstrated significant increases in terminal elongation of seedlings located in the filtered-air chambers compared to those in the open plots. Red oak and Virginia pine not only demonstrated increases in terminal elongation of seedlings in the filtered-air chambers over those in the open plot, but also demonstrated increases in terminal elongation of the filtered-air compared to the non-filtered air grown seedlings.

The senescence ratings of seedlings of the deciduous trees were also divided into individual species among all three stations from which an average senescence rating was obtained for each species within each exposure situation (Table 4). These ratings were based on leaf coloration due either to air pollution injury or natural fall coloration of the foliage along with leaf fall (seasonal or air pollution induced) and utilized to evaluate the comparative stage of senescence of the seedlings. The major differences to be evaluated were between extremes of green vigorous foliage to a completely defoliated seedlings. This would allow the differentiation between seedlings still capable of further growth and those which were obtaining or had already obtained the majority of growth for that season. The analysis demonstrated that seedlings located in the non-filtered chambers and open plots were consistently in later stages of senescence than those in the filtered-air chambers.

Sweetgum demonstrated an inverse relationship between the average terminal elongation of the seedlings and the corresponding average

Table 4. The average senescence ratings[1] of seedlings of six deciduous forest tree species established in field chambers and open plots at three locations associated with relatively high ambient air pollution levels.

Species	Chamber type		Open
	Filtered	Non-filtered	
Sycamore	1.4	2.6	2.5
Yellow poplar	1.9	3.3	2.6
Sweetgum	1.6	2.4	2.6
White ash	1.5	2.0	2.2
Green ash	1.2	1.5	1.4
Red oak	1.6	1.7	2.2

[1] Ratings were: 1 = 0-10%; 2 = 11-50%; 3 = 51-90%; 4 = 91-100% based on leaf fall and leaf coloration.

senescence rating. Interactions between terminal elongation and leaf senescence were complicated due to the fact that all of the other deciduous species subjected to the ambient air pollution failed to consistently exhibit visible foliar symptoms of air pollution injury during the growing season. Red oak, irrespective of the occurrence of consistent visible symptoms during the growing season, demonstrated an inverse relationship between foliar senescence and average terminal elongation. These differences, however, were very small. The remaining four deciduous species failed to exhibit any correlation of average terminal elongation with average senescence ratings other than differences between seedlings maintained in the filtered-air chambers compared to those subjected to ambient air pollution.

Annual Radial Growth Studies

A regression analysis consisting of four simple linear regression analyses and four multiple linear regression analyses was performed. The four simple regression analyses were conducted 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 multiple regression analyses also 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 total linear regression analyses were conducted within all of the sample stands. The results of these analyses along with a graphical comparison of annual radial increment growth and average annual production levels of the Arsenal were placed in the Appendix.

The annual radial increment growth of the sample trees within loblolly pine stand #1 did not demonstrate a significant linear relationship with annual production levels of the Arsenal (Appendix: Figure 1; Table 1). A positive linear relationship significant at the 0.001 level was found to exist between annual radial increment growth and age of the sample trees. The two rainfall variables also failed to correlate linearly with radial increment growth in a simple linear regression analysis. The multiple linear regression analyses were then utilized to compare annual radial increment growth to annual production levels of the Arsenal while the effects of other variables independently and/or simultaneously were removed. Annual radial increment growth demonstrated an inverse correlation to annual production levels which was significant at the 0.001 level when the effect of age was removed. A significant linear relationship was not demonstrated between growth and production when either of the two rainfall variables were removed first. A significant inverse linear relationship was also demonstrated between increment growth and production levels when age and the two rainfall variables were removed first. This relationship was significant at the 0.001 level and had a higher F-value and partial correlation coefficient than any of the previous regression analyses.

In loblolly pine stand #2 all of the independent and multiple regression variables demonstrated a significant inverse linear relationship with annual radial increment growth (Appendix: Figure 2; Table 2). The highest F-values and correlation coefficients were demonstrated by the simple linear regression of production on growth, the regression analysis in which age was removed and production regressed on growth, and when production was regressed on growth after removing all other variables. This last analysis maintained the greatest degree of correlation and the largest F-value (indicating a higher level of significance).

The annual radial increment growth of sample trees in loblolly pine stand #3 demonstrated a positive linear relationship to annual production levels which was significant at the 0.005 level (Appendix: Figure 3; Table 3). Age also demonstrated a positive correlation with increment growth which was significant at the 0.01 level. An inverse relationship between total annual rainfall and increment growth significant at the 0.01 level was also found. A significant relationship was not exhibited between increment growth and annual seasonal rainfall within the sample trees. The use of the multiple linear regression analyses brought many changes in the correlation of production levels to increment growth. When either of the two rainfall variables were removed first and production was compared to radial growth, an increase in positive correlation and significance was exhibited. Removing the effect of one or more variables and then evaluating the partial correlation of a remaining variable is equivalent to holding the removed variables constant. However, when all other variables were removed or age alone was removed, the relationship between growth and production was non-significant.

Loblolly pine stand #4 which was utilized as the control stand exhibited an inverse relationship when annual increment growth was compared to production levels or age (Appendix: Figure 4; Table 4). These linear relationships were significant at the 0.001 level. Total annual rainfall was positively correlated to annual radial increment growth which was also significant at the 0.001 level. Annual seasonal rainfall again did not demonstrate a significant linear relationship with increment growth. Annual radial increment growth retained a highly significant inverse relationship with the Arsenal's production levels when total rainfall or annual seasonal rainfall were removed independently. The relationship between increment growth and production levels was non-significant when evaluated after removing the variable of age. Increment growth and annual production levels were compared after removing all remaining variables and a positive linear relationship between growth and production was exhibited which was significant at the 0.05 level.

The annual radial increment growth of the sample trees within white pine stand #1 demonstrated a positive linear relationship with annual production levels of the Arsenal which was significant at the 0.001 level (Appendix: Figure 5; Table 5). Between the two rainfall variables, annual seasonal rainfall was positively correlated to increment growth at the 0.001 level while total annual rainfall failed to exhibit a significant relationship with increment growth. The linear regression of production on growth remained positively oriented and highly significant when subjected to the four multiple linear regression analyses but when age or when all variables except production levels and growth were removed, the F-value and partial correlation coefficient of the regression were greatly reduced.

The sample trees within white pine stand #2 demonstrated linear relationships which were significant at the 0.001 level for all eight regression analyses (Appendix: Figure 6; Table 6). These were inverse relationships in all of the analyses except when either of the two rainfall variables were regressed on annual radial increment growth of the sample trees in which case a positive correlation was found. Of the regression analyses conducted, the comparison of growth with age had the highest F-value and correlation coefficient, yet all comparisons of production levels with growth demonstrated higher correlation coefficients and F-values than the comparison of growth to the rainfall variables. No drastic changes in the correlation of growth to production levels were found in the multiple regression analyses irrespective of removing the other variables simultaneously or independently.

The annual radial increment growth of sample trees within white pine stand #3 which was to act as a control demonstrated inverse relationships which were significant at the 0.001 level with age, production levels, production removing either of the two rainfall variables first, and production removing all variables first (Appendix: Figure 7; Table 7). An inverse relationship significant at the 0.005 level was found between growth and production after removing age. A positive relationship significant at the 0.001 level was again found between growth and the rainfall variables. The regression of age upon radial increment growth was the relationship with the highest correlation coefficient and the largest F-value. After age was removed independently or when all variables were removed beside production (which included age), a drastic decrease was found in the size of the F-value and the degree of correlation in the linear regression of production levels on annual radial increment growth of the sample trees.

When the independent variables of annual production levels, total annual rainfall, and the annual seasonal rainfall were compared by means of linear regression analyses, annual seasonal rainfall demonstrated a significant positive correlation with increment growth of sycamore at the 0.05 level (Appendix: Table 8). As previously mentioned, age was not available for comparison with growth and the remaining two variable failed to significantly correlate with growth. The regression of annual production levels on growth was non-significant when the other two variables of rainfall were first removed individually or simultaneously.

Hidden Injury Studies

The sample trees within white pine stand #2 were divided into four crown injury categories. As previously described, these ratings were:

1 = the crowns of tress within this class demonstrated tipburn of more than 25% of the needles;

2 = the crowns of trees within this class demonstrated tipburn of not more than 25% of the needles;

3 = the crowns of trees within this class exhibited chlorosis but not tipburn of the needles and thin crowns due to stunted short needles or defoliation;

4 = the crowns of trees within this class were symptomless.

The number of trees within each rating class were: rating level #1, 5; rating level #2, 9; rating level #3, 16; and rating level #4, 20. The average age of the trees within each rating class were: rating level #1, 74; rating level #2, 86; rating level #3, 69; and rating level #4, 77. The growth rates of trees within the individual rating groups were then subjected to the multiple linear regression analysis previously used on the entire stand data. The results of these analyses were then compared to the results found in the analysis of the complete stand. The sample trees within rating level #1 when subjected to the regression analyses demonstrated the same significant linear relationships as the analysis of the complete stand except with the two rainfall variables which became non-significant (Appendix: Table 9). The other analyses involving production levels within this rating demonstrated increases in their associated negative correlation coefficients over those of the non-differentiated stand (all ratings included). The correlation coefficient associated with the regression involving age, however, was reduced. The major difference found between the analyses of sample trees within rating level #2 and that of the undifferentiated stand was that total annual rainfall failed to correlate significantly with growth within rating level #2 (Appendix: Table 10). A reduction in the correlation coefficients and significance levels 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 that of the one rainfall variable were significant at a minimum of 0.05 level. Sample trees within rating level #3 (Appendix: Table 11) did not differ in analysis in regard to significant relationships from the undifferentiated stand. There was an increase in the associated correlation coefficients of all eight of the regression relationships along with a reduction in the significance level of the regression of total annual rainfall on radial increment growth from a 0.001 level to a 0.01 level. No other differences were found between the two analyses. The multiple linear regression analysis of annual radial increment growth of sample trees within rating level #4 was similar to rating level #3 in that the only differences from the analysis of the undifferentiated stand was in the significance level of the total annual rainfall variable and size of the correlation coefficients (Appendix: Table 12). The correlation coefficients associated with the regression of production levels on growth were smaller and the correlation coefficients associated with age and the two rainfall variables when regressed on growth were larger.

The regression of annual production levels of the Arsenal on the annual radial increment growth of sample trees within white pine stand #2 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 variable within the five analyses. Total annual rainfall failed to show a significant relationship to growth in levels #1 and #2 and this relationship was also non-significant for annual seasonal rainfall in rating level #2 trees. Among the five multiple linear regression analyses, the highest associated correlation coefficient with the individual variable analyses was found in the regression of age on annual increment growth. Age, however, did not have to be held constant to find a significant inverse correlation of production levels at the Arsenal and annual radial increment growth of the sample trees.

