AGE-SPECIFIC LEAD DISTRIBUTION IN URBAN FOREST TREE RINGS IN ATLANTA, GEORGIA

By

Charles Frederick Baes, III

I have attempted to create a faithful electronic copy of my master's thesis. My copy of the original (which I have scanned for this PDF file) is a poor, faded xerox copy. Additionally, the original was typed on a turn-of-the century Oliver manual typewriter with a faded ribbon, and the maps and several figures were drawn by hand with a rapidograph and a French curve set. The model outputs were created on a pen plotter, and final figures were done by hand by tracing over an original on a light table. If I can find the original slides that were used to create Figure 4, I will update it.

In presenting this thesis as a partial fulfillment of the requirements for an advanced degree from Emory University, I agree that the Library of the University shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish, this thesis may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate School when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this thesis which involves potential financial gain will not be allowed without written permission.

____

NOTICE TO BORROWERS

Unpublished theses deposited in the Emory University Library must be used only in accordance with the stipulations prescribed by the author in the preceding statement.

The author of this thesis is:

Charles Frederick Baes, III
1184 Briarcliff Road N.E.
Apartment 2
Atlanta, Georgia 30306

The director of this thesis is:

Dr. H. L. Ragsdale
Department of Biology
Emory University
Atlanta, Georgia 30322

Users of this thesis not regularly enrolled as students at Emory University are required to attest acceptance of the preceding stipulations by signing below. Libraries borrowing this thesis for the use of their patrons are required to see that each user records here the information requested.

Name of user	Address	Date	Type of use (Examination only or copying)

AGE-SPECIFIC LEAD DISTRIBUTION IN URBAN FOREST TREE RINGS IN ATLANTA, GEORGIA

Approved for the Department:

____

Adviser

____

Date

Accepted:

____

Dean of the Graduate School

____

Date

AGE-SPECIFIC LEAD DISTRIBUTION IN URBAN FOREST TREE RINGS IN ATLANTA, GEORGIA

By
Charles Frederick Baes, III
B.S., University of Tennessee, 1972

Adviser: Dr. H. L. Ragsdale

An Abstract of
A Thesis submitted to the Faculty of the Graduate School
of Emory University in partial fulfillment
of the requirements of the degree of
Master of Science

Department of Biology

1977

ABSTRACT

Lead concentration was measured in four tree species, Liriodendron tulipifera, Quercus alba, Carya spp., and Pinus taeda, near and far from a major roadway in Atlanta, Geogia. Three cores from each of 39 trees were cut into bark and 4-yr xylem sections and analyzed on a Perkin-Elmer 306 Atomic Absorbtion Spectrophotometer with HGA-2100 Graphite Furnace in gas-interrupt phase and deuterium arc background correction. Bark lead concentrations varied greatly between cores, trees, and species. No site- or species-specific lead concentrations were observed. Xylem lead concentrations were both site- and species- specific. Carya was most sensitive to environmental lead and accumulated the highest xylem lead concentrations at both sites. Generally, the order of xylem lead concentrations was Carya > Liriodendron ≥ Quercus ≥ Pinus. Historical lead accumulation patterns were highly species-specific and resembled the shapes of a Gaussian distribution, exponential or linear curve, and logistic growth curve for Liriodendron, Quercus, and Carya trees, respectively. Pinus showed no pattern of historical lead accumulation. Soil and xylem lead correlations were poor. However, relations between xylem lead concentration and surface area to volume ratio of the leaves indicate the possibility of leaf-derived lead. Peak xylem lead concen-

trations prior to 1975 in Carya and Liriodendron trees and the success of model simulations suggest that lateral transport is an important phenomena in these species.

ACKNOWLEDGMENTS

I would like to thank Mr. Ed Hunt for his assistance in sampling, Dr. James N. Skeen of Fernbank Science Center for his time and patience, the members of my committee, Dr. W. H. Murdy and Dr. D. J. Shure for their suggestions, and Dr. H. L. Ragsdale for his patience and guidance.

AGE-SPECIFIC LEAD DISTRIBUTION IN URBAN FOREST TREE RINGS IN ATLANTA, GEORGIA

By
Charles Frederick Baes, III
B.S., University of Tennessee, 1972

Adviser: Dr. H. L. Ragsdale

A Thesis submitted to the Faculty of the Graduate School
of Emory University in partial fulfillment
of the requirements of the degree of
Master of Science

Department of Biology

1977

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Anthropogenic lead pollution of the environment is a consequence of modern civilization, and global lead pollution is increasing fast. Presently, the two major sources of anthropogenic lead are emissions from the burning of coal and leaded gasoline. Historically, more than a 400-fold increase in lead deposition from 800 B. C. to 1965 is indicated from analysis of Greenland and Antarctic snow strata (Murozumi, et al., 1969). The natural background lead values before and up to 800 B. C. are thought to result from volcanic activity and from weathering of geologic structures. Three phases of global pollution are evident: a gradual 25-fold increase from 800 B. C. to 1750 from minor European lead production activities, a more rapid 6-fold increase from 1750 to 1933 from intensive coal combustion and smelting activities during the industrial revolution, and a very rapid 3-fold increase from 1933 to 1965 from widespread use of tetraethyl leaded gasoline. Sediment cores from Lake Michigan confirm this lead pollution pattern. Steady accumulations from 1830 to 1920 correspond to a period of increasing coal burning and a sharp increase after 1920 is from automotive sources (Edgington and Robbins, 1976).

The prognosis for the future is that lead emissions from coal combustion will increase. As natural gas and oil reserves dwindle, there will be increased dependence on coal to meet energy demands. Fortunately, most lead transported through coal-fired power plants is retained in the slag and is an on-site problem. However, Klein, et al. (1975) estimate 0.2 g Pb min^{-1} or 10^5 Kg Pb yr^{-1} is discharged to the atmosphere from Allen Steam Plant in Memphis, Tennessee where the best available technology in electrostatic precipitators is in operation (approximately 98% Pb is removed). Klein's figure is more than an order of magnitude less than the 1088 Kg Pb yr^{-1} atmospherically discharged from TVA coal-fired steam plants in the Oak Ridge, Tennessee area (Harris, et al., 1975). Global coal consumption is approaching 2.7×10^{12} Kg yr^{-1} (Klein, et al., 1975) and 3.2×10^5 Kg Pb would be atmospherically discharged if all coal-fired steam plants were as efficient as the Allen Steam Plant and only low-lead (5.9 ppm) coal were used. This figure approximates the lowest possible lead discharge with current technology and power demand.

If combustible municipal wastes were recycled to conserve fossil fuels, the lead pollution problem could grow worse. Lead in coal ranges from 5.9-8.2 ppm (Campbell, 1976). Lead in recyclable combustibles is far greater, ranging from 6-1600 ppm. Approximately 50% of this material is paper. The lead concentration in newspaper is 9 ppm, in comic books 45 ppm, and in cardboard 6 ppm (Campbell, 1976).

If stack lead emissions from coal burning are reduced or eliminated, the automotive lead source would still remain. Lead additives in gasoline, introduced in 1923, are the single most significant source of anthropogenic lead pollution today (Patterson, 1965). Currently, the lead content of gasoline ranges from 0.40-0.73 g Pb l^{-1} (Huntzicker, et a1., 1975). The consumption of gas in the U. S. was 3.86×10^{11} l yr^{-1} in 1974 (The World Almanac and Book of Facts 1976). Huntzicker et al. estimate 76% of the lead in gasoline is discharged from the automobile with the exhaust. Thus, in the U. S. alone 5.9×10^7 Kg Pb yr^{-1} was discharged to the environment if only 50% of the gas consumed was leaded. The actual value should be much higher since the above figure is based on low-lead (0.40 ppt) gas only. However, this figure is almost 200-fold greater than the lowest estimate of global output for coal previously given.

On individual terms, each driver is responsible for a portion of the lead pollution problem, and his driving habits determine the extent of his responsibility. A driver using non-leaded gasoline puts no lead into the environment. A driver traveling only 10,000 mi yr^{-1} in a car averaging 35 mpg on low-lead gasoline puts approximately 0.33 Kg Pb yr^{-1} into the environment. A less conservative driver who drives 15,000 mi yr^{-1} in a car averaging 15 mpg on high-lead gasoline is responsible for 2.1 Kg Pb yr^{-1}.

The fate of lead aerosols discharged in automobile exhaust is not well understood; however, the majority of automotive lead emissions is particulate (Olson and Skogerboe, 1975). The smaller particulate fractions may be carried away from the point source and eventually settle out. The larger particulate fractions are retained within a zone of 30 m from the roadside with variations depending on traffic conditions, wind patterns, ground cover, and topography (Goldsmith, et al., 1976). Street dusts may be washed out and eventuate in streams, rivers, lakes, and coastal waters, but the accumulation of lead in soil, flora, and fauna along roadways has been well documented (Cannon and Bowles, 1962; Chow, at a1., 1970; Motto, et al., 1970).

Lead concentration in roadside soils varies inversely with soil depth and distance from the roadside. Lead from automobile exhaust has been measured on roadside foliage (Smith, 1973; Dedolph, et a1., 1970; Purves and Mackenzie, 1969; Ault, et a1., 1970), tree twigs (Smith, 1973), and tree bark (Ward, et al., 1974; Laaksovirta, et al., 1976), and bark lead concentrations have been positively correlated with traffic density (Laaksovirta, et al., 1976). The origin and uptake of lead by plant roots is not completely understood, but it is known that larger roots accumulate relatively low lead concentrations (Nilsson, 1971), and smaller roots, particularly root hairs, accumulate much higher concentrations (Harris, et al., 1975).

While the occurrence and distribution of roadside lead has been well documented, continuous on-site monitoring and historical pollution records in most areas are not available. Trees seem the most logical natural monitors of environmental lead because they are much more widely distributed than snow strata and lake sediments, they are relatively stable through time, and they are easily accessible to sampling. Lepp (1975) discusses tree rings as possible monitors of heavy metal pollution and raises questions of metal entry into the tree, pathways of transport, and the effect of lateral transport between the annual growth rings. Thus, whether trees can accurately reflect changes in environmental lead levels and preserve an historical record of lead pollution is not known.

This study will assess tree-ring analyses by measuring and comparing xylem lead concentrations in four dominant tree species of an urban forest ecosystem growing near and far from a major lead source. The most sensitive of these tree species will be indicated, and any species- or site-specific lead accumulation patterns will be closely examined. Analysis of these patterns may give indirect evidence of metal entry into the tree, pathways of transport to the xylem, and the existence of lateral movement of lead between the annual growth rings. Xylem lead accumulation patterns will be related to traffic growth in Atlanta, and thus, the relative usefulness of such studies in monitoring lead pollution and constructing historical lead pollution records will be indicated.

MATERIALS AND METHODS

Two study areas were chosen: Deepdene Park, a small "finger park" located approximately 3.8 mi northeast of the Georgia State Capitol Building in downtown Atlanta, and Fernbank Forest, a mature, mixed-deciduous forest 400 m north of Deepdene Park. The park, approximately 600 m × 180 m, is bordered along its eastern, southern, and western margin by Ponce de Leon Avenue, a major traffic route (30,000 vehicles day^{-1}) between Decatur and downtown Atlanta. The northern border of the park is defined by N. Ponce de Leon Avenue, a small residential side street (Fig. 1), Fernbank Forest, approximately 475 in × 420 m, is protected and maintained by the staff of Fernbank Science Center. Crisscrossing pathways and a high chain-link fence surrounding the forest minimize disturbances from motor and pedestrian traffic (Fig. 2). A strip of residential dwellings separates the two sites which were originally a continuous forest ecosystem.

Five individuals of each of the four dominant tree species (Skeen, 1974), *Liriodendron tulipifera*, *Quercus alba*, *Carya* spp., and *Pinus taeda*, were selected at Deepdene Park, and 10, 5, 3, and 1 individuals of these four species, respectively, were selected at Fernbank Forest. Larger, older trees were chosen over younger trees, and trees with heart rot, dead limbs, signs of insect attack, or lightning damage were not sampled. Two Ailanthus altissima (tree-of heaven) trees growing in downtown Atlanta were also selected for study. In addition to these 41 trees, 2 trees at Deepdene Park were sampled at various aboveground heights. A standing Carya tree was sampled at 0.27, 2.0, 3.1, and 4.2 m along the southernmost side, and a fallen Liriodendron tree was sampled along the bole at points which were originally 0.56, 7.0, and 12 m above ground. Sampling was done from April to June 1976.

Each of the 41 trees was measured for diameter at breast height (dbh), marked at 120°, 240°, and 360° from a north-south or south-north axis (Fig. 3), and cored with a stainless steel corer, 45.7 cm × 4.3 mm in diameter. All stainless steel surfaces exposed to xylem tissue were washed with a 10% solution of the quartenary amide chloride "aliquat 336-S" (Moore, 1972) in 2-heptanone and rinsed with acetone before coring. Each core was removed with the pre-washed extracting spoon and placed in a plastic storage tube. The core was filled with plastic wood, and a small cork was forced past the cambium. Plastic wood was applied over the cork and sculptured to match the bark texture (Fig. 4).

Three 30 cm soil cores were taken along the axes used for coring the tree. Each soil core was subdivided into 0-15 cm and 15-30 cm fractions and placed in plastic bags. In areas where rock strata, terrain, or natural obstacles prevented a 30 cm core, the nearest accessible area was used, or a 15 cm core was taken.

All laboratory glassware was acid washed with 6 N HCl, and clean laboratory procedures were used to minimize contamination of the samples. Distilled-deionized water (DDH_2O) was used for all reagent and sample preparations. Only analytical grade chemical reagents were used.

Annual growth rings were counted under magnification, and 4-yr sections were cut out with a stainless steel knife and put in glass vials. Each core section was washed by shaking 30 sec with 0.1 N HNO_3 and dried for 24 hr at 100°C in an oven. Dried sections were weighed to the nearest 0.1 mg in a desiccated atmosphere maintained by a glove box (Fig. 5) which enclosed analytical balance and samples (Hygroscopic action was found to significantly influence sample weights because of their relatively low mass and high surface area.). The cores were transferred to 10 ml class A volumetric flasks and ashed at 400°C for 24 hr or until a fine ash remained. Ash was taken up with 1.0 ml of 2.0 N $HClO_4$, transferred to 12 × 75 mm polypropylene test tubes, capped and stored.

Soil samples were dried for 24 hr at 100°C and sieved through a 500 μ sieve. Approximately 10 g of soil was weighed to the nearest 0.1 mg and placed in a 125 ml Erlenmeyer flask which contained 10 ml DDH_2O. The 1:1 slurry was measured for pH on a Heath-Schlumberger EU-200-30 pH/pion Electrometer with digital indicator. The pH was taken after 15 sec vigorous stirring and 15 sec standing equilibration of the electrodes.

After pH determination, 10 ml conc HNO_3 was added, and each flask was heated to subboiling for 24 hr. The samples were filtered through Whatman #42 filter papers, taken up to volume in 50 ml volumetric flasks, transferred to 17 × 100 mm polypropylene test tubes, capped, and stored.

Analysis of tree samples incorporated a Perkin-Elmer 306 Atomic Absorbtion Spectrophotometer, HGA-2100 Graphite Furnace with controller in the gas-interrupt phase, and deuterium arc background correction. The N_2 purge gas flowmeter was set to 40 cc min^{-1}, and the controller was programmed to dry 15 sec at 110°C, char 10 sec at 375° C, and atomize 4 sec at 2500° C. Three sample aliquots of 20 μl were injected into the furnace, and absorbance was indicated on a Leeds and Northrup A1-Speedomax XL Strip Chart Recorder.

Soil sample analysis incorporated the same spectrophotometer in the air-acetylene flame mode. Triplicate readings, taken at 283.3 μ ultraviolet, were averaged for each sample, and blank $HClO_4$ aliquots were analyzed with every lot of 20 samples to monitor reagent purity. All standards were made up in the specific acid and normality of the unknowns, and all standard calibration curves were visually scrutinized and statistically analyzed to insure good fit.

For presentation purposes, the xylem core sections are grouped into 10-yr intervals by taking the weighted mean of all 4-yr sections within the decade. For example, lead concentration for xylem sections in the 1960-1969 decade is derived as follows:

$$\frac{4(1960\text{-}1963) + 4(1964\text{-}1967) + 2(1968\text{-}1971)}{10}$$

The values in parenthesis are lead concentrations in ppm for the 4-yr interval indicated, and the mean of 3 such derivations (120° + 240° + 360° cores) is used for the tree mean.

Soil pH values given herein are the mean of 6 samples for each tree. The 0-15 cm and 15-30 cm fractions are pooled.

The statistical terms, "mean," "standard deviation," and "standard error," used in this paper are defined in Principles and Procedures of Statistics (Steel and Torrie, 1960). However, other terms used in this paper are defined as follows:

1. Relative standard error $\frac{\text{standard error}}{\text{mean}}$ (1)

2. Index of decrease (I_d) = (2)

$$\frac{\text{ppm Pb in 0-15 cm soil fraction}}{\text{ppm Pb in 15-30 cm soil fraction}}$$

RESULTS

The percent weight change for 2-0.1 g Liriodendron tree core sections showed that after 5 min the section weighed in ambient air gained more than 3% of its initial dry weight by hygroscopic action (Fig. 6). The other sections weighed in the dry atmosphere, showed no detectable weight gain. These results demonstrated the importance of the glove box in minimizing weighing error.

The accuracy of the sample preparation procedure was assessed by comparing replicate lead determinations on Quercus nigra bark, Liriodendron xylem, and 2.0 N $HClO_4$ blanks (Fig. 7). The reproducibility of results was good for all sample types, and the accuracy of lead determinations on bark and xylem was essentially the same. The mean lead concentration of bark, xylem and blanks was 19.3 ppm, 1.50 ppm, and 2.20 ppb, respectively. Eighty, 75, and 60% of these three sample types fell within 1 standard deviation of their respective mean, and all replicate lead determinations were within 2 standard deviations of their respective mean. The relative standard errors for bark, xylem, and blanks were 0.046, 0.044, and 0.16, respectively. The relatively high error term associated with $HClO_4$ blanks was likely a reflection that absorbance readings for these samples were very near the detection limits of the spectrophotometer (Fig. 8).

Soil pH is generally higher and more normally distributed (Fig. 9) at Fernbank Forest although pH values at both sites are acidic ($4.41 \leq pH \leq 5.94$). The pH values for soils arranged by species are quite similar between sites (Table 1). There is no significant statistical difference ($p < 0.001$) between soils under Liriodendron trees at each site and between soils under Carya trees at each site. The means of pHs for soils under Liriodendron canopies differ by 0.03 pH units, and the respective means for soils under Carya canopies differ by 0.02 pH units. In all cases the mean soil pH is lower at Deepdene Park, and the standard error of the mean is less at Fernbank Forest. This phenomena of similar soil pH is more likely a matter of coincidence, rather than a direct result of tree influence. Although leaf litter, flaking bark, fallen branches, dead roots, and throughfall all affect soil composition, and thus pH, the soil pH is most strongly affected by geophysical weathering.

Generally, soil lead concentrations were higher at Deepdene Park (Table 2) than at Fernbank Forest (Table 3). The soil lead range for the 0-15 cm fraction was 43-233 ppm at Deepdene Park, and the range at Fernbank Forest was 33-65 ppm. Soil lead concentrations in the 15-30 cm fraction ranged from 17-96 ppm and from 18-37 ppm for Deepdene and Fernbank soils, respectively.

Soil lead varies inversely with distance from the road and soil depth. The correlation between soil lead and distance from Ponce de Leon Avenue is stronger for the 0-15 cm soil fraction ($r = -0.71$) than for the 15-30 cm soil fraction ($r = -0.49$), and without exception, there is a higher lead concentration in the 0-15 cm fraction than in the 15-30 cm fraction. No correlation was found between soil lead and distance to the nearest traffic light for either soil fraction, although cars decelerating, idling, and accelerating at that point are potentially greater lead polluters than cars rapidly passing by that point.

