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VARIATION IN CERTAIN WOOD PROPERTIES OF EASTERN WHITE PINE (*PINUS STROBUS*)

by
Albert Neil Foulger

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1965

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Acknowledgements

I wish to express my appreciation to the many persons who have aided me during the course of the research described herein. To the several members of my Doctoral Committee for their constructive criticism and timely advice I am primarily indebted, and to the Ohio Agricultural Experiment Station which financed the project. Dr. P. H. Struthers, Dr. D. M. Van Doren, Dr. C. R. Weaver, and Mr. J. H. Wilson of the Ohio Agricultural Experiment Station have given generously of their time and experience on various occasions. The form and extent of the project owe much to the patience of Miss Diana Smith of the Forest Products Laboratory, Madison, Wisconsin, who, at its inception, pointed out several pitfalls of which I was blissfully unaware. I am especially indebted to Dr. Robert Zahner of the School of Natural Resources, University of Michigan, without whose advice, perseverence and good humor, calculation of the moisture deficits and analysis of the data as a whole would have been a longer, wearier task. Finally, I am forever grateful to my wife who carried out the several thousand calculations required to prepare the observations for statistical analyses and has given encouragement throughout the work.

To each and all of the above I wish to set forth my sincere thanks, while reserving to myself the responsibility for such weaknesses as remain in the paper.

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Though there are many things in nature which are singular and unmatched, yet it (the human understanding) devises for them parallels and conjugates and relatives which do not exist.

Bacon.

Introduction

The objectives of the study are twofold, the first being to examine variation in cell number in the annual ring, ring width, percentage of latewood, longitudinal shrinkage, and specific gravity existing at different heights in the stem and distances from the pith in eastern white pine (*Pinus strobus*). Second, to examine to what extent change in the above variables is associated with annual and seasonal levels of soil moisture availability.

Wood properties vary not only with position in the stem but also by virtue of the position of the tree in its environment. The many factors comprising the site, e.g., weather, topography, competing vegetation, all exert an influence on the tree to a greater or lesser degree. In the present study, the primary concern was with the effect on wood structure and properties of position in the main stem, with ancillary study of the extent to which soil moisture deficits modify the variation pattern due to position. It is not suggested that soil moisture deficit typifies the effect of the entire environment. However, soil moisture availability is one of the major influences

on tree growth and, as determined herein, is an estimate of soil type, precipitation, and air temperature effects in combination.

The present intensive study of three co-dominant trees from a single site is designed primarily to establish a characteristic pattern of variation in several wood properties within the stem. Having determined this pattern, it should be possible to design a system of less intensive sampling, using large increment cores, to compare the wood structure pattern of other eastern white pine growing under different conditions. It is fully realized that data from three trees on one site do not constitute a tenable base for the total evaluation of the intrinsic and extrinsic factors controlling wood formation in eastern white pine. However, they do provide one of the bases from which to explore the structure of the white pine stem.

Investigation of wood property-growth condition relationships has proceeded apace during the past few years. The broad field of moisture-tree growth relationships has been thoroughly reviewed by Glock (1955), Kramer and kozlowski (1960), and, in conifers, by Zahner (1963), while research covering the entire gamut of environmental effects on wood properties has been aggregated in a recent Tappi bibliography (1962).

In general approach, the study is akin to those of Duff and Nolan (1953), Richardson (1961), and Smith and Wilsie (1961). Duff and Nolan, having described three axes within the stem of red pine along which meaningful comparisons of anatomic properties might be made, showed the existence of a repetitive pattern of ring width along successive growth sheaths. This pattern illustrated a strong positional effect within the tree, curves for values along a series of growth sheaths from apex to base having the same general form, particularly within the topmost internodes. Using the same technique with Corsican pine, Richardson was able to develop families of curves illustrative of a similar physiologic positional influence on tracheid length within the stem. Combination of soil moisture deficits with growth sheath measurements in loblolly pine for specified growing seasons permitted Smith and Wilsie to develop ring width, percentage of latewood, and specific gravity relationships demonstrating the effects of soil moisture deficit on the values within the growth sheath.

Specific gravity is of considerable economic importance, being descriptive of the amount of actual wood substance in a sample and is frequently indicative of the wood's utility in terms of strength, machinability, pulping, etc. Therefore, stem analyses to determine variation of this property within the stem have been conducted on

numerous occasions. However, these have been accompanied rather infrequently by concurrent examinations of other stem variables, though the work of Hamilton with red oak (1961), is an exception. The literature on this property has been thoroughly reviewed by Spurr and Hsiung (1954), Larson (1957), and more recently by Paul (1963).

While specific gravity has been much studied, longitudinal shrinkage, i.e., parallel to the vertical axis of the stem, has received comparatively little attention, being much less than shrinkage in either the radial or the tangential directions. Generally, longitudinal shrinkage is greatest close to the pith and becomes important in boards only one edge of which is within ten rings of the pith. In such instances, the difference in shrinkage between the inner and the outer edges of the board may be sufficient to cause severe warping. Koehler (1931), and Pillow and Luxford (1938), reported a direct relationship between ring width and longitudinal shrinkage, the wider rings showing greater shrinkage. Cockrell (1949) was unable to agree with this conclusion, stating that when marked longitudinal shrinkage occurred in coniferous wood it could be traced to proximity to the pith, compression wood, or irregular grain. Previously Cockrell (1947) had proposed a mathematical explanation of longitudinal shrinkage which he ascribed to a combination of four factors namely the interaction of chain molecules, fibril

angle, the cellulose chain-molecule length, and the micro-capillary width. Recently Australian workers have shown considerable interest in the longitudinal shrinkage of wood and in its variation within the stem, e.g., Jacobs, 1954; Dadswell and Nicholls, 1959.

In subsequent sections, location of the sample trees, collection of soil data for combination with weather information to compute soil moisture deficits, and preparation of the specimens for examination, precede a discussion of the observations.

Location of Sample Trees

Three co-dominant 52-year old eastern white pine with well-developed crowns were selected from a stand planted in the fall of 1913. Trees number 1 and 2 were from within the stand, while tree 3 was exposed slightly on the southeast. The trees were chosen on the basis of straightness of stem, absence of lean, and position in the canopy. A general picture of the stem dimensions of the three trees is given in Figure 1.

The particular white pine stand was chosen for its proximity to a weather station, being less than half a mile from that at the Ohio Agricultural Experiment Station where weather data have been collected since 1887. Thus, daily temperature and precipitation readings were available for a location relatively close to the stand. It is conceded that meteorological studies have shown significant temperature and rainfall differences between stations within and without the forest boundary, and experience indicates that this is so in the present instance. Though the weather station observations do not give a definitive measure, it is assumed for this study that these data do give a relative measure of conditions within the stand during its growth.

The average climate at Wooster is characterized by an evenly distributed rainfall without great temperature

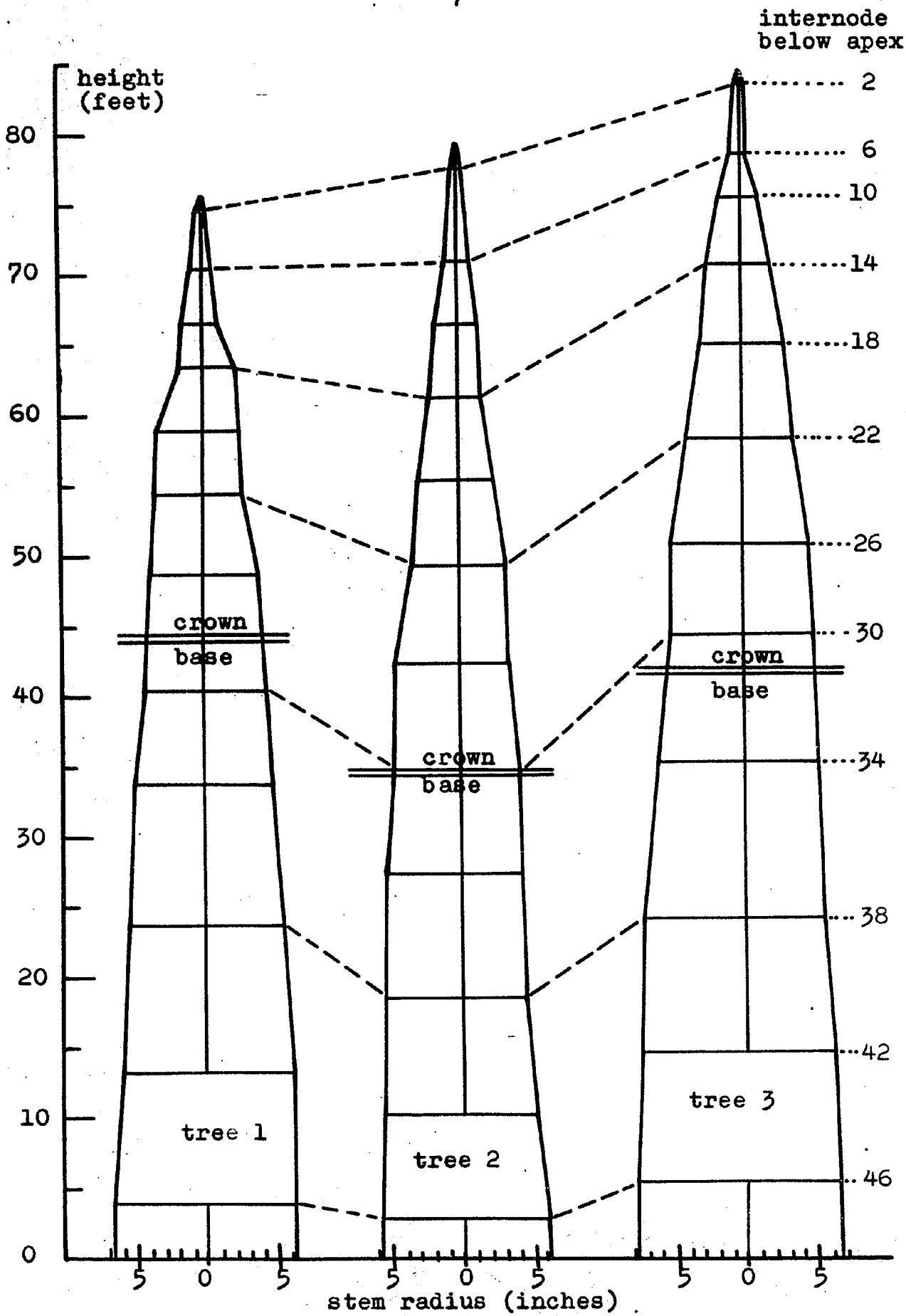


Figure 1. Stem diagram of sample trees.

extremes. The average annual rainfall is 36 inches, but has varied between 29 and 54 inches. Average precipitation figures for the four seasons are 7, 10, 11, and 8 inches for winter, spring, summer, and autumn respectively. Snowfall records give an average value of 35 inches per year, the recorded maximum being 75 inches.

Mean monthly temperatures, which range from 28.2°F. in January to 72.3°F. in July, are listed in Table 1 together with monthly rainfall means. A high temperature of 105°F. has been noted in August, while the lowest, which occurred in January, was -24°F. There is a growing season of 152 days, extending from the last killing frost on 10 May to the first severe frost of 7 October. On the average, precipitation occurs on 129 days each year, while there are 138 clear days.

Topographically, the region is one of gently rolling uplands, with most of the streams flowing into the Ohio River drainage. At Wooster a deep pre-glacial drainage channel cuts through the uplands, but this declivity has been partially filled with drift material during the glacial period. The hilltops stand between 100 and 200 feet above the stream levels, with the area as a whole being some 1000 feet above sea level.

Underlying rock formations are principally Carboniferous conglomerates and Lower Coal Measures. Glacial till masks the effects of the basal rock in places but generally

Table 1. Mean monthly rainfall and mean temperature at Wooster, Ohio, based on records for years 1921 to 1950.