Growth Loss Studies

The differences between predicted mean annual radial increment growth of trees subjected to past air pollution levels of the Arsenal 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 stand #1, loblolly pine stand #2, and white pine stand #2 demonstrated the necessary significant inverse relationship of radial increment growth to annual production levels of the Arsenal needed to provide an estimate of growth reduction. The predictive model for mean annual radial increment growth in loblolly pine stand #1 was $Y = 7.26356 - 0.07698X_1 + 0.75930X_2 - 0.02541X_3 - 0.16941X_4$. The variables, as previously mentioned, were:

Y = mean annual radial increment

X_1 = annual production levels of the Arsenal

X_2 = age

X_3 = total annual rainfall

X_4 = annual seasonal rainfall.

This provided an estimated diameter-inside-bark (d.i.b.) growth of 4.5" (56.7 mm) for trees subjected to the Arsenal's ambient air pollution levels and 8.1" (103.2 mm) for the same trees in a hypothesized pollution-free condition over a 12-year period. This resulted in a growth inhibition of 3.6" (46.5 mm) in diameter growth which indicated a 45% reduction in d.i.b. due to the Arsenal's ambient air pollution levels.

The statistical model provided for the prediction of mean annual radial increment growth for loblolly pine stand #2 was $Y = 9.17036 - 0.10275X_1 + 0.71510X_2 + 0.16040X_3 - 0.53127X_4$. The estimated d.i.b. growth over a 12-year period for sample trees in this stand subjected to the Arsenal's air pollution levels was 6.2" (78.7 mm) while pollution-free growth was estimated as 11.2" (142.5 mm). The resulting growth inhibition was 5.0" (63.8 mm) or a 45% reduction in d.i.b.

White pine stand #2 had the predictive model of $Y = 3.17301 - 0.00628X_1 - 0.02039X_2 - 0.01963X_3 - 0.05152X_4$. Sample trees in white pine stand #2 had a predicted d.i.b. growth of 6.4" (81.0 mm) for trees subjected to the ambient pollution levels of the Arsenal over a 37-year period and 7.1" (90.2 mm) for pollution-free growth. The predicted inhibition in growth was 0.7" (9.2 mm) or a 10% reduction in d.i.b. growth.

It should be pointed out that a pollution-free environment (i.e., production levels, X_1, equal zero) is an extrapolation of the regression equations. Furthermore, if diameter growth were increased for any tree in the stand, it would produce a corresponding increase in intra-specific competition. Therefore the percentage increases computed here are merely indicators of the possible order of growth loss due to air pollution.

DISCUSSION

Field Chamber Studies

A large number of studies concerning the effect of air pollutants on forest tree species have been performed with seedlings. These studies have dealt primarily with symptomatology and generally were conducted as short-term, high-concentration fumigations with single pollutants. The effect of low-level, long-term ambient air pollutants upon the growth of seedlings has not been emphasized. The majority of work dealing with the effect of ambient air pollutants on the height growth of young trees has been field reports of air pollution injury (18, 36).

The seven species established at the three field stations provided information dealing with the effect of ambient air pollutants upon the height growth of 1-0 seedlings. As previously mentioned, these species were: sycamore, sweetgum, yellow poplar, green ash, white ash, red oak, and Virginia pine. All of these forest tree species except red oak were previously classified in the work of Wood (51) and Davis (13) as demonstrating a susceptible reaction to ozone. Green ash and white ash were also classified by Pollanschultz (33) as susceptible to SO_2 injury. The effect of SO_2 on Virginia pine has also been indicated as a susceptible reaction (35). Consistent increases in height growth of sweetgum, yellow poplar, green ash, white ash, red oak, and Virginia pine seedlings maintained in the filtered-air chambers substantiated the susceptibility of these six species to a NO_X-SO_2 air pollution regime. This same increased height growth between the two respective exposure chambers was also true of sycamore at two of the three stations. The results for sycamore at Station II were complicated by one of the seedlings in the non-filtered chamber which obtained a terminal elongation of 97.0 cm in comparison to a mean of approximately 30.0 cm for all other sycamore seedlings. This one seedling, therefore, greatly altered the mean of the six seedlings in this chamber. Santamour (34) has previously reported a decrease in height growth of sycamore artificially fumigated with ozone and SO_2. The occurrence of a susceptible reaction in two of the three stations for sycamore substantiated these findings.

Red oak has been rated by many investigators (13, 27, 39, 51) as resistant to oxidant air pollutants. The red oak seedlings examined in this study demonstrated a decrease in growth due to the effect of an ambient NO_X-SO_2 air pollution regime. The differences in these results may be due to several factors. Most of the previous studies have dealt with seedlings or trees which were older than the 1-0 seedlings utilized in this study. The seedlings in this study were subjected to a low-level, long-term exposure to an ambient pollution mixture of oxidants and SO_2.

Red oak and Virginia pine seedlings maintained in the filtered-air chambers demonstrated significant increases in terminal elongation compared to the seedlings maintained in the non-filtered air chamber and open plot. The majority of the seedlings of these two species maintained in the non-filtered air chamber and open plots failed to exhibit typical foliar symptoms of air pollution injury. This indicates that the majority of the seedlings within these exposure situations were exhibiting reductions in growth due to a NO_X-SO_2 air pollution regime without the presence of visible air pollution injury. However, the average terminal elongation of red oak seedlings demonstrated an inverse relationship with the average senescence rating among the filtered chamber, non-filtered chamber, and open plot.

The seedlings of the deciduous species located in the non-filtered chambers and open plots were consistently in later stages of senescence than those located in the filtered chambers. Skelly and Stone (37) in a similar experiment had also found premature senescence of seedlings exposed to the NO_X-SO_2 air pollution regime of the Arsenal. A premature needle loss was also demonstrated in the chlorotic-dwarf disease of eastern white pine by Dochinger and Seliskar (16). This reduction in foliar efficiency has been directly linked to the growth capabilities of the trees (25, 41). Sweetgum and red oak seedlings in the field chamber studies exhibited decreased height growth which corresponded to an increase in amount of foliage undergoing senescence. Therefore, the reduction in growth of these seedlings may have been partially due to their premature senescence. Piskornik (32) had previously suggested the earlier aging of leaves and earlier leaf fall as a means by which invisible injury may occur in trees. The majority of seedlings of red oak subjected to ambient pollutants in the field chamber studies had failed to exhibit symptoms of air pollution injury. Therefore, the significant reductions in growth of these seedlings may have been partially due to premature senescence. Stoklasa

(43) has demonstrated an inhibition of respiration in spruce subjected to SO_2 without the presence of visible injury. He has suggested that this inhibition in respiration indicates an inhibition of photosynthesis and that this may be one method by which invisible injury occurs in trees. Botkin (8) demonstrated reductions in net photosynthesis of white pine after exposure to ozone. This reduction in foliar efficiency has been directly linked to the growth capabilities of trees (25, 41). Premature senescence and/or an inhibition of photosynthesis may therefore be a means by which growth reduction occurs in trees with or without the presence of symptoms.

Annual Radial Growth Studies: Loblolly Pine

The measurement of annual radial increment growth of forest trees has been utilized by several investigators to determine the growth-impact of ambient air pollutants. This method of determining the impact of air pollutants was incorporated by Treshow *et al*. (46) in his research with Douglas fir subjected to atmospheric fluorides. It was also utilized in conjunction with mortality rates in Linzon's (29) economic impact studies with white pine and SO_2. Pollanschultz (33) and Donobauer (17) used this method in Europe to analyze the effect of industrial air pollution sources on the growth of the surrounding forests. The distinctive delineation of annual radial increment growth in the wood of trees acts as a constant historical record of the tree's growth rate. Stone (39) and Stone and Skelly (40) utilized the historical nature of annual radial increments in trees in their work at the U. S. Radford Army Ammunition Plant (Arsenal) with white pine, yellow poplar, and red oak. A simple linear regression was used to determine if correlations existed between the past production levels of the Arsenal (as an indicator of air pollution levels) and the annual radial growth of the sample trees. The analysis demonstrated that a significant inverse correlation existed between past pollution levels of the Arsenal and growth of the sample trees. This work initiated studies by the author with other species at the Arsenal and was a basis for the continuation of the studies with white pine. The analysis was modified to remove the effect of two rainfall variables and the age of the sample trees on growth before analyzing the partial correlation of air pollution with the tree's growth rate. This was accomplished by means of a multiple linear regression analysis.

The simple linear regression analysis with annual radial increment as the dependent variable and annual production levels as the independent variable evaluated the relationship between air pollution levels and growth of the sample trees without considering any environmental or physiological variables. The main consideration in the statistical analysis conducted with annual radial increment growth, tree age, total annual rainfall, annual seasonal rainfall, and annual production levels was to determine what relationship, if any, existed between increment growth and production levels and what effect the other three variables had upon this relationship. This analysis was designed to predict the effects of fluctuating air pollution levels upon the growth of the sample trees and the effect of environmental and physiological factors upon distinguishing this interaction between air pollution and growth. The four multiple linear regression analyses which were conducted allowed the two rainfall variables and the age variable to be removed before evaluations of their effect upon the relationship of air pollution and growth. The multiple linear regression analysis in which annual production levels were regressed on the variable of annual radial increment growth after removing the rainfall and age effects was considered the most valid appraisal of the effect of air pollutants on the growth of the sample trees.

Loblolly pine is now considered the leading commercial timber species in the southern United States (23). This species' affinity for growth in the Coastal Plain and Piedmont often results in the plantations being encompassed by urban sprawl. The ambient pollution level in these areas has become an increasingly more important criteria in the growth of these trees. Berry (5) worked with two-to-ten week old seedlings in order to determine the sensitivity of loblolly pine to air pollutants. These seedlings were subjected to controlled fumigations with SO_2 and ozone independently. He found that loblolly pine seedlings demonstrated foliar symptom reactions similar to those of Virginia pine seedlings which are known to be highly susceptible to ozone and SO_2. These two constituents are common in the ambient air at the Arsenal.

The variability of a plant's reaction to air pollutants is often due to the physiological variable of age. This variation in susceptibility to air pollutants due to age has been demonstrated with seedlings of Virginia pine (14) subjected to fumigations with ozone and also with seedlings of loblolly pine fumigated independently with SO_2 and ozone (5). This interaction of age with pollution sensitivity was also demonstrated within loblolly pine stands #1 and #2 located within the Arsenal. Loblolly pine stand #1 failed to demonstrate a significant relationship when annual radial increment growth and annual production levels of the Arsenal were compared. The effect of age on the growth of the sample trees, however, was highly 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 #2. In this stand, both production levels and age were independently 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 growth to production levels was present which had not been realized with a simple linear regression analysis. The effect of age on air pollution-growth interactions in this situation had not completely disguised the significant relationship but the failure to consider this variable reduced the negative correlation between air pollution and growth.