Fernbank soils are much less disturbed by urban influences than Deepdene soils, and thus, are more homogenous. The means for soil lead concentration in both 0-15 cm and 15-30 cm fractions are higher at Deepdene Park than at Fernbank Forest (Fig. 10), and there is a stronger correlation between these fractions at Fernbank Forest ($r = 0.82$) than at Deepdene Park ($r = 0.49$). The index of difference between soil fractions also shows Fernbank soils to be more homogenous than Deepdene soils (Fig. 11). The I_d distribution is more normally distributed and the mean I_d is lower at Fernbank Forest (2.0) than at Deepdene Park (2.9). The highest range of values (3.2-10) is also found at Deepdene Park.

Tree species are generally of comparable age and size within and between sites (Tables 2 & 3). The age range at Deepdene Park is 43-144 yrs with an average of 100 yrs. At Fernbank Forest the range is 107-157 yrs with an average of 131 yrs. Bark lead concentrations for all species range from 0.15-6.76 ppm at Deepdene Park (Table 4) and from 0.09-1.18 ppm at Fernbank Forest (Table 5). No species- or site-specific patterns can be found; however, the highest bark lead concentrations occur more often at Deepdene Park. There is a high degree of variability between replicates of the same tree and between trees of the same and different species.

It is postulated that bark lead is mostly surface-adhered (Ward, et al., 1974; Laaksovirta, et al., 1976), and lead concentration sharply decreases from bark surface inward. The bark often separated from the xylem and fragmented into several pieces during extraction and manipulation of the fragile core. Care was taken to maintain the integrity of the core, but often several pieces were lost. The high variability associated with bark lead concentrations may reflect sampling losses or spatial heterogenity of lead distribution on the bark surface.

Unlike bark lead concentrations, xylem lead concentrations show definite species- and site-specific patterns.

The range of lead concentrations in Carya xylem sections is from 1.2-32 ppm at Deepdene Park and from 0.31-3.1 ppm at Fernbank Forest. The respective ranges for Liriodendron xylem sections are an order of magnitude less, 0.09-1.8 ppm and 0.01-0.16 ppm. Lead concentration in Quercus xylem is approximately the same as in Liriodendron xylem, 0.02-0.37 ppm and 0.02-0.13 ppm, respectively. Pinus is the only species which has higher xylem lead concentrations at Fernbank Forest than at Deepdene Park. The xylem lead range at Deepdene Park is 0.002-0.06 ppm, and the range for the single tree sampled at Fernbank Forest is 0.06-0.19 ppm.

Comparison of xylem lead accumulations by each tree species at Deepdene Park (Fig. 12) and at Fernbank Forest (Fig. 13) shows similar patterns of relative lead accumulation between the tree species. One Carya tree (#11), which did not have xylem concentrations of the same order of magnitude as the other Carya trees at Deepdene Park, was determined to be a statistical outlier, and it is excluded from all subsequent analyses. Xylem lead concentrations of all species, except Pinus, drop approximately an order of magnitude from Deepdene Park to Fernbank Forest. Carya trees at both sites consistently accumulate at least an order of magnitude more lead than the other species. Generally, the order of xylem lead concentration is Carya > Liriodendron ≥ Quercus ≥ Pinus.

Species-specific differences occur in the historical pattern of lead accumulation for all species of tree except Pinus. Since Pinus has minimal and unpatterned historical xylem lead accumulations, this species will not be considered further. The pattern of lead accumulation for Liriodendron (Fig. 14) is approximately Gaussian-shaped. Quercus (Fig. 15) has a more exponential- or linear-shaped pattern, and Carya (Fig 16) has a pattern resembling a logistic growth curve or a Gaussian distribution skewed to the right. Xylem lead concentrations in Fernbank Carya and Liriodendron trees are significantly lower ($p < 0.01$) than in Deepdene Carya and Liriodendron trees for the pre-tetraethyl lead period 1880-1927 and the post-tetraethyl lead period 1928-1975. Lead accumulations in Fernbank Quercus trees are significantly lower ($p < 0.01$) than in Deepdene Quercus trees in the post-tetraethyl lead period (1928-1975) only. No significant difference ($p > 0.05$) can be shown in the pre-tetraethyl lead period (1880-1927). Thus, background xylem lead concentrations are essentially the same between sites for Quercus and different between sites for Carya and Liriodendron. Xylem lead accumulations above background begin in the interval 1920-1930 for Liriodendron, Quercus, and Carya at Deepdene Park, but only Carya has xylem lead concentrations above background in the post-tetraethyl lead period at Fernbank Forest.

The shapes of the species-specific lead accumulation patterns imply that *Liriodendron* trees would have peak lead concentrations in earlier xylem rings than *Quercus* trees. By the same logic, *Carya* trees would have peak xylem lead concentrations before *Quercus* trees and after *Liriodendron* trees. The data support this hypothesis (Fig. 17). *Liriodendron* trees have no tendency to peak during any specific time period, but 80% of these trees peak before 1959. Sixty-three percent of the *Carya* trees have peak accumulations in the 1964-1967 interval, and no trees peak before 1960. Although *Quercus* trees peak before 1960, 80% of these trees peak after 1959, and 40% peak in the interval 1972-1975.

Xylem lead concentrations are standardized against the 1928-1931 xylem section (Fig. 18) to examine the post-tetraethyl lead period more closely. For each species a linear regression approximation is presented. The slope of the regression equation may be considered the yearly increase in xylem lead. The slopes of the regression approximation equations are always higher a Deepdene Park than at Fernbank Forest, although slopes for *Liriodendron* trees at both sites art negative. Deepdene *Carya* and *Quercus* trees have relatively similar slopes of 8.90 and

10.1, respectively. Fernbank Carya and Quercus trees have less similar slopes of 5.54 and 1.48, respectively.

The relatively higher slopes of xylem lead accumulation since 1928 at Deepdene Park indicate an association between xylem lead and proximity to the lead source. Records of traffic volume on Ponce de Leon Avenue at Deepdene Park are not available before 1972 (Georgia Department of Transportation). However, historical traffic density records for other similar roads are available (Table 6). Traffic density records for Ponce de Leon Avenue since 1972 indicate a growth rate of approximately 9.7% yr^{-1}. This value is consistent with the estimated rate of traffic growth for a contiguous road section (US 78) and similar sections of US 23, north and south of Atlanta. The relatively high per annum traffic growth on US 23 at I-85 is undoubtedly influenced by interstate traffic. The range of 7-12% yr^{-1} traffic growth is likely a good approximation for the Metropolitan Atlanta area, and the 9.7% yr^{-1} traffic growth on Ponce de Leon Avenue at Deepdene Park is quite similar to the yearly increase in xylem lead for Carya and Quercus at Deepdene Park.

Analysis of xylem lead and corresponding soil lead concentration at the coring angles shows no correlations between the 0-15 cm% fraction and 1972-1975 xylem section, the 0-15 cm fraction and peak xylem lead value, or between the 15-30 cm fraction and either 1972-1975 xylem section or peak xylem lead value. The strongest correlation is between the 0-15 cm soil fraction and peak xylem lead value (Fig. 19). Analysis of the scatter diagram of this correlation shows that although the data points tend to group into Deepdene and Fernbank populations, neither soil nor xylem lead concentration can be predicted from the corresponding value. The correlation coefficients for the linear regression approximation for <u>Liriodendron</u>, <u>Quercus</u>, and <u>Carya</u> are 0.35, 0.43, and 0.22, respectively. For each species there is a greater range of xylem and soil lead values at Deepdene Park. However, soil lead concentrations associated with each species are essentially the same at each site. Mean lead concentrations in the 0-15 cm fraction under <u>Liriodendron</u>, <u>Quercus</u>, and <u>Carya</u> trees at Deepdene Park are 117, 90.9, and 62.3 ppm, respectlively. The same means for Fernbank trees are 39.6, 40.1, and 40.4 ppm. No statistical differences were found between soils collected under different tree species at Deepdene Park and at Fernbank Forest ($p > 0.05$).

<u>Ailanthus</u> <u>altissima</u> xylem sections range from 0.04-0.29 ppm lead. Thus, the xylem lead concentrations in this urban species are much lower than in <u>Carya</u> trees. <u>Ailanthus</u> is a fast-growing species, and its annual growth rings may range up to 3 cm wide. In one tree the 1975 and

1976 rings of one core were subdivided into early (xylem tube-associated) wood and late (cambium-associated) wood sections. Statistical analyses of the results are not appropriate since replicate samplings were not made; however, a trend is suggested (Fig. 20). The 1976 cambium-associated wood has 1.4-fold greater lead concentration than the 1976 xylem tube-associated wood. The 1975 xylem sections have this trend reversed, but the lead values are more nearly equal. It is possible that these results indicate that xylem lead is not a function of the water transport system of the tree.

If xylem lead is not transported via xylem transport, then it may be leaf derived and moved across the cambium to the xylem. If this is true, then a direct relationship between above-ground height and xylem lead concentration might be expected. Unfortunately, analyses of the 2 trees sampled at various above-ground heights at Deepdene Park show no clear-cut patterns (Table 7). Xylem lead concentration tends to decrease with height in the _Liriodendron_ tree, but this trend is not very apparent in the _Carya_ tree. The highest point sampled on the fallen _Liriodendron_ tree was approximately 60% of the tree height, and the highest point on the _Carya_ tree was no more than 20% of the tree height. Thus, the sampling points do not represent the best possible or most representative points, and results for the Liriodendron tree may be confounded by the possibility of leaching of lead from the wood and wood decomposition.

DISCUSSION

The analytical methods used in this study have several advantages over the methods used by Rolfe (1974). Possible sample loss from transfer of ached material between containers was eliminated by ashing and taking up the ash with acid in the same volumetric flask. Loss of sample from volatilization while heating the acid solution was also eliminated by using cold acid to take up the ash. The graphite furnace greatly increased precision over the flame mode, and samples containing only 0.1 ng lead could be accurately read. The methods used by Ward, et al. are not reported clearly enough for direct comparison.

Future analyses of this type might incorporate small (5 or 10 ml) Erhlenmeyer flasks instead of 10 ml volumetric flasks for two reasons: First, the geometry of an Erhlenmeyer flask allows better gas circulation from the inside to outside of the flask. More efficient exchange of hot gasses during the ashing process should reduce ash time by enhancing O_2-CO_2 exchange and maintaining oxidizing conditions inside of the flask. The sample lot might also be increased. Second, the daily heating and cooling cycle from 20°C-400°C-20°C makes pyrex glass more brittle. Thin-walled volumetric flasks break easily after several ashings. Erhlenmeyer flasks, with thicker walls, less likely to break.

Soil and xylem lead concentrations reported herein compare well with literature values, with some exceptions. The age-specific pattern of ^{210}Pb activity shown for hickory by Holtzman (1970) is quite similar to the stable lead pattern shown for Deepdene _Carya_ trees. Holtzman's hickory tree had a peak xylem lead activity 20 yrs prior to the latest growth ring, and the peak xylem lead concentration reported for Deepdene _Carya_ trees is approximately 11 yrs prior to the latest growth ring. Differences in the slopes of lead accumulation may be attributed to the 21-yr half-life of ^{210}Pb. Holtzman found a linear ^{210}Pb accumulation pattern for white oak, and Deepdene _Quercus_ trees also show a linear pattern of xylem lead accumulation. Furthermore, the stable lead concentrations that he reported for white oak (0.44-0.65 ppm) are within the same order of magnitude as Deepdene _Quercus_ xylem lead concentrations.

Xylem lead concentrations reported by Ward, et al. for trees along a New Zealand thoroughfare are expressed in ppm ash weight, and no direct comparison of results can be made. However, if the formula ash wt = 10% dry wt is used to convert their numbers, then the xylem lead concentrations for all species along the thoroughfare are within the range 1-100 ppm dry wt. The only species in this study with comparable xylem lead accumulations is

Carya. Ault, et al. report xylem lead concentrations of 0.14-0.34 ppm in red oak along the New Jersey Turnpike, and this range agrees well with the xylem lead concentrations in Deepdene *Quercus*. The lead concentrations reported by Rolfe for red oak more closely agree with the estimated concentrations in the Ward, et al. study, and they are higher than those reported herein. The relatively high xylem lead concentrations in red oak reported by Rolfe are hard to explain. The mature woodland he sampled was near minor roads with only 5-20 % of the traffic of Ponce de Leon Avenue, the New Jersey Turnpike, and the New Zealand thoroughfare.

Rolfe's study showed xylem lead concentrations of 5 ppm in *Pinus* *taeda* growing 30 m from an interstate with 15,000 vehicles day^{-1}. The xylem lead concentrations for Deepdene *Pinus* are an order of magnitude less, although the trees at Deepdene Park are less than 20 m from Ponce de Leon Avenue. Again, Rolfe's data is hard to explain, unless tree age is a factor. The soil lead concentrations for Deepdene Park and Fernbank Forest agree well with those reported by Rolfe, but the xylem/soil ratios for *Pinus* in this and Rolfe's study are approximately 1/4000 and 1/13, respectively. Thus, there is an indication that the two forest ecosystems are quite different.

Soil lead concentrations reported for Deepdene Park and Fernbank Forest agree well with literature values for soils both near and far from roads with heavy traffic (Rolfe, 1974; Gish and Christensen, 1973; Wards et al., 1974; Goldsmiths et al., 1976). However, the 0-15 cm and 15-30 cm soil fractions are at best a gross indication of the actual soil lead profile. Soil lead profiles reported by Ward, et al. show that the lead concentration may decrease by as much as 50% within the top 2.5 cm of soil in heavily polluted soils. Through a depth of 15 cm many chemical and physical interactions occur between lead compounds and organic complexes and mineral surfaces which quickly bind the lead and retain it in upper soil fractions. Undoubtedly, stronger correlations than shown exist between lead in the surface soil layer and distance from Ponce de Leon Avenue. Site differences would also be greater than shown if only the top 1 cm of soil were compared.

This study has not resolved whether the soil lead environment strongly affects or directly determines the corresponding xylem lead concentrations, but there are indications that factors other than soil lead are in operation. Ward, et al, state that the most likely origin of xylem lead is via the root system, but indications from this and other studies question this statement. Ault, et al. showed similar $^{206}Pb/^{204}Pb$ isotopic ratios in topsoil and tree leaves and twigs. However, the similarity of isotopic ratios may simply indicate a common lead source, rather than root uptake and transport to twigs and leaves. Actually, the 206Pb/204Pb ratios in 3 red oak xylem ring sections (17.73-17.83) from the same study more closely resemble topsoil values (18.73 ± 0.22) than deeper soil values (19.92 ± 0.27) where tree roots occur, although the xylem lead isotopic ratios are quite distinct from either soil fraction ratio. Furthermore, xylem lead concentrations during the pre-tetraethyl lead period (1880-1927) in Deepdene and Fernbank Liriodendron and Carya trees vary with respect to site. Since these sites were originally contiguous, it must be assumed that these soils received similar or equal lead inputs before the tetraethyl lead era. Thus, xylem lead concentrations must be regulated by some other factor, possibly lateral transport between xylem rings, than soil lead concentration. Additionally, no correlations are found between xylem and soil lead in cores and fractions spatially associated with each other at Deepdene Park and Fernbank Forest. Soil fractions along a core may not be associated with the particular root system supplying the xylem section, but no correlations are found when the xylem cores and soil fractions for each tree are pooled. Finally, Deepdene Park soils are very heterogenous with respect to color, texture, pH, and lead concentration, and xylem lead accumulations are very consistent, patterned, and predictable. Soil lead concentrations may vary 500% at the 15-30 cm depth between sampling areas, but the species-specific xylem lead concentrations are constant. Clearly, xylem lead is both internally regulated and species-specific, and not merely a simple function of the soil lead concentration.

Internal regulation of xylem lead implies that the historical lead accumulation patterns may be quite different in diffuse porous and ring Porous trees because the spatial distribution and functional lifetime of the conducting xylem tubes differ in these tree types. Diffuse porous trees have xylem tubes randomly distributed throughout the early and late wood of each ring. The tubes are relatively short in length and small in diameter, and most are able to withstand winter freezing without mechanical breakage or loss of integrity from air embolisms (Zimmermann and Brown, 1971). In general, the xylem tubes of diffuse porous trees remain functional for many years, and water conduction takes place in historical rings as well as in the most current ring. Xylem tubes of ring porous trees are found closely grouped in the early-wood, and they are relatively long and large in diameter. Generally, they cannot withstand winter freezing without loss of integrity, and therefore, they are functional for usually one growing season. It follows that water transport in ring porous species is in the most current xylem rings rather than across the breath of the bole.

If xylem lead is a function of or influenced by the xylem transport systems, then the historical patterns of xylem lead distribution will differ in ring and diffuse porous trees, especially in latitudes where yearly winter freezing is prevalent. Diffuse porous trees and conifers would have higher xylem lead accumulations in older sapwood because the older rings would have been exposed to much more lead than younger rings. However, in ring porous trees the historical rings would have lead concentrations reflective of the year in which they were formed. Thus if the relative amount of lead available to the tree increased yearly, then the highest xylem lead concentration would be expected in the most current ring. Unfortunately, the patterns described above may be confounded by the fact that xylem tubes gradually become non-functional with age in diffuse porous trees, and water conduction may take place to a lesser extent in small xylem vessels in the late wood of ring porous trees. Thus, peak xylem lead concentrations might be expected in xylem rings prior to the oldest sapwood in diffuse porous trees and conifers and several years earlier than the most current growth, ring in ring porous trees.

In order to access the role of xylem transport in the distribution pattern of xylem lead in ring porous and diffuse porous trees, it is necessary to determine whether xylem lead is leaf- or root-derived. If the origin of xylem lead is via the roots, as suggested by Ward, et al., then the accumulation pattern shown for *Pinus* by Rolfe is not readily explained. Rolfe's data would be typical of a ring porous tree, not a conifer. However, if the lead were leaf-derived, carried down the tree via phloem transport, moved across the cambium, and passed to the most current xylem ring. Rolfe's results may be easily explained. Recent studies by Cropper (1977) indicate that this pathway may be the mode of lead transport in *Ailanthus* trees. Cropper found greater lead concentrations in *Ailanthus* phloem than in the corresponding xylem from May 1975 to early October 1975. This trend was reversed after mid-October through early December, perhaps indicating lead translocation in a basipetal direction.

Species-specific lead concentrations in Deepdene tree species provide further evidence supporting leaf-derived xylem lead. *Pinus taeda* leaves are long, needle-shaped, and covered with a thick cuticle. The low surface area to volume ratio of these leaves, combined with the finding that lead does not pass through leaf cuticles (Zimdahl, 1972), could account for the very low xylem lead concentrations in Pinus. Liriodendron tulipifera and Quercus alba leaves have much larger surface area to volume ratios than Pinus leaves, which could account for the relatively higher xylem lead concentrations in these deciduous trees. Furthermore, Liriodendron and Quercus leaves are galabrous and Carya leaves are tomentose underneath. The trichomes on Carya leaves greatly increase the surface area, and they may be more efficient at trapping and holding small lead particulates than the smooth surface of Liriodendron or Quercus leaves.

Finally, the differences in xylem lead accumulation between Deepdene and Fernbank Carya trees are much greater than corresponding differences in soil lead concentration underneath the Carya canopies. Soil lead concentrations in the deeper fractions where roots occur differ by a factor of approximately 1.3, and xylem lead concentrations differ by a factor of roughly 10 between the sites. If Carya xylem lead is root-derived, the site-specific lead concentrations are difficult to explain, and, therefore, the leaf-derived lead hypothesis must be accepted.

If xylem lead is leaf-derived, then the species-specific accumulation patterns at Deepdene Park for the ring porous species, Quercus and Carya, and the diffuse porous species, Liriodendron, must be explained. A simple conceptual model (Fig. 21) was constructed to simulate the various lead accumulation patterns in these tree species. The model assumes that the lead first enters the most current xylem ring before any lateral redistribution of the lead occurs. It follows that the model applies to all ring porous trees in which xylem lead is root-derived and all trees in which xylem lead is leaf-derived.

In the simulation model lead enters the most current xylem ring in the third year after tree germination. Lead concentrations in the first years of growth are considered to be constant background values (b). During the growing season lead (x) from an outside source enters the tree and is transported to the xylem tissue. The portion of lead retained (a) in the most current xylem ring is the relative amount absorbed or adsorbed onto the wood (ax), where $0 \leq a \leq 1$. The amount of lead passed laterally onto the next older xylem ring is the amount imputed less the amount retained in the first ring, $x - ax$. Of this portion, $a(x - ax)$ or $ax(1 - a)$ is retained in the second ring. Likewise, the amount of lead passed to the oldest ring is $x - (ax + ax(1 - a))$ or $(x - ax)(1 - a)$. The amount retained there is $a(x - ax)(1 - a)$ or $ax(1 - a)^2$.