Month	Rainfall (inches)	Temperature (Fahrenheit)
January	2.84	28.2
February	2.20	29.3
March	3.23	37.7
April	3.07	48.1
May	3.82	58.6
June	4.13	68.4
July	3.68	72.3
August	3.40	70.4
September	2.98	64.4
October	2.17	52.9
November	2.52	40.7
December	2.42	30.5

the soils derive much of their character from the underlying material. Wooster silt loam, Wooster series, on which the stand is located, is a deep residual soil derived principally from sandstones and shales of the Waverly Group and Lower Coal Measures. In addition to the sandstone and shale fragments, there are lesser amounts of limestone and igneous material. The rather loose nature of the soil permits good surface and internal drainage. It is a soil of medium acidity and is easily worked.

Collection of Soil Data

Since it was desired to calculate periodic soil moisture deficits existing during the life of the trees, an estimate of physical soil conditions was necessary to supplement the weather data. Therefore a soil analysis was made to determine whether the sample trees had grown on a uniform soil type. Three soil pits were dug equidistantly about each tree, the inner wall of the pit being located four feet from the center of the tree. While these did not sample the entire soil mass traversed by the tree roots, they did provide a measure of the soil conditions in the immediate neighborhood of each tree and permitted a comparison of the three locations within the stand.

Examination of the profiles in the nine pits showed the A_{oo} and A_1 layers to be quite uniform in thickness, being approximately one inch and two inches respectively. A diagram of the soil profile, with the ranges of variation encountered, is shown as Figure 2. The A_2 layer ranged from 10 to 14 inches in thickness and consisted of a light brown silty loam with occasional small sandstone and shale fragments. While the transition from A_1 to A_2 was distinct, that between A_2 and B was variable both in depth and in clarity. In two pits, for example, the 12-inch deep A_2 showed an abrupt interface with the B horizon. In two other pits an A_2 of nine inches, beneath which lay



Figure 2. Stylized profile of Wooster silt loam, Wooster series, under eastern white pine, Compartment K2, Secrest Arboretum, Wooster, Ohio.

a six-inch transition zone, merged gradually into B horizon. The A_2 consisted of a yellow-brown silt loam and contained an increasing number of shale and sandstone particles.

The transition from B to C was quite indefinite, the soil in this lowest horizon tending towards a brownish gritty loam with increasing depth. Clay content appeared to increase with depth. The rounded lumps of sandstone and shale increased in size and frequency at the deeper levels, while occasional pockets of gravel were encountered at all depths.

Root development was concentrated in the A_1 and upper three to four inches of the A_2, though a few roots were present to the bottom of the deepest pit, approximately 5.5 feet. In all cases markedly thicker lateral roots had been developed on the uphill side of the tree, particularly in the uppermost eight to ten inches of soil.

Three 3-inch core samples were taken from the A_2, B, and C horizons in each pit, giving a total of 81 core samples, made up of nine samples per horizon per tree locale. Soil trimmed from core samples was used for bulk samples. In the laboratory, the cores were soaked in water for two days, then placed in a pressure chamber at one-third atmosphere pressure for three days. Field capacity was calculated as bulk density of the soil multiplied by percent by weight of moisture remaining in the soil on removal from the pressure chamber.

Bulk samples were lumped together by horizon within each pit, this composite sample being ground and thoroughly mixed. Wilting point was determined for the A_1, B, and C horizons in each pit using a pressure membrane cell and converting to volume of water. Thus in the area adjacent to a tree, each of the four horizons was sampled nine times. Field capacity and wilting point data are summarized in Table 2.

The volume of available water per foot of soil in each horizon was obtained by difference between field capacity and wilting point. Total soil storage was calculated by multiplying available water in the horizon by the horizon depth in feet, (Table 3). No data were obtained for available water in the A_1 horizon but an arbitrary value of 150 per cent of the A_2 value was assigned to this horizon. It was assumed that root occupancy in the A_1, A_2, B, and C horizons was 100, 100, 90, and 75 percent respectively. The attainable water, i.e. that which tree roots actually encounter, was estimated by multiplying available water in a horizon by the appropriate root occupancy. Total attainable water in the root zone amounted to 7.4 inches, while total soil storage in the root zone was 8.7 inches.

Table 2. Summary of field capacity and wilting point data for A_2, B, and C horizons expressed as inches of available water per foot of soil. Each figure is the mean of three observations except where noted.

Tree No.	Pit	Field Capacity			Wilting Point		
		A_2	B	C	A_2	B	C
1	A	3.2	3.2	3.4	0.62	1.76	1.85
	B	3.2	3.3	3.4	0.75	1.65	1.86
	C	3.3	3.3	3.5	0.65	1.54	1.76
2	D	3.3	3.5	3.1	1.12	1.99	1.77
	E	3.2	3.4	3.1	0.97	1.84	1.64
	F	3.2	3.5	3.0	1.26	1.98	1.96
3	G	3.2+	3.2*	3.1	0.92+	1.92+	1.86+
	H	-	-	3.2	-	-	1.89
	I	3.1*	3.6+	3.5	1.31+	2.00+	1.86+

\+ Mean of five observations

* Mean of four observations

Table 3. Summary of soil water storage and attainable water data.

Variable	Horizon			
	A_1	A_2	B	C
Wilting point ins/ft. soil	-	0.9+	1.8+	1.8*
Field capacity ins/ft. soil	-	3.2"	3.4"	3.2"
Available water ins/ft. soil	3.5	2.3	1.6	1.4
Horizon depth in feet	0.17	1.00	1.42	2.50
Water in horizon	0.60	2.30	2.27	3.50
Total soil storage	8.7			
Root occupancy as percent of horizon	100	100	90	70
Attainable water ins. per horizon	0.60	2.30	2.01	2.50
Attainable water in total root zone	7.4			

\+ Mean of 29 observations

* Mean of 31 observations

" Mean of 27 observations

Combination of Soil and Weather Data to Obtain Periodic Moisture Deficits

Available soil storage, calculated as described in the previous section, was required to compute daily moisture deficits. A computer program developed by Zahner and Stage (1964) to obtain deficit values, requires knowledge of the following variables:

a) daylength at the test latitude expressed as a percentage of a 12 hour day,

b) daily rainfall, maximum and minimum temperatures for 365 days per year, with 29 February omitted from each leap year,

c) a mathematical function to express realistic soil moisture depletion for the soil under consideration, based on total soil storage and soil texture,

d) estimates of available soil moisture for various periods of the year or growing season.

Moisture deficit is the difference between potential evapotranspiration and moisture removed from the soil, while the rate and amount of water removed is a function of the volume of water in storage and potential evapotranspiration. Thornthwaite's (1948) equation was used in the computer program to calculate potential evapotranspiration.

Daily weather observations for the period 1 January,

1912, to 31 December, 1961, were obtained from the Statistics Laboratory at the Ohio Agricultural Experiment Station, and consisted of daily maximum and minimum temperatures in degrees Fahrenheit and precipitation in 0.01-inch units. The observations were entered on IBM cards according to standard Weather Bureau practice.

Based on the soil observations summarized in Table 3, a soil moisture depletion curve typical of a loam soil with a total storage capacity of eight inches was used in the computation of cumulative and daily moisture deficits. Though the program computes several other deficit values, only daily cumulative moisture deficits were used in this study.

Cumulative moisture deficts were selected for five periods during any two successive growing seasons as being those most likely to have a significant effect on tree growth during a single growing season. The growing season in central Ohio extends from mid-April to early October, therefore, to fully cover the growing season, moisture deficits were calculated for the period 1 March to 31 October. This was done for each year, producing two external variables, total deficit in the current growing season and total deficit in the previous growing season. The August-October period in the previous year was included since conditions in this period may permit accumulation of food materials and influence growth in the subsequent

growing season. For the current year, the June-August period was chosen as being that most likely to affect termination of shoot elongation. This in turn limits cambial development by reducing the flow of carbohydrates and growth regulating substances from the apical regions and needles of the upper crown (Wareing et al., 1964). The September-October period in the current year was included to cover the possibility that growth might extend into this period to a greater extent than supposed. The period March-May in the current growing season was not included since moisture is seldom a limiting factor during this period at Wooster. Thus, the five growing season moisture deficit periods were;

1. 1 March to 31 October, previous year
2. 1 August to 31 October, previous year
3. 1 March to 31 October, current year
4. 1 June to 31 August, current year
5. 1 September to 31 October, current year

The cumulative deficit for each period was read from the computer print-out and was used in analyses as an independent moisture deficit variable.

Collection, Preparation, and Examination of Wood Specimens

FIELD WORK:

The site from which the three 52-year old sample trees were cut in March, 1962, sloped down from east to west, and all three trees showed considerable compression wood development on the western side of the stem. It was decided that, while a greater variation in shrinkage would certainly be found on comparing east and west radii, samples from the north-south diameter would give a truer picture of "normal" development. For this purpose compression wood is regarded as an abnormal wood form, though it is recognized that few, if any, coniferous species attain merchantable size without the presence of some compression wood. Thus, since all specimens were to be taken along a north-south diameter in the stem, it was necessary to identify the cardinal positions on the stem before felling.

In an attempt to minimise the effect of annual branch whorls on the wood properties of the specimens, a sample section 0.5 feet long was cut from the middle of each internode. The sections were taken to the laboratory where ring counts were made on each sample section to ensure that a sample had been obtained from each year's growth, and identified as to tree number, height in the stem, north and east aspect. When a complete series had

been assembled with minimum delay the sections were placed in polyethylene bags, wired closed, and stored at -15°C.

LABORATORY WORK:

To achieve a balance between the amount of work which was feasible while providing observations along the entire stem, it was decided to sample every fourth internode beginning with the second internode from the tip , i.e., 2, 6, 10, 14, etc. In all, twelve internodes were sampled, the smallest having two growth rings and the largest, forty-six.

The selected 0.5 foot stem sections each were cut transversely to give:

a) one 0.5 inch thick section providing material for cell number and ring width measurements.

b) one 5.5 inch thick section providing material for specific gravity and longitudinal shrinkage analysis.

Details of specimen preparation and the type of observations made are given in the following paragraphs. All physical measurements were taken at 21°C. and at a relative humidity of between 25 and 35 per cent.

Cell number and ring width.

To prepare a specimen for ring width measurment a north-south diameter was drawn through the pith of the

0.5 inch thick sample, which had been soaked in water over-night, and an area along this diameter trimmed with a scalpel, giving a clean surface for microscopic examination. The cleaned surface was stained with a weak safranin solution making the cell walls easily visible under the microscope. The block was mounted on a moving stage based on the design by Echols and Baldwin (1961), movement being recorded by means of a Starrett dial guage reading in 0.001-inch units. By observing the moving surface through a microscope, with a cross-hair eyepiece at 125x magnification, it was possible to count the number of earlywood and latewood cells along each radius, and measure the widths of the respective bands.

Mork's (1928) definition of latewood was used throughout, namely that a latewood cell is one wherein twice the width of the common cell wall, in the radial direction, is greater than the cell lumen.

To obtain the distance from the center of the pith to the edge of the first growth ring, the diameter of the entire first year's growth was measured and divided by two.

Two readings were made along both radii. In subsequent analysis, data representing number of earlywood cells, number of latewood cells, and widths of these zones, were averages of the two observed measurements. Percentage of latewood was calculated from mean latewood width and

and mean total ring width.

Longitudinal Shrinkage

Specimens for shrinkage measurements were cut from the 5.5 inch thick section in the following manner. A north-south diameter was drawn through the pith on the transverse face of the section, and lines parallel to this marked two inches on either side of the diameter, Figure 3. The peripheral portions of the block were removed by sawing along the outside parallels. Even-numbered growth rings from the pith were cut from the central block by sawing tangentially through the intervening growth rings. From each of these plates in turn, three specimens were split off, giving specimens with the fiber direction parallel to the long axis. Each such specimen was trimmed to consist solely of the desired growth ring and cut to approximately two inches in length, (2 $\pm$ 0.06 inches). The specimens were placed in identified cheesecloth bandoliers in deionized water awaiting measurement. Three specimens from each second ring on a north-south diameter at twelve levels in the stem, resulted in 864 specimens from each tree, or a total of 2592 specimens from the three stems.