It was necessary to consider age in the remaining two stands of loblolly pine for a different reason. In the sixteen-to-nineteen year old stands at the Arsenal, only one peak in Arsenal production occurred during the life history of the stand. This resulted in steadily rising production levels which demonstrated a high intercorrelation with the increasing age of the sample stand. In loblolly pine stand #3, a significant positive correlation between age and radial increment growth was demonstrated. However, the simple linear regression analysis with production levels and growth also presented a significant positive linear relationship. The removal of variation due to age within this stand did not increase the significance and/or correlation of production levels regressed on radial increment growth but instead reduced the linear correlation of these variables to an insignificant level. The high intercorrelation of age and production levels in this young stand may have resulted in the exhibition of a significant positive relationship of air pollutants on growth of loblolly pines when age was not removed first. The evaluation of the control stand, loblolly pine stand #4, demonstrated similar results to that of loblolly pine stand #3. Both simple linear regression analyses with production alone and age alone when compared independently to annual radial increment growth demonstrated a highly significant inverse relationship. The removal of the variation due to age resulted in a nonsignificant partial correlation between growth and air pollution. If loblolly pine stand #4 had been evaluated by a simple linear regression analysis with the variables of annual radial increment growth predicted by annual production levels of the Arsenal, it could have resulted in the erroneous conclusion that this stand was invalid as a control or that this means of analyzing the effect of air pollutants on growth was invalid. The inclusion of age in the regression analysis indicated that there was no actual relationship between air pollution levels of the Arsenal and growth of sample trees within the control stand. This substantiated the control situation within this stand and therefore enforced the results of the effect of the Arsenal's pollution levels upon loblolly pine trees subjected to these ambient pollutants.

Similar results concerning the variability in susceptibility of trees to air pollutants due to environmental factors were presented by Wilhour (50) in which he demonstrated variations in the susceptibility of white ash seedlings to ozone fumigations due to the influence of relative humidity and temperature. The environmental factors considered within the study at the Arsenal consisted of two rainfall variables: a 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. When these two variables plus age were removed first, the inverse correlations of production to increment growth became stronger in loblolly pine stands #1 and #2, which were shown to have a significant inverse relationship between the two variables. In contrast, when the effect of all three variables was removed and the relationship of air pollution levels to growth evaluated in loblolly pine stand #3 was smallest and the inverse correlations in the control stand were changed from a significant negative correlation to a significant positive correlation.

The multiple linear regression analysis which compared annual radial increment growth to annual production levels of the Arsenal while variation due to age, total annual rainfall, and the annual seasonal rainfall was removed first was felt to give a valid indication of the effects of fluctuating air pollution levels on the growth of the sample trees. Two of the tree sample stands of loblolly pine evaluated within the Arsenal demonstrated a significant inhibition of radial increment growth due to the effect of the NO_X-SO_2 air pollution regime. Similar results, as previously mentioned, had been found by Stone (39) and Stone and Skelly (40) with white pine and yellow poplar subjected to the Arsenal's fluctuating air pollution levels. Linzon (29), in his economic impact studies with white pine in the smelter district around Sudbury, Canada, demonstrated a gradual decline in radial increment growth of trees subjected to the ambient pollution levels. Control trees located outside the influence of ambient pollution levels exhibited a fairly constant rate of growth. Donobauer (17) working in Europe with several forest tree species subjected to various ambient air pollutants demonstrated decreases in radial increment growth of the trees subjected to these pollutants when compared to growth of the same trees prior to source initiation. The sample trees within loblolly pine stands #1 and #2 failed to exhibit foliar symptoms which were characteristic of air pollution injury in deference to the significant effect of air pollutants on growth within these stands.

Loblolly pine stand #3 exhibited air pollution injury symptoms on the majority of the sample trees and was located only 1.4 km from the main emission area of the Arsenal. Loblolly pine stands #1 and #2 were located 2.6 and 2.7 km from the main emission area of the Arsenal. Therefore, loblolly pine stand #3 was probably subjected to higher air pollution concentrations than loblolly pine stands #1 and #2 due to greater diffusion of the pollutants by the time they had reached the more distant stands. Loblolly pine stand #3 was also situated proximal to an oleum plant within the Arsenal which had previously been an emission source of sulfuric acid mist. However, this stand failed to demonstrate a significant effect of the Arsenal's fluctuating pollution levels on its growth. This phenomenon could be due to the tolerance of the sample trees within this stand to air pollution injury. The sensitivity expressed by the other two stands which were further removed from the sources of air pollution and without visible injury present preclude this conjecture. The answer may be in the analysis itself. If these sample trees demonstrated an inhibition of growth even at the lower levels of production at the Arsenal which may be conjectured due to the differential distance from the source and foliar symptoms present within this stand compared to the remaining two stands of loblolly pine, the statistical analysis would probably not detect this influence of air pollution on growth. The growth of these trees, if reduced consistently at even the lower production levels would not respond to changes in production levels with changes in growth. The consistency of this inhibition would have changed the total yearly growth present but not the varying year to year growth which was evaluated in the regression analysis.

Loblolly pine trees planted within the Arsenal may be undergoing an inhibition in growth which is proportional to the production levels (or pollution levels) of the Arsenal and which is influenced by tree age and rainfall. This inhibition in growth is occurring without the presence of symptoms and therefore may be considered hidden (or invisible) injury. It is possible that some loblolly pine trees may exhibit a tolerance to the NO_X-SO_2 air pollution regime of the Arsenal. The basis of this tolerance is unknown.

White Pine

The effect of air pollutants on white pine is an area that has been extensively researched. Berry and Ripperton (6) in 1962 suggested ozone injury as a possible cause of white pine emergence tipburn. Another obvious and well-known response of white pine to atmospheric pollutants is the "chlorotic dwarf condition," (16) in which the trees demonstrate severe foliar injury and a stunting of growth. Drummond and Wood (18) presented results of an increase in height growth of white pine seedlings subjected to a decrease in ambient pollution levels, while Skelly et al. (36) and Stone (39) working at the Arsenal also demonstrated reductions in height growth and annual radial increment growth respectively of white pine subjected to the NO_X-SO_2 air pollution regime of the Arsenal.

Age, as in the loblolly pine stands, again exhibited a major influence in determining the most valid appraisal of the effects of air pollutants on the growth of trees. As previously mentioned, Berry (5) and Davis (14) had demonstrated the influence of age on the susceptibility of fumigated conifer seedlings. The correlation of annual radial increment growth to annual production levels by means of a simple regression analysis demonstrated a highly significant positive relationship in white pine stand #1. The direct correlation of age and increment growth also demonstrated this highly significant and highly correlated positive relationship. However, the removal of variation due to age within this stand did not change the correlation of growth production level from significantly positive to insignificant or negative as previously experienced with the loblolly pine studies. Instead, the size of the correlation coefficient was reduced by approximately one-half. The removal of the effect of rainfall simultaneous with age lowered the correlation coefficient to approximately one-third of the size indicated in the simple linear regression analysis. The high intercorrelation of age and production levels was again demonstrated in this sixteen-year-old stand. The removal of the variation resulting from rainfall, however, did not completely change the positive effect of air pollutants on growth indicated by the regression analysis. White pine stand #2 demonstrated a significant negative relationship of growth and production levels which, though affected slightly by the removal of variation due to age and rainfall within the analysis, remained a highly significant inverse relationship. These results correspond to those found by Stone (39) and Linzon (29) in which the annual radial increment growth of white pine was significantly affected by air pollutants. The control stand, white pine stand #3, demonstrated a significant inverse relationship between growth and production levels. The removal of the effect of age on the growth of sample trees reduced the correlation coefficient between growth and production levels to 0.075 which, though significant, could have very little actual effect on the growth of the sample trees. The correlation coefficients associated with increment growth and the Arsenal's production levels are the smallest that were associated with a significant relationship in any of the regression analyses performed within all other pine stands. This resulted in the acceptance of white pine stand #3 as a valid control.

The results demonstrated in white pine stand #1 deserve further consideration. This indication that air pollutants aided the growth of the sample trees is in contradiction to the majority of research conducted with air pollution and white pines prior to this time. The possibility exists that this relationship is due to the inefficiency of the statistical analysis and the variables measured in evaluating all possible types of susceptible responses of the sample trees to air pollutants. However, in loblolly pine stand #3, foliar symptoms of air pollution were present over the majority of the stand; therefore, it was probable that the trees were being consistently injured. The question involved here is why, when symptoms were present, a significant inverse relationship of growth to production was not present. One reason is that these symptoms could be due to factors other than air pollution. However, in white pine stand #1, symptoms were not present over the majority of the trees and a significant positive relationship between growth and production levels existed. The comparison of the results within white pine stand #1 to those of white pine stand #2 and the work of Stone (39) and Linzon (29) is limited due to the large differences in ages of the sample stands. Skelly _et al_. (36) conducted research on a 13-year-old stand within the Arsenal which demonstrated differences in growth between trees expressing symptoms and those lacking symptoms. They failed, however, to examine growth fluctuations within individual trees and among the trees failing to exhibit symptoms. The positive relationship between growth and production levels, irrespective of the removal of variation due to age and rainfall and the general lack of foliar symptoms within this stand, indicates that possibly the NO_X-SO_2 air pollution regime within the Arsenal stimulated growth of the sample trees. Several investigators such as Treshow et al. (46) who worked with effects of fluorides on Douglas fir have suggested that in cases of nutrient dificiency, air pollutants may stimulate growth. The recently published work of Bennett et al. (4) on the apparent stimulations of plant growth by air pollutants indirectly substantiates the results from the analysis of white pine stand #1. Bennett et al. (4), in considering the effect of nitrogen dioxide on plant growth, hypothesized that under conditions of nitrogen and sulphur deficiency, NO_X and SO_2 air pollutants would aid the growth of certain species of plants. The work of Schuman and Burwell (2) also demonstrated that nitrogen received in rainfall can account for two-thirds of the soluble nitrogen in surface runoff from cropland. This indicates that with the NO_X-SO_2 air pollution regime at the Arsenal substantial contributions of nitrogen to the soil through rainfall are possible.