In the fourth year of growth $x + r$ units of lead enter the xylem, where r is the yearly rate of increase in lead pollution. In a similar manner, the current year's wood retains $a(x + r)$ units of lead, the next older

$a(x + r)(1 - a)$, the next older $a(x + r)(1 - a)^2$ and so forth. In the fifth year $x + 2r$ units of lead are imputed into the most current xylem rings and $a(x + 2r)$ units of lead are retained there. Earlier years retain, similarly, $a(x + 2r)(1 - a)$, $a(x + 2r)(1 - a)^2$, $a(x + 2r)(1 - a)^3$, and so forth.

If y_1 = the most current xylem ring (y_1 = fifth year) and k = number of years of lead input ($k = 3$) then the total amount of lead in each xylem ring is as follows:

$$y_1 = a(x + (k - 1)r) + b. \tag{3}$$

$$y_2 = a(x + (k - 1)r)(1 - a) + a(x + (k - 2)r) + b. \tag{4}$$

$$y_3 = a(x + (k - 1)r)(1 - a)^2 + a(x + (k - 2)r\ (1 - a) + a(x + (k - 3)r) + b. \tag{5}$$

$$y_4 = a(x + (k - 1)r)(1 - a)^3 + a(x + (k - 2)r)(1 - a)^2 + a(x + (k - 3)r)(1 - a) + b. \tag{6}$$

$$y_5 = a(x + (k - 1)r)(1 - a)^4 + a(x + (k - 2)r)(1 - a)^3 + a(x + (k - 3)r)(1 - a)^2 + b. \tag{7}$$

Subtracting b from all equations the equations become:

$$y_1 = a(x + (k - 1)r). \tag{8}$$

$$y_2 = (y_1)(1 - a) + a(x + (k - 2)r). \tag{9}$$

$$y_3 = (y_2)(1 - a) + a(x + (k - 3)r). \tag{10}$$

$y_4 = (y_3)(1 - a).$ (11)

$y_5 = (Y_4)(1 - a)^2.$ (12)

If $(1 - a) = d$ (diffusion rate) and $y_0 = 0$, then the following general equations result:

$y_t = (y_{t-1})d + a(x + (k - t)r) + b$, if $t \le k$. (13)

$yt = (y_k)d^{t-k} + b$, if $t > k$. (14)

Simulations of the model (Fig. 22) show that the slope of historical lead accumulations is determined by a and r. As a → 0, the accumulation pattern becomes less linear, the accumulation slope → 0, and the peak xylem lead concentration occurs at an earlier date. As r increases the accumulation slope also increases. If all parameters are constant while x increases, the total xylem lead increases, and the peak xylem lead concentration is at an earlier date. If all parameters are constant while b increases, only the total lead accumulated increases, and the accumulation slope and peak year remain the same.

Model simulations were made of actual lead concentrations in Deepdene <u>Liriodendron</u>, <u>Quercus</u>, and <u>Carya</u> trees (Fig. 23). The model simulations, poorly approximated the actual accumulation patterns, and a simple modification was made to improve simulations. The rate of lead increase (r) was made to increase exponentially (r, r^2, r^3, ..., r^{k-1}), rather than linearly (r, $2r$, $3r$, ..., $(k - 1)r$), and the general equations 13 and 14 in the modified model become:

$$y_t = (y_{t-1})d + a(x + r^{k-t}) + b, \text{ if } t \leq k. \qquad (15)$$

$$y_t = (y_k)d^{t-k} + b, \text{ if } t > k. \qquad (16)$$

Simulations of the modified model much more closely approximated the actual patterns of historical xylem lead accumulation (Fig. 24).

The model simulations show that knowledge of the actual lead pollution history is essential to determine the accuracy of the model. If the lead pollution history is known, then the physiology of lead movement in tree species must be understood. In both simulations, each tree species is associated with a unique a and r value. Undoubtedly, the lateral movement of lead (a) is determined by the structure and function of the lateral rays. Since both structure and distribution of the rays varies between tree species as well as between coniferous and deciduous trees, variations in occurrence, extent, and direction of lateral lead movement must be identified for each species modeled. Similarly, the portion of lead entering the most current xylem ring each year (r) is a value unique to each species. Thus, before the model may be generally applied, the portion of lead which enters the tree and the portion which is transported to the xylem must be identified by species.

Although the model simulations (both linear and exponential) do not exactly coincide with the empirical data, they show that lateral transport of lead from the most current xylem ring to more historical xylem rings may account for peak xylem lead concentrations prior to the latest ring. Also, lateral transport of lead may account for xylem lead concentrations which are higher than background values in the pre-tetraethyl lead era. Thus, the model is consistent with phenomena observed in lead accumulation patterns in tree species at Deepdene Park and Fernbank Forest.

CONCLUSIONS

Soil lead concentration varies inversely with distance from Ponce de Leon Avenue at Deepdene Park and with soil depth at both sites. There is no correlation between soil lead and distance to the nearest traffic light at Deepdene Park. Deepdene soils are slightly more acidic, are more heterogenous, are much more disturbed by urbanization, and have greater lead burdens than Fernbank soils.

There are no site- or species-specific bark lead concentration patterns, but there are both site and species-specific xylem lead concentrations and accumulation patterns. All species, except Pinus, have higher xylem lead concentrations at Deepdene Park than at Fernbank Forest. The differences in xylem lead concentrations between sites is approximately an order of magnitude for these species. At both sites xylem lead concentrations in Carya are greater by an order of magnitude than xylem lead concentrations in any other species, and the order of xylem lead concentration is: Carya > Liriodendron ≥ Quercus ≥ Pinus.

Xylem lead accumulations above background values occur in the 1920-1930 period in Carya, Liriodendron, and Quercus at Deepdene Park, and only Carya has accumulations above background at Fernbank Forest. The pattern of historical xylem lead accumulation resembles the shape of a Gaussian distribution for Liriodendron, the shape of an exponential or linear curve for Quercus, and the shape of a logistic growth curve for Carya. The rate of lead accumulation in Liriodendron, Quercus, and Carya is higher at Deepdene Park than at Fernbank Forest, and the lead accumulation rates of Carya and Quercus at Deepdene Park approximate the estimated rate of traffic increase on Ponce de Leon Avenue.

There is very poor correlation between soil and xylem lead concentrations for all tree species, and there is direct evidence that xylem lead is not root-derived in Carya. However, relationships between xylem lead concentration and the surface area to volume ratio of tree leaves provide indirect evidence of leaf-derived xylem lead.

This study has shown that it is feasible to study lead pollution histories by tree ring analyses, but an understanding of tree physiology, lateral movement of lead, and the origin of xylem lead is essential for meaningful interpretation of results. Carya, which is the most sensitive to environmental lead, has the highest xylem lead concentrations, and approximates the estimated traffic increase near the lead source, is considered the best environmental monitor of lead of the trees studied.

LITERATURE CITED

Ault, Wayne U., Ronald G. Senachal, and Woodland E. Erlebach, 1970. Isotopic composition as a natural tracer of lead in the environment. Environ. Sci. & Technol. 4(4): 305-313.

Campbell, William J. 1976. Metals in the wastes we burn? Environ. Sci. & Technol. 10(5): 436-439.

Cannon, H. L. and J. M. Bowles. 1962. Contamination of vegetation by tetraethyl lead. Science 137: 765-766.

Chow, T. J., R. Senechal, and W. Erlebach. 1970. Lead accumulation in roadside soil and grass. Nature 225: 295-296.

Cropper, Wendell P. 1977. Lead distribution in canopy tissues of *Ailanthus altissima* Swingle, collected in Urban Atlanta, Georgia. Master's thesis, Emory University. 77 pp.

Dedolph, Richard, Gary Ter Haar, Richard Holtzman, and Henry Lucas, Jr. 1970. Sources of lead in perennial ryegrass and radishes. Environ. Sci. & Technol. 4(3): 217-223.

Edgington, David N. and John A. Robbins. 1976. Records of lead deposition in Lake Michigan sediments since 1800. Environ. Sci. & Technol. 10(3): 266-274.

———————— Georgia Department of Transportation. 3013 Rainbow Drive. Decatur, Georgia. 30034.

Gish, Charles D. and Robert E. Christensen. 1973. Cadmium, nickel, lead, and zinc in earthworms from roadside soil. Environ. Sci. & Technol. 7(11): 1060-1062.

Goldsmith, C. Douglas, Jr., Patrick F. Scanlon, and Walter R. Pirie. 1976. Lead concentrations in soil and vegetation associated with highways of different traffic densities. Bull. Environ. Contam. & Toxicol. 16(1): 66-70.

Harris, W. F., A. W. Andren, and G. S. Henderson. 1975. Environmental assessment of SO_2 and trace element emissions from coal utilization. Report to NSF-RANN Environmental Aspects of Trace Contaminants Program under NSF interagency agreement AG-389 with the USAEC. 17 pp.

Holtzman, Richard B. 1970. Isotopic composition as a natural tracer of lead in the environment (discussion). Environ. Sci. & Technol. 4(4): 314-317.

Huntzicker, James J., Sheldon K. Friedlander, and Cliff I. Davidson. 1975. Material balance for automobile-emitted lead in Los Angeles basin. Environ. Sci. & Technol. 9(5): 448-457.

Klein, David H., Anders W. Andren, Joel A. Carter, Jeul F. Emery, Cyrus Feldman, Jack C. Ogle, Yair Talmi, Robert I. Van Hook, and Newell Bolton. 1975. Pathways of thirty-seven trace elements through coal-fired power plant. Environ. Sci. & Technol. 9(10): 973-979.

Laaksovirta, K., H. Olkkonen, and P. Alakuijala. 1976. Observations on the lead content of lichen and bark adjacent to a highway in southern Finland. Environ. Pollut. 11: 247-255.

Lepp, N. W. 1975. The potential of tree-ring analysis for monitoring heavy metal pollution patterns. Environ. Pollut. 9: 49-61.

Moore, Fletcher L. 1972. Solvent extraction of mercury from brine solutions with high-molecular-weight amines. Environ. Sci. & Technol. 6(6): 525-529.

Motto. H. L., R. H. Daines, D. M. Chilko, and C. K. Motto. 1970. Lead in soils and plants: its relationship to traffic volume and proximity to highways. Environ. Sci. & Technol, 4(3): 231-237.

Murozumi, M., Tsaihwa J. Chow, and C. Patterson. 1969, Chemical concentrations of pollutant lead aerosols, terrestrial dusts and sea salts in Greenland and Antarctic snow strata. Geochim. Cosmochim. Acta. 33: 1247-1294.

Nilsson, Ingvar. 1972. Accumulation of metals in spruce needles and needle litter. Oikos 23: 132-136.

Olson, Kenneth W. and Rodney K. Skogerboe. 1975. Identification of soil lead compounds from automotive sources. *Environ. Sci.* & *Technol*. 9(3): 227-230.

Patterson, C. C. 1965. Contaminated and natural lead environments of man. *Arch. Environ. Health* 11: 344-358.

Purves, D. and E. Jean Mackenzie. 1969. Trace-element contamination of Parklands in urban areas. *J. Soil Sci*. 20(2): 288-290.

Rolfe, Gary L. 1974. Lead distribution in tree rings. *Forest Sci*. 20: 283-286.

Skeen, James N. 1974. Composition and biomass of tree species and maturity estimates of a suburban forest in Georgia. *Bull. Tor. Bot. Club* 101(3): 160-165.

Smith, William H. 1973. Metal contamination of urban woody plants. *Environ. Sci.* & *Technol*. 7(7): 631-636.

Steel, Robert G. D. and James H. Torrie. 1960. *Principles and Procedures of Statistics*. McGraw-Hill Book Co., Inc., New York. 481 pp.

Ward, N. I., R. R. Brooks, and R. D. Reeves. 1974. Effect of lead from motor-vehicle exhausts on trees along a major thoroughfare in Palmerston North, New Zealand, *Environ. Pollut*. 6: 149-158.

―――――――― *World Almanac and Book of Facts 1976*. Doubleday. p. 98.

Zimdahl, R. L. 1972. Lead in soils and plants. In Impact on man of environmental contamination by lead, interim report, supported by NSF grant GI-4. Colorado State University. 239 pp.

Zimmerman, Martin H. and Claud L. Brown. 1971. *Trees Structure and Function*. Springer-Verlag, New York, 336 pp.

TABLES

Table 1. Mean of soil pHs collected under the canopies of tree species at Deepdene Park and Fernbank Forest with the standard error of the mean indicated (n ≤ 15).

Site	*Liriodendron*	*Carya*	*Quercus*
Fernbank	5.45 ± 0.06	4.83 ± 0.11	5.39 ± 0.11
Deepdene	5.42 ± 0.19	4.81 ± 0.24	4.76 ± 0.12

Table 2. Tree species, year of germination, DBH, soil pH, and soil lead concentration for Deepdene Park.

Tree	1st Year	DBH (cm)	Soil pH*	Soil Lead (ppm)**	
				0-15 cm	15-30 cm
Liriodendron tulipifera					
1	1866	81.8	5.94	150.	38.6
2	1923	69.6	5.63	78.5	27.6
3	1907	68.3	4.78	99.5	26.3
4	1927	65.3	5.29	97.3	17.5
5	<1920	89.2	5.46	163.	—
Quercus alba					
6	<1911	86.1	4.99	131.	95.7
7	<1900	88.1	5.02	110.	80.9
8	1883	78.5	4.42	49.7	17.3
9	1840	62.7	4.59	71.2	27.1
10	1841	72.6	4.77	94.9	49.5
Carya spp.					
11	1918	42.3	5.66	94.0	52.4
12	<1880	51.6	4.44	53.0	25.5
13	1836	48.8	4.47	37.5	18.0
14	1832	45.5	5.03	50.4	23.3
15	1850	38.9	4.47	43.2	18.0
Pines taeda					
16	1861	71.4	5.17	126.	34.3
17	1861	68.6	5.65	116.	80.0
18	1865	75.2	5.29	116.	59.8
19	1866	53.6	4.95	83.8	26.3
20	1933	58.7	4.81	233.	45.1

* mean value (n ≤ 6)

** mean value (n ≤ 3)

Table 3. Tree species, year of germination, DBH, soil pH, and soil lead concentration for Fernbank Forest.

Tree	1st Year	DBH (cm)	Soil pH*	Soil Lead (ppm)**	
				0-15 cm	15-30 cm
Liriodendron tulipifera					
21	1864	70.9	5.13	48.6	21.2
22	1856	78.7	5.54	32.6	19.5
23	1854	54.1	5.62	38.6	20.9
24	1849	65.5	5.31	38.2	20.6
25	1848	83.1	5.53	39.0	26.0
26	1819	83.6	5.49	39.5	20.4
27	1869	72.6	5.79	47.1	25.9
28	1828	74.7	5.37	35.9	19.0
29	1826	93.5	5.35	35.7	19.7
30	1823	89.4	5.46	65.1	37.2
Quercus alba					
31	1846	42.9	5.18	43.0	22.0
32	1845	72.1	5.37	42.6	19.7
33	1840	65.0	5.16	34.4	22.2
34	1835	52.1	5.75	41.2	22.4
35	1834	61.2	5.51	39.8	17.7
Carya spp.					
36	1841	56.4	4.99	43.1	25.8
37	1851	56.6	4.63	38.9	19.6
38	1865	43.2	4.87	38.7	17.8
Pines taeda					
39	1863	37.7	5.11	38.2	19.3

* mean value (n ≤ 6)

** mean value (n ≤ 3)

Table 4. Lead concentration in ppm in bark and xylem sections from Deepdene Park.

Tree	Bark	1970-1975	1960-1969	1950-1959	1940-1949	1930-1939	1920-1929	1910-1919	1900-1909	1890-1899	1880-1889
Liriodendron tulipifera											
1	.353	.127	.149	.233	.273	.255	.241	.192	.157	.168	.384
2	.397	.131	.192	.311	.152	.082	.092	----	----	----	----
3	.230	.378	.631	.865	1.09	.775	.295	.312	----	----	----
4	1.78	.153	.441	.457	.900	.430	.302	----	----	----	----
5	.845	.189	.536	.474	.285	.202	.224	----	----	----	----
mean	.721	.196	.390	.468	.539	.349	.231	.252	----	----	----
Quercus alba											
6	3.46	.204	.190	.123	.177	.060	.030	.099	----	----	----
7	.520	.358	.205	.143	.094	.076	.041	.049	----	----	----
8	----	.259	.175	.143	.135	.123	.183	.103	.121	.099	.089
9	.520	.070	.089	.095	.054	.044	.040	.035	.083	.073	.021
10	.400	.287	.368	.151	.077	.052	.028	.025	.153	.023	.020
mean	1.23	.236	.205	.131	.107	.071	.064	.062	.119	.065	.043
Carya spp.											
11	1.92	.111	.091	.083	.044	.030	.050	.020	----	----	----
12	1.10	12.3	14.9	10.4	9.69	4.71	2.23	2.34	2.23	1.80	1.21
13	.510	9.36	22.6	13.3	11.5	7.96	4.87	3.56	2.48	1.88	2.06
14	2.23	9.52	16.1	6.10	5.00	3.82	3.16	3.02	1.63	1.53	.829
15	----	25.4	32.0	9.69	5.45	2.86	2.50	2.33	1.64	1.83	1.87
mean	1.44	11.3	17.1	7.91	6.34	3.87	2.56	2.25	1.99	1.76	1.49
Pinus taeda											
16	.257	.006	.007	.002	.006	.003	.005	N.D.	.012	.033	.106
17	.150	.023	.019	.016	.041	.020	.024	.032	.024	.020	.032
18	2.57	.041	.019	.017	.023	.015	.024	.022	.014	.017	.023
19	1.16	.061	.041	.009	.007	.021	.038	.027	.021	.030	.039
20	6.76	.037	.027	.032	.025	.040	----	----	----	----	----
mean	2.18	.034	.023	.015	.020	.020	.023	.020	.018	.025	.050

Table 5. Lead concentration in ppm in bark and xylem sections from Frenbank Forest.

Tree	Bark	1970-1975	1960-1969	1950-1959	1940-1949	1930-1939	1920-1929	1910-1919	1900-1909	1890-1899	1880-1889
Liriodendron tulipifera											
21	1.18	.163	.135	.129	.139	.132	.125	.092	.069	.084	.144
22	1.05	.029	.025	.026	.047	.021	.047	.038	.029	.038	.043
23	.430	.013	.017	.061	.041	.031	.027	.066	.038	.049	.030
24	.030	.030	.055	.059	.055	.050	.045	.059	.031	.074	.034
25	.377	.059	.050	.040	.057	.045	.037	.055	.045	.079	.050
26	.073	.028	.041	.049	.029	.035	.022	.030	.017	.033	.047
27	.415	.030	.035	.025	.071	.082	.051	.062	.053	.031	.031
28	----	.018	.037	.063	.047	.089	.049	.132	.056	.054	.027
29	.073	.034	.027	.039	.024	.033	.035	.025	.055	.053	.021
30	.183	.037	.037	.026	.059	.029	.041	.049	.068	.044	.023
mean	.416	.043	.046	.052	.057	.055	.048	.061	.046	.054	.045
Quercus alba											
31	----	.041	.042	.061	.029	.023	.036	.033	.042	.037	.030
32	.375	.132	.098	.082	.091	.080	.063	.061	.083	.057	.091
33	.090	.073	.059	.032	.021	.026	.029	.045	.029	.037	.040
34	.227	.034	.016	.023	.015	.025	.031	.022	.025	.027	.053
35	.090	.021	.025	.026	.031	.033	.069	.071	.031	.038	.066
mean	1.96	.060	.048	.045	.037	.037	.046	.046	.042	.039	.056
Carya spp.											
36	.357	1.68	2.81	2.16	1.72	.861	.586	.602	.403	.333	.517
37	.617	1.11	1.93	1.60	.829	.659	.736	.669	.517	.487	.345
38	.913	2.98	3.10	2.28	1.47	1.63	.709	.563	.693	.473	.307
mean	.629	1.93	2.61	2.01	1.34	1.05	.676	.611	.538	.431	.390
Pinus taeda											
39	.283	.131	.108	.115	.187	.089	.102	.105	.069	.048	.055

Table 6. Traffic volume (vehicles day^{-1}) on four road sections in Atlanta, Georgia with the estimated annual rate of increase indicated.