The length of each specimen was measured in the green, air-dry, and oven-dry condition, using the apparatus shown in Figure 4. Divisions on the gauge allowed measure-

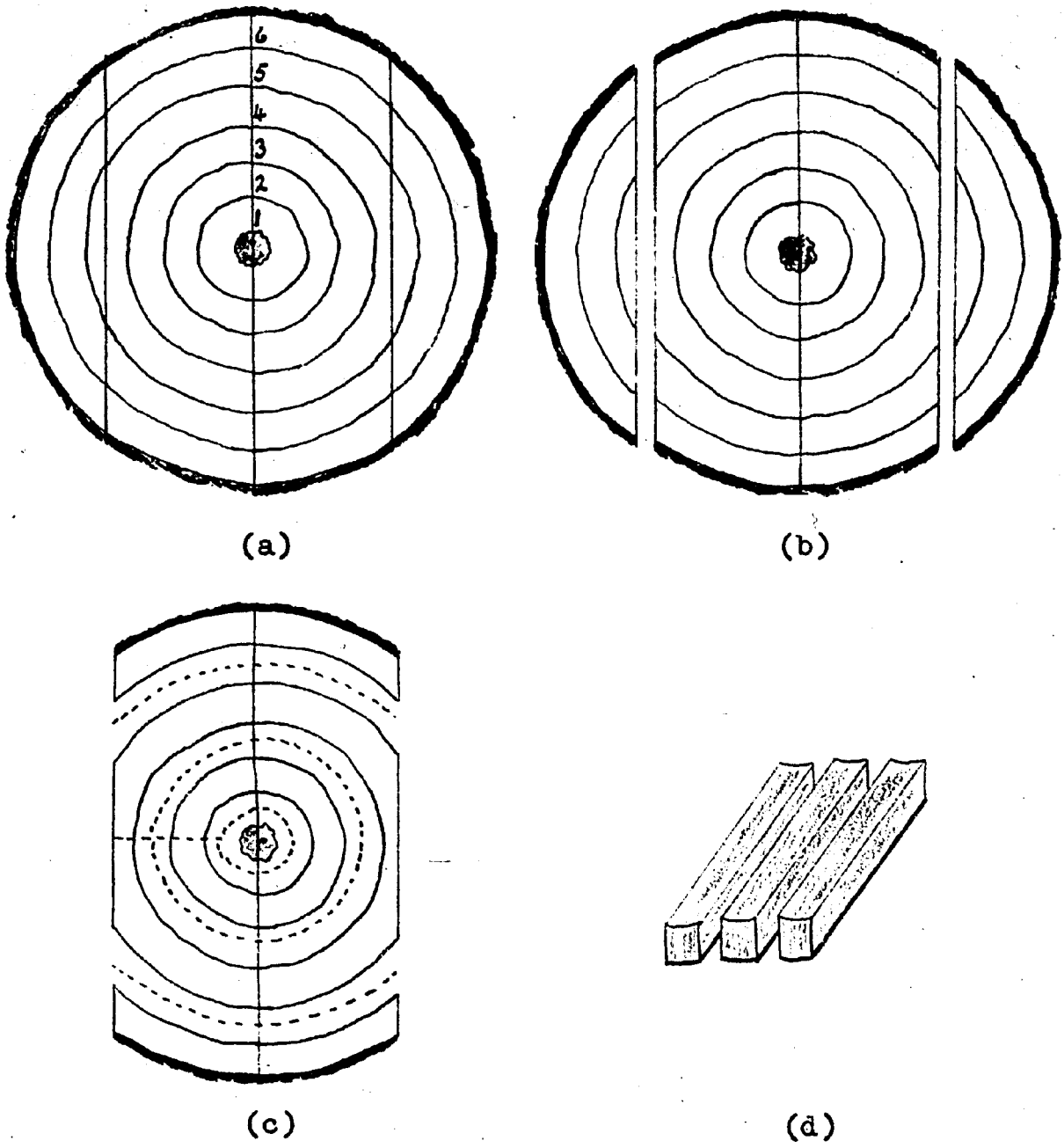


Figure 3. Diagram of cross-section showing north-south radius and parallels (a), slabs cut away (b), dotted path of saw in separating annual rings (c), and three specimens from an annual ring (d).

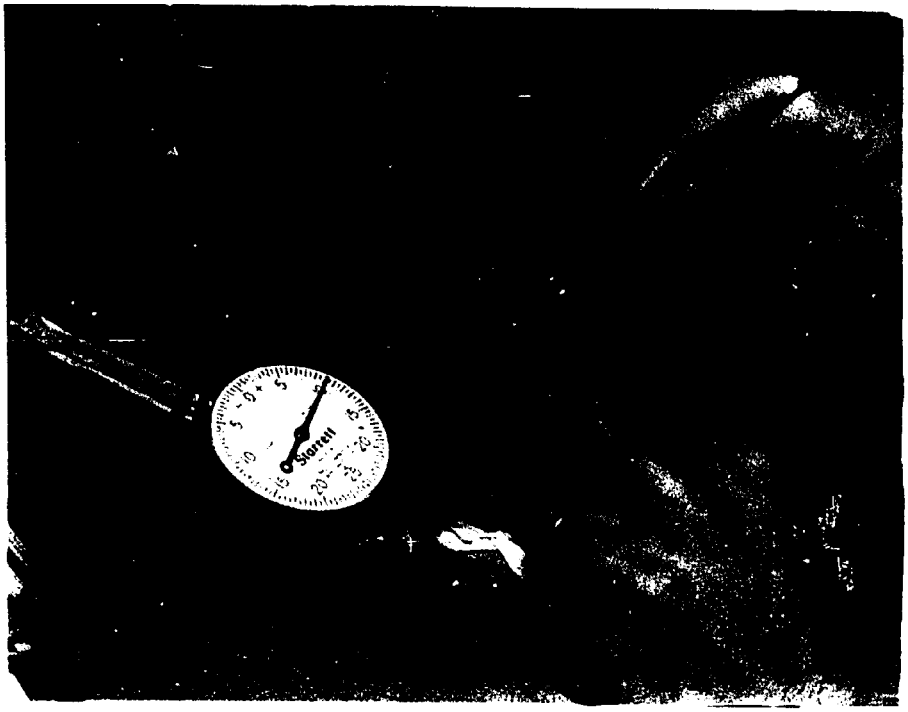


Figure 4. Device used to measure longitudinal shrinkage with specimen being placed in position.

ment to 0.0005 inch. Following the green measurement, the specimens were allowed to reach approximately 12 per cent moisture content by standing over a saturated sodium bromide solution which was agitated periodically with a magnetic stirrer to prevent stratification, (Figure 5). On reaching 12 per cent moisture content the specimens were removed from the chamber, remeasured, and weighed to the nearest 0.0001 gram. They were placed then in an oven at 105°C. and held there for 16 hours. On removal from the oven the specimens were put into a desiccator over "Drierite", a commercial desiccant containing calcium sulphate, and allowed to cool to room temperature. Specimens were removed individually through a small aperture in the desiccator cover, and weighed to the nearest 0.001 gram to obtain oven-dry weight. After weighing, oven-dry length was obtained using the apparatus noted above.

Longitudinal shrinkage was obtained by difference between green and oven dry lengths and expressed as a percentage of oven-dry length:

$$\text{Longitudinal shrinkage per cent} = \frac{\text{green length} - \text{oven-dry length} \times 100}{\text{oven-dry length}}$$

In the present study oven-dry length was used as the base, though shrinkage frequently is calculated as a percentage of the green dimension. The actual comparative base is of no great significance other than that it be



Figure 5. Magnetic stirrer (inset) and humidity chambers used to bring specimens to known moisture content.

consistently observed throughout the study, since the values obtained are used essentially for comparative purposes. It is the relationship existing among the values from various positions in the tree with which we are primarily concerned, rather than with absolute values themselves.

Values were obtained for three specimens from each growth ring. These were averaged and the mean used in subsequent analyses. Only total shrinkage, i.e., from the green to the oven-dry state, is discussed in the present paper though intermediate observations were recorded. These will be reported subsequently should they appear of sufficient importance.

Specific Gravity

The shrinkage specimens referred to above were used to determine specific gravity for the individual growth rings. Immediately following weight and length measurements on each oven-dry specimen, the block was impaled on a dissecting needle and totally immersed in a graduated cylinder partially filled with mercury. The cylinder was graduated in 0.1 ml. units and, by means of a burette magnifier, the level of the meniscus was read to 0.01 ml. Oven-dry volume of the specimen was obtained by direct reading of the mercury level displacement and specific gravity was calculated as,

$$\text{Specific gravity} = \frac{\text{oven-dry weight of block in grams}}{\text{volume of mercury displaced in mls.}}$$

Specific gravity may be calculated either on a green volume or on an oven-dry volume basis. Oven-dry volume was used in the present study as it was more convenient to obtain, and was more desirable since the specimens to be analysed spectrographically later.

Values were obtained for three specimens from each growth ring. These were averaged and the mean used in subsequent analysis.

Methods of Data Presentation

One aim of the study was to determine in what manner the number of tracheids in the annual growth ring, ring width, percentage of latewood, longitudinal shrinkage, and specific gravity varied with position in the main stem, while a second objective was to examine the extent to which variation in wood properties was related to fluctuations in soil moisture availability during, or prior to, wood formation. Since the observations were recorded in terms of entire growth rings at various heights in the stem, it was most profitable to consider them in the manner expounded by Duff and Nolan (1953) which is described briefly below.

Arrangement of stem observations

Data collected at several distances from the pith and heights in the stem may be compared along three major axes termed oblique, horizontal, and vertical, and which are illustrated in Figure 6. The oblique sequence, describing variation from top to bottom of a stem within the growth sheath laid down in a given year, portrays change due to position in the stem which may be measured in terms of physiologic or physical intervals from the current stem apex. This sequence, therefore, eliminates variation due to differences in growing seasons since, by definition, all of the material being examined grew in the same season.