The results demonstrated by white pine stand #2 indicate that the fluctuating pollution levels at the Arsenal may have significantly inhibited the growth of the trees with the severity which was directly proportional to the levels which existed during the year of the trees' growth. These results are similar to those found in loblolly pine stands #1 and #2. However, the results for white pine stand #1 also indicate the possibility that in some instances NO_X-SO_2 air pollution regime may supply nutrients which increase the growth of the trees. The analysis of white pine stand #3 along with loblolly pine stand #4 emphasized the practicality of a multiple linear regression analysis in detecting the influence of air pollutants, environmental variables, and physiological variables upon the growth of sample trees.

<u>Sycamore</u>

The pulp and paper industry considers sycamore to be a promising species which can be utilized in short rotation production methods. The effect of air pollutants on sycamore is an area which has experienced very little research due to the prior general noncommercial aspect of this tree. Santamour (34) has demonstrated a reduction in height growth of sycamore seedlings subjected to controlled fumigations with ozone and SO_2 as previously mentioned. These results along with the results demonstrated within the previously mentioned field chamber studies would indicate that sycamore is susceptible to the NO_X-SO_2 air pollution regime within the Arsenal.

In the statistical analysis of the sycamore stand sampled at the Arsenal, age was unobtainable. The previously discussed importance of age within both the young and old stands of pines prohibited the acceptance of the validity of any results concerning the influence of air pollutants on growth that could have been demonstrated without this variable. The analysis failed to demonstrate a significant relationship of air pollution levels at any point. The lack of reaction in the growth of the sample trees unless the plants were tolerant may have been due to the inability to consider the variable age in the statistical analysis or to the effect of sycamore anthracnose incited by *Gnomonia platani* Kleb. on the trees. During the two years in which research was conducted at the Arsenal, sycamore trees exhibited relatively severe levels of anthracnose. The similarity between anthracnose and air pollutants in their effect on the foliar portions of the trees indicates that the effect of these two pathogens may have been indistinguishable.

A significant positive relationship was demonstrated between the radial increment growth of the sample trees and annual seasonal rainfall which is logical for a wet site species such as sycamore (23). The environmental requirement of moisture in the infection of sycamore by *Gnomonia platani* is also a consideration in correlations of rainfall to growth and may have been one reason for the low correlation coefficients between these variables. Sycamore failed to exhibit a significant effect of the Arsenal's ambient pollution levels on radial increment growth but this emphasized the necessity of considering all possible physiological environmental, and pathological influences in evaluating the effect of air pollutants on the growth of plants.

Hidden Injury

The concept of hidden or invisible injury has been a debated point since its proposal by Stoklasa (43) in 1923. The proposed action of reduced productivity or biomass without symptoms places hidden injury in the Class II relationship established by Smith in his evaluation of the effect of air pollution on a forest ecosystem. The Class II and Class III type of relationships have already been substantiated in forested areas of the Arsenal (39). Reductions in the growth of forest trees without the presence of visible injury have been indicated by several researchers. Treshow *et al.* (46), working with Douglas fir subjected to atmospheric fluorides, indicated a reduction in radial increment growth of sample trees with or without the presence of foliar symptoms. Pollanschultz (33), working with larch, white pine, spruce, fir, aspen, beech, and maple, found that growth loss could occur in some species without the appearance of macroscopic symptoms. Donobauer (17) had also substantiated the concept of hidden injury in forest trees working in Austria.

The results which were observed in the field chamber with seedlings of red oak and Virginia pine along with the increment growth studies of loblolly pine stands #1 and #2 suggested the possibility of hidden injury in the forests at the Arsenal. White pine stand #2 had exhibited a variety of symptom expression among the sample trees. Similar diversity at the Arsenal had previously been reported by Skelly *et al.* (36). These trees varied from a lack of symptoms to trees which were on the verge of death with sparse and severely burned crown foliage. The effect of air pollution on the growth of trees within rating levels #1 and #2 (the severely affected classes) appears to have been so restrictive that normal annual variations in rainfall did not significantly affect the trees' growth. This was indicated by the insignificant relationship of both or one of the rainfall variables in rating levels #1 and #2, respectively.

The analysis of the stand according to data groups based on severity of air pollution symptoms provided two important facts. The first fact was that within the statistical analysis of the undifferentiated stand, trees which expressed symptoms of air pollution injury did not produce an inverse correlation of air pollution and growth regardless of whether this relationship was present in the trees without symptoms. The results of the differentiated analysis also indicated that the Arsenal's fluctuating air pollution levels had a significant effect on growth of the sample trees in all categories. Therefore, in trees which failed to exhibit symptoms, the significant correlation of growth and air pollution levels indicates that hidden injury occurred. This conclusion that symptom expression is not a prerequisite for or proportional to growth loss places severe restrictions upon growth loss estimates such as those conducted in Pennsylvania (49) which are based on symptom expression alone. The use of symptoms in the assessment of growth loss in forests may be considered invalid due to the results demonstrated in the field chamber studies with Virginia pine and red oak along with white pine stand #2 and loblolly pine stands #1 and #2. It is therefore highly possible that growth loss in the forests of the United States subjected to low-level and long-term exposures to air pollutants may be occurring unnoticed and/or unevaluated.

Growth Loss Studies

The effect of air pollutants on the growth of trees is the primary factor of importance for the forest industry of the United States. Growth loss also functions as both an economical and environmental criteria that should be considered in environmental impact statements and air quality criteria standards. Douglas fir (23) which comprises approximately 50% of the standing timber in western forests and produces more timber than any other American species has been demonstrated by Treshow *et al*. (46) to experience a 50% reduction in diameter growth due to the effect of atmospheric fluorides. Linzon (29), working with white pine mortality and growth inhibition due to SO_2, indicated a total volume loss of 0.40 cubic foot per acre per year. Horntvedt (26) presented results which exhibited up to a 45% reduction in diameter growth of spruce subjected to SO_2. However, the effect of air pollutants on the growth of trees has yet to be realized in totality until more work has been accomplished with other species. The effect of air pollutants on the growth of loblolly pine has not been evaluated prior to this study.

The results of growth differences from the multiple linear regression analysis provided an indication measure of growth loss for loblolly pine stands #1 and #2 and white pine stand #2. This analysis of the young sample stands of loblolly pine within the Arsenal indicated a reduction in growth of 45% due to the effect of the fluctuating NO_X-SO_2 air pollution regime of the Arsenal. White pine stand #2 which contained trees from 35 to well in excess of 100 years old demonstrated a 10% reduction in diameter growth. These predicted results, though large, can be substantiated by comparison with results found by the previously mentioned investigators (26, 29, 46). It should be realized that these levels are to be considered as relative maximums due to the high levels of pollution present at the Arsenal during peak periods, the edge effect on sample loblolly trees, and the lack of consideration of the effect of competition on the growth of the trees. However, the consideration that loblolly pine and Douglas fir, two of the most important timber species in the United States, may undergo substantial reductions in growth is a fact that the forest industries of the United States can no longer ignore and still continue to meet the present demands for forest products.

SUMMARY

The purpose of this investigation was to determine the effect of a NO_X-SO_2 air pollution regime upon the growth of forest trees. The U. S. Radford Army Ammunition Plant, or Arsenal, located in Radford, Virginia, is a geographically isolated source of relatively high levels of NO_X and SO_2. Since its establishment in 1940, the Arsenal's manufacture of nitrogenous ammunitions has been linked to the military and security efforts of the United States. Peak production periods at the Arsenal occurred during World War II, the Korean conflict, and the Vietnam conflict. These peaks in production were separated by periods of little or no production at the Arsenal.

Seedlings of yellow poplar, sycamore, red oak, green ash, sweetgum, and Virginia pine were established in three locations within and surrounding the Arsenal. The seedlings were separated within each location into three treatments: open-grown; chamber-grown receiving charcoal-filtered air; and chamber-grown receiving non-filtered air. The seedlings were maintained at these locations from June until October 1973 at which time measurements of terminal elongation and senescence ratings were obtained. Green ash, red oak, and Virginia pine seedlings maintained in the filtered-air chambers demonstrated significant increases in terminal elongation compared to the seedlings maintained in the open plot. Only red oak and Virginia pine demonstrated significant increases in the terminal elongation of

seedlings maintained in the filtered-air chambers over those in the non-filtered air chambers. The analysis of the senescence ratings demonstrated that seedlings of the deciduous species in the non-filtered chamber and open plot were consistently in later stages of senescence than those located in the filtered-air chambers. The height-growth of seedlings of red oak and Virginia pine was significantly inhibited by the ambient NO_X-SO_2 air pollution regime and premature senescence may have been one method by which growth inhibition occurred.

Annual radial increment growth studies were conducted to determine:

(1) if correlations exist between the annual emission levels of a source and annual radial growth of forest trees;

(2) the influence of symptom expression upon correlations of annual emission levels of a source and annual radial growth of forest trees;

(3) a relative estimate of long-term growth loss due to ambient air pollutant conditions within the Arsenal grounds.

Three stands of loblolly pine, two stands of white pine, and one stand of sycamore were sampled within the Arsenal. The stands were sampled by obtaining a 3.2 mm diameter increment core at d.b.h. of fifty trees from the dominant or codominant crown classes. The increment cores were measured (to the nearest 0.01 mm) and dated by means of a DeRouen Dendrochronograph. All stands were evaluated by a multiple linear regression analysis utilizing annual readial increment growth as the dependent variable, while independent variables included annual production levels of the Arsenal (as an indicator of emission levels), total annual rainfall, annual seasonal (April-September) rainfall, and tree age. An inverse relationship significant at the 0.001 level between production levels of the Arsenal and radial increment growth of the sample trees after removing the effect of all other variables was demonstrated in two stands of loblolly pine and one stand of white pine. This indicates that ambient air pollutant levels inhibited the growth of white pine and loblolly pine, and this inhibition was directly proportional to the levels of pollution present. A significant positive relationship of radial growth and production levels was exhibited in the second stand of white pine. The remaining loblolly pine stand and the stand of sycamore failed to exhibit a significant correlation between production levels and radial growth. A stimulatory rather than inhibitory effect of ambient air pollutants was indicated in the second white pine stand, while the stand of sycamore and one stand of loblolly pine were seemingly unaffected by air pollution.

An experiment was also conducted to determine the effect of symptom expression on correlations of radial increment growth and production levels at the Arsenal. Sample trees within the stand of white pine which demonstrated a significant inverse relationship of growth to production were subjected to a visual crown rating. The ratings were divided into four categories based upon visible air pollution injury. These categories were: healthy (no symptoms), chlorotic, slight tip burn, and severe tip burn. The previously mentioned statistical analysis was repeated utilizing the data groups from the four individual foliage categories. Results demonstrated that the inverse correlation of radial increment growth with manufacturing levels of the source remained highly significant irrespective to the foliage ratings. These observations indicate that symptoms may not be expressed though growth retardation in white pine has occurred.