	Road section			
Year	US 23 north of Atlanta	US 23 at I-85	US 78	US 23 south of Atlanta
1973		73,100	12,000	19,600
1972		69,300	11,000	18,600
1971		79,200	14,200	15,100
1970		56,100	10,400	14,100
1969		51,700	9,900	13,500
1968		36,400	7,500	11,900
1967		25,500	7,100	10,600
1966		21,600	7,000	7,000
1965			6,800	7,500
1964			5,000	7,000
1963			5,000	7,000
1962			6,000	6,000
1961				6,000
1960	10,000			8,000
1959	8,600			7,100
1958	8,800			7,100
1957	11,300			7,000
1956	13,200			7,200
1955	11,500			7,000
1954	8,300			5,400
1953	7,300			5,000
1952	6,400			
1951	6,000			
1950	5,300			
1949	5,900			
	Rate of increase			
	7.4	39.2	12.3	11.8

Table 7. Lead concentration in ppm in xylem sections from Deepdene. Park sampled at various above-ground heights.

Section	Lead concentration			
	0.27 m	2.0 m	3.1 in	4.2 m
<u>Carya</u>				
1968-75	2.76	17.5	11.6	5.44
1960-67	9.57	4.38	1.94	3.59
1952-59	1.65	5.30	1.65	1.92
1944-51	2.73	3.37	2.80	1.84
	0.56 m	7.0 m	12 m	
<u>Liriodendron</u>				
1973-75	0.27	0.33	N.D.	
1970-72	0.75	0.28	0.16	
1967-69	1.04	0.95	0.31	
1964-66	1.41	1.24	1.87	
1961-63	1.82	1.42	1.35	
1958-60	4.26	1.37	0.82	

FIGURES

Figure 1. Map of Fernbank Forest and Deepdene Park.

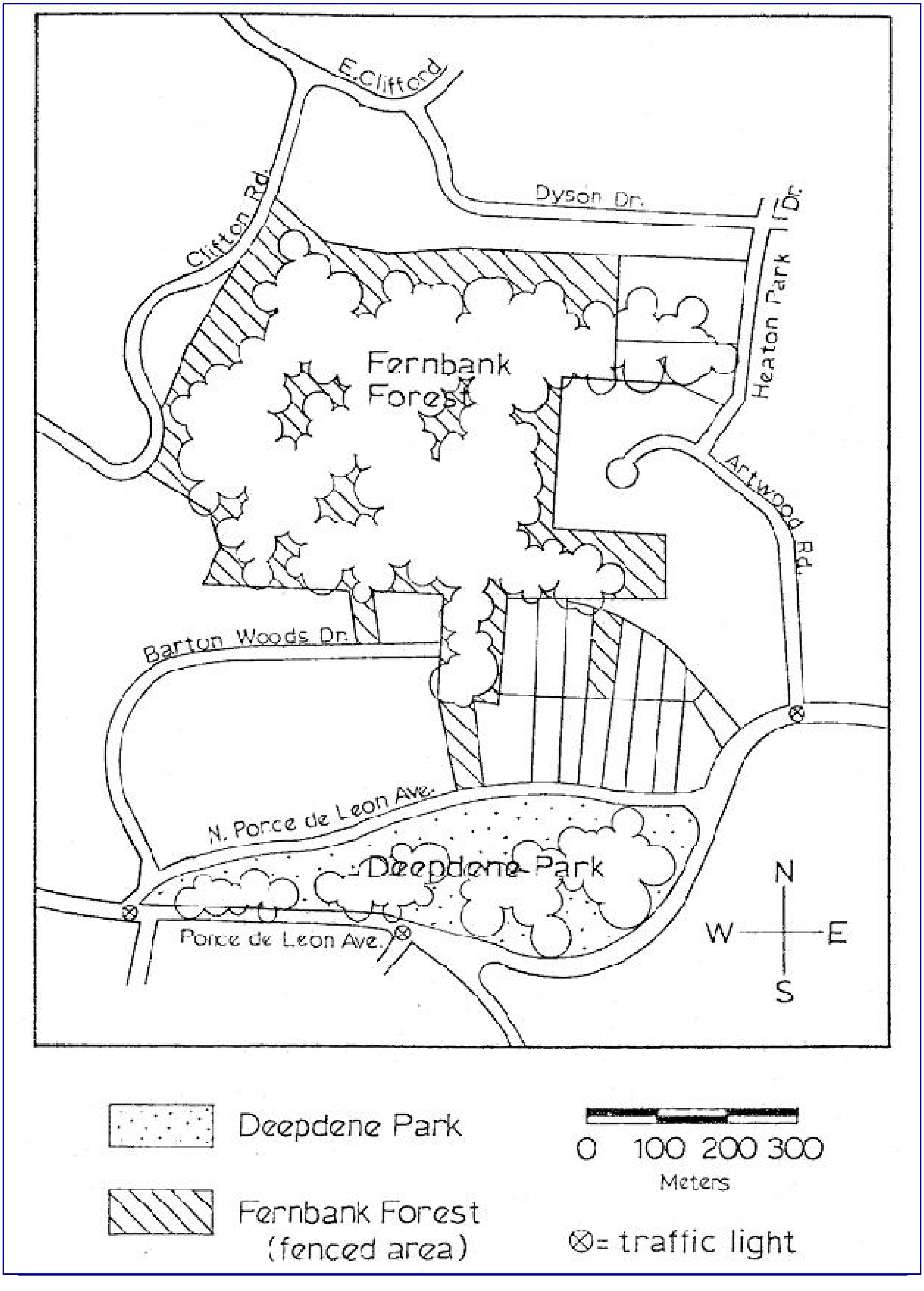

E. Clifford
Dyson Dr.
Clifton Rd.
Heaton Park Dr.
Fernbank Forest
Artwood Rd.
Barton Woods Dr.
N. Ponce de Leon Ave.
Deepdene Park
Ponce de Leon Ave.
N
W
E
S
Deepdene Park
Fernbank Forest (fenced area)
0 100 200 300
Meters
⊗= traffic light

Figure 2. Map of Fernbank Forest showing Fernbank Science Center, fence, paved pathways, and study area.

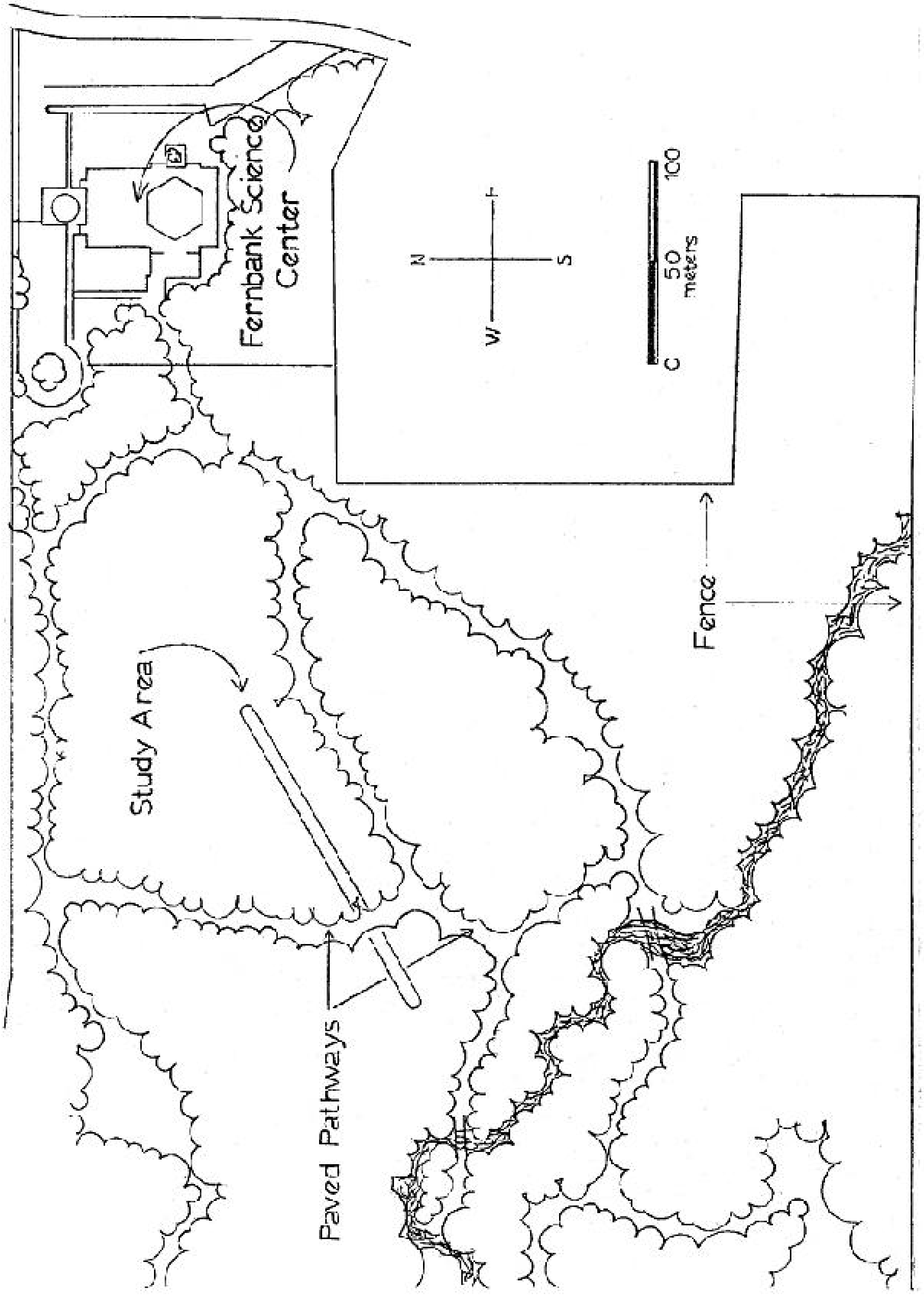

Fernbank Science Center
N
E
S
W
0
50
100
meters
Fence
Study Area
Paved Pathways

Figure 3. Coring angles for trees sampled at Deepdene Park and Fernbank Forest.

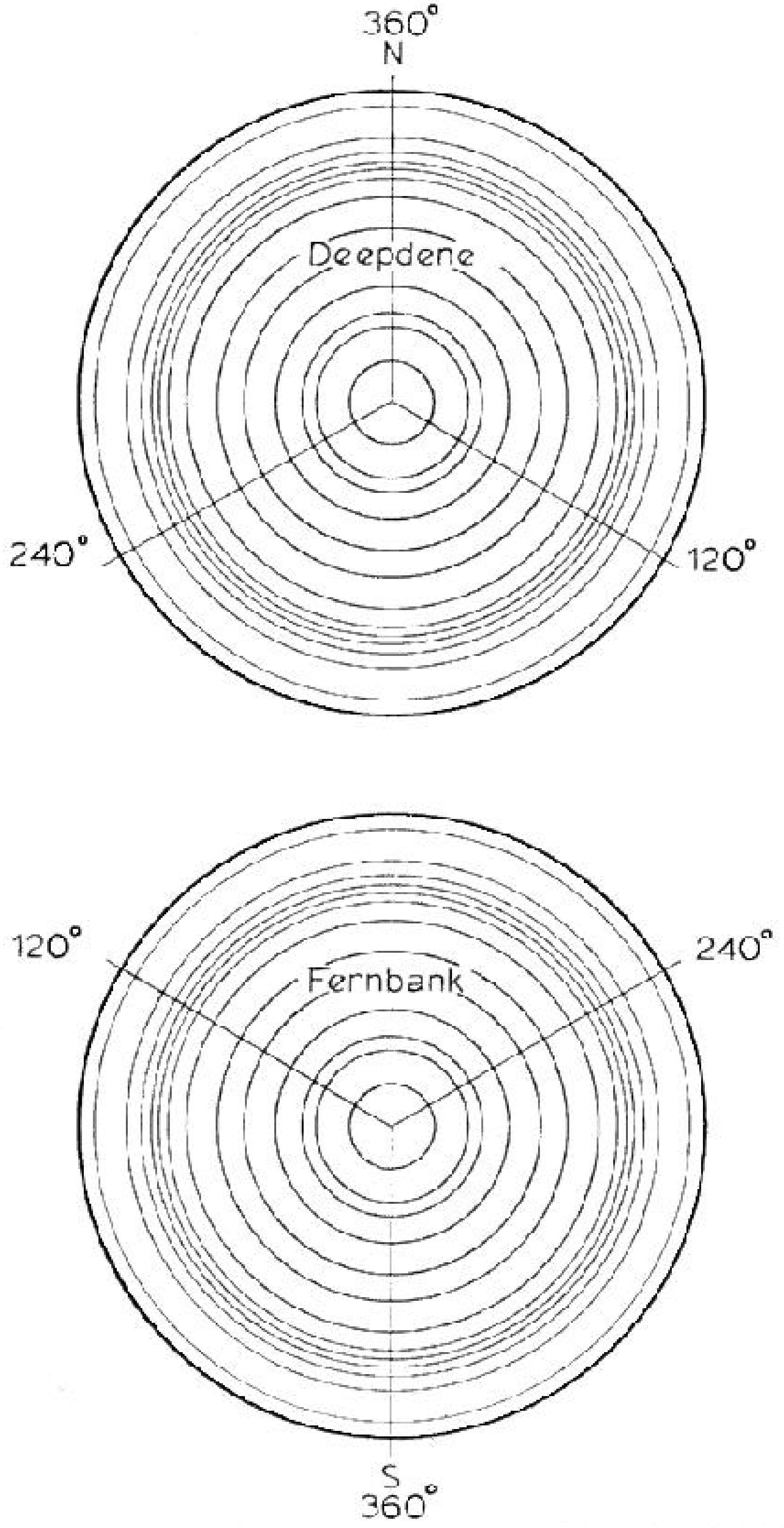
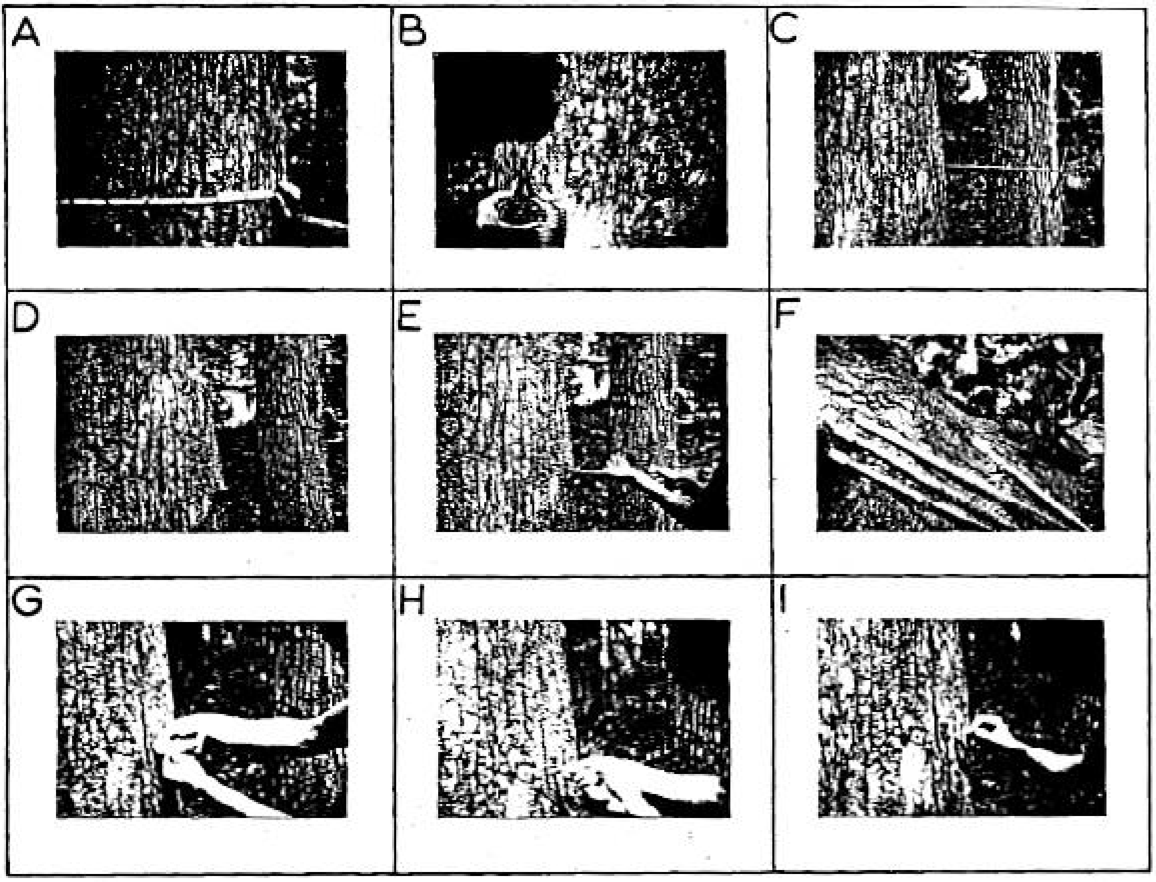

360°
N
Deepdene
240°
120°
120°
240°
Fernbank
S
360°

Figure 4. Nine operations and stages in the tree coring process. Operations wee performed in sequential order.



A. Taking DBH

B. Determining core angles

C. Partially inserted corer

D. Fully inserted corer

E. Extracting the core

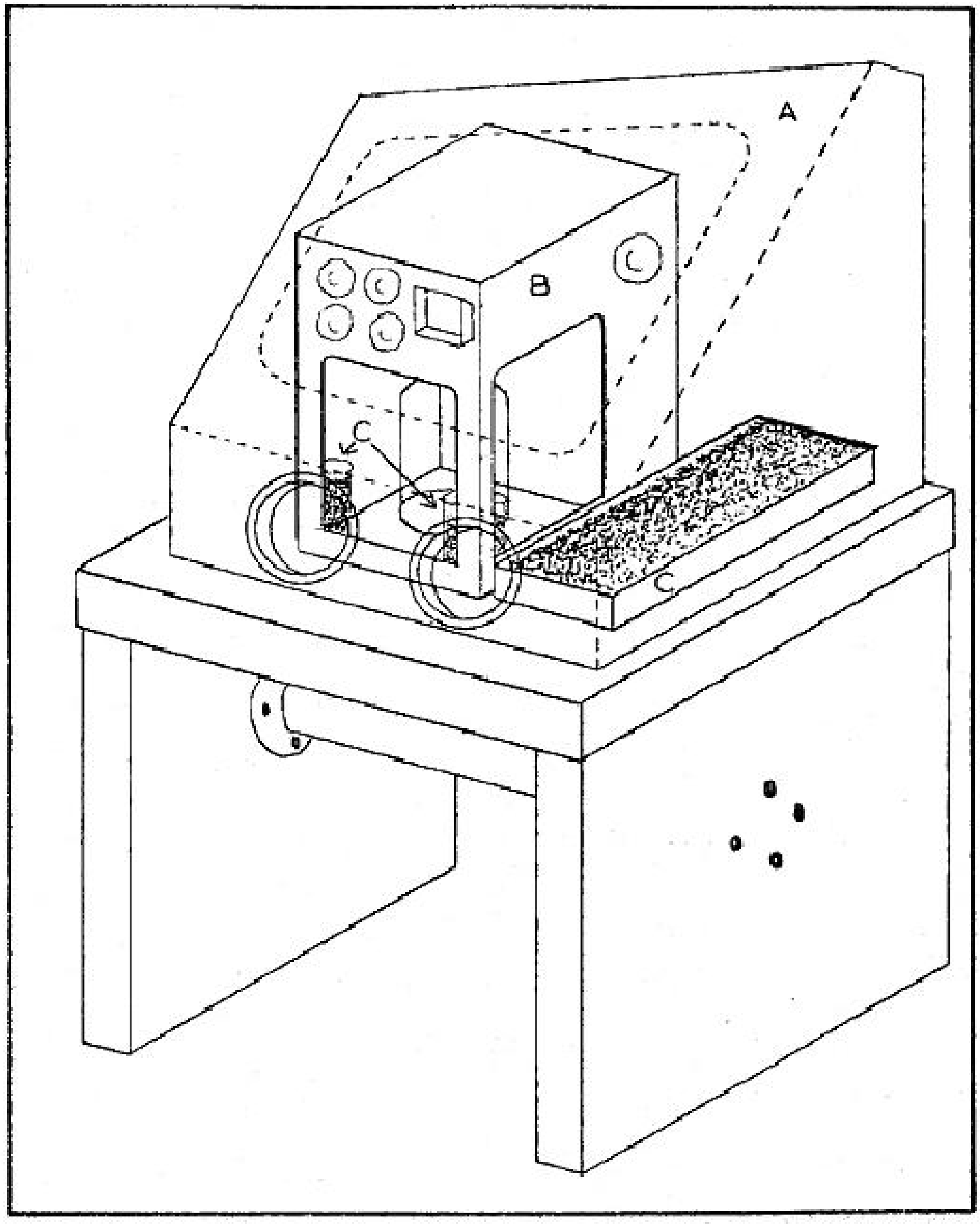
F. Xylem cores in plastic tubes

G. Filling the hole with plastic wood

H. Inserting the cork

I. Sculpting the plastic wood

Figure 5. Glove box set up used to weight bark and xylem cores.



