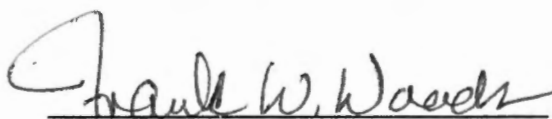
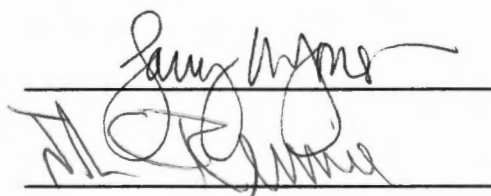


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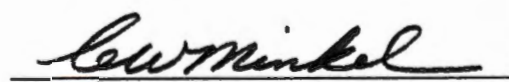
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Frank W. Woods, Major Professor

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WOOD DENSITY OF THREE OAK SPECIES IN EAST TENNESSEE:
1940-45 AND 1970-75

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Mark Loudin Hughes
August 1985

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ABSTRACT

The oak-hickory forests of East Tennessee were investigated at five locations in the vicinity of two coal-fired power generating facilities operated by the Tennessee Valley Authority. Three oak species (Quercus spp.) were sampled to determine whether wood cell density is related to air pollution (NO_x , SO_2) or acidified rain. Increment cores were collected and two periods (1940-45 and 1970-75) were analyzed by gamma-densitometric technique (Woods and Lawhon 1974). Wood densities were partitioned by latewood and earlywood and the component densities (density variables) which were average earlywood, average latewood, minimum earlywood, maximum latewood, and average period (1940-45, 1970-75) were statistically compared. When all trees of each species on all sites were analyzed, all component densities for white (Quercus alba L.) and chestnut (Quercus prinus L.) oaks were greater for the period of 1940-45 than for the period 1970-75. Only for the minimum earlywood density of chestnut oak was the level of significance less than $P=0.01$. For black oak (Quercus velutina L.) differences between the two time periods were found only for the mean earlywood ($P=0.05$), maximum latewood ($P=0.05$) and mean period densities ($P=0.01$). There were no differences between mean latewood and minimum earlywood values.

Mean period density was less for period 2 ($P=0.01$) for all three species. Only for the components which comprise this measure of density were there any differences, and non-significant differences

($P=0.05$) were found in only two component densities for black oak.

The lower component densities in the period 1970-75 are discussed in terms of air pollution affects on tree growth rates and on forest productivity.

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CHAPTER I

INTRODUCTION AND OBJECTIVES

Phytotoxic effects of anthropogenic, gaseous pollutants on plants have been studied for several decades (Solberg and Adams 1956, Daines 1968, Malhotra 1976, Carlson 1979, Keller 1980, McLaughlin et al. 1982). Ozone, oxides of sulfur and nitrogen, fluorides and peroxyacyl nitrates are included among those known to produce adverse physiological effects (Mudd 1975, Miller and McBride 1975).

The relationship of air pollution to white pine (Pinus strobus L.) death and injury has been reported in East Tennessee since 1955 (Anon. 1969), when the species underwent a massive dieback (Berry and Hepting 1964, Anon. 1969, Ellertson 1976). Symptoms of the disease were similar to fumigation injury (Ellertson 1976) but no specific causal agent was identified. However, the initial dieback took place following the initiation of a coal-fired power generating facility located in the Kingston-Oak Ridge-Harriman area of Roane and Anderson Counties, Tennessee, which indicates a possible anthropic origin of the fumigant.

Sulfur dioxide is among the most harmful of air pollutants (Ziegler 1972, Malhotra and Hocking 1976). A byproduct of coal combustion, SO₂ is now ubiquitous in the earth's atmosphere. SO₂ produces visible injury to leaves, interferes with normal metabolic processes (Ziegler 1972, Malhotra and Hocking 1976, Keller and Schwager

1977), depresses photosynthesis (Ziegler 1972, Sij and Swanson 1974, Carlson 1979), and restricts plant growth.

Studies of the decline of forest tree growth have typically dealt with coniferous species that are highly sensitive to abiotic stresses (Phillips et al. 1977a, Johnson et al. 1981, Benoit et al. 1982, Siccama et al. 1982, Scott et al. 1984). The study reported here deals with differences in the wood density of selected species of oak (Quercus spp.) in Anderson and Roane Counties, Tennessee.