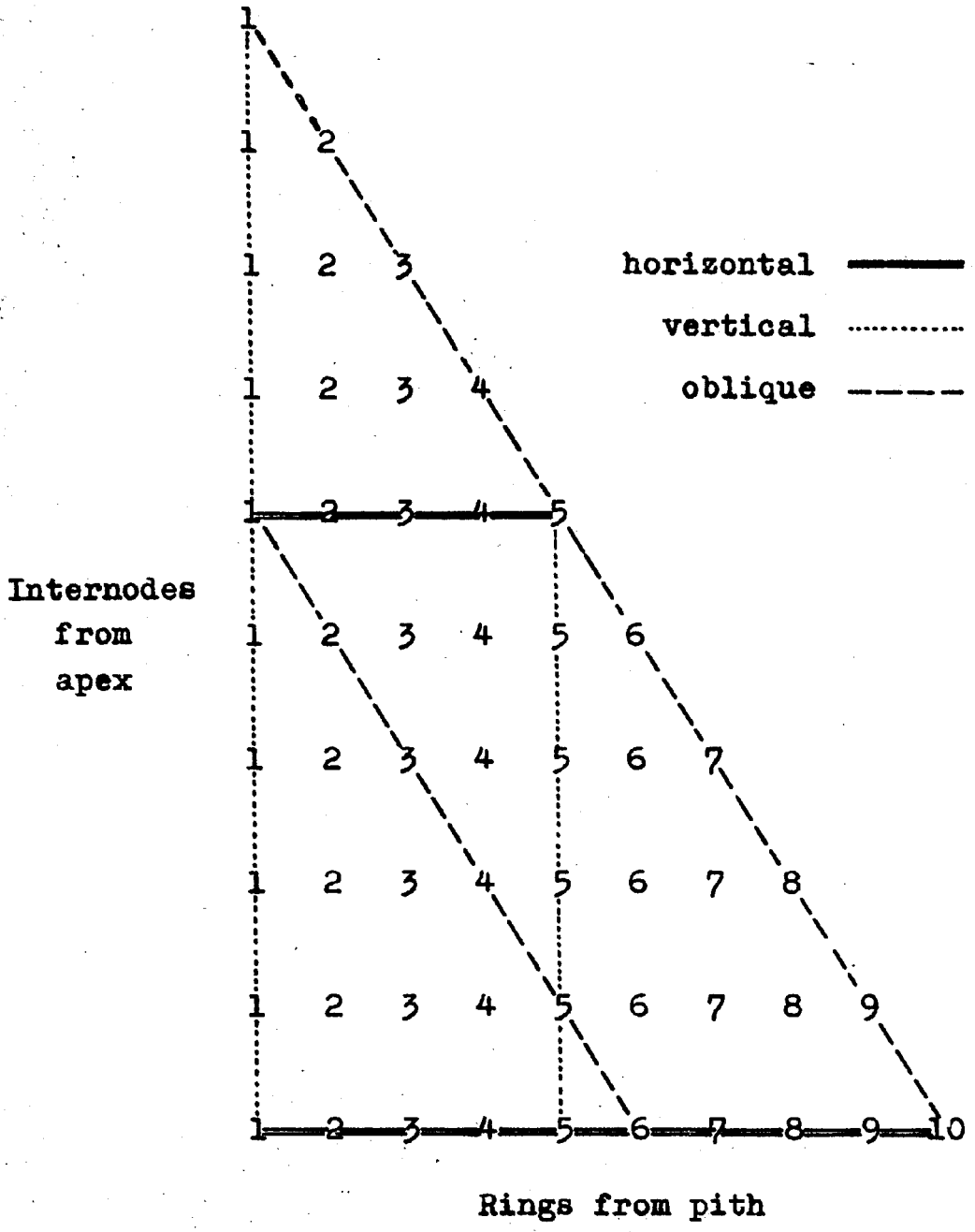


Figure 6. Diagram showing three sequences in which annual ring observations may be grouped.

That the confounding effect of environmental differences is not avoided entirely is due to the size of a large tree, precluding its existence within a wholly uniform environment. However, throughout this paper it will be assumed that all wood comprising a given growth sheath was formed under the same environmental conditions. It is apparent that while annual environmental variation is minimized on examining data within a single oblique sequence, comparison of one oblique sequence with another provides a means of estimating the effect of annual environmental differences on the pattern engendered by position in the stem.

The horizontal sequence, being applied to observations of successive rings from the pith along a pith - circumference radius at a given height in the stem, is the sequence which has received the greatest attention historically, primarily because it is that most easily observed. It is useful in comparing wood properties over a period of years at a specified height in the stem. Changes between points along the sequence may be due to increasing age of the cambium, the ever-increasing distance between the sampling level and the stem apex, and to yearly variation in temperature, soil moisture availability, and other inconstant factors comprising the environment. Thus, in this sequence, there is a confounding of the influences of environmental factors with those of factors intrinsic to the tree.

On plotting observations in the oblique sequence, it

will be shown subsequently that in each growth sheath, the relationship between values obtained at the first and second internodes below the stem apex is persistent for a given wood property. This is true also for the second and third internodes, the third and fourth, and so progressively down the stem. Thus a substantially predictable relationship will be shown to exist between internodal values within an oblique sequence curve and that this relationship is relatively constant among such curves, or growth sheaths, representative of different growing seasons. Such families of curves have been demonstrated for ring width in red pine (Duff and Nolan, 1953) and for tracheid length and wood density in Corsican pine (Richardson, 1961). While the relationship between a pair of internodal values, e.g., second and sixth below the apex, may be relatively constant in several growth sheaths, the actual values of the observations in the various sheaths may differ considerably.

Looking again at Figure 6 it can be seen that the values comprising the horizontal sequence at the fifth internode below the tree apex are values from five successive growth sheaths. Given the proportionality between internodal values in oblique sequences discussed above, one would expect to find the horizontal and oblique sequences for the first five rings from the pith and for the first five internodes from the tree apex similar in general form.

There would be greater variation in the horizontal sequence since it is composed of material created in five different growing seasons. Thus, horizontal and oblique sequences incorporating identical numbers of rings from the pith and internodes below the stem apex should show similarity of form. The horizontal curve would show greater variation between individual values for properties markedly affected by the environment than for properties relatively independent of a protean environment. Comparison of these two sequences for a given property, therefore, will illustrate the extent to which an attribute is affected by factors outside the tree itself.

Within each third, or vertical, sequence, values are compared of wood laid down by cambium of the same physiologic age as measured from the pith, but at different heights in the stem and during a succession of growing seasons, e.g., a comparison of values of the fifth ring from the pith in all internodes five years of age or older. Since cambial age is held constant this sequence illustrates the effect of environmental changes on meristems of the same physiologic age, the same physiologic distance below the stem apex, but at an ever-increasing distance above ground level. Therefore, variation is primarily determined by environmental factors as opposed to the oblique sequence from which yearly weather and similar variables are removed.

In discussion of the observations, horizontal sequences will be discussed in terms of the number of rings from the pith. Oblique sequences will be described in numbers of internodes below the current stem apex. Reference to Figure 6 shows that for each oblique growth sheath the stem apex is at a different level above ground, therefore the term current stem apex will refer to the stem apex existing at time of formation of any given growth sheath, or oblique sequence. When the top of the felled sample tree is used as a point of reference, as in the case of the vertical sequences, it will be identified as the final stem apex. Thus all sample positions will be identified in terms of temporal or physiologic units, either annual rings or annual internodes, and not in linear units.

As noted above, observations were recorded at twelve levels in the three stems, values being obtained for all even-numbered rings from the pith along a north-south diameter. To obtain a general pattern of development in white pine it was desirable to treat the three stems as block replications within a single population. The mean value and standard deviation for each physical variable was found by tree and for pooled observations from the three trees. The means and standard deviations, shown in Table 4, indicated that the data were sufficiently uniform to permit treating the three stems as being from a single population. In all analyses, therefore, data for a given

Table 4. Average value (m) and standard deviation (s) of dependent variables by tree and pooled.

Variable		Tree			
		1	2	3	Pooled
Specific gravity	m	0.341	0.372	0.345	0.353
	s	0.036	0.035	0.032	0.037
Shrinkage percent	m	0.23	0.20	0.23	0.22
	s	0.13	0.09	0.12	0.12
Earlywood cells	m	93.0	95.3	104.9	97.7
	s	48.9	38.8	37.1	42.2
Latewood cells	m	4.8	5.6	3.6	4.7
	s	2.7	3.6	2.1	3.0
Total cells	m	97.8	100.9	108.5	102.4
	s	49.4	38.5	36.9	42.2
Earlywood width in inches	m	0.141	0.137	0.162	0.147
	s	0.072	0.049	0.051	0.059
Latewood width in inches	m	0.003	0.004	0.003	0.003
	s	0.002	0.003	0.002	0.002
Total ring width in inches	m	0.144	0.140	0.164	0.150
	s	0.071	0.049	0.051	0.059
Percentage of latewood	m	2.54	2.62	1.69	2.28
	s	1.72	1.69	1.12	1.59

locus represent the mean of north and south observations from three trees at the location specified.

Regression analysis

When studying the concurrent relationships among several independent variables and a dependent variable, as is the case here, stepwise multiple regression is a useful tool in ranking the independent variables in order of magnitude of effect. Not only is it possible to obtain a qualitative positioning of the independent variables, but also a qualitative measure of the dependent variability accounted for by each of the independent variables. Thus the technique arrays the independent factors in decreasing order of association with the dependent variable, and ascribes to each a portion of the total variation of the dependent variable.

The present observations were analyzed using the stepwise regression program developed by Westerveldt (1962) for use with the IBM 7090 computer. Since specific gravity and longitudinal shrinkage had been measured only on the even-numbered rings from the pith, while cell number and ring width were observed for every ring, the physical data were treated as two series with different values for the number of observations, N. In analyses involving the former two variables, the number of observations possible per aspect per tree was 144, or a total of 864 for data pooled from the three trees. Due to missing data at eight

locations, the actual number of observations used in the analyses was 856.

The first annual ring was measured as one-half of the diameter of the one year old stem. Since this included the pith, the counting of the number of cells was deemed of little value due to the disorganized nature of the area. There were, therefore, 72 observations involving the pith which consisted of total ring width but with no cell measurements. These would have required a separate series of analyses on total ring width alone without direct relation to cell number, width of earlywood or latewood bands, or to percentage of latewood. It was decided that the additional work which this involved would not produce a commensurate increase in information. Therefore, these 72 observations were excluded, and the number of observations used in the pooled data analyses of cross-section variables was 1728 - 72 = 1656.

The pooled data were tested using linear, quadratic, and reciprocal functions of the in-stem independent variable alone and in association with linear functions of the five soil moisture deficit variables, Table 5. Results of the analyses are presented in later discussion of the various dependent variables, though some general observations may be made here. In all instances it was found that the number of internodes from the apex accounted for slightly more of the variation due to vertical position

Table 5. Functions of independent variables tested in regression analyses.

	Position in Stem	Interactions	
X_1	Aspect		
X_2	Number of internode from apex	X_{19}	$X_2 \times X_{15}$
X_3	(Number of internode from apex)^2	X_{20}	$X_2 \times X_{16}$
X_4	(Number of internode from apex)$^{-1}$	X_{21}	$X_2 \times X_{17}$
X_5	Number of feet from apex	X_{22}	$X_5 \times X_{15}$
X_6	(Number of feet from apex)^2	X_{23}	$X_5 \times X_{16}$
X_7	(Number of feet from apex)$^{-1}$	X_{24}	$X_5 \times X_{17}$
X_8	Number of ring from pith	X_{25}	$X_8 \times X_{15}$
X_9	(Number of ring from pith)^2	X_{26}	$X_8 \times X_{16}$
X_{10}	(Number of ring from pith)$^{-1}$	X_{27}	$X_8 \times X_{17}$
X_{11}	Number of inches from pith	X_{28}	$X_{11} \times X_{15}$
X_{12}	(Number of inches from pith)^2	X_{29}	$X_{11} \times X_{16}$
X_{13}	(Number of inches from pith)$^{-1}$	X_{30}	$X_{11} \times X_{17}$

Soil Moisture Deficit

X_{14}	Previous year, 1 March to 31 October
X_{15}	Previous year, 1 August to 31 October
X_{16}	Current year, 1 March to 31 October
X_{17}	Current year, 1 June to 31 August
X_{18}	Current year, 1 September to 31 October

than did distance in feet from the apex. Similarly, the number of rings from the pith was a more definitive measure of horizontal distance than was inches from the pith. Therefore, in subsequent discussion, variation within the stem is considered in terms of rings from pith and internodes from apex.

In discussing each dependent variable, there is presented a family of curves derived from the equation accounting for the greatest amount of ascribable variation. For number of earlywood cells per growth ring and total ring width, the regression-based horizontal sequence curves do not adequately describe conditions within the ten rings closest to the pith, since none of the tested equations described a sigmoid curve. Beyond the 15th ring, however, the curves do portray the changes to be expected with increasing distance from the pith, and illustrate the relationships between various levels in the stem. Changes in longitudinal shrinkage, specific gravity, and percentage of latewood, are shown adequately along the entirety of the computed horizontal sequences for these variables.

Presentation and Discussion of Data

In the following paragraphs observations of number of cells, ring width, percentage of latewood, longitudinal shrinkage, and specific gravity, will be discussed in turn and in that order.

Number of Cells in the Growth Ring

As has been described above, the number of cells in a growth ring was determined along a north-south diameter on transverse sections at twelve levels, each four internodes apart, in each of the three stems. Two stages of tracheid development were recognized, designated earlywood and latewood, the separation being made on the basis of Mork's (1928) definition which states that a latewood cell is one wherein twice the width of the common radial cell wall is greater than the cell lumen.