A. Glove Box

B. Analytical Balance

C. Dessiccant

Figure 6. Weight change of xylem sections weighed in dessicated and ambient air.

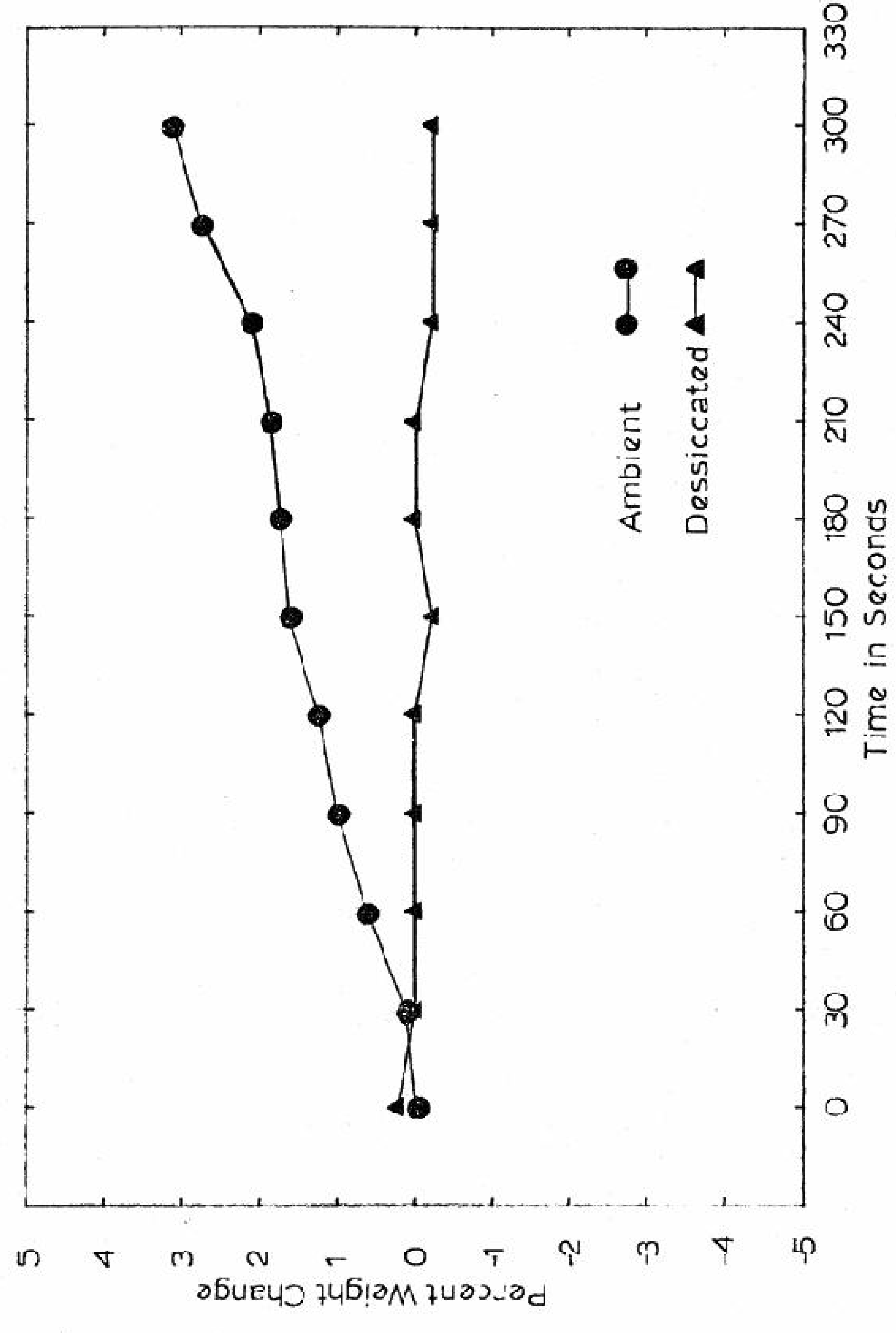

Percent Weight Change
5
4
3
2
1
0
-1
-2
-3
-4
-5
Time in Seconds
0
30
60
90
120
150
180
210
240
270
300
330
Ambient
Dessiccated

Figure 7. Replicate lead determinations on bark, xylem and $HClO_4$ samples with mean ± 1 standard deviation indicated.

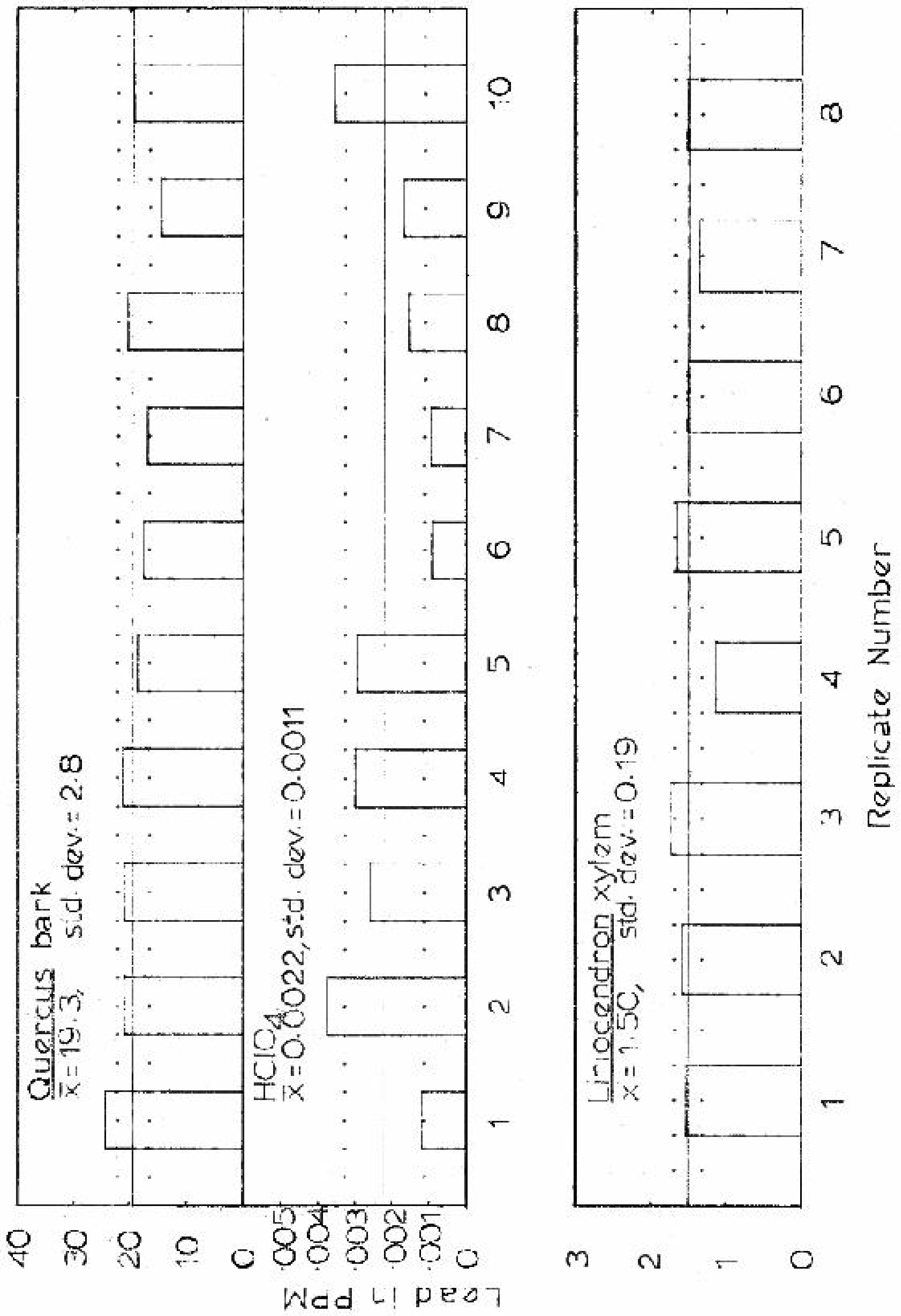

Quercus bark
x̄ = 19.3, std. dev. = 2.8
HClO4
x̄ = 0.0022, std. dev. = 0.0011
Liriodendron xylem
x̄ = 1.50, std. dev. = 0.19
Load in PPM
40
30
20
10
0
.005
.004
.003
.002
.001
0
3
2
1
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
7
8
Replicate Number

Figure 8. Typical calibration curve with approximate absorbance values for each replicate type indicated.

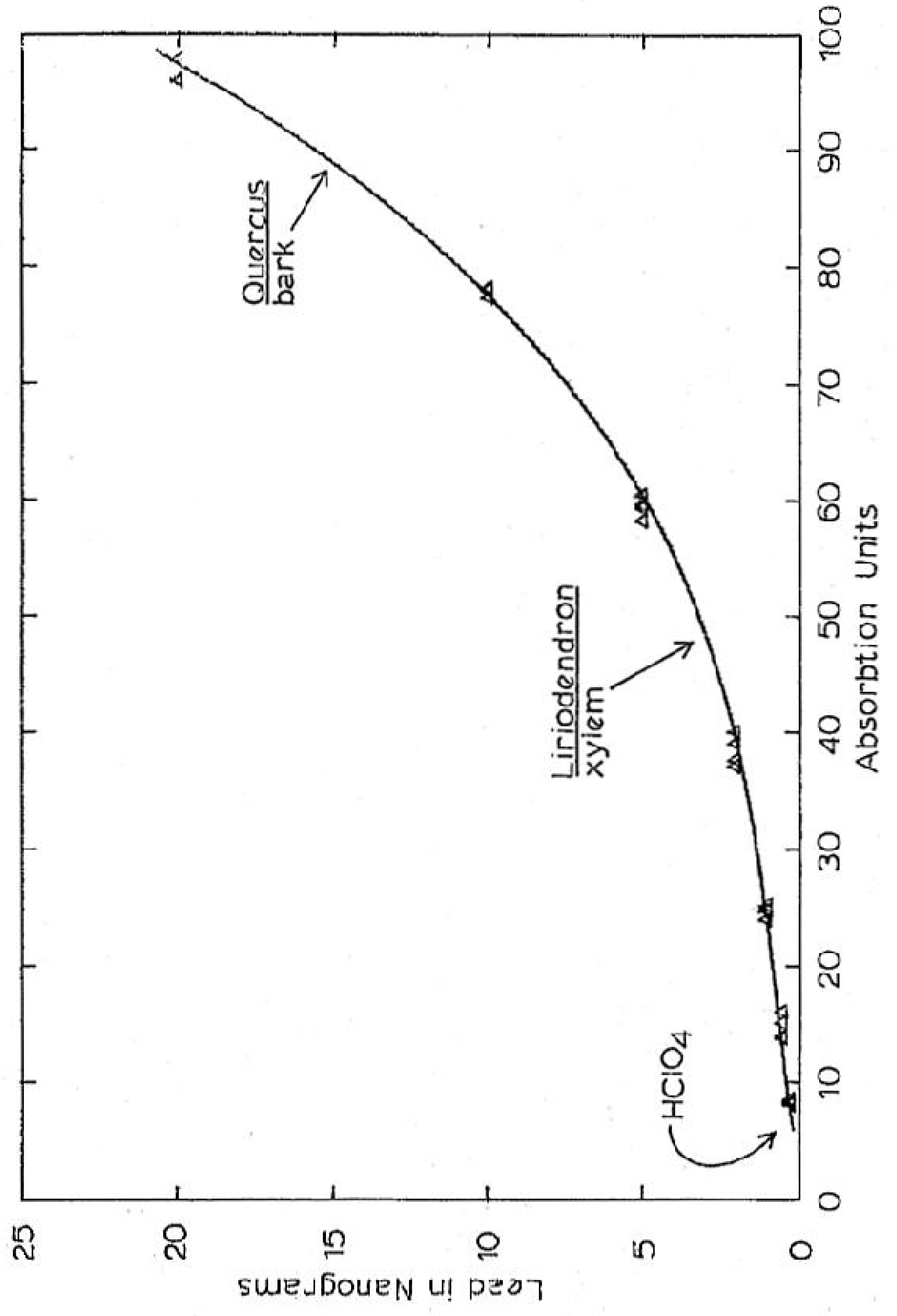

Lead in Nanograms
0
5
10
15
20
25
Absorbtion Units
0
10
20
30
40
50
60
70
80
90
100
HClO$_4$
Liriodendron xylem
Quercus bark

Figure 9. Frequency distribution of soil pHs at Deepdene Park and Fernbank Forest.

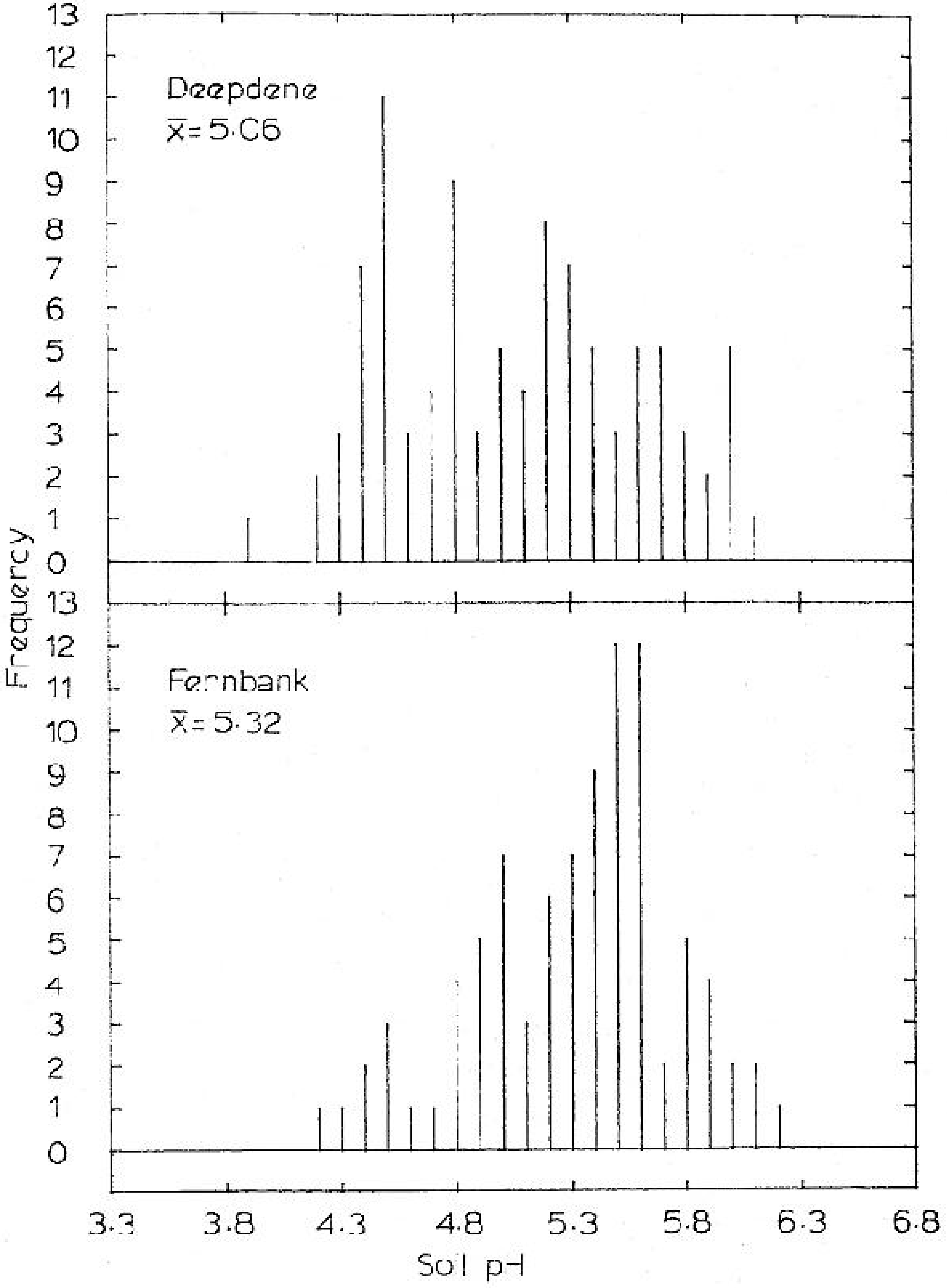

Deepdene
$\bar{x}$ = 5·06
Fernbank
$\bar{x}$ = 5·32
Frequency
0
1
2
3
4
5
6
7
8
9
10
11
12
13
3·3
3·8
4·3
4·8
5·3
5·8
6·3
6·8
Soil pH

Figure 10. Mean soil lead concentration in 0-15 cm and 15-30 cm soiul fractions at Deepdene Park and Fernbank Forest with standard error of the mean indicated.

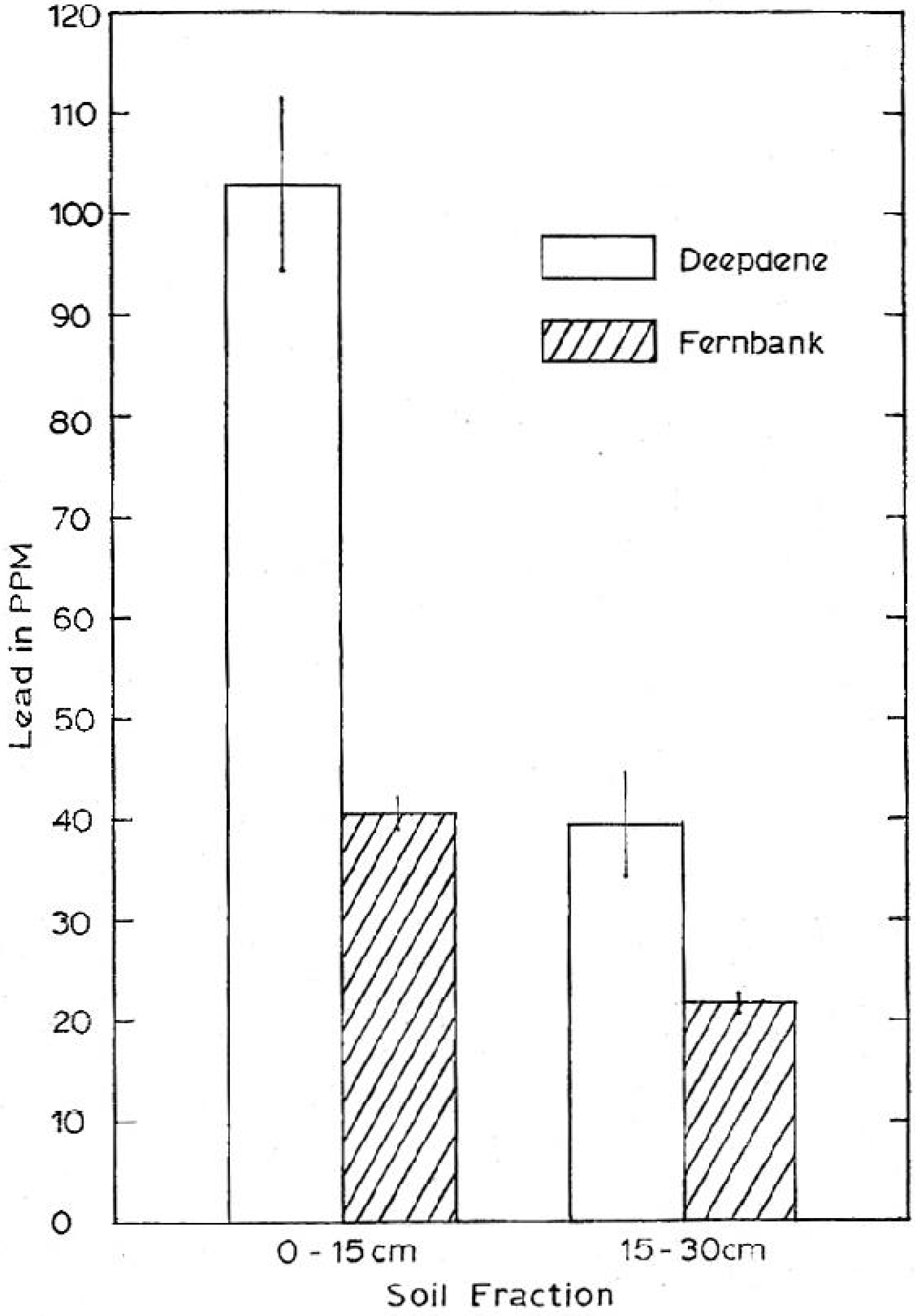

Lead in PPM
120
110
100
90
80
70
60
50
40
30
20
10
0
Deepdene
Fernbank
0 - 15 cm
15 - 30 cm
Soil Fraction

Figure 11. Frequency distributions of the index of decrease in soil lead concentration at Deepdene Park and Fernbank Forest.