The objectives of this study were (1) to determine if wood density is different in pre- and post-pollution periods for the same trees and (2) to test the hypothesis that such changes were synchronous with operation of nearby coal fired generating plants.

CHAPTER II

MATERIALS AND METHODS

This study was carried out in the Great Valley of Tennessee. Three sites were selected for study which were from 3 to 14 miles from Bull Run Steam Plant in Anderson County and 2 were selected within 6 miles of the Kingston Steam Plant in Roane County. They were chosen using several criteria: (1) each site must be free from apparent recent disturbances such as logging or fire; (2) each site must have at least two dominant tree species; and (3) sites must be located in forests produced by natural regeneration. All five sites were selected in the oak cover types that are typical of the Tennessee Valley. Each site was sampled systematically by traverses perpendicular to the slope. Individuals of two dominant species were selected until the predetermined population sample size was achieved for each species. Chestnut oak (Quercus prinus L.) and hickory (Carya spp.) were sampled at site 1 (Bull Run), Chestnut oak and white oak were sampled at site 2 (Harriman), Chestnut oak and white oak (Quercus alba L.) were sampled at site 3 (Oak Ridge), at site 4 (Norris State Park) white oak and black oak (Quercus velutina L.) were sampled, and at site 5 (Kingston) white and chestnut oaks were sampled.

Individual trees were selected on the basis of Kraft's Tree Classification (Daniel et al. 1979). Canopy dominant or codominant trees were inspected to see that they were free from apparent

perturbations such as fire, soil, wind damage, abrasions, ice damage, disease and debilitating insect infestations.

From each sample tree two 4-millimeter increment cores were extracted from opposite sides and perpendicular to the prevailing slope. The diameter at 1.3 m, species, core number, percent slope and aspect of each tree were recorded. A total of 250 trees was sampled from five locations, yielding a total of 500 increment cores. They were then prepared for analysis using the method of Moschler and Woods (1975). Cores were prepared by gluing them inside two hemispherically routed (3.8 mm) strips and then machined to $0.9 \text{ mm} \pm 0.04 \text{ mm}$. Core sections were then crossdated (Fritts 1976) and two time periods of interest were defined on each sample, 1940 to 1945 (pre-pollution) and 1970 to 1975 (post-pollution). The establishment of an ore reduction plant in the Harriman area during 1946 defined the control time boundary. The ages of samples at diameter breast height (d.b.h. = 1.4 m above the ground) were obtained by dating each core to the pith (Applequist 1958).

Crossdated core sections were analyzed by gamma densitometric technique. These analyses produced digital data that are a function of ring width and wood density. The gamma densitometer used in this study is an improved version of a prototype developed by Woods and Lawhon (1974). It has been used in dendroecological, silvicultural and wood density investigations (Lawhon 1973, Ross 1975, Ross et al. 1979, McRae 1981). The methodology is similar to that used by other authors using radiation to study radial increment density

(Harris 1969a, Harris 1969b, Parker and Meleskie 1970, Polge 1970, Jones and Parker 1970, Parker and Jozsa 1973) in that radiation is used to measure differences in wood density.

Mounted cores were traversed across a collimated photon "beam" (5.3 kev) synchronously stepped every 0.127 mm. Radiation passing through the wood was counted by a NaI(Tl) counter coupled to a photo-multiplier. A variable aperture in front of the detector, which controls the area scanned, was set at 0.127 mm. Control and treatment time periods were delimited on the mounted cores by opaque brass plates. Samples were counted for 2 seconds per step across the defined periodic increments. Six annual increments were scanned in each period. Data were transferred to a DEC-PDP11 computer (Digital Corp.) and then to disk structure (DECsystem-10 Univ. Tenn.). For analysis data were read to IBM disk packs (IBM 3380 magnetic disk Univ. Tenn.) and to magnetic tape for storage.

Programs were written in Statistical Analysis System (SAS Institute, Inc. 1982a) and Fortran 77 to generate summary data for each of the two time periods as follows: (1) annual increment width in each time period; (2) earlywood width and latewood width within increments; (3) minimum earlywood density; (4) maximum latewood density; (5) average earlywood density; (6) average latewood density; and (7) average density.