An estimate of growth loss of forest trees due to the periodic air pollution levels of the Arsenal was also obtained. The multiple linear regression equation were utilized to predict theoretical differences in growth between trees subjected to the historical pollution levels of the Arsenal and a pollution-free condition. Those stands of trees which exhibited a significant inverse relationship of radial increment growth to production levels of the Arsenal were subjected to this analysis. The two stands of loblolly pine and the one stand of white pine which exhibited this relationship were indicated to have undergone, respectively, a 45%, 45%, and 10% theoretical reduction in predicted diameter growth.

Extrapolation of these results to other areas of Virginia and the United States is limited by the relatively high ambient pollution levels present at the Arsenal. However, the qualitative rather than quantitative nature of these studies concerning the growth-impact of air pollution on forest trees is relevant. The results of this research indicate that the forest industry of Virginia and the Southeastern United States may be undergoing greater losses from the effect of ambient air pollutants than previously realized. The possibility of hidden injury due to chronic air pollution levels indicates that a quantitative analysis based on growth measurements is necessary to obtain a valid estimate of the economic impact of air pollution on the forest industry of the United States.

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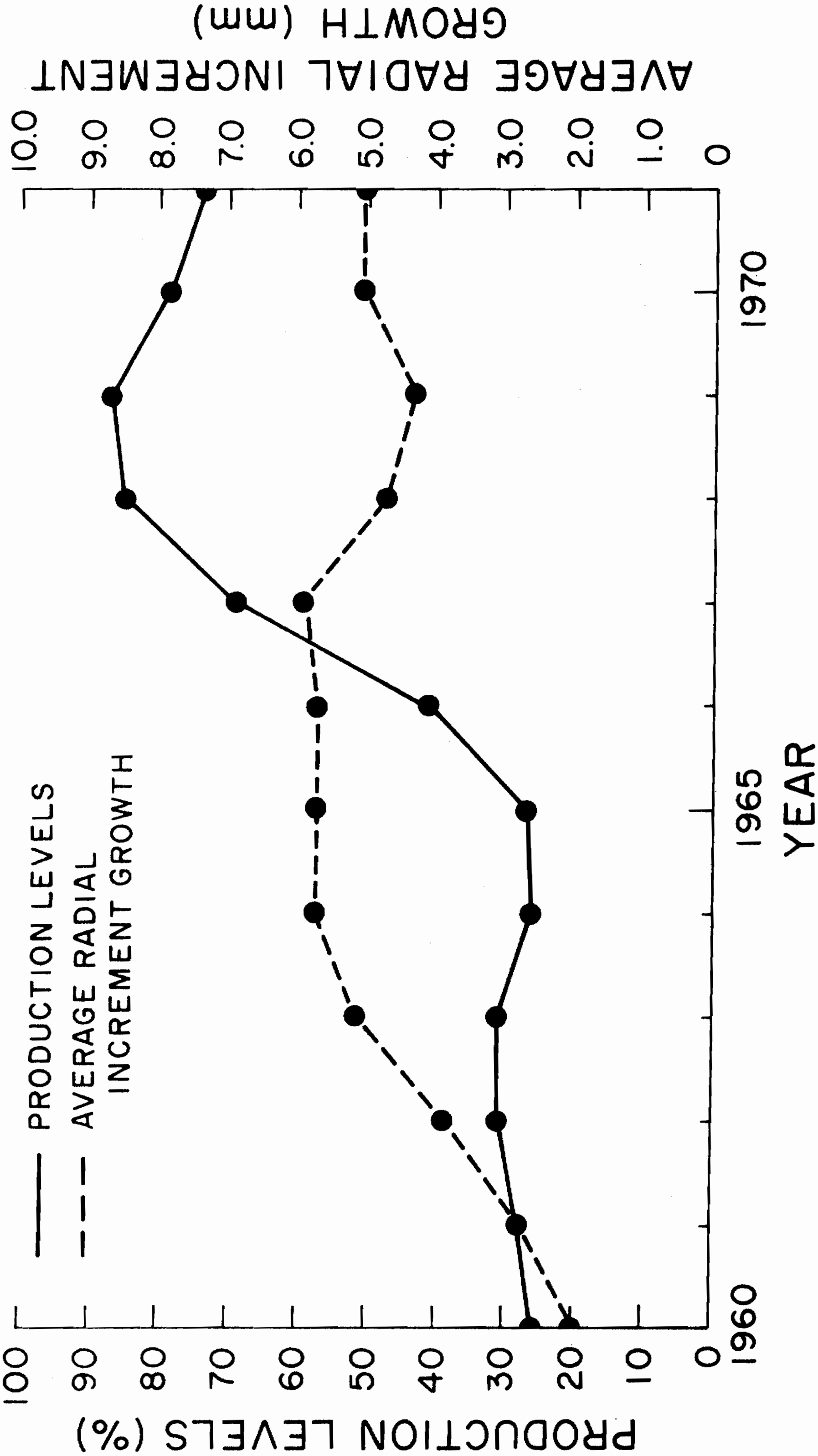
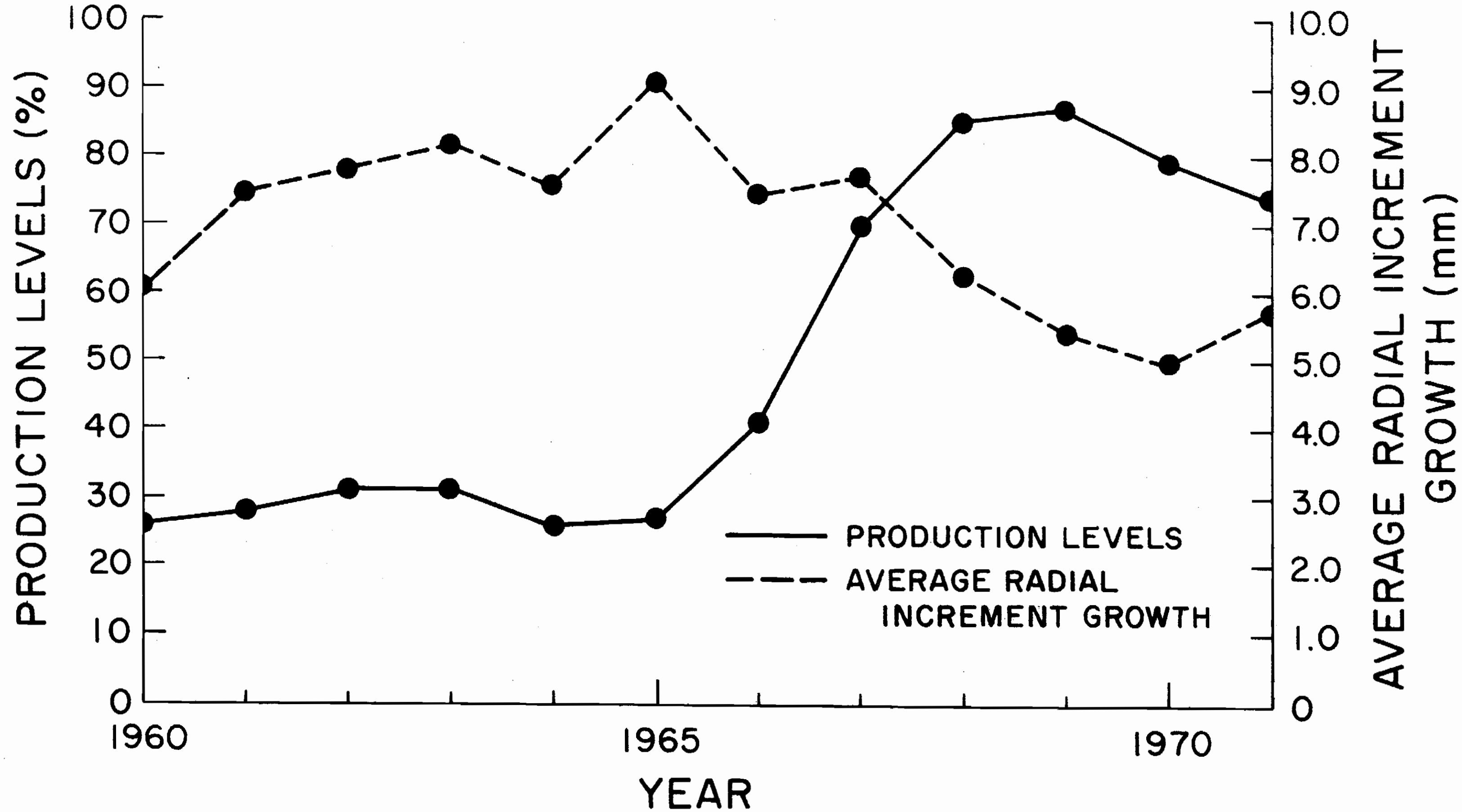
A P P E N D I X

Figure 1. Loblolly pine stand #1: Average annual radial increment growth compared to annual production levels of the Arsenal.



AVERAGE RADIAL INCREMENT GROWTH (mm)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
1960
1965
1970
YEAR
PRODUCTION LEVELS (%)
0
10
20
30
40
50
60
70
80
90
100

Figure 2. Loblolly pine stand #2: Average annual radial increment growth compared to annual production levels of the Arsenal.



PRODUCTION LEVELS (%)
100
90
80
70
60
50
40
30
20
10
0
AVERAGE RADIAL INCREMENT GROWTH (mm)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1960
1965
1970
YEAR
PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH

Figure 3. Loblolly pine stand #3: Average annual radial increment growth compared to annual production levels of the Arsenal.