This definition was coined for use with Norway spruce, a species showing relatively sharp transition between the two cell forms, and for which wood it is effective. By common usage it has become the customary means of defining latewood, at least in North American parlance. It does leave something to be desired, however, in the case of eastern white pine, in which there is a gradual change from early to late cell type with a progressive color and shape change spread over several cells. Therefore, there

is a possibility that the physiologic boundary between the two forms is not precisely identified by rigid application of the definition. Yet while this situation exists, efforts to produce alternative criteria which would define the transition zone in objective reproducible terms were unsuccessful. Therefore the Mork definition is used here since it is applicable, though it is done so with the reservation that, for eastern white pine, it is the best useable definition rather than the best physiologic definition.

As may be seen from the curves in Figures 7 and 8, earlywood tracheids preponderate in the growth ring. The average number per annual ring was 98, ranging from 24 to 244, while the average number of latewood cells varied between 1 and 23, the average being 5. Four oblique sequence curves appear in Figure 7, with the soil moisture deficit for the current 1 March to 31 October of the year in which the sheath was formed. This particular periodic soil moisture deficit is shown since, of the five deficits tested, regression analysis indicated it to be most closely related to earlywood formation. The curves ascend to approximately the eighth internode below the current stem apex, thereafter declining rapidly at first and then more gradually with increasing distance from the apex. While this pattern is clearly discernible, the actual level of the curves varies with soil moisture deficit, the sheath

Figure 7. Oblique sequences for earlywood and latewood cells. Soil moisture deficit in inches is for current 1 March to 31 October.

Fig. 7

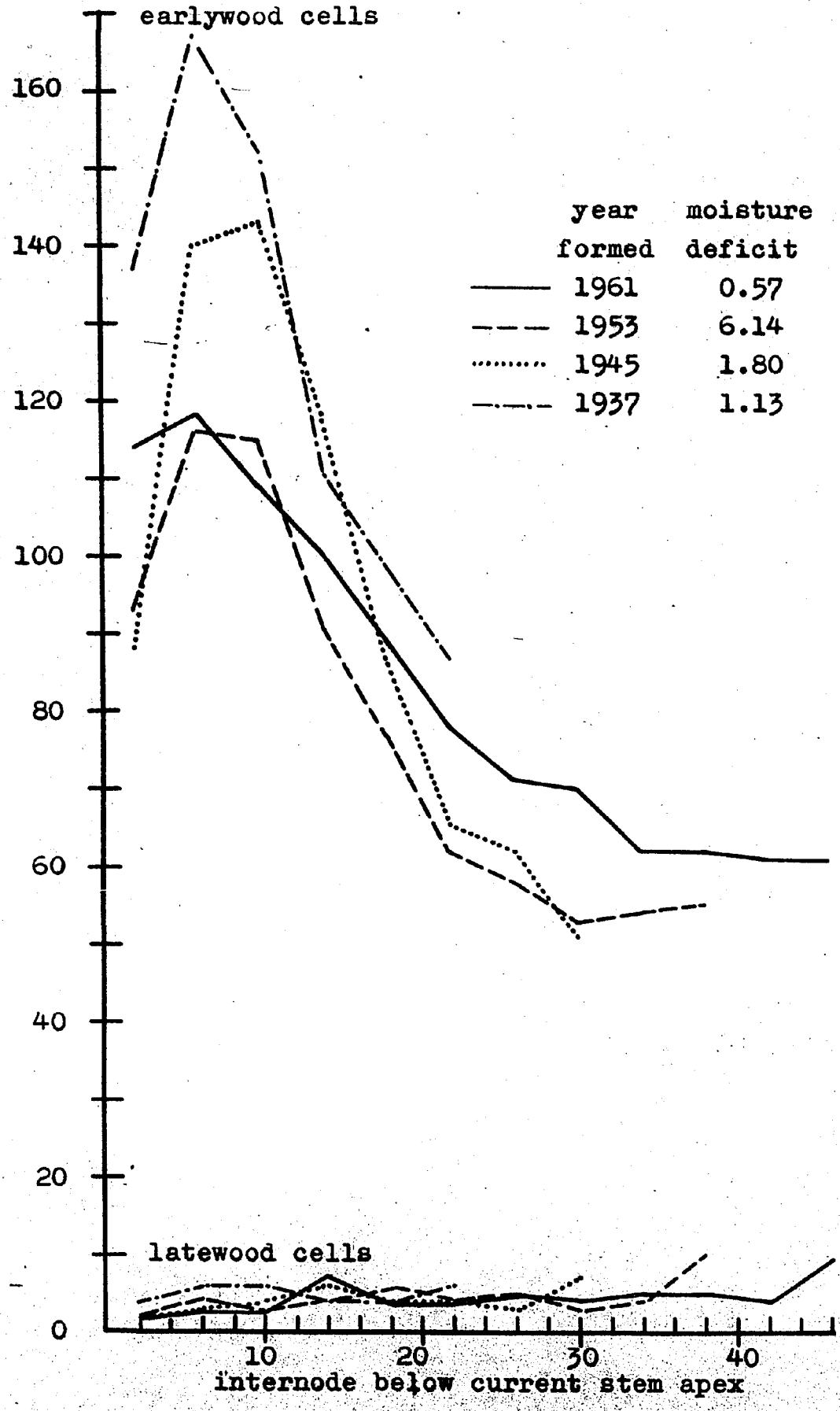
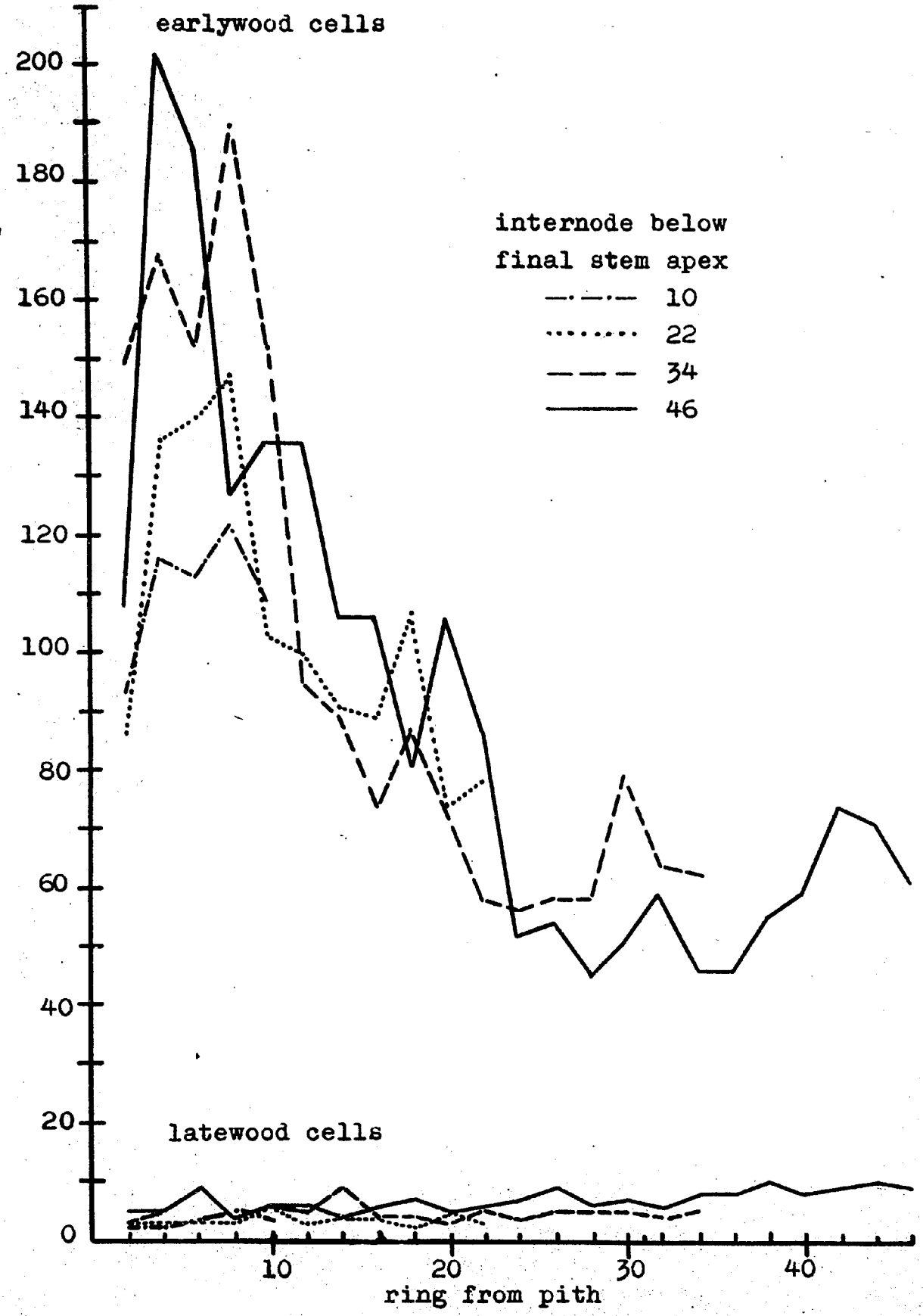

earlywood cells
160
140
120
100
80
60
40
20
0
year formed
moisture deficit
1961 0.57
1953 6.14
1945 1.80
1937 1.13
latewood cells
10
20
30
40
internode below current stem apex

Figure 8. Horizontal sequences for earlywood and latewood cells.

Fig. 8


earlywood cells
200
180
160
140
120
100
80
60
40
20
0
internode below
final stem apex
10
22
34
46
latewood cells
10
20
30
40
ring from pith

formed under high deficit conditions having fewer cells than that formed in a season of low deficit. Latewood tracheid formation appears less affected by moisture availability, with each sequence showing a gradual, though small, increase in number of cells with progression down the growth sheath. There is a visible, repetitive pattern with position in the growth sheath relative to the current stem apex, and though the absolute values along the curves vary in association with external factors, the relative position of one value to another within a given growth sheath is largely predictable.

Variation with a fluctuating environment is evident in the horizontal sequence curves comprising Figure 8, representing change from pith to circumference at the 10th, 22nd, 34th, and 46th internodes below the final stem apex. There is a marked rise and fall between the second and eighth rings from the pith, and though the curves tend to level off, or even ascend beyond the 35th ring from the pith, divergencies are substantial. Both the horizontal and oblique sequences, in effect, represent variation with distance from the current stem apex, the difference being that within the oblique sequence all values were formed in the same growing season, while in the horizontal sequence each value was formed in a different growing season. Thus the earlywood obliques are smoother in outline than are the horizontals, as one would expect for an attribute markedly

affected by a changeable environment. Latewood data, apparently less directly related to soil moisture level, provide horizontal curves hardly more erratic than the obliques.

To illustrate the variation in earlywood and latewood tracheid formation associated with current moisture level, horizontal sequences were plotted against year of formation together with the current soil moisture deficits, Figure 9. There is a general coincidence of many earlywood cells with years of low defcit, and vice versa, throughout the growth ring. Even within the eight rings closest to the pith the abrupt rise, and equally abrupt decline, in the number of earlywood cells does coincide with variation in the soil moisture deficit. However, in this region the effect of proximity to the main source of carbohydrate synthesis at time of ring formation is probably of greater significance than moisture deficit level.