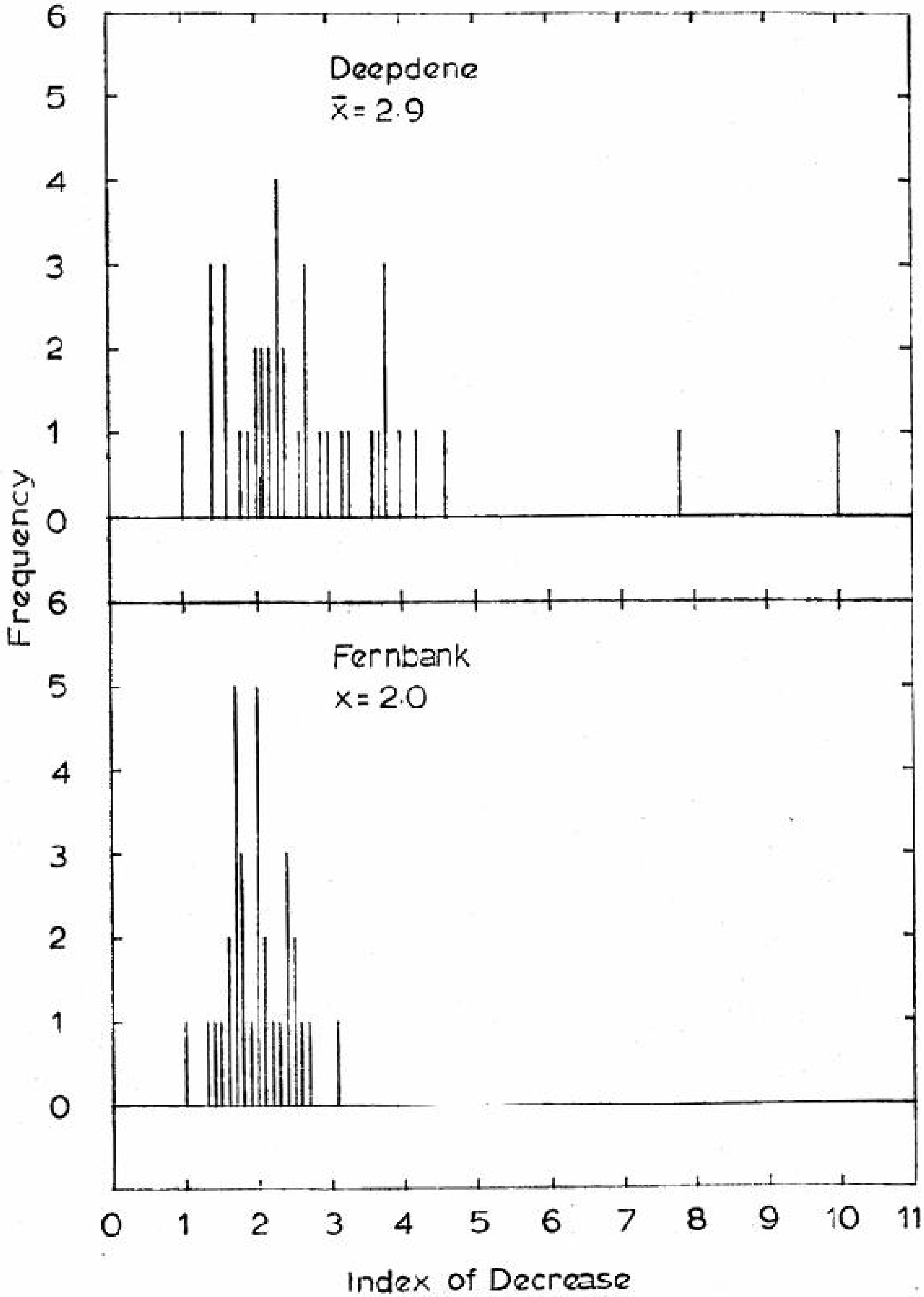

Deepdene
$\bar{x}$ = 2.9
Fernbank
x = 2.0
Frequency
0
1
2
3
4
5
6
Index of Decrease
0
1
2
3
4
5
6
7
8
9
10
11

Figure 12. Xylem lead concentration in Deepdene tree species. Solid areas represent mean ± 1 standard error of the mean.

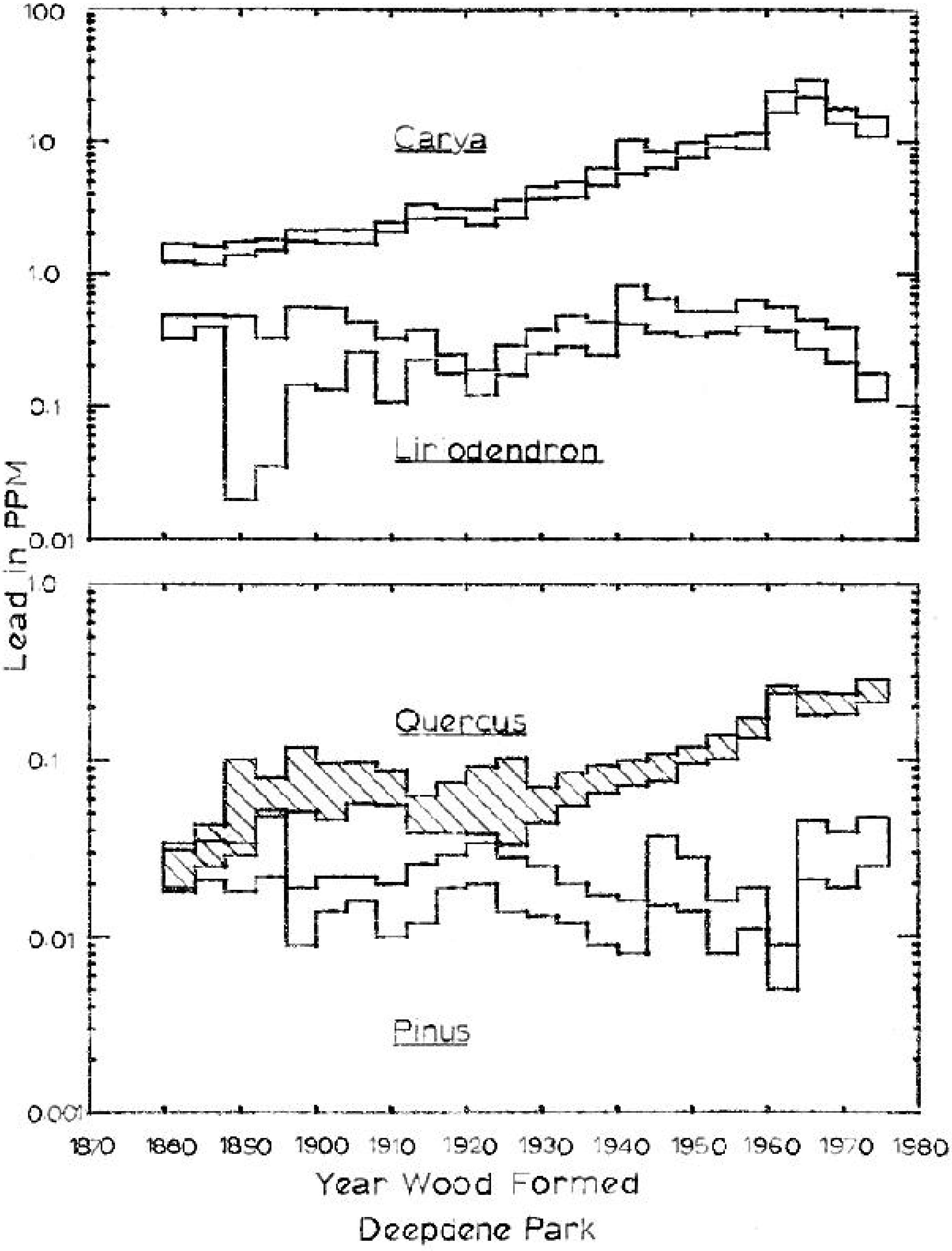

100
10
1.0
0.1
0.01
Carya
Liriodendron
Lead in PPM
1.0
0.1
0.01
0.001
Quercus
Pinus
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year Wood Formed
Deepdene Park

Figure 13. Xylem lead concentration in Fernbank tree species. Solid areas represent mean ± 1 standard error of the mean.

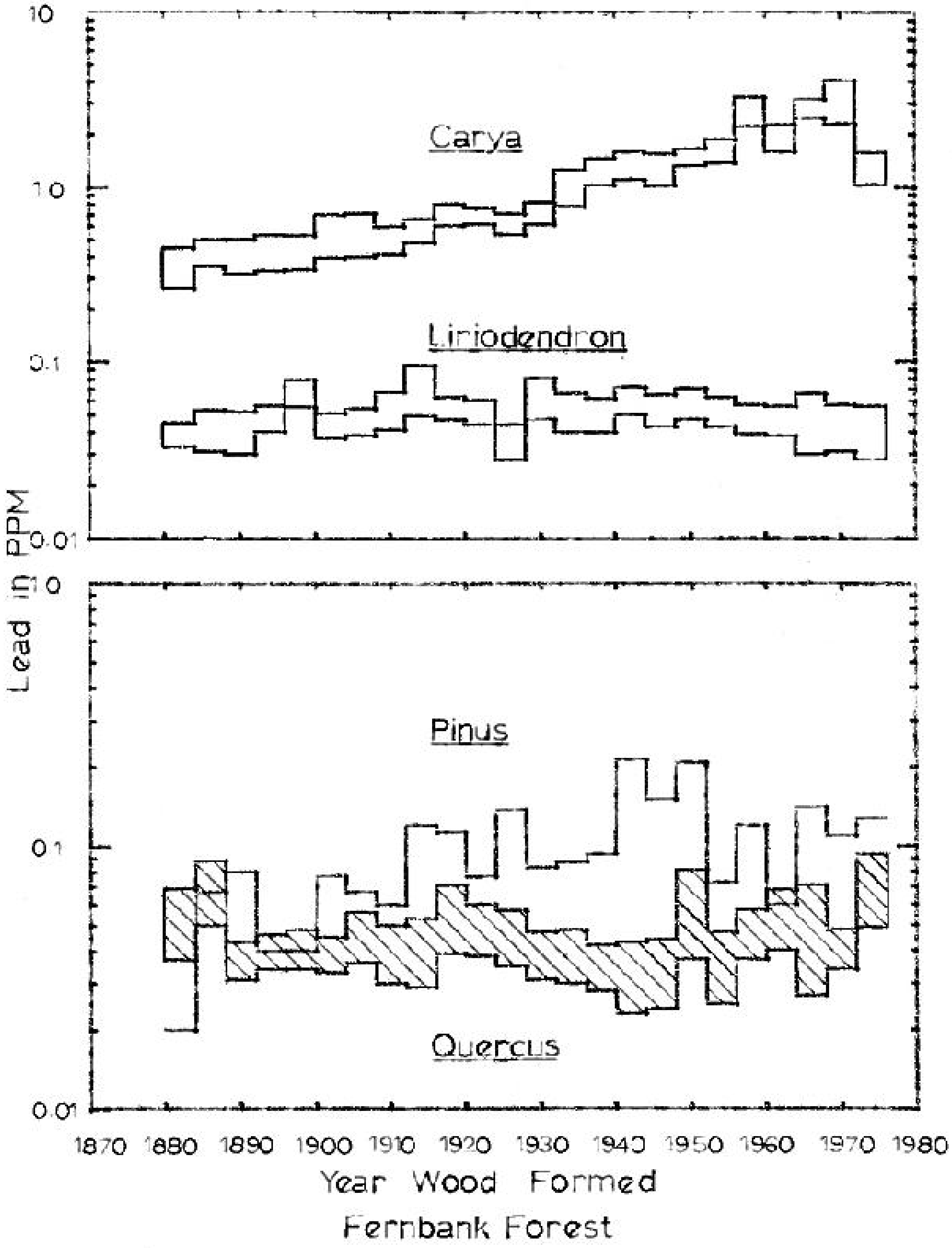

10
1.0
0.1
0.01
Carya
Liriodendron
Lead in PPM
1.0
Pinus
0.1
Quercus
0.01
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year Wood Formed
Fernbank Forest

Figure 14. Xylem lead concentration in *Liriodendron* trees at Deepdene Park and Fernbank Forest with standard error of the mean indicated.

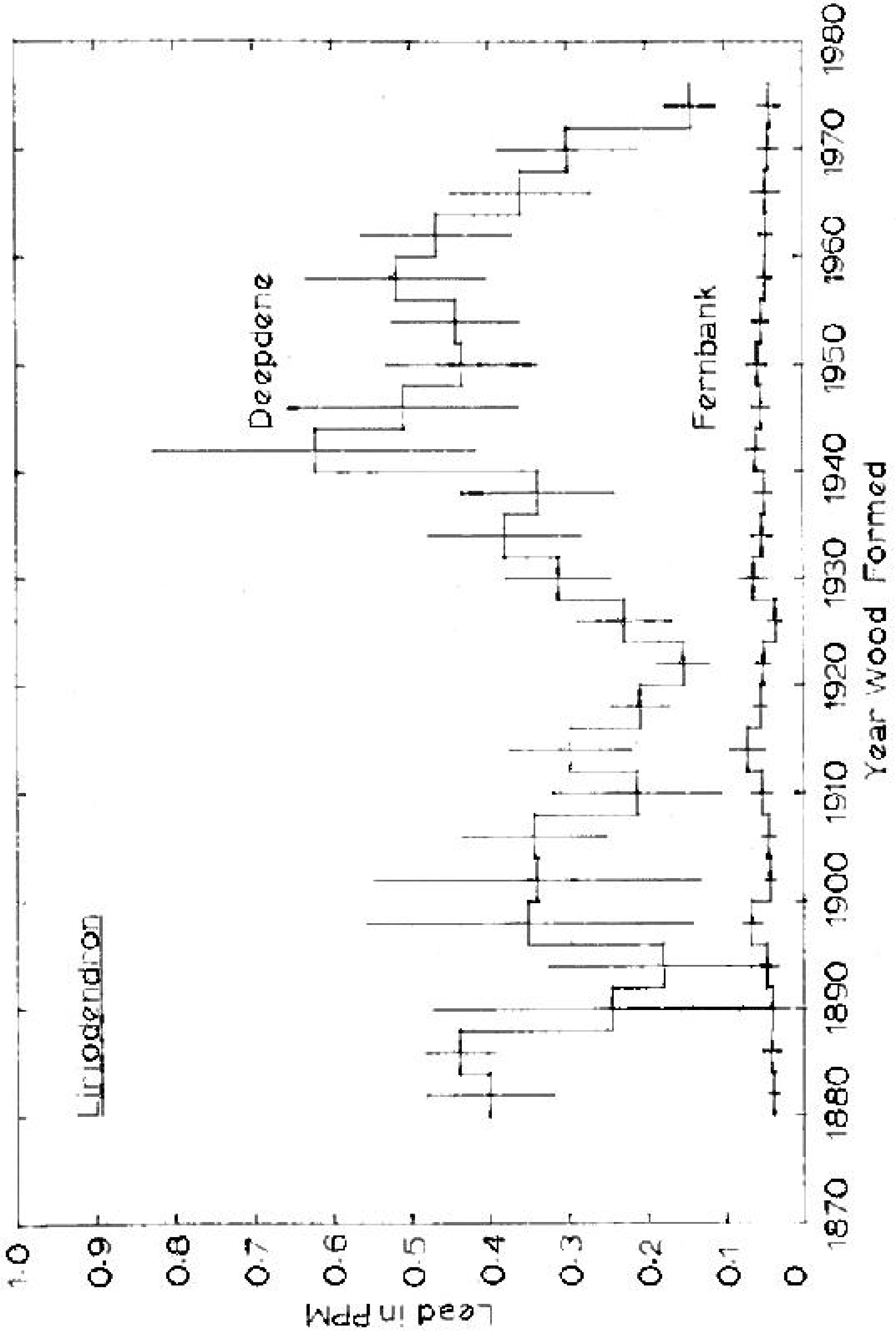

Liriodendron
Deepdene
Fernbank
Lead in PPM
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year Wood Formed

Figure 15. Xylem lead concentration in _Quercus_ trees at Deepdene Park and Fernbank Forest with standard error of the mean indicated.

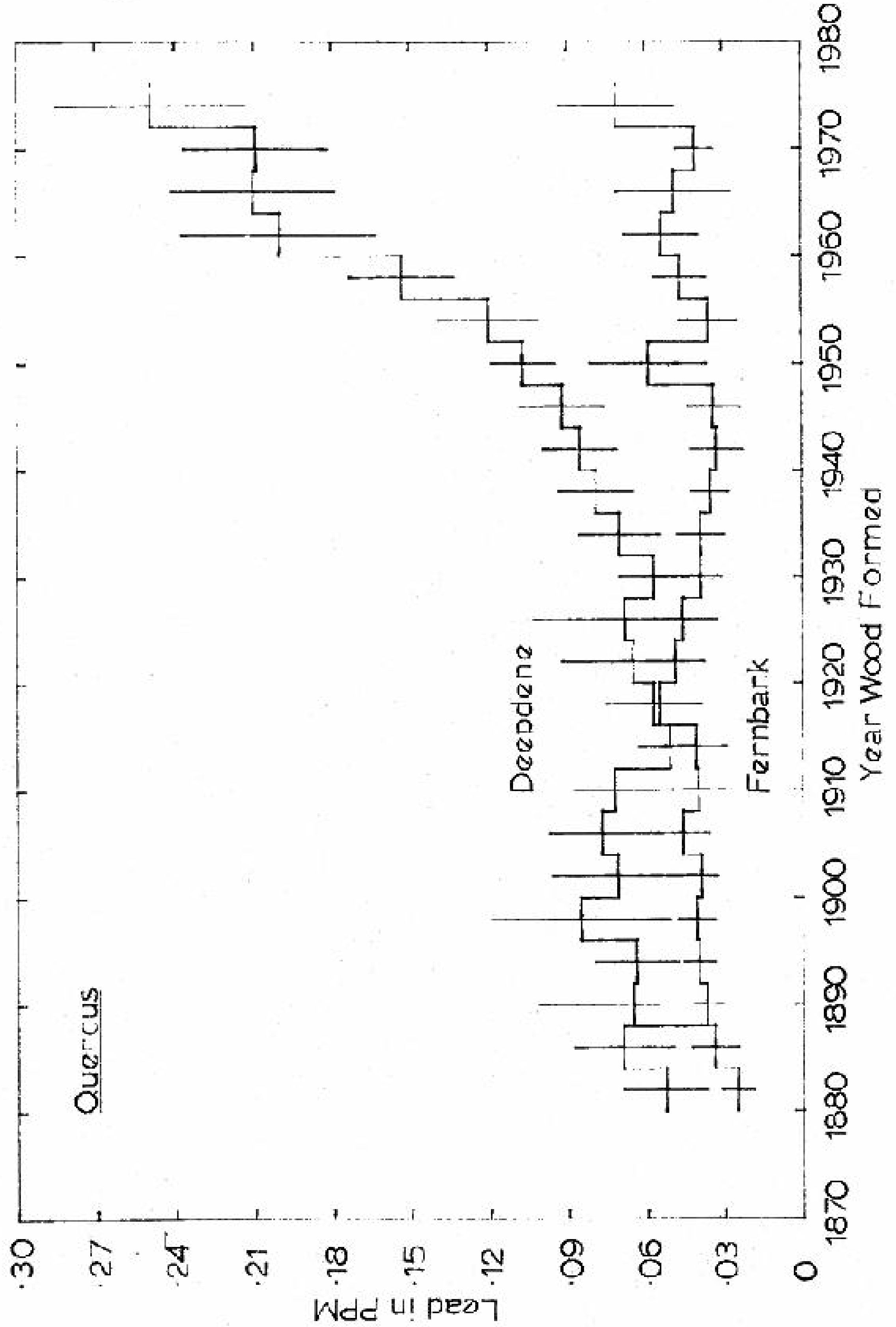

Quercus
Deepdene
Fernbank
Lead in PPM
Year Wood Formed
·30
·27
·24
·21
·18
·15
·12
·09
·06
·03
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980

Figure 16. Xylem lead concentration in _Carya_ trees at Deepdene Park and Fernbank Forest with standard error of the mean indicated.