Monthly precipitation data were assembled for each year in both time periods. Rainfall totals for the months of February through September were recorded from the nearest weather station's

climatological data volumes (National Oceanic and Atmospheric Administration Environmental Data Service). Kingston, Oak Ridge and Norris weather station records were used. Precipitation data were tested using paired and non-paired comparisons using the t-test.

The hypothesis that density in the two time periods was different was tested using linear and curvilinear regression models, analysis of variance, paired comparisons and sample mean comparisons. Parallelism and coincidence were tested using regression models (SAS Institute, Inc. 1982b). Density variables were statistically tested using the model:

$$\begin{aligned}
 Y_{ijklm} = & \text{Site}_m + \text{Tree}_1 (\text{Site}_m) + \text{Time}_j \\
 & + \text{Site}_m * \text{Time}_j + \text{Tree}_1 * \text{Time}_j (\text{Site}_m) \\
 & + Y_{rk} (\text{Time}_j \text{ Tree}_1 \text{ Site}_m),
 \end{aligned}$$

Where:

Y_{ijklm} = the i th independent variable

Time_j = 1940-45, 1970-75

Y_{rk} = 1 through 5 years inclusive

Tree_1 = 1 through 25 sampled trees

Site_m = 1 through 5 sampled.

CHAPTER III

RESULTS AND DISCUSSION

When all trees of each species on all sites were analyzed, all component densities (Table 1) for white (Quercus alba L.) and chestnut (Quercus prinus L.) oaks were greater for period 1 (1940-45) than for period 2 (1970-75). Only for minimum earlywood density of chestnut oak was the level of significance less than $P=0.01$. For black oak (Quercus velutina L.) differences between the two time periods were found only for the mean earlywood ($P=0.05$), maximum latewood ($P=0.05$) and mean period densities ($P=0.01$). There were no differences between mean latewood and minimum earlywood values.

Mean period density was less for period 2 ($P=0.01$) for all three species. Only for components which comprise this measure of density were there any differences, and non-significant differences ($P=0.05$) were found in only two component densities for black oak. The analysis of variance tables, corresponding to the model for the density response variables, are given (Tables 2-6).

Precipitation was not significantly different ($P=0.05$) during the two periods and was not considered in any further analysis. However, precipitation means were greater during period 2 (1970-75) than during period 1 (1940-45), which would have contributed to a greater density pattern, which was the opposite from the one obtained (Tables 7 and 8). Wood density values for the species studied are within values reported by Panshin and DeZeeuw (1980) and Summit

Table 1. Density of three tree species for two time periods (g/cc).

Component Density	White Oak		Chestnut Oak		Black Oak	
	1940- 1945	1970- 1975 Diff.	1940- 1945	1970- 1975 Diff.	1940- 1945	1970- 1975 Diff.
Mean earlywood	0.690	0.664 0.026**	0.720	0.697 0.023**	0.628	0.605 0.023*
Mean latewood	0.740	0.716 0.024**	0.775	0.738 0.037**	0.683	0.659 0.024
Mean minimum earlywood	0.639	0.612 0.027**	0.667	0.651 0.016*	0.580	0.569 0.011
Mean maximum latewood	0.844	0.823 0.021**	0.873	0.838 0.035**	0.796	0.767 0.029*
Mean periods (6 years)	0.730	0.702 0.028**	0.762	0.726 0.036**	0.671	0.644 0.027**

* = Significant F-value at P=0.05.

** - Significant F-value at P=0.01.

Table 2. Analysis of variance table for mean earlywood density.

Source	White Oak			Chestnut Oak			Black Oak		
	D.F.	Mean Square	F	D.F.	Mean Square	F	D.F.	Mean Square	F
Site	3	0.2637	1.22	3	0.0947	3.56*	0		
Tree (Site) ^a	65	0.0216		40	0.0266		18	0.0081	
Time	1	0.1574	32.88**	1	0.0859	10.76**	1	0.0302	6.04**
Site* Time	3	0.0279	5.84**	3	0.0072	0.90	0		
Tree* Time (Site)	65	0.0048	4.16**	40	0.0080	6.29**	18	0.0050	2.75**
Yr (Time Tree Site) ^b	690	0.0012		440	0.0013		190	0.0018	

* = Significant F-value at P=0.05.

** = Significant F-value at P=0.01.

^aError term for whole plot.

^bError term for subplot.

Table 3. Analysis of variance table for mean latewood density.