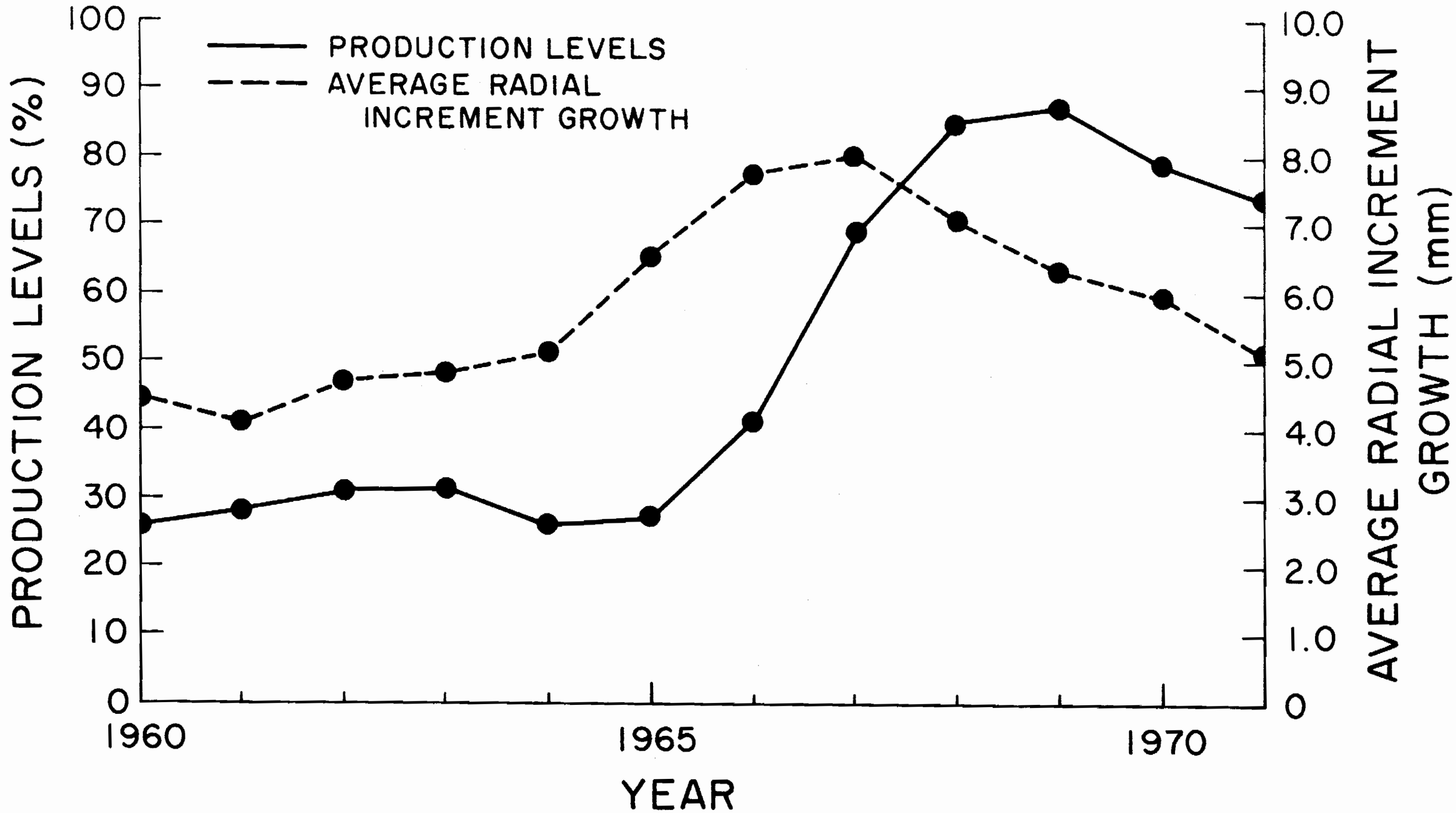

PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
PRODUCTION LEVELS (%)
100
90
80
70
60
50
40
30
20
10
0
AVERAGE RADIAL INCREMENT GROWTH (mm)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1960
1965
1970
YEAR

Figure 4. Loblolly pine stand #4: Average annual radial increment growth compared to annual production levels of the Arsenal.

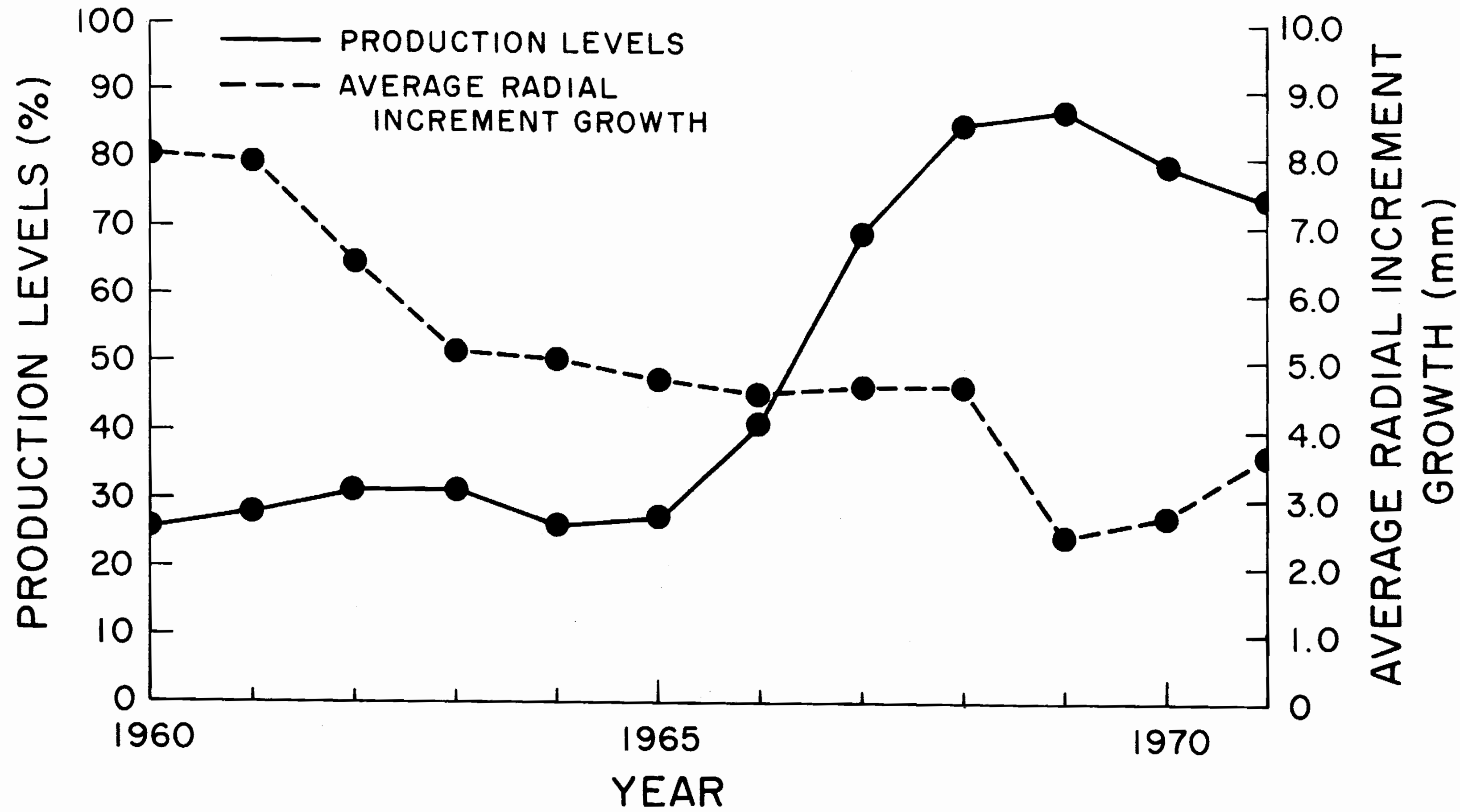

PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
PRODUCTION LEVELS (%)
100
90
80
70
60
50
40
30
20
10
0
AVERAGE RADIAL INCREMENT GROWTH (mm)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1960
1965
1970
YEAR

Figure 5. White pine stand #1: Average radial increment growth compared to annual production levels of the Arsenal.