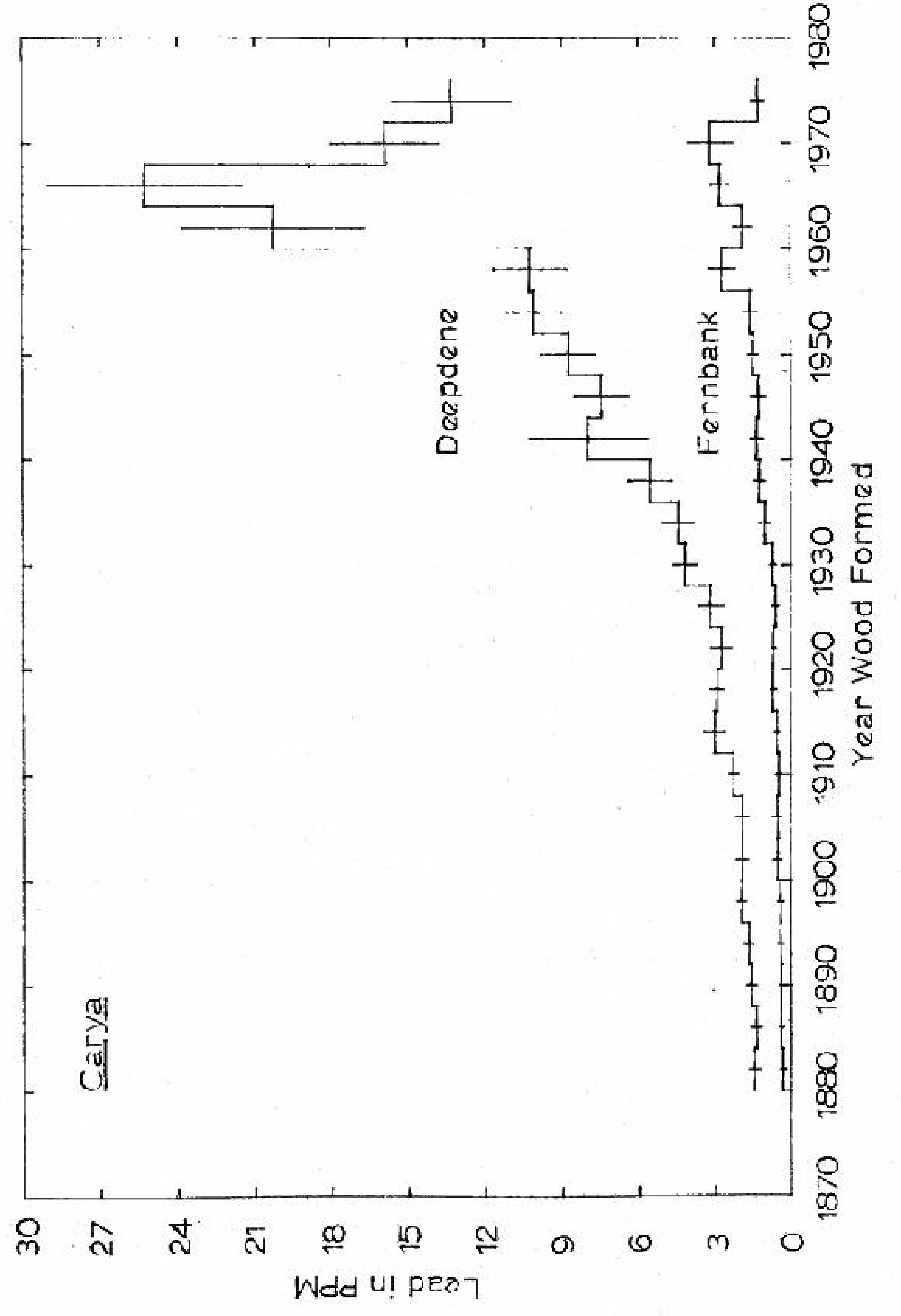

Carya
Deepdene
Fernbank
Lead in PPM
0
3
6
9
12
15
18
21
24
27
30
Year Wood Formed
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980

Figure 17. Frequency distributions of peak xylem lead concentrations for Liriodendron, Quercus and Carya trees (all trees combined).

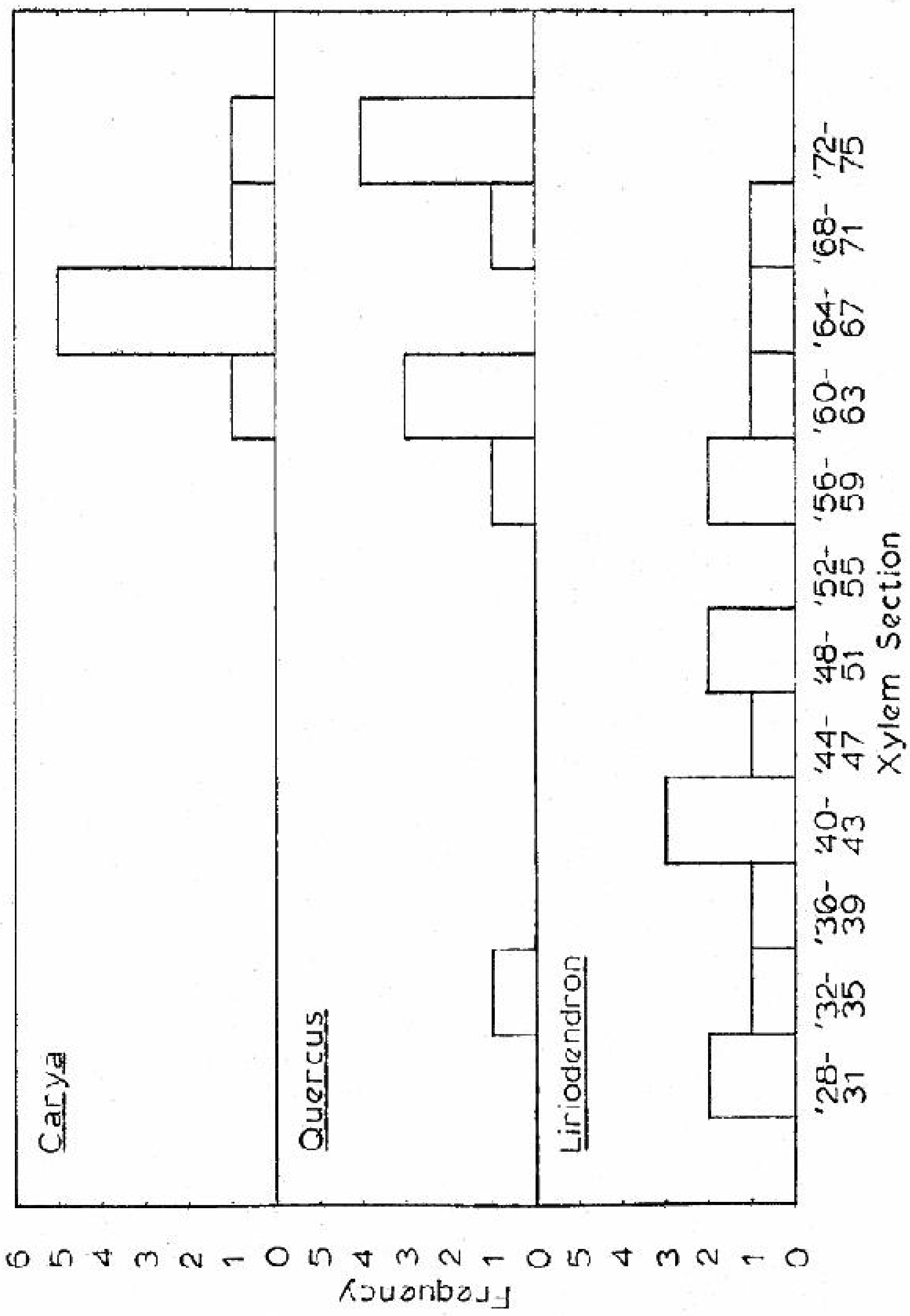

Carya
Quercus
Liriodendron
Frequency
6 5 4 3 2 1 0 5 4 3 2 1 0 5 4 3 2 1 0
'28-31
'32-35
'36-39
'40-43
'44-47
'48-51
'52-55
'56-59
'60-63
'64-67
'68-71
'72-75
Xylem Section

Figure 18. Percent increase of xylem lead in the post-tetraethyl lead era (1931-1975) for Deepdene and Fernbank trees. Xylem sections are standardized against the 1928-1931 xylem section of the same core.

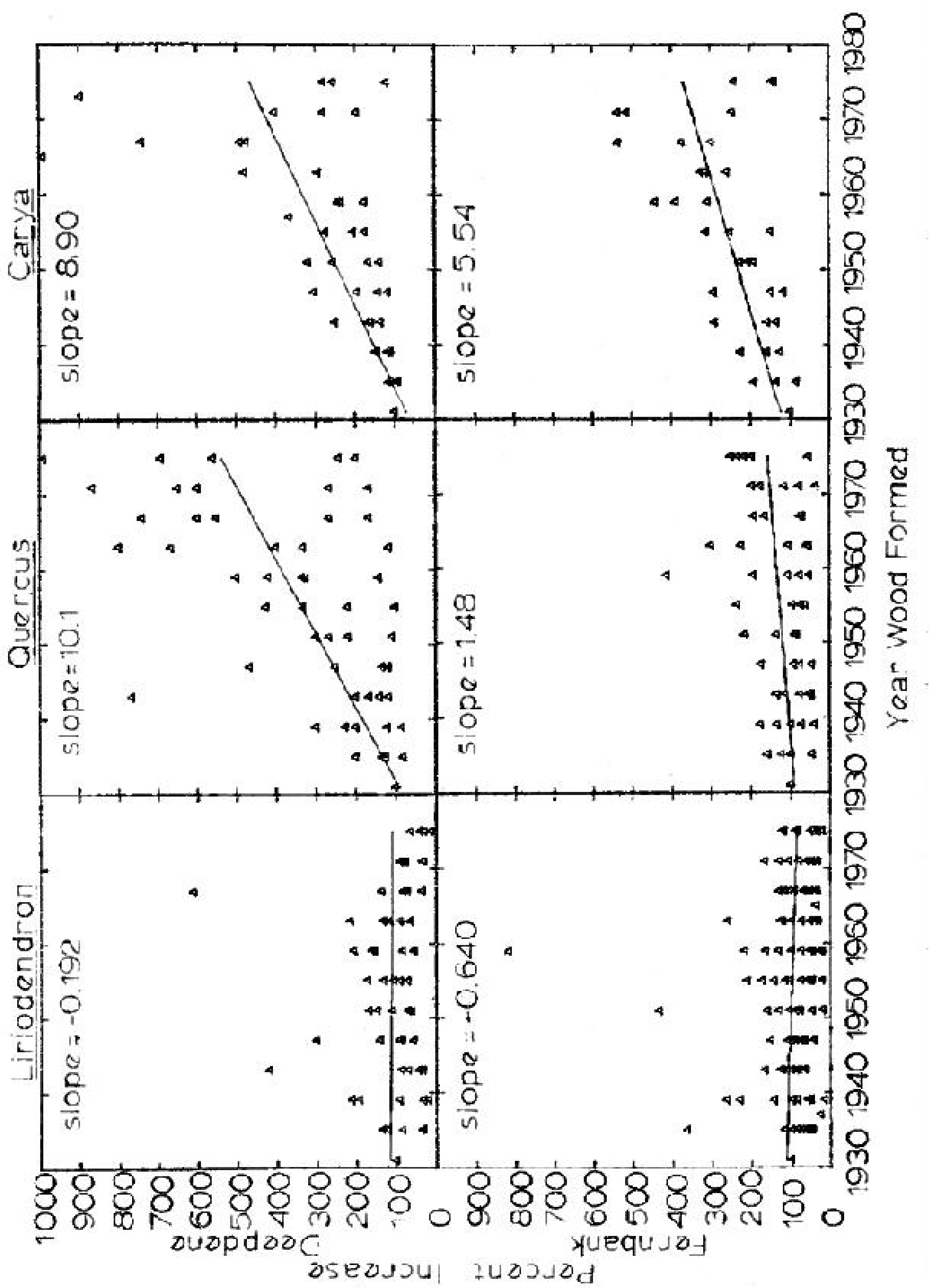

Liriodendron
Quercus
Carya
slope = -0.192
slope = 10.1
slope = 8.90
slope = -0.640
slope = 1.48
slope = 5.54
Percent Increase
Deepdene
Fernbank
Year Wood Formed
1930 1940 1950 1960 1970 1980
0 100 200 300 400 500 600 700 800 900 1000

Figure 19. Soil xylem lead concentrations of spatially oriented samples at Deepdene Park and Fernbank Forest.

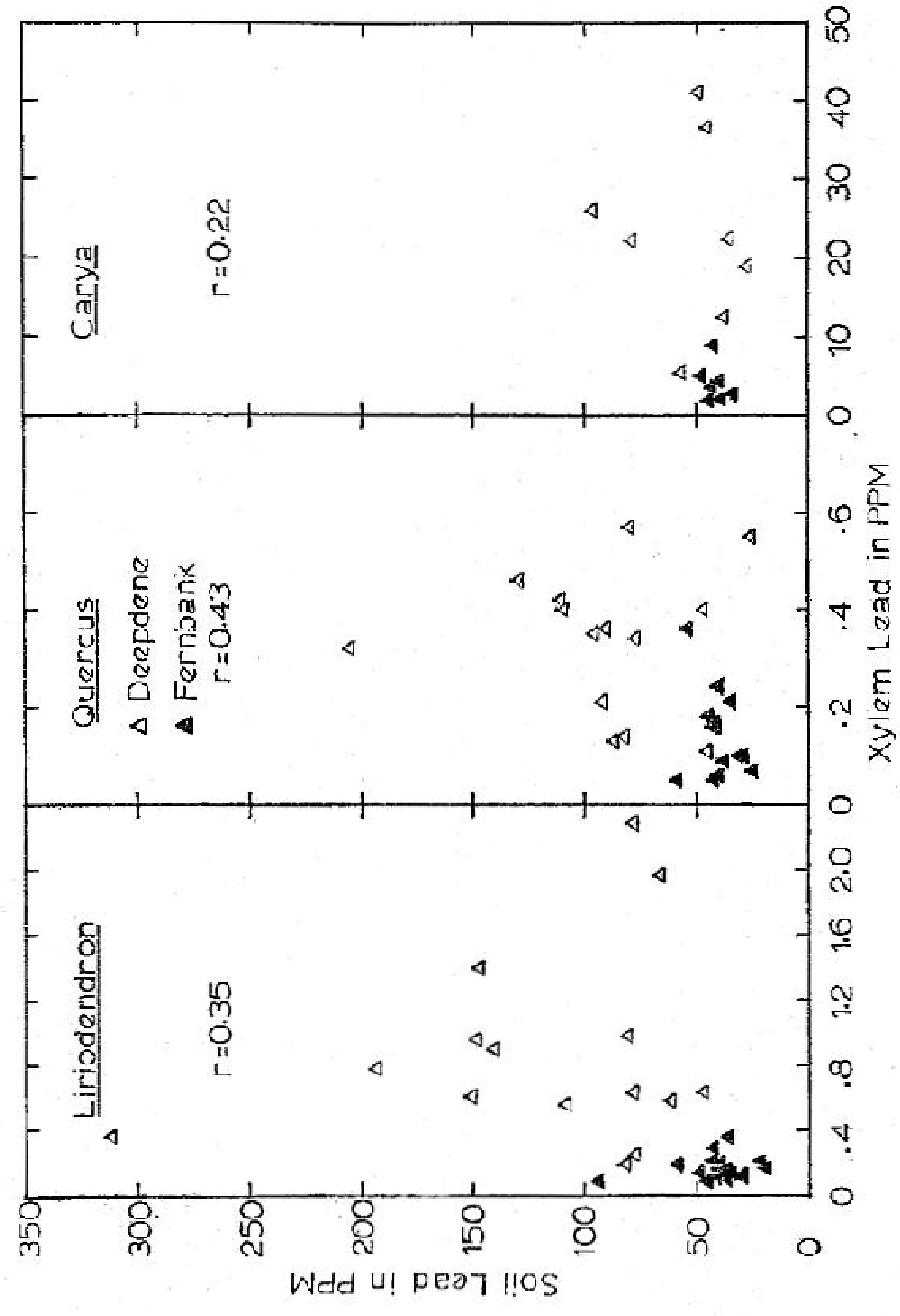

Liriodendron
r=0.35
Quercus
△ Deepdene
▲ Fernbank
r=0.43
Carya
r=0.22
Soil Lead in PPM
0
50
100
150
200
250
300
350
Xylem Lead in PPM
0
.4
.8
1.2
1.6
2.0
0
.2
.4
.6
0
10
20
30
40
50

Figure 20. Lead distribution in an *Ailanthus* tree core.