Source	White Oak			Chestnut Oak			Black Oak		
	D.F.	Mean Square	F	D.F.	Mean Square	F	D.F.	Mean Square	F
Site	3	0.0658	2.47	3	0.0694	2.66	0		
Tree (Site) ^a	65	0.0266		40	0.0261		18	0.0018	
Time	1	0.1187	24.58**	1	0.1784	22.06**	1	0.0318	4.38
Site* Time	3	0.0074	1.54	3	0.0044	0.55	0		
Tree* Time (Site)	65	0.0048	1.76**	40	0.0081	3.76**	18	0.0073	1.73**
Yr (Time Tree Site) ^b	690	0.0026		440	0.0021		190	0.0042	

* = Significant F-value at P=0.05.

** = Significant F-value at P=0.01.

^aError term for whole plot.^bError term for subplot.

Table 4. Analysis of variance table for mean minimum earlywood density.

Source	White Oak			Chestnut Oak			Black Oak		
	D.F.	Mean Square	F	D.F.	Mean Square	F	D.F.	Mean Square	F
Site	3	0.0111	0.55	3	0.1424	5.01**	0		
Tree (Site) ^a	65	0.0201		40	0.0284		18	0.0076	
Time	1	0.1700	23.87**	1	0.0472	5.07*	1	0.0076	0.79
Site* Time	3	0.0492	6.91**	3	0.0119	1.28	0		
Tree* Time (Site)	65	0.00712	4.12**	40	0.0093	5.00**	18	0.0096	4.05**
Yr (Time Tree Site) ^b	690	0.0017		440	0.0019		190	0.0024	

* = Significant F-value at P=0.05.

** = Significant F-value at P=0.01.

^aError term for whole plot.

^bError term for subplot.

Table 5. Analysis of variance table for mean maximum latewood density.

Source	White Oak			Chestnut Oak			Black Oak		
	D.F.	Mean Square	F	D.F.	Mean Square	F	D.F.	Mean Square	F
Site	3	0.0591	2.19*	3	0.0546	1.92	0		
Tree (Site) ^a	65	0.0270		40	0.0283		18	0.0094	
Time	1	0.0891	14.57**	1	0.1746	20.40**	1	0.0476	7.15*
Site* Time	3	0.0058	0.94	3	0.0074	0.86	0		
Tree* Time (Site)	65	0.0061	0.73	40	0.0074	1.34	18	0.0067	0.52
Yr (Time Tree Site) ^b	690	0.0084		440	0.0064		190	0.0126	

* = Significant F-value at P=0.05.

** = Significant F-value at P=0.01.

^aError term for whole plot.^bError term for subplot.

Table 6. Analysis of variance table for mean period density.

Source	White Oak			Chestnut Oak			Black Oak		
	D.F.	Mean Square	F	D.F.	Mean Square	F	D.F.	Mean Square	F
Site	3	0.0111	2.85**	3	0.0144	3.37*	0		
Tree (Site) ^a	65	0.0039		40	0.0043		18	0.0013	
Time	1	0.0278	55.26**	1	0.0296	23.80**	1	0.0068	9.39**
Site* Time	3	0.0017	3.32*	3	0.0008	0.66	0		
Tree* Time (Site)	65	0.0005		40	0.0012		18	0.0007	
Yr (Time Tree Site) ^b	690			440			190		

* = Significant F-value at P=0.05.

** = Significant F-value at P=0.01.

^aError term for whole plot.^bError term for subplot.

Table 7. Precipitation February through September for three weather stations¹ (inches).

Yr	Period1 (1940-45)			Yr	Period2 (1970-75)			Difference2		
	Station				Station			Station		
	OR	K	N		OR	K	N	OR	K	N
40	4.17	4.28	4.50	70	4.50	4.83	4.88	0.33	0.55	0.38
41	3.87	3.95	3.10	71	4.68	4.69	4.88	0.81	0.74	1.78
42	4.16	4.49	4.22	72	4.24	4.55	4.51	0.08	0.06	0.29
43	2.63	4.70	4.73	73	6.39	6.13	5.32	3.76	1.43	0.59
44	4.90	5.83	5.36	74	4.53	4.52	4.50	0.37	1.28	0.86
45	4.69	4.43	4.60	75	5.39	5.18	5.58	0.70	0.75	0.98

¹OR = Oak Ridge; K = Kingston; N = Norris.