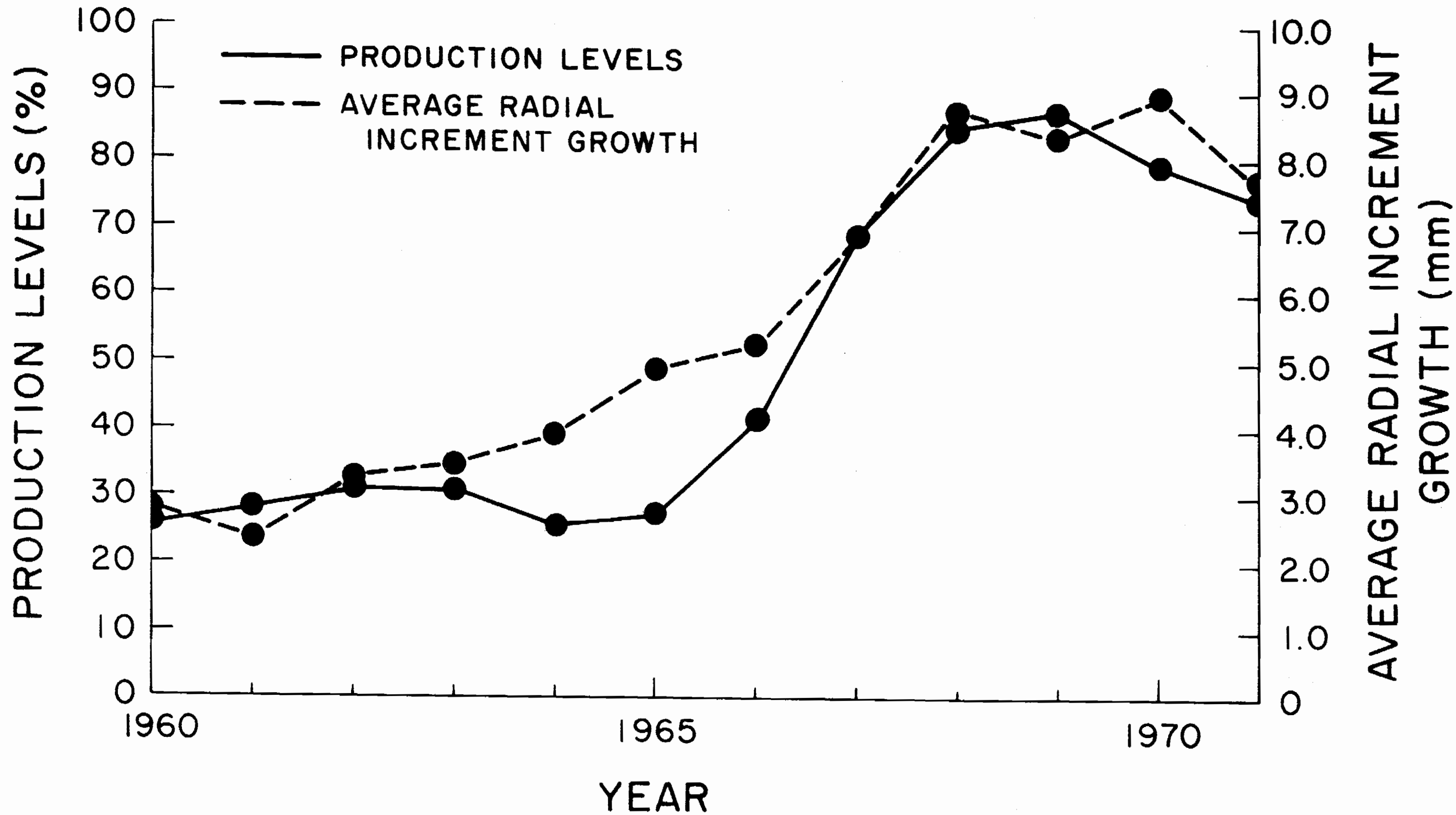
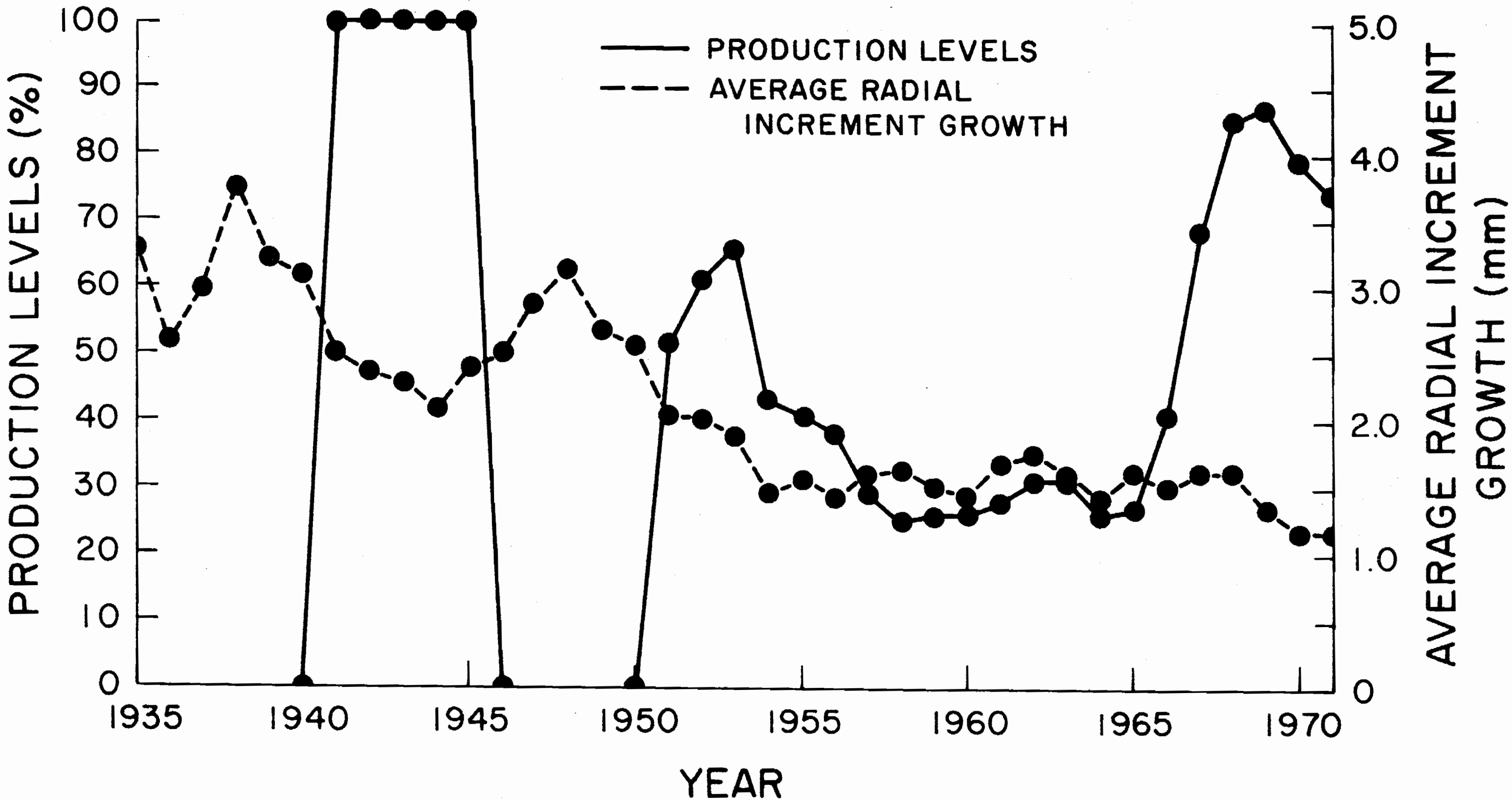

PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
PRODUCTION LEVELS (%)
AVERAGE RADIAL INCREMENT GROWTH (mm)
YEAR
1960
1965
1970
0
10
20
30
40
50
60
70
80
90
100
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

Figure 6. White pine stand #2: Average annual radial increment growth compared to annual production levels of the Arsenal.



PRODUCTION LEVELS (%)
100
90
80
70
60
50
40
30
20
10
0
PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
AVERAGE RADIAL INCREMENT GROWTH (mm)
5.0
4.0
3.0
2.0
1.0
0
1935
1940
1945
1950
1955
1960
1965
1970
YEAR

Figure 7. White pine stand #3: Average annual radial increment growth compared to annual production levels of the Arsenal.

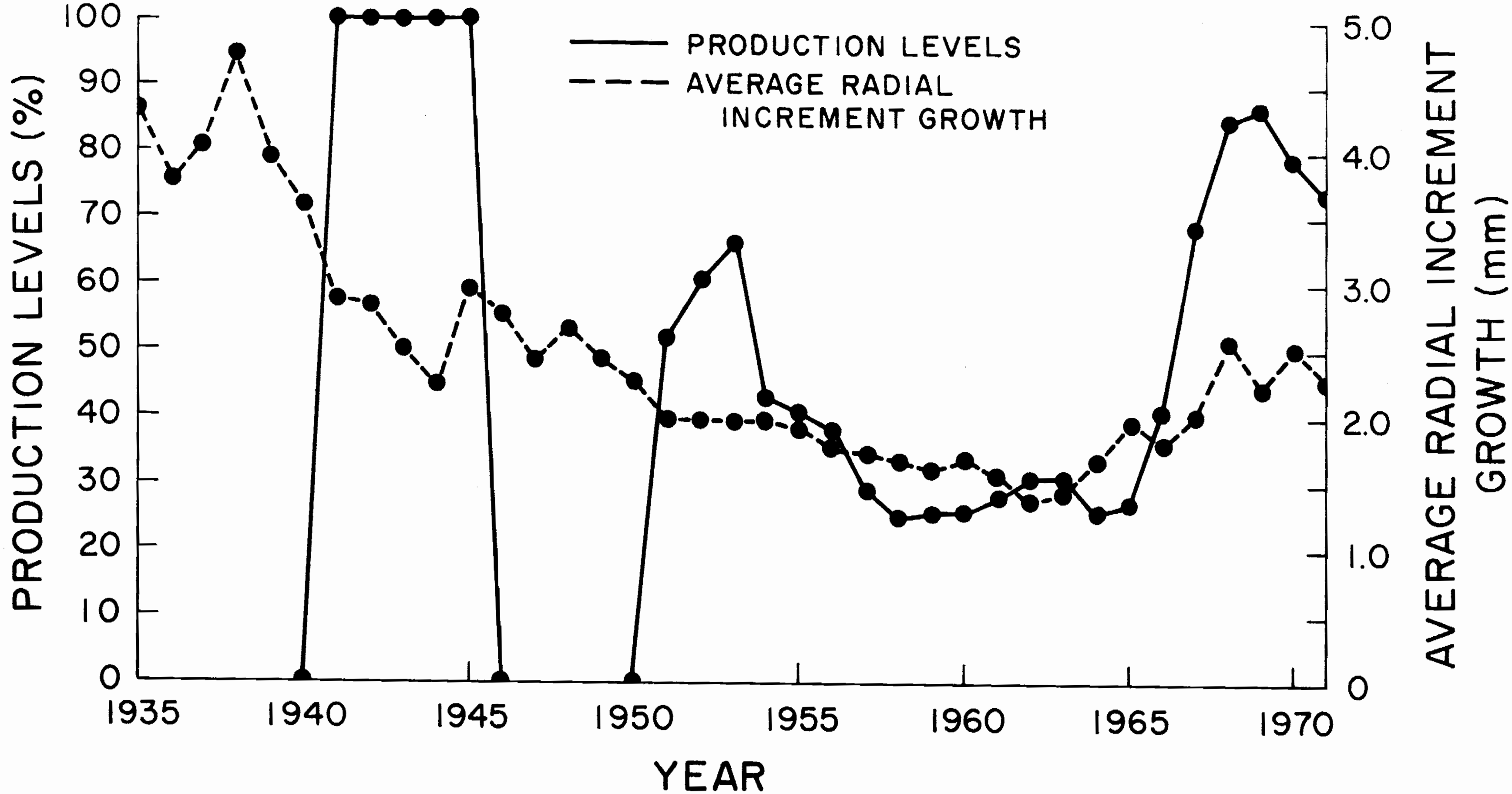

PRODUCTION LEVELS
AVERAGE RADIAL INCREMENT GROWTH
PRODUCTION LEVELS (%)
AVERAGE RADIAL INCREMENT GROWTH (mm)
YEAR
100
90
80
70
60
50
40
30
20
10
0
5.0
4.0
3.0
2.0
1.0
0
1935
1940
1945
1950
1955
1960
1965
1970

Table 1. Multiple linear regression analysis results for loblolly pine stand #1.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1960-71	0.37	+ 0.026
2	Annual radial increment	Age	1960-71	18.60††	+ 0.180
3	Annual radial increment	Total annual rainfall	1960-71	2.21	- 0.063
4	Annual radial increment	Annual seasonal rainfall	1960-71	3.16	+ 0.075
5	Annual radial increment	Average annual production[1]	1960-71	44.60††	- 0.273
6	Annual radial increment	Average annual production[2]	1960-71	0.66	+ 0.034
7	Annual radial increment	Average annual production[3]	1960-71	0.01	- 0.004
8	Annual radial increment	Average annual production[4]	1960-71	57.88††	- 0.308

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 2. Multiple linear regression analysis results for loblolly pine stand #2.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1960-71	43.76††	- 0.265
2	Annual radial increment	Age	1960-71	9.44†	- 0.126
3	Annual radial increment	Total annual rainfall	1960-71	12.78††	- 0.147
4	Annual radial increment	Annual seasonal rainfall	1960-71	28.75††	- 0.217
5	Annual radial increment	Average annual production[1]	1960-71	63.55††	- 0.314
6	Annual radial increment	Average annual production[2]	1960-71	39.78††	- 0.253
7	Annual radial increment	Average annual production[3]	1960-71	24.69††	- 0.202
8	Annual radial increment	Average annual production[4]	1960-71	105.81††	- 0.393

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 3. Multiple linear regression analysis results for loblolly pine stand #3

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial Correlation
1	Annual radial increment	Average annual production	1960-71	10.66†	+ 0.151
2	Annual radial increment	Age	1960-71	6.97**	+ 0.123
3	Annual radial increment	Total annual rainfall	1960-71	8.76	- 0.137
4	Annual radial increment	Annual seasonal rainfall	1960-71	1.96	- 0.066
5	Annual radial increment	Average annual production[1]	1960-71	3.72	+ 0.090
6	Annual radial increment	Average annual production[2]	1960-71	14.58††	+ 0.176
7	Annual radial increment	Average annual production[3]	1960-71	15.77††	+ 0.183
8	Annual radial increment	Average annual production[4]	1960-71	0.36	- 0.028

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

* Significant F-value at the 0.05 level.
** Significant F-value at the 0.01 level.
† Significant F-value at the 0.005 level.
†† Significant F-value at the 0.001 level.