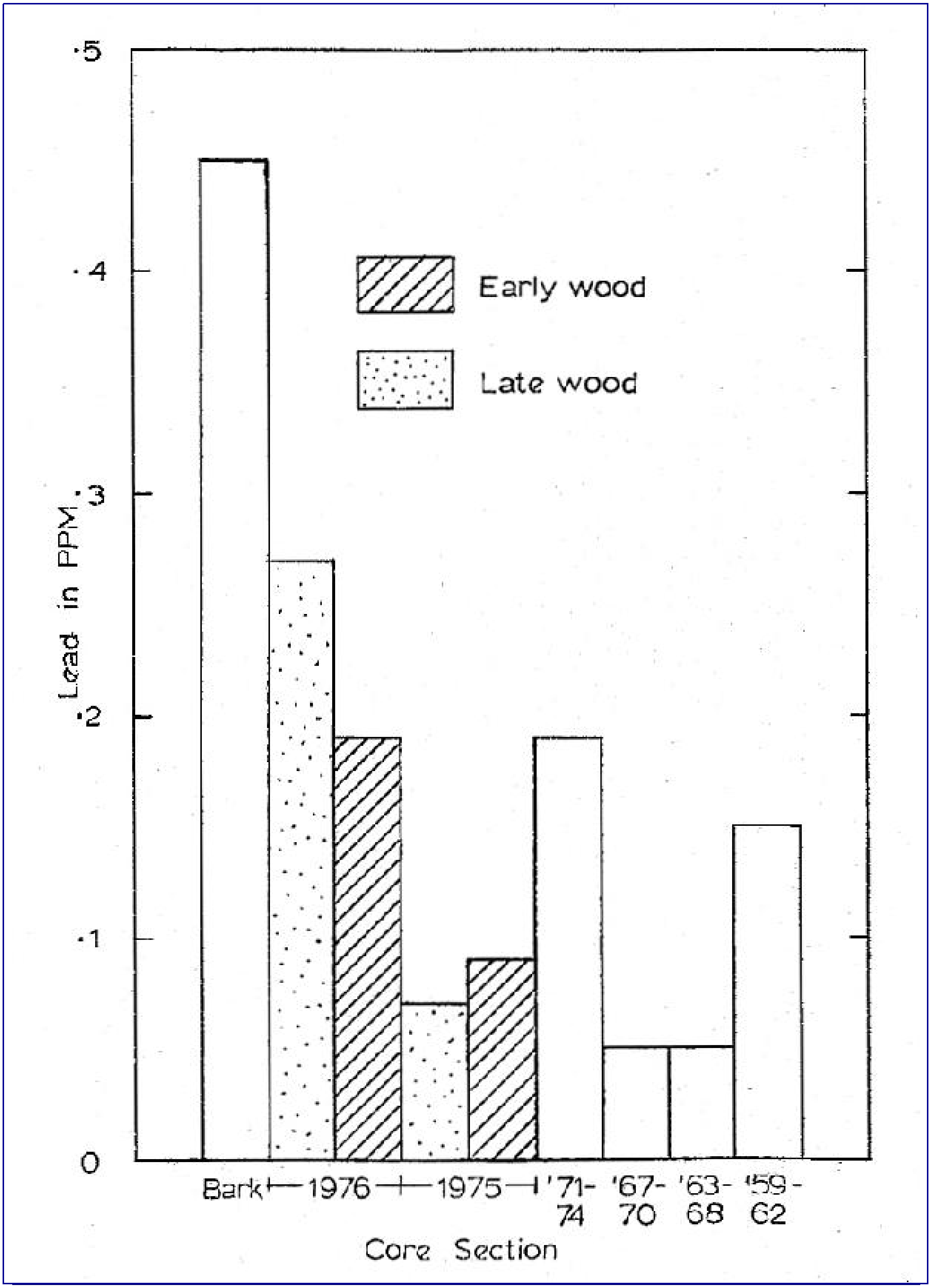

·5
·4
·3
·2
·1
0
Lead in PPM
Early wood
Late wood
Bark
1976
1975
'71-74
'67-70
'63-68
'59-62
Core Section

Figure 21. A model of lead accumulation in tree wood. Xylem lead concentrations in the first two years are background (b). Lead from an outside source enters the tree, and a portion of it enters the xylem (x). Each year there is a constant rate of increase (r) of xylem lead. Lead is laterally transported from left to right, and the xylem lead concentrations are totaled from top to bottom.

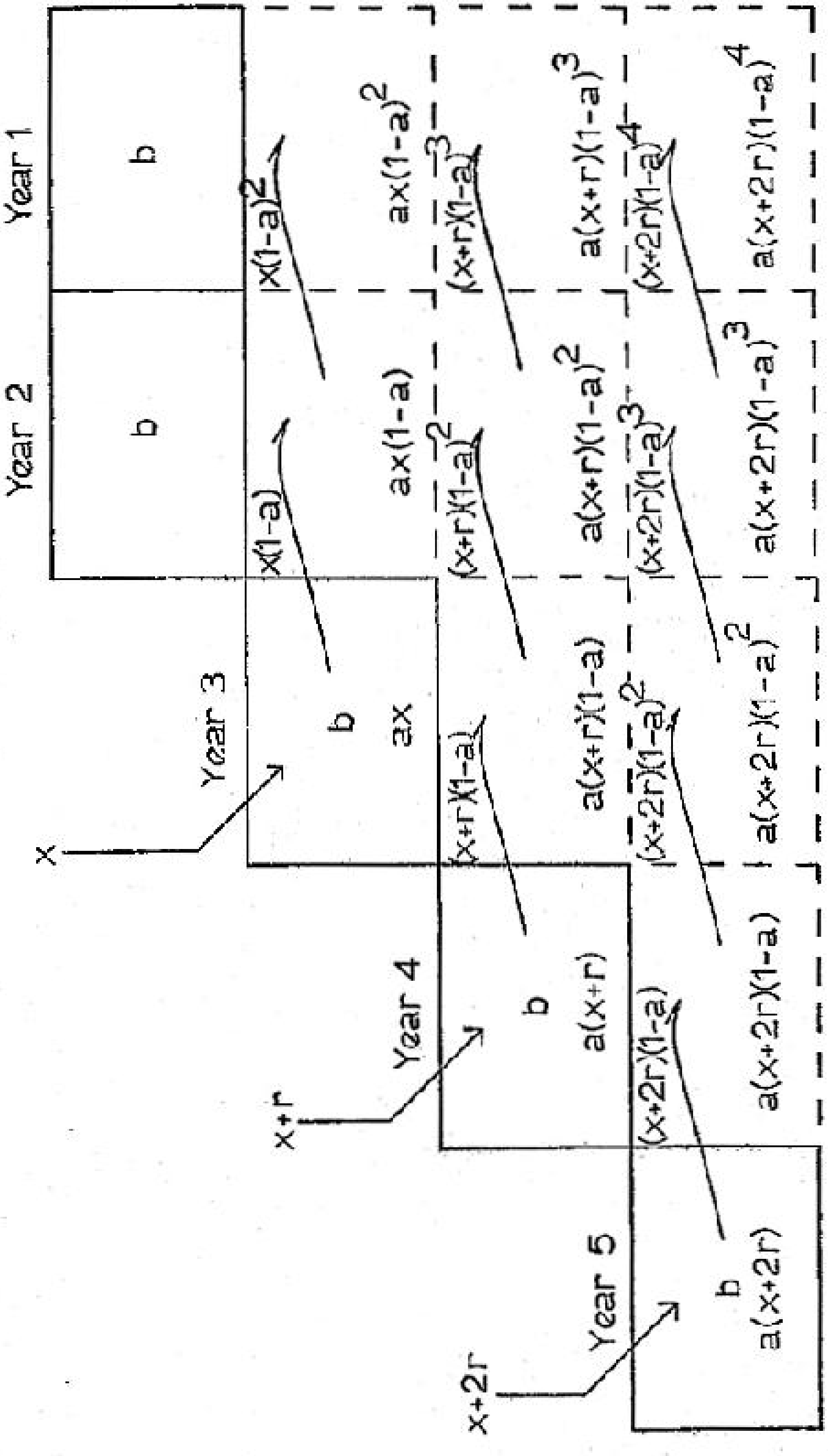

Year 1
Year 2
Year 3
Year 4
Year 5
x
x+r
x+2r
b
b
b
b
b
ax
x(1-a)
ax(1-a)
x(1-a)2
ax(1-a)2
(x+r)(1-a)
a(x+r)
a(x+r)(1-a)
(x+r)(1-a)2
a(x+r)(1-a)2
(x+r)(1-a)3
a(x+r)(1-a)3
(x+2r)(1-a)
a(x+2r)
a(x+2r)(1-a)
(x+2r)(1-a)2
a(x+2r)(1-a)2
(x+2r)(1-a)3
a(x+2r)(1-a)3
(x+2r)(1-a)4
a(x+2r)(1-a)4

Figure 22. Several simulations of the lead accumulation model with model parameters indicated.

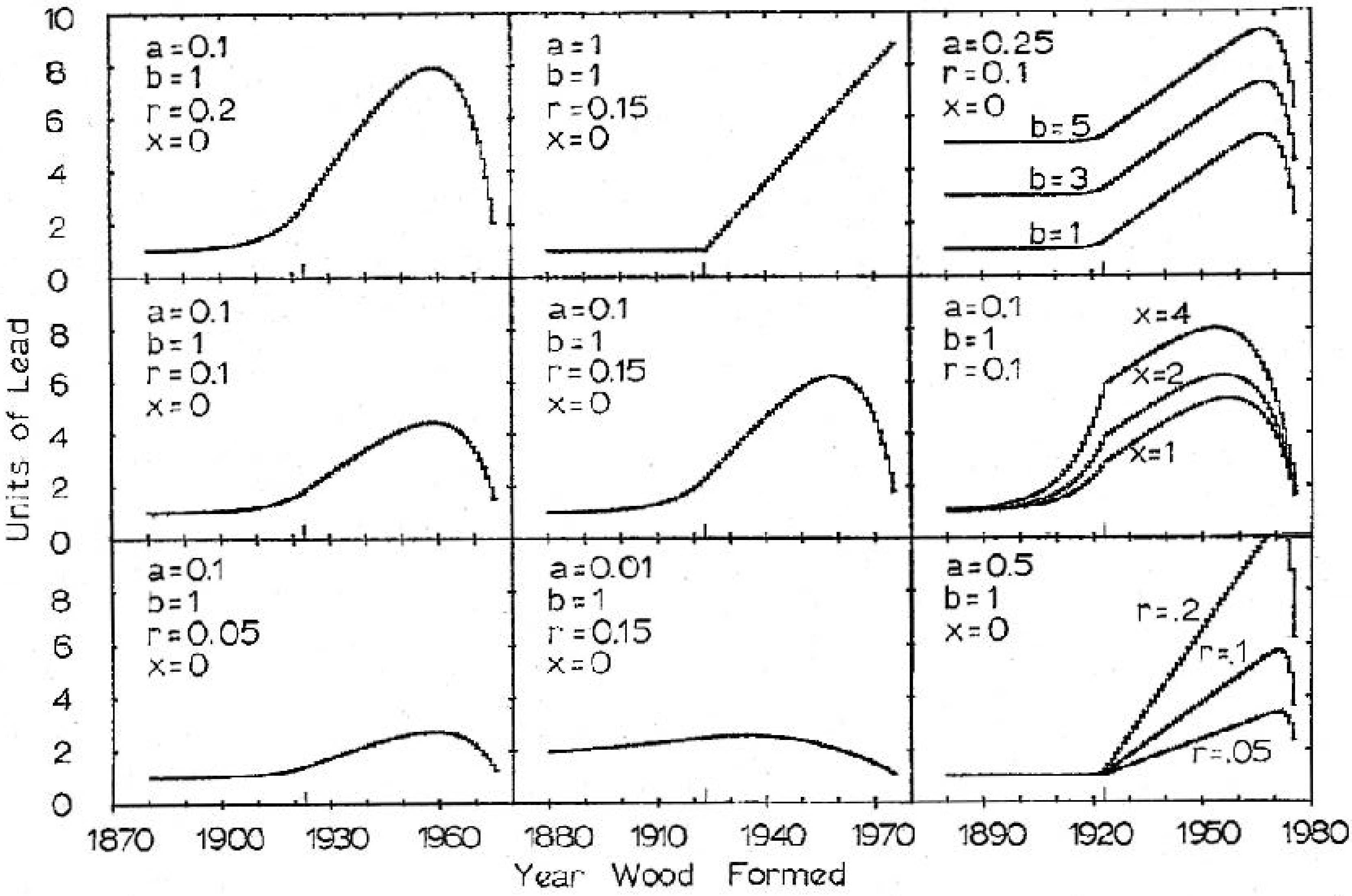

Units of Lead
10
8
6
4
2
0
a=0.1
b=1
r=0.2
x=0
a=1
b=1
r=0.15
x=0
a=0.25
r=0.1
x=0
b=5
b=3
b=1
a=0.1
b=1
r=0.1
x=0
a=0.1
b=1
r=0.15
x=0
a=0.1
b=1
r=0.1
x=4
x=2
x=1
a=0.1
b=1
r=0.05
x=0
a=0.01
b=1
r=0.15
x=0
a=0.5
b=1
x=0
r=.2
r=.1
r=.05
1870
1900
1930
1960
1880
1910
1940
1970
1890
1920
1950
1980
Year Wood Formed

Figure 23. Model simulations of lead accumulation in *Liriodendron*, *Quercus*, and *Carya* trees at Deepdene Park. Model parameters not indicated equal 0.

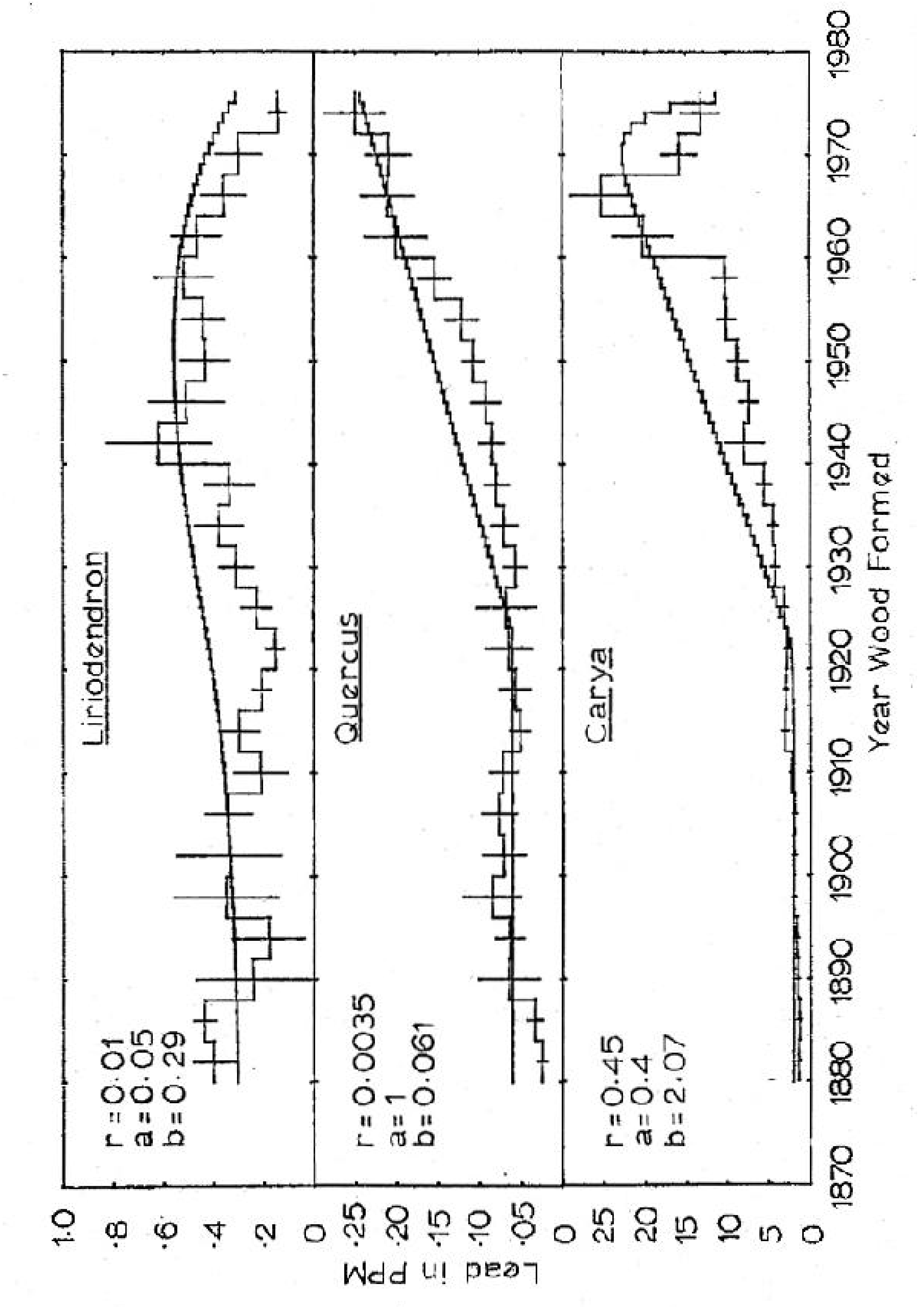
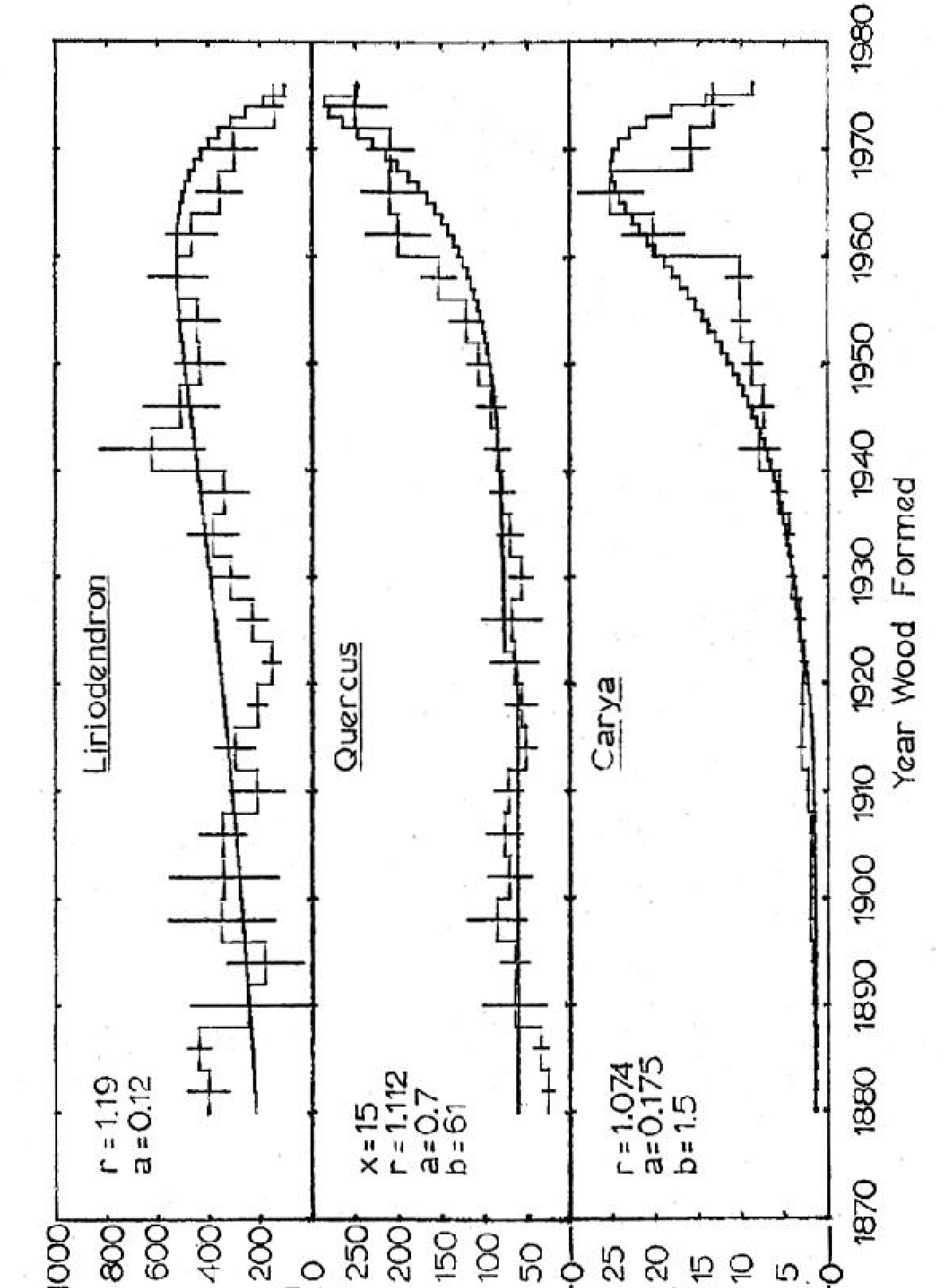

Liriodendron
r = 0.01
a = 0.05
b = 0.29
Quercus
r = 0.0035
a = 1
b = 0.061
Carya
r = 0.45
a = 0.4
b = 2.07
Lead in PPM
1.0
.8
.6
.4
.2
0
.25
.20
.15
.10
.05
0
25
20
15
10
5
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year Wood Formed

Figure 24. Modified-model simulations of lead accumulation in *Liriodendron*, *Quercus*, and *Carya* trees at Deepdene Park. Model parameters not indicated equal 0.


Liriodendron
r = 1.19
a = 0.12
Quercus
x = 15
r = 1.112
a = 0.7
b = 61
Carya
r = 1.074
a = 0.175
b = 1.5
Lead
PPB
PPM
1000
800
600
400
200
0
250
200
150
100
50
0
25
20
15
10
5
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year Wood Formed