²No significant differences (P=0.05).

Table 8. Monthly period means and period totals for three weather stations (inches).

Period	Station					
	Oak Ridge		Kingston		Norris	
	Mean	Total	Mean	Total	Mean	Total
1940 to 1945	4.21	189.53	4.56	215.36	4.42	212.05
1970 to 1975	4.96	237.90	4.98	239.21	4.95	222.05
Diff. ^a	0.75	48.37	0.40	23.85	0.53	10.64

^aNo differences are significant ($P=0.05$).

and Sliker (1980). Slight variations in density for a species are expected and can be attributed to genetic diversity which is enhanced by different local site and climate conditions.

Mean density is inversely correlated with radial increment width in ring porous oak species (Panshin and DeZeeuw 1980), a result of the decreasing proportion of latewood fibrous tissue and the increasing proportion of earlywood vessel elements as growth slows (Maeglin and Quirk 1984). This, in part, may account for the decrease in period density reported, but it does not explain the differences in component densities. In addition, any hypothetical abiotic or biotic factor affecting photosynthesis would accentuate, retard or at least confound this trend.

Assuming that the change in component densities is not time dependent, it seems that some biotic or abiotic factor must have influenced the development of wood of trees sampled in this study. The limited information available indicates that changes in independent cell densities are not a function of tree age or growth rates in mature trees (Panshin and DeZeeuw 1980, Maeglin and Quirk 1984).

Meristems are affected by local environments. The cambium, a diffuse meristematic tissue, and its associated xylem, are intimately related to meristematic and photosynthetic regions which produce metabolites (Kozlowski 1962, Larson 1969). Cell diameter and secondary cell wall thickening are dependent on foliar development (Wareing and Roberts 1956, Gordon and Larson 1968, Larson 1969). For example, temperature affects the reaction rates of biochemical processes.

Temperature then, is a determinant of physiological development. Increased temperature is associated with increased tracheid wall thickness in Pinus resinosa Ait. (Larson 1964). Temperatures have also been shown to be correlated with radial growth of Quercus ellipsoidalis Hill (Kozlowski et al. 1962).

Cyclic changes in photoperiod can either initiate or terminate annual growth (Wareing 1953, Wareing and Roberts 1956, Larson 1960, Downs 1962). Cambial growth is inhibited by controlled "short day" illumination while "long day" photoperiods stimulate cambial activity (Wareing and Roberts 1956, Larson 1964).

Water stress reduces the translocation of photosynthates (Kramer 1964). Roberts (1964) observed 86 percent reduction in the translocation of C^{14} labeled photosynthate in water stressed Liriodendron tulipifera L. seedlings. Such reduction in translocation, in turn, may restrict distribution of organic molecules (sugars and hormones) to the developing cambium (Kramer 1964). Furthermore, auxin translocation is synchronous with carbohydrate translocation (Kozlowski 1962, Kramer 1964). Auxin and other hormones, e.g., gibberellins and cytokinins, are involved in xylem differentiation (Wareing et al. 1964, Digby and Wareing 1966, Larson 1969). It is generally accepted that cell diameter is controlled by auxin while secondary cell wall thickness is regulated by carbohydrate concentration (Kramer 1964, Larson 1969). The thick cell walls reported for tropical pines are explained by this theory (Panshin and DeZeeuw 1980).

Tracheid diameter and cell wall thickness can be altered independently or in concert by manipulation of auxin and photosynthate synthesis, via controlled growth conditions, in Pinus resinosa seedlings (Larson 1969). By promoting high auxin and photosynthate synthesis Larson (1969) produced cells with large diameters and thick walls. When he restricted photosynthesis while maintaining auxin synthesis, cells of large diameter and thin walls were formed. Narrow diameter, thick-walled cells were produced by inhibiting auxin synthesis while maintaining photosynthesis. Reduced auxin and photosynthate resulted in cells with narrow diameters and thin walls.

Auxin and gibberellin originate in apical meristems (Larson 1969, Salisbury and Ross 1978). The location of biosynthesis then explains how photoperiod, temperature, water supply, defoliation and any other biotic input may act to reduce the number of xylem cells or alter the density of xylem cells produced, or both. Any biotic stress that affects meristematic or photosynthetic regions will also affect photosynthate and hormone production, thereby indirectly affecting cell number and composition.