A further illustration of positional and moisture deficit effects is afforded by Figure 10, showing vertical sequences plotted over year of formation. Each curve represents cambium of a given age with ascending position in the sample stem from left to right in the figure. The two rings closer to the pith, 2 and 10, show a general decline in the number of earlywood cells formed with increasing height in the stem, while these further removed

Figure 9. Horizontal sequences for earlywood and latewood cells arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Fig. 9

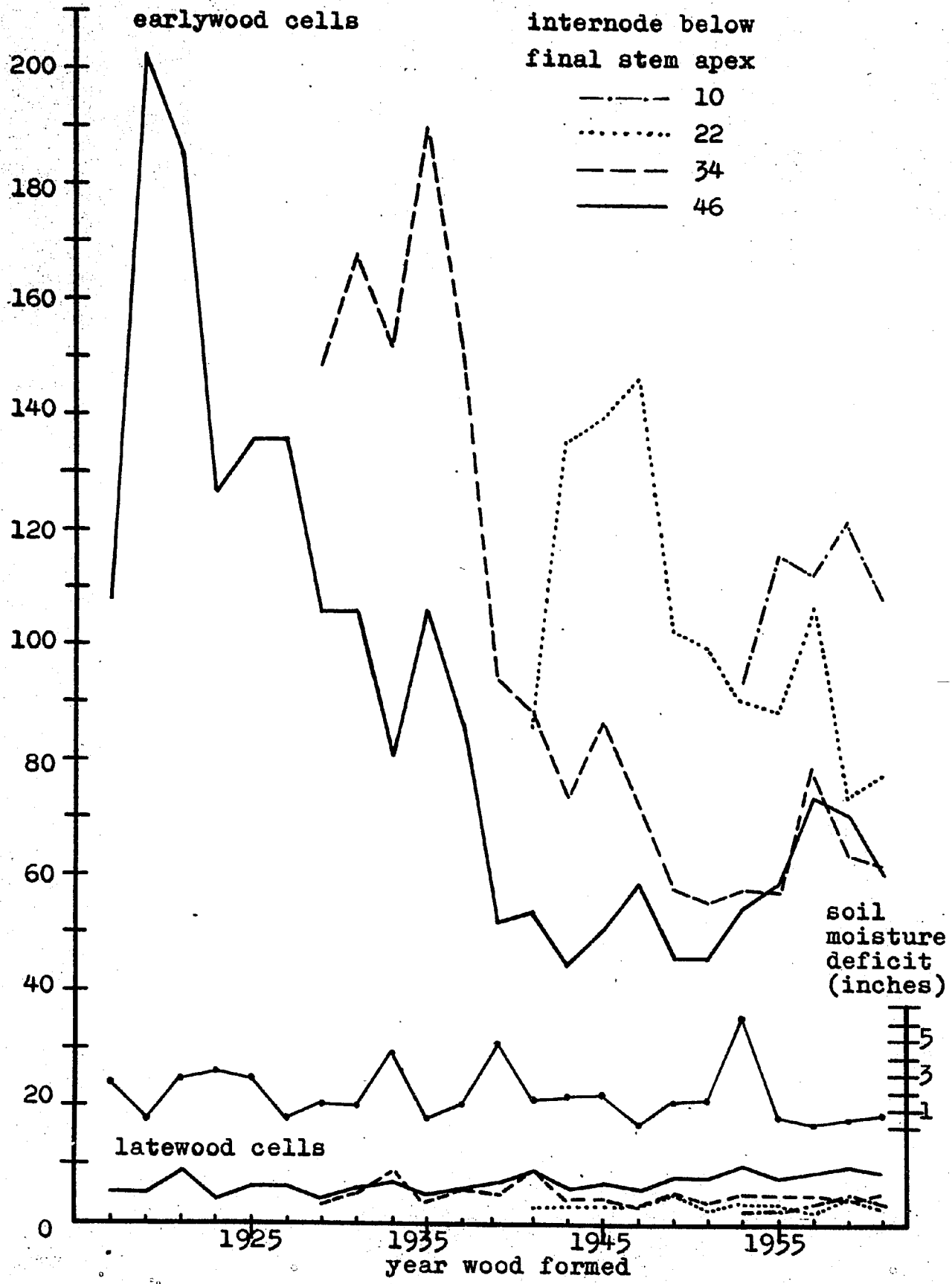
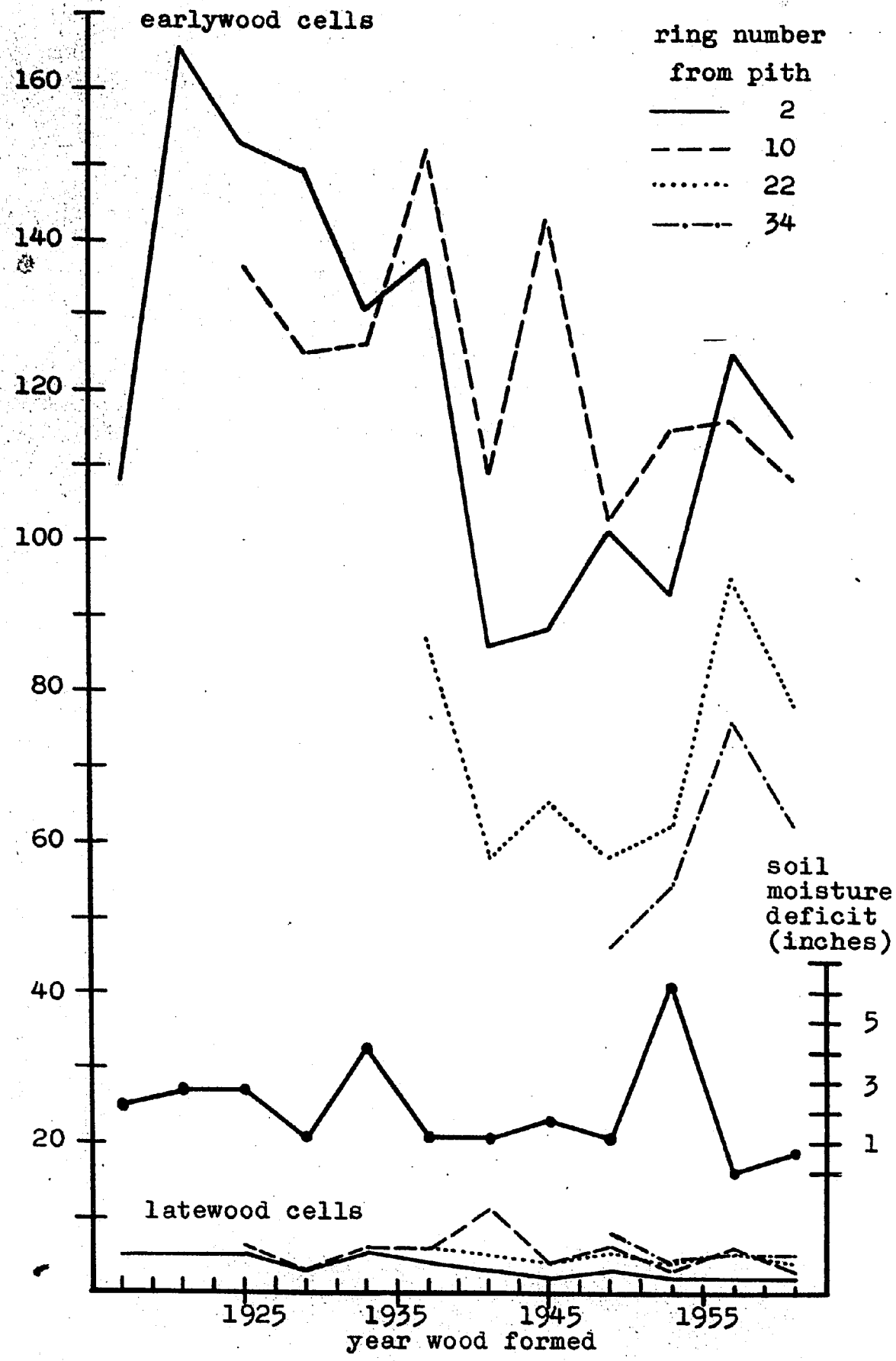

earlywood cells
internode below
final stem apex
10
22
34
46
200
180
160
140
120
100
80
60
40
20
0
soil
moisture
deficit
(inches)
5
3
1
latewood cells
1925
1935
1945
1955
year wood formed

Figure 10. Vertical sequences for earlywood and latewood cells arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Fig. 10


earlywood cells
ring number from pith
2
10
22
34
160
140
120
100
80
60
40
20
soil moisture deficit (inches)
5
3
1
latewood cells
1925
1935
1945
1955
year wood formed

appear to increase slightly. Correspondence with moisture deficits is not especially marked. This is particularly true of the latewood cell number vertical sequence.

Cell number observations were analysed using stepwise regression, and combinations of the independent variables shown in Table 5 were tested in turn. For earlywood cells the best estimate of association was obtained with the equation given below which had a coefficient of determination (R^2) of 0.663, i.e., the variables in the equation accounted for 66 per cent of the total variation in number of earlywood cells formed in the growth ring, and a standard error of estimate of $\pm$ 24.6.

$$Y = 137.302 + 2.842X_2 - 0.0332X_3 - 6.980X_8 + 0.0928X_9 - 0.0622X_{16}$$

where X_2 = internode from apex

X_3 = (internode from apex)^2

X_8 = ring from pith

X_9 = (ring from pith)^2

X_{16} = current year deficit, 1 March to 31 October

An analogous regression of the number of latewood cells data proved quite ineffective, the best estimate giving R^2 = 0.115 with a standard error of $\pm$ 2.8. No regression curves are presented for latewood cells, since apparently factors affecting latewood cell formation were inadequately sampled in the study.

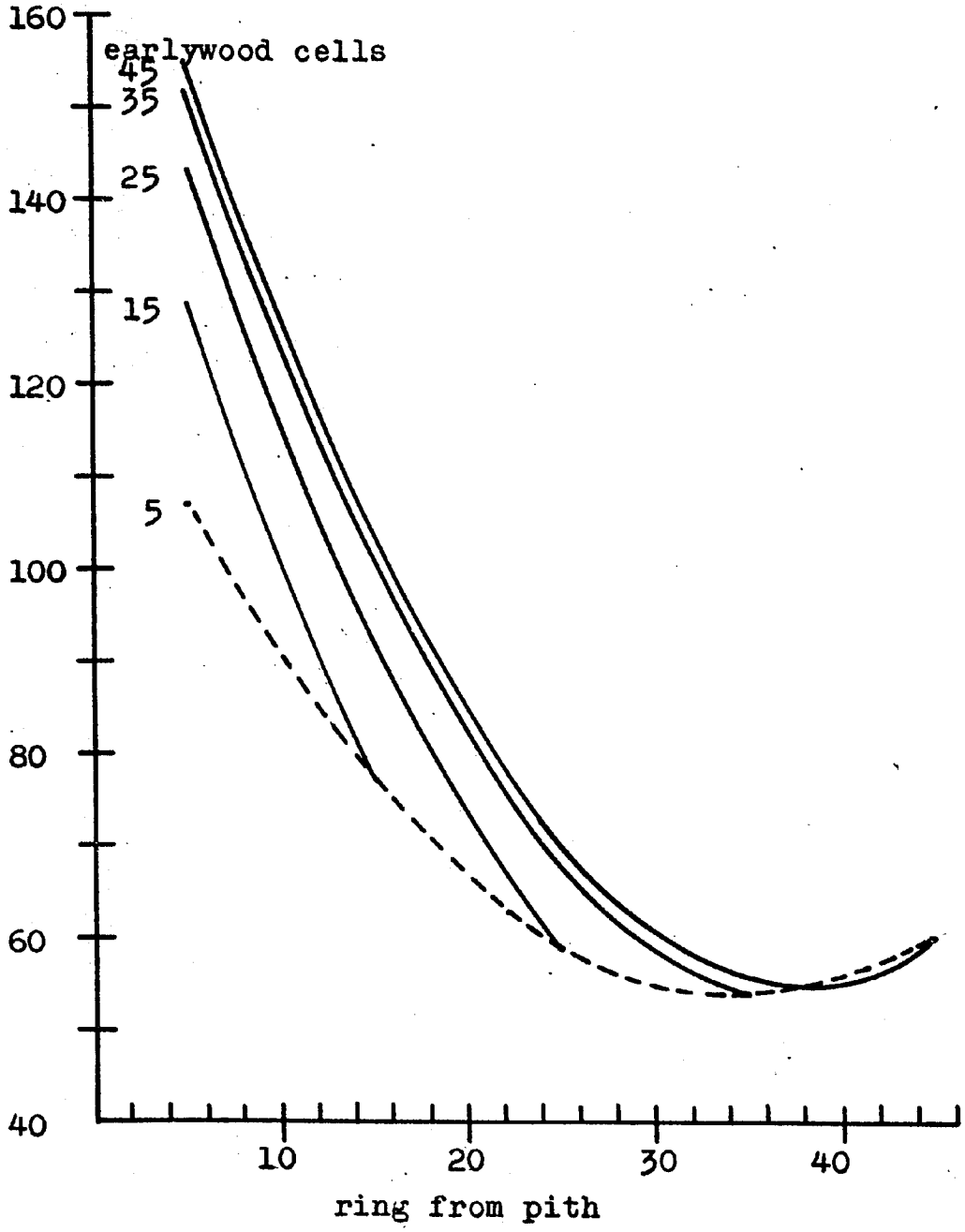
Series of horizontal and vertical sequences for