Table 4. Multiple linear regression analysis results for loblolly pine stand #4.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1960-71	177.99††	- 0.479
2	Annual radial increment	Age	1960-71	305.54††	- 0.582
3	Annual radial increment	Total annual rainfall	1960-71	44.17††	+ 0.262
4	Annual radial increment	Annual seasonal rainfall	1960-71	0.07	+ 0.011
5	Annual radial increment	Average annual production[1]	1960-71	3.41	+ 0.075
6	Annual radial increment	Average annual production[2]	1960-71	171.76††	- 0.473
7	Annual radial increment	Average annual production[3]	1960-71	203.93††	- 0.505
8	Annual radial increment	Average annual production[4]	1960-71	4.56*	+ 0.087

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

* Significant F-value at the 0.05 level.
** Significant F-value at the 0.01 level.
† Significant F-value at the 0.005 level.
†† Significant F-value at the 0.001 level.

Table 5. Multiple linear regression analysis results for white pine stand #1.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1960-71	369.97††	+ 0.640
2	Annual radial increment	Age	1960-71	315.40††	+ 0.610
3	Annual radial increment	Total annual rainfall	1960-71	0.51	+ 0.031
4	Annual radial increment	Annual seasonal rainfall	1960-71	37.41††	+ 0.256
5	Annual radial increment	Average annual production[1]	1960-71	45.21††	+ 0.241
6	Annual radial increment	Average annual production[2]	1960-71	372.27††	+ 0.642
7	Annual radial increment	Average annual production[3]	1960-71	310.42††	+ 0.607
8	Annual radial increment	Average annual production[4]	1960-71	15.15††	+ 0.167

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 6. Multiple linear regression analysis results for white pine stand #2.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	95.84††	- 0.218
2	Annual radial increment	Age	1935-71	412.43††	- 0.420
3	Annual radial increment	Total annual rainfall	1935-71	15.51††	+ 0.089
4	Annual radial increment	Annual seasonal rainfall	1935-71	44.47††	+ 0.150
5	Annual radial increment	Average annual production[1]	1935-71	75.92††	- 0.195
6	Annual radial increment	Average annual production[2]	1935-71	82.87††	- 0.203
7	Annual radial increment	Average annual production[3]	1935-71	79.99††	- 0.200
8	Annual radial increment	Average annual production[4]	1935-71	70.22††	- 0.188

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 7. Multiple linear regression analysis results for white pine stand #3.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	48.59††	- 0.162
2	Annual radial increment	Age	1935-71	327.39††	- 0.392
3	Annual radial increment	Total annual rainfall	1935-71	23.55††	+ 0.113
4	Annual radial increment	Annual seasonal rainfall	1935-71	57.99††	+ 0.176
5	Annual radial increment	Average annual production[1]	1935-71	10.23†	- 0.075
6	Annual radial increment	Average annual production[2]	1935-71	29.85††	- 0.127
7	Annual radial increment	Average annual production[3]	1935-71	22.83††	- 0.112
8	Annual radial increment	Average annual production[4]	1935-71	13.64††	- 0.087

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 8. Multiple linear regression analysis results for sycamore.

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	2.90	- 0.049
2	Annual radial increment	Age	---	--	---
3	Annual radial increment	Total annual rainfall	1935-71	3.34	+ 0.053
4	Annual radial increment	Annual seasonal rainfall	1935-71	4.86*	+ 0.064
5	Annual radial increment	Average annual production[1]	---	--	---
6	Annual radial increment	Average annual production[2]	1935-71	2.03	- 0.041
7	Annual radial increment	Average annual production[3]	1935-71	2.26	- 0.043
8	Annual radial increment	Average annual production[4]	1935-71	2.21	- 0.043

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

* Significant F-value at the 0.05 level.

** Significant F-value at the 0.01 level.

Table 9. Multiple linear regression analysis results for white pine stand #2. (Rating Level #1)

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	21.17††	- 0.322
2	Annual radial increment	Age	1935-71	23.94††	- 0.340
3	Annual radial increment	Total annual rainfall	1935-71	3.32	+ 0.134
4	Annual radial increment	Annual seasonal rainfall	1935-71	2.41	+ 0.114
5	Annual radial increment	Average annual production[1]	1935-71	17.47††	- 0.296
6	Annual radial increment	Average annual production[2]	1935-71	18.33††	- 0.302
7	Annual radial increment	Average annual production[3]	1935-71	19.44††	- 0.311
8	Annual radial increment	Average annual production[4]	1935-71	15.05††	- 0.278

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

Table 10. Multiple linear regression analysis results for white pine stand #2. (Rating Level #2)

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	8.99†	- 0.163
2	Annual radial increment	Age	1935-71	5.31*	- 0.126
3	Annual radial increment	Total annual rainfall	1935-71	0.24	+ 0.027
4	Annual radial increment	Annual seasonal rainfall	1935-71	4.63*	+ 0.118
5	Annual radial increment	Average annual production[1]	1935-71	8.14†	- 0.155
6	Annual radial increment	Average annual production[2]	1935-71	8.77†	- 0.161
7	Annual radial increment	Average annual production[3]	1935-71	7.38**	- 0.148
8	Annual radial increment	Average annual production[4]	1935-71	8.72†	- 0.161

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

* Significant F-value at the 0.05 level.
** Significant F-value at the 0.01 level.
† Significant F-value at the 0.005 level.
†† Significant F-value at the 0.001 level.

Table 11. Multiple linear regression analysis for white pine stand #2. (Rating Level #3)

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	48.71††	- 0.269
2	Annual radial increment	Age	1935-71	204.42††	- 0.496
3	Annual radial increment	Total annual rainfall	1935-71	6.76**	+ 0.103
4	Annual radial increment	Annual seasonal rainfall	1935-71	17.63††	+ 0.166
5	Annual radial increment	Average annual production[1]	1935-71	35.77††	- 0.233
6	Annual radial increment	Average annual production[2]	1935-71	42.82††	- 0.253
7	Annual radial increment	Average annual production[3]	1935-71	41.86††	- 0.251
8	Annual radial increment	Average annual production[4]	1935-71	33.51††	- 0.226

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

* Significant F-value at the 0.05 level.
** Significant F-value at the 0.01 level.
† Significant F-value at the 0.005 level.
†† Significant F-value at the 0.001 level.

Table 12. Multiple linear regression analysis results for white pine stand #2. (Rating Level #4)

Regression number	Dependent variable	Independent variable	Time span	F-Value	Simple or partial correlation
1	Annual radial increment	Average annual production	1935-71	32.40††	- 0.200
2	Annual radial increment	Age	1935-71	239.06††	- 0.485
3	Annual radial increment	Total annual rainfall	1935-71	8.13†	+ 0.102
4	Annual radial increment	Annual seasonal rainfall	1935-71	23.50††	+ 0.171
5	Annual radial increment	Average annual production[1]	1935-71	25.98††	- 0.180
6	Annual radial increment	Average annual production[2]	1935-71	26.39††	- 0.181
7	Annual radial increment	Average annual production[3]	1935-71	25.56††	- 0.178
8	Annual radial increment	Average annual production[4]	1935-71	23.34††	- 0.171

[1] Average annual production is correlated to annual radial increment after removing the effect of age.

[2] Average annual production is correlated to annual radial increment after removing the effect of total annual rainfall.

[3] Average annual production is correlated to annual radial increment after removing the effect of annual seasonal rainfall.

[4] Average annual production is correlated to annual radial increment after removing the effect of all other variables.

† Significant F-value at the 0.005 level.

†† Significant F-value at the 0.001 level.

VITA

Sylvester Olin Phillips was born in Chester, South Carolina, on August 22, 1951. He graduated from Durham Senior High School in Durham, North Carolina, in June of 1969. He entered Virginia Polytechnic Institute and State University in the Division of Forestry and Wildlife in the option of Forest Management. He received a Bachelor of Science degree in Forestry and Wildlife in June 1973. The same year he entered the Department of Plant Pathology and Physiology at Virginia Polytechnic and State University to pursue work leading to the Master of Science degree in Plant Pathology and Physiology.

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Sylvester Olin Phillips

GROWTH LOSS OF LOBLOLLY PINE (Pinus taeda L.),
WHITE PINE (P. strobus L.) AND SYCAMORE (Platanus occidentalis L.)
PROXIMAL TO A PERIODIC SOURCE OF AIR POLLUTION.

by

Sylvester Olin Phillips

(ABSTRACT)

The effect of a periodic source of a NO_X-SO_2 air pollution regime on the growth of forest trees was investigated. Radial increment growth studies were conducted to determine if correlations existed between emission levels of a source (predicted by production levels) and radial increment growth of forest trees. Three stands of loblolly pine, two of white pine, and one of sycamore proximal to the emission source were sampled by obtaining increment cores at d.b.h. (1.37 m from the base of the tree) from 50 trees in the dominant or codominant crown class of each stand. A multiple linear regression analysis 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 all stands. An inverse relationship significant at the 0.001 level was demonstrated between growth and production levels in two loblolly pine stands and one white pine stand. The further analysis of these stands indicated respectively a 45%, 45%, and 10% theoretical reduction in diameter growth which was independent of symptom expression in white pine. Growth and production levels were not significantly correlated in the remaining loblolly pine stand and the

sycamore stand; however, a positive relationship was exhibited in the second white pine stand.

A field chamber study (utilizing charcoal filtered and non-filtered air) with seedlings of red oak, sycamore, sweetgum, yellow poplar, white ash, green ash, and Virginia pine indicated significant inhibition of terminal elongation in Virginia pine and red oak in three locations surrounding the emission source.