Peroxyacetyl nitrate (PAN) and ozone have been shown to inactivate indoleacetic acid (IAA, also auxin) irreversibly (Ordin and Propst 1962). The addition of either ascorbic acid (AA) or glutathione prevent IAA inactivation by reducing the oxidant pollutants. Decreased AA also has been correlated with SO₂ susceptibility of Picea excelsa (Lam.) Link and SO₂ fumigation of cedar (Thuja plicata

Donn ex D. Don) (Keller and Schwager 1977). They suggest that AA detoxifies pollutants by reducing sulfur dioxide and other oxidants, and they conclude that conditions which lead to lower AA levels, such as shading or stresses brought on by air pollutants, alter metabolism and predispose trees to other environmental stresses such as aphid attack.

SO_3^{-2} inhibits the activity of ribulose-1,5-diphosphate (RuDPH), the first enzyme in the Calvin cycle (Ziegler 1972), and decreases carbon fixation. This may partially explain lower photosynthetic rates following fumigation with sulfur dioxide. Kinetic studies dealing with the reduction in photosynthesis by sulfur dioxide have shown photosynthetic rate reductions of 90% for primary leaves of pinto bean (Phaseolus vulgaris L. cv. Pinto) (Sij and Swanson 1974). Sulfur dioxide fumigation increased transpiration rates, decreased chlorophyll content and height and root growth in Robinia pseudoacacia L. seedlings (Suwannapinunt and Kozlowski 1980) these decreases in growth were apparently due to reduction in growth hormones and photosynthetic product. Forest grown saplings of sugar maple (Acer saccharum Marsh), black oak and white ash (Fraxinus americana L.) fumigated with sulfur dioxide and ozone showed reduction in net photosynthesis (Carlson 1979). In this study different factor levels of SO_2 , O_3 , light intensity and relative humidity produced 74, 43, and 7% reductions in photosynthesis for black oak, sugar maple and white ash, respectively.

The study reported here has dealt with wood density during two periods. Period 1 was, in some respects, a control, while oxidant pollution and acidified precipitation characterized period 2. A number of regional investigations of tree decline in the eastern United States have indicated effects attributable to the air pollution-acid rain complex. Growth reduction in 3 species of pine (Pinus rigida Mill., Pinus echinata Mill., Pinus taeda L.) was correlated with decreases in stream pH in southern New Jersey in which stream pH was used as an index of precipitation pH. Acid rain was suggested as a possible factor (Johnson et al. 1981). In southeastern New York, analysis of tree-ring indices for coniferous and deciduous species revealed recent changes in growth response not associated with climate and which coincide with recent increases in acid rain and air pollution (Puckett 1982). Again, air pollution is the suspect.

The work reported here is necessarily without experimental controls, and without controls a definite cause and effect between tree growth and acid precipitation cannot be unequivocally substantiated (Johnson et al. 1981). Neither can observed reductions in forest productivity that are temporally linked to increases in regional pollutant levels be directly attributed to air pollution. Other investigators reporting reductions in tree growth and changes in forest ecosystems have reached a similar conclusion (Cogbill 1977, Scott et al. 1984, Siccama et al. 1982).

However, studies investigating point-source polluted forests have reported tree mortality and unequivocal reductions in tree

vigor, growth and species composition (Scheffer and Hedgcock 1955, Linzon 1965, Oleksyn 1983). In addition, similar studies involving periodic (acute) air pollution levels (NO_x , SO_2) report growth to be inversely correlated with recorded episodic pollutant levels for Pinus taeda L., Pinus strobus L. and Liriodendron tulipifera L. (Stone and Skelly 1974, Phillips et al. 1977a, Phillips et al. 1977b). These studies represent a quasi control while laboratory controlled experiments indicate more conclusively the detrimental effects of sulfur dioxide fumigation (Keller 1980, Carlson 1979).