number of earlywood cells in the growth ring were derived from the above equation, Figure 11 and 12 respectively. As noted previously, the horizontal curves do not portray the true nature of the variation within the ten rings closest to the pith, but beyond this are descriptive of the change found in the stem. There is a strong effect of position relative to the pith which is reduced only beyond the thirtieth ring. The dotted line, in Figure 11, representing the oblique sequence curve at age 45, likewise is of significance only beyond the tenth internode. The vertical sequences in Figure 12 show clearly the rapid decrease in number of earlywood cells with increasing height in the stem, particularly in the upper portion of rings close to the pith.

Considering once more the oblique sequences in Figure 7, it is apparent that there is a predictable pattern of earlywood cell formation within the top eight to ten internodes of any growth sheath, indicating a dominating within-stem control. The increase in cell numbers immediately below the apex for some eight internodes is due, probably, to a progressively increasing flow of carbohydrates and growth regulators into this portion of the stem from the needles and elongating shoots of the uppermost branch whorls. Below this region, total utilization increases more rapidly than does the amount of photosynthate contributed by the needles of the lower branches.

Figure 11. Calculated horizontal sequences for earlywood cells at five levels in the stem. Numbers at left of curves show the number of internodes below the apex. Broken line indicates oblique sequence for internodes 5 to 45 below the apex.

Fig. 11


160
140
120
100
80
60
40
earlywood cells
45
35
25
15
5
10
20
30
40
ring from pith

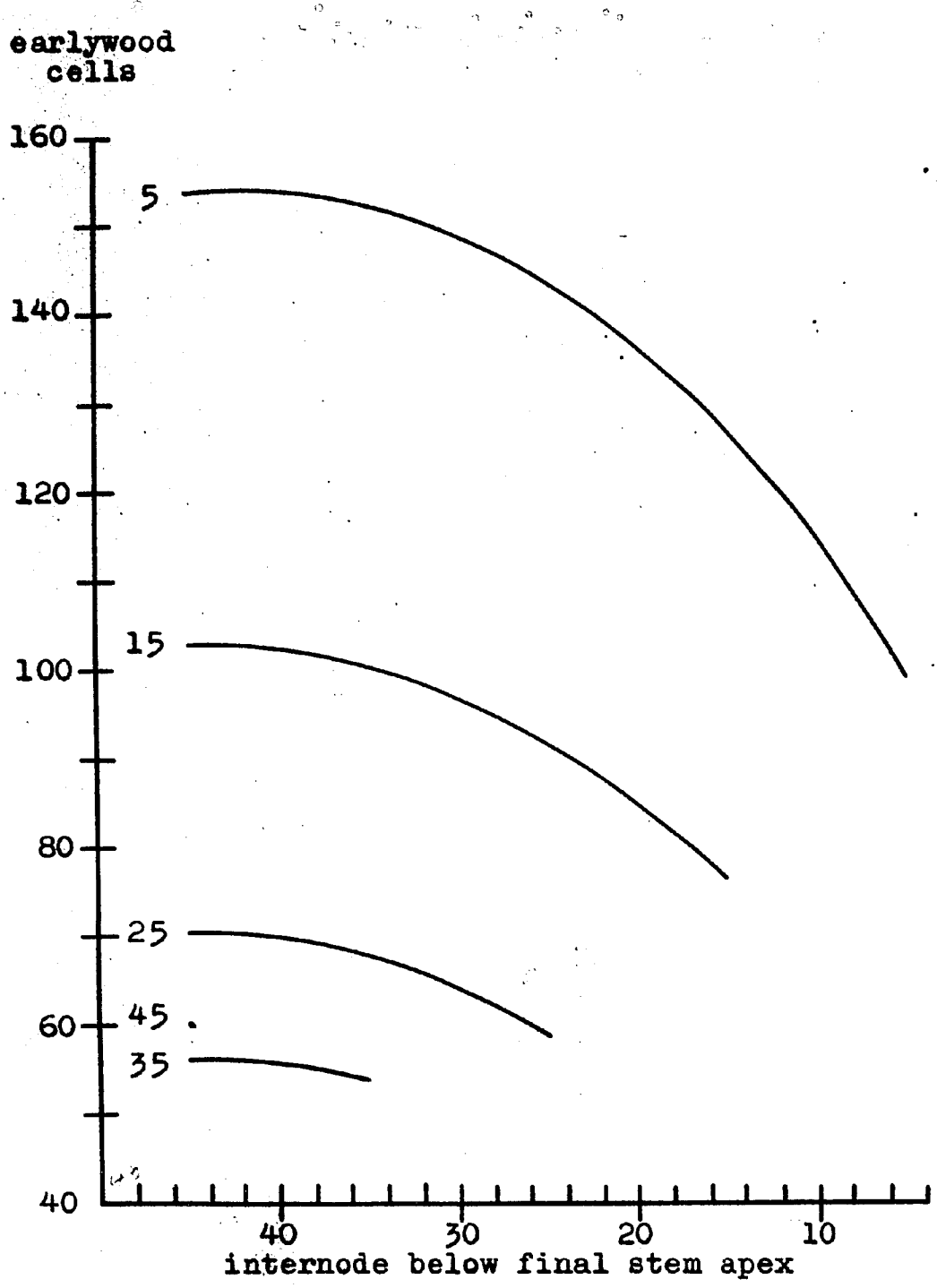


Figure 12. Calculated vertical sequences for earlywood cells at five distances from the pith. Numbers to left of curves indicate ring from pith.

Thus, on descending a growth sheath, there is a combination of increasing stem cambial area, a decrease in the amount of food material contributed to the stem cambium by each successively lower branch whorl, and, in the lowest portion of the crown, the possibility of carbohydrates being diverted to the branches. When this combination is coupled with increasing distance from the upper crown, i. e., the region of greatest carbohydrate and growth regulator synthesis, the result is an ever-diminishing supply of food substances per unit area of cambium with increasing distance from the stem apex. This, in turn, is reflected in a progressive diminution in the number of cells formed on moving basipetally from the tenth internode along a growth sheath.

The production, translocation, and utilization of photosynthate follows approximately the same pattern each year, but as may be seen from Figure 7, the level of activity is higher in a wet than in a dry growing season. This has been demonstrated by Roberts (1964) who measured uptake and translocation of $C^{14}O_2$ by yellow poplar seedlings exposed to various levels of water stress. He was able to show that increased internal water stress reduced both uptake of $C^{14}O_2$ and translocation from the treated leaf. A similar decrease in the flow of carbohydrates to the cambium in white pine would result in reduced cambial activity and the formation of fewer tracheids. Since the

flow of auxin to the cambium would be reduced also by the effect of increased water stress on stem and needle elongation, (Hatcher, 1959; Larson, 1963), there would be a reduction in the enlargement of cambial derivatives and developing tracheids. These consequences are in agreement with Bannan's (1962) findings that in Pinus strobus there exists an inverse relationship between ring width and tracheid length.

To these indirect effects of high soil moisture deficit, and resultant increased water stress in the tree, must be added the direct effect of moisture stress on the cambium and maturing tracheids. Reduced cell turgor decreases the frequency of mitosis and stunts cell enlargement, as has been shown by Ordin (1958) working with Avena coleoptile. Should the soil moisture deficit be slight, it may reduce cambial activity before affecting appreciably the level of photosynthesis in the crown. In this case a greater amount of carbohydrates would be available to fewer developing tracheids, resulting in increased secondary thickening,(Zahner, 1963). It is conceivable that the gradual onset of these conditions at the cambium, coupled with a gradual decrease in terminal elongation, may contribute to the serial earlywood-latewood transition found in eastern white pine. In 1934, Keinholz showed that cessation of leader growth was more gradual in white pine than in red pine or pitch pine, the latter

two normally showing a more abrupt earlywood-latewood transition than eastern white pine. Similarly, Buckland (1956) found that apical growth ended more sharply in Douglas fir than in grand fir, western hemlock, or western red cedar. The earlywood-latewood transition is more distinct in Douglas fir than in the other three species. Since, according to Wareing (1964), the onset of latewood formation is due, in part, to a decline in the amount of auxin translocated to the cambium from the more slowly elongating apical zones, the gradualness with which terminal growth ends may be reflected in the transition from earlywood to latewood.

Ring Width.

Each total ring width value used in plotting the observations was the average of the north and south values from the three trees at the appropriate ring - internode location. Comparison of the oblique sequences for ring width, Figure 13, with those for number of earlywood cells, Figure 7, illustrates the close relationship which must exist between the two properties since earlywood cells form the preponderance of the growth ring. The high correlation of number of earlywood cells in the growth ring with total ring width, + .91, indicates that increase in ring width is due to greater production of earlywood tracheids by the cambium in a wet year than in a dry year,