The decrease in component densities found in this study is in agreement with a controlled fumigation experiment (Keller 1980). These decreases in component densities also conflict with the uniform component densities reported for Quercus spp. Earlywood and latewood fractions which were formed under slow, medium and fast growing conditions were found to have identical component densities (Maeglin and Quirk 1984). The densities changes found here therefore suggest abnormal growth. Component density values for red oak were calculated from increment cores (d.b.h.) taken from 240, 50 to 100 year old, dominant or codominant trees; values for white oak were derived from pulp chips and log samples. They found that the specific gravity (g/cm^3) of the component cell types (earlywood, latewood) which had been produced under different growth rates (slow, medium and fast) was the same. According to present understanding of long-term researchers in this field, cell diameter and cell wall thickness should remain constant with respect to time if formed under the

same environmental conditions (personal communication, H. A. Core, 1985) and based on past work no change in cell wall density between annual rings over time is expected (personal communication, J. T. Quirk, 1985). These studies support the hypothesis put forward here that factors have altered tree health and hence wood cell density and further, these changes are synchronous with industrial activity in the region. When differences in annual ring width and structure are considered in the light of known physiological processes, current biochemical hypothesis and results from previous studies, a relation between air pollution, acid rain or synergistic combinations and tree growth in the study area is strongly indicated.

Oxidant-air borne pollutants at subnecrotic levels may affect foliar development and photochemical reactions thereby altering the amount of diffusible auxin and photosynthate available to developing cambium. Such changes could alter normal cambial cell development producing earlywood and latewood cells with density, diameter and cumulative radial width differences similar to those recorded experimentally (Larson 1969, Keller 1980) and to those observed in the trees sampled in this study. Such changes may be caused indirectly by acid rain, air pollution or the additive effects of both (Puckett 1982), and, if so, could be responsible for decreases in forest productivity.

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APPENDIX

APPENDIX

USE OF RADIAL GROWTH AS A POLLUTION INDICATOR

Included in the preliminary objectives of this study was the use of annual radial increment data. Increment width and component earlywood, latewood widths were recorded for the years 1940-45 and 1970-75. Total ring, earlywood, latewood and period widths were calculated from computer programs defining maxima, minima and inflection points at defined widths (0.127 mm). Maximum and minimum data values were generated by iterative do-loop comparisons of 10 lagged data values where the central value was greater or less than all other lagged values on either side of the data curve, while 4 preceding absolute values were consistently greater with respect to a change in slope. Points of inflection were delimited by a similar manner but identified by 4 sequentially greater absolute value changes with respect to slope following the preceding minimum, thus representing the transition from latewood to earlywood. One maximum and one minimum represented one increment while six maximum and six minimum represented one period. This structured programming, for data base, delimited annual increments, six year periods, and partitioned earlywood and latewood fractions by differences in wood density in ring porous tree species. Analysis of growth, using ring width, was not reported because a statistically valid comparison of growth during the two periods could not be achieved. In order to statistically compare growth at different times, or growth during

a period of time, the biological variation due to trend must be removed from any changes in growth to be tested.

A conclusive comparison is not reported here because (1) the sample trees were of varying biological age, as they were taken from natural populations, (2) growth models for the species examined were not available or not suitable, as growth and yield models typically describe even age forests, or are not applicable to the small responses encountered in dendroecological investigations, (3) time and resource constraints were present and although several models were tested in analyses, they lacked the data base used in regional studies reporting growth responses to climate or pollution, and (4) a covariate model that would correlate growth changes was not available.

Growth analyses could have been reported if one of the following had been available: (1) suitable growth models (reason 2), (2) access to tree ring indices that were for the species studied and geographically extensive (reason 3). In addition, a pollutant indicator used as a covariate (e.g., stream pH or ambient pollutant levels as a function of time (reason 4)) would help form more conclusive results. If point-source pollution is being investigated, the selection of sampling locations at varying distances along established plumes, or concentration vectors would provide a covariate and simplify evaluations, and might be considered as a "backup" or corroborative result. A point-source evaluation, however, was not the intent of this study as a regional approach was taken. Regional studies of this type are normally and necessarily without experimental control.

We suggest that researchers anticipating regional investigations of tree response to pollutant stresses should anticipate the problems associated with the analysis of autocorrelated data in the absence of experimental controls.

VITA

Mark Loudin Hughes was born in Quakertown, Pennsylvania, on March 27, 1955. He was graduated from Governor Mifflin High School in Reading, Pennsylvania in June 1973. In September 1978 he entered The University of Tennessee, Knoxville, and in June 1982 received the B.S. degree in Forestry. In September of that year he began graduate studies at The University of Tennessee, Knoxville, and in August 1985 received the M.S. degree in Forestry.