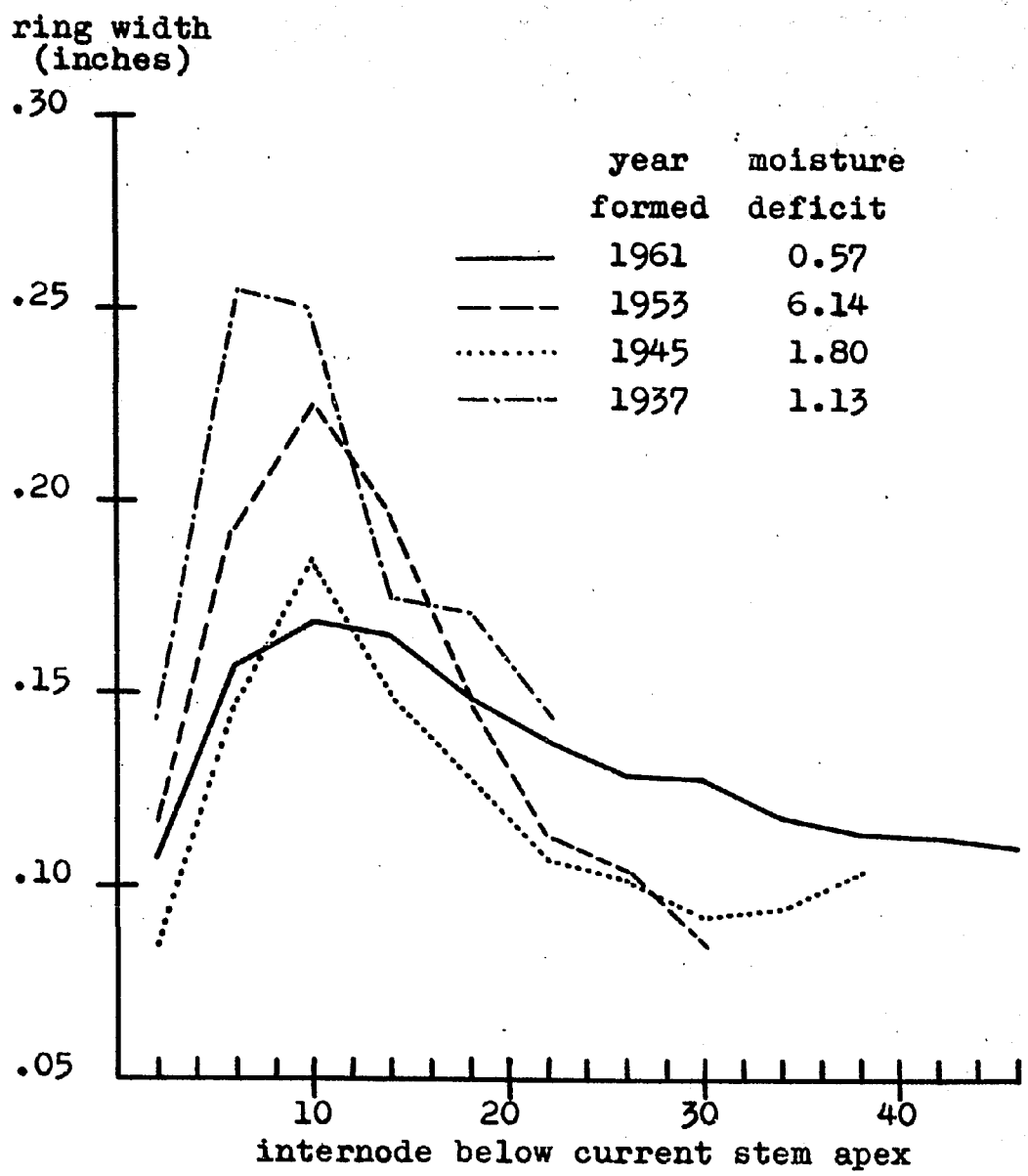


Figure 13. Oblique sequences for ring width. Soil moisture deficit in inches is for current 1 March to 31 October.

rather than to the formation of an equivalent number of larger cells. Ring width is virtuallyindependent of variation in the number of latewood cells formed, the correlation coefficient being -.01. As with number of earlywood cells, ring width proved to be most closely related to total current moisture deficit of the five deficits tested.

Comparison among the oblique sequence curves in Figure 13 repeats the form discussed with regard to earlywood formation. The inherent pattern is repeated of rapid increase from the apex to the eighth or tenth internode below the current stem apex, followed by a decline in width to the base of the growth sheath. Absolute values at a given distance from the current apex in the several curves vary with different growing seasons, but the proportionality between specific internodes is relatively uniform from one growth sheath to another. It is apparent that in the year of high deficit, 6.14 inches, ring width was generally narrower than at comparable positions in the stem during a year when soil moisture was in greater supply, e.g. 0.57 inch deficit.

Four horizontal sequence curves representing internodes 10, 22, 34, and 46 below the sample tree stem apex make up Figure 14, and show an increase in width to approximately the eighth ring from the pith followed by a progressive, if somewhat erratic, decrease in width out-

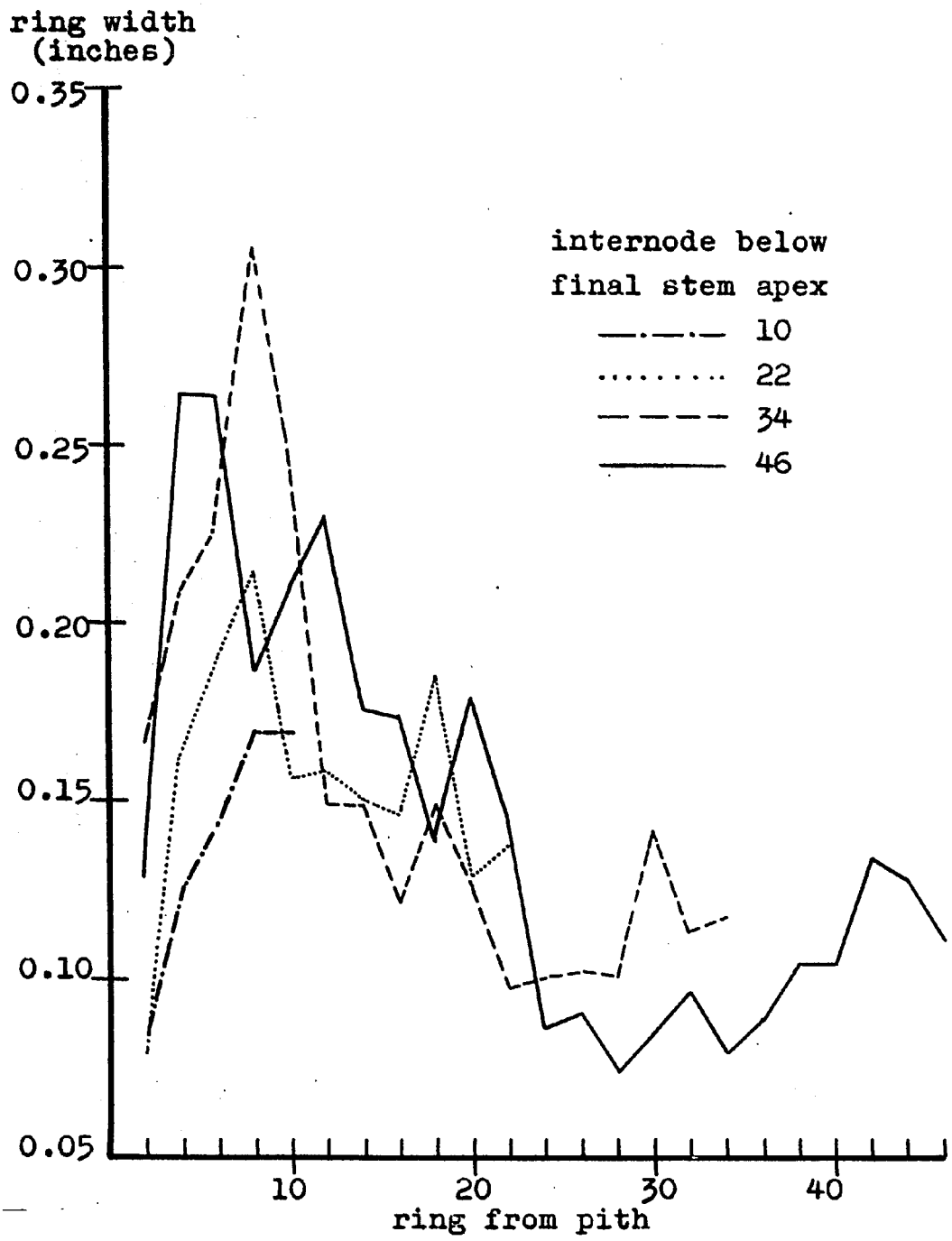


Figure 14. Horizontal sequences for ring width.

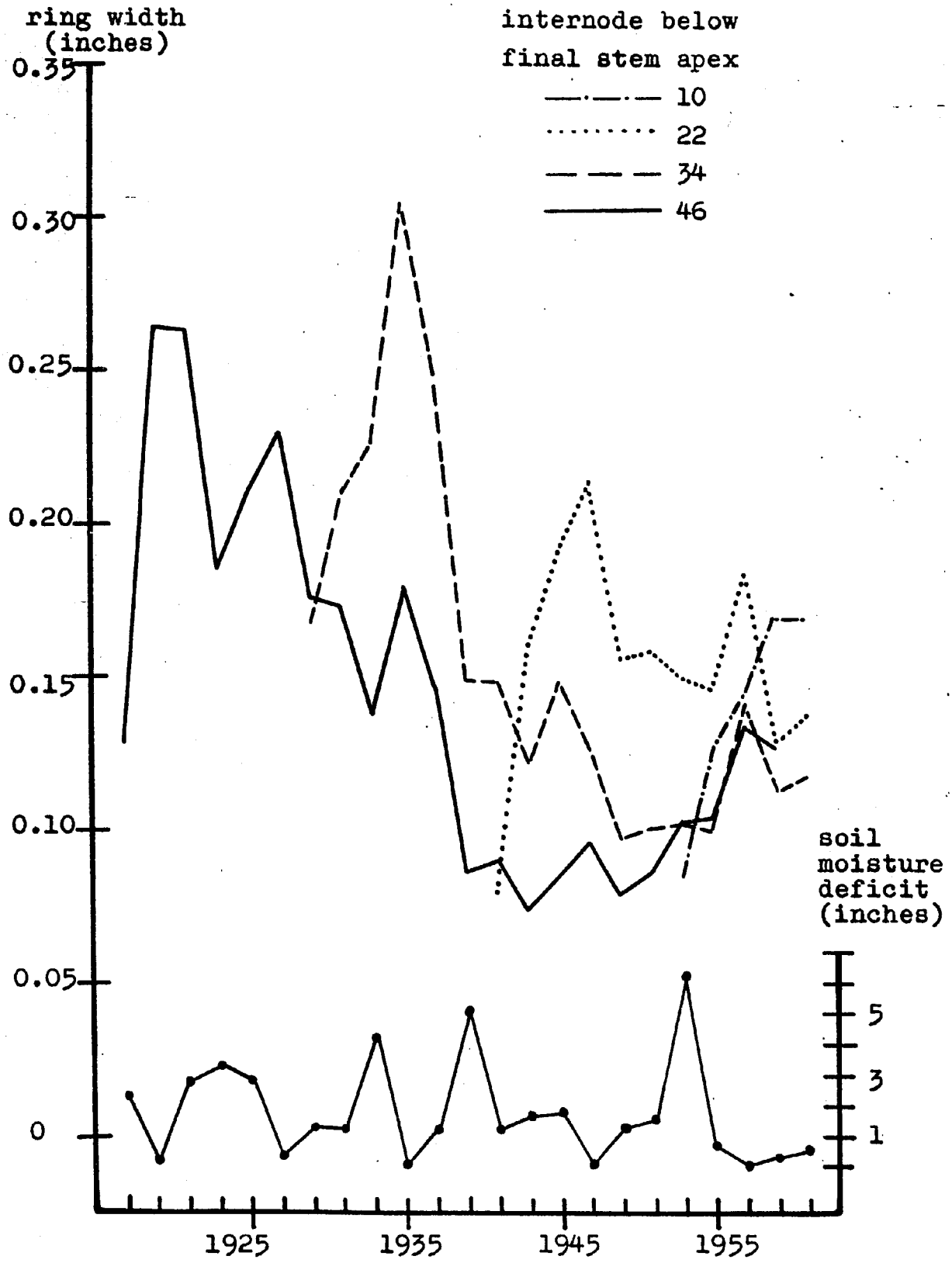
wards to the circumference. The general pattern of the curves is similar to that for the oblique sequences, but with greater irregularity among the values along a given curve, as might be expected for material susceptible to seasonal changes and laid down under different growing conditions. Annual effects are more evident when the horizontal curves are moved to the right and positioned according to year of formation, as in Figure 15, with the right-hand value in each sequence being that of the ring formed in 1961. Total current soil moisture deficits are shown below the horizontal sequences in this figure and reveal a broad correspondence between years of high deficit and narrow ring width, or low deficit and wide rings. As with number of earlywood cells this correspondence extends even within the eight rings closest to the pith.

Four vertical sequence curves are shown in Figure 16, in which the curves are arranged above year of formation. The influence of a changeable environment, including soil moisture deficit, is evident. Further, there is a trend of decreasing ring width with increasing height in the stem, for rings closer to the pith and of decreasing ring width with increasing horizontal distance from the pith. This is demonstrated with greater clarity by the regression derived sequences comprising Figure 18.

Regression analyses of the observations showed that the independent variables making up the following equation to-

Figure 15. Horizontal sequences for ring width arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Fig. 15


ring width
(inches)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
internode below
final stem apex
10
22
34
46
soil
moisture
deficit
(inches)
5
3
1
1925
1935
1945
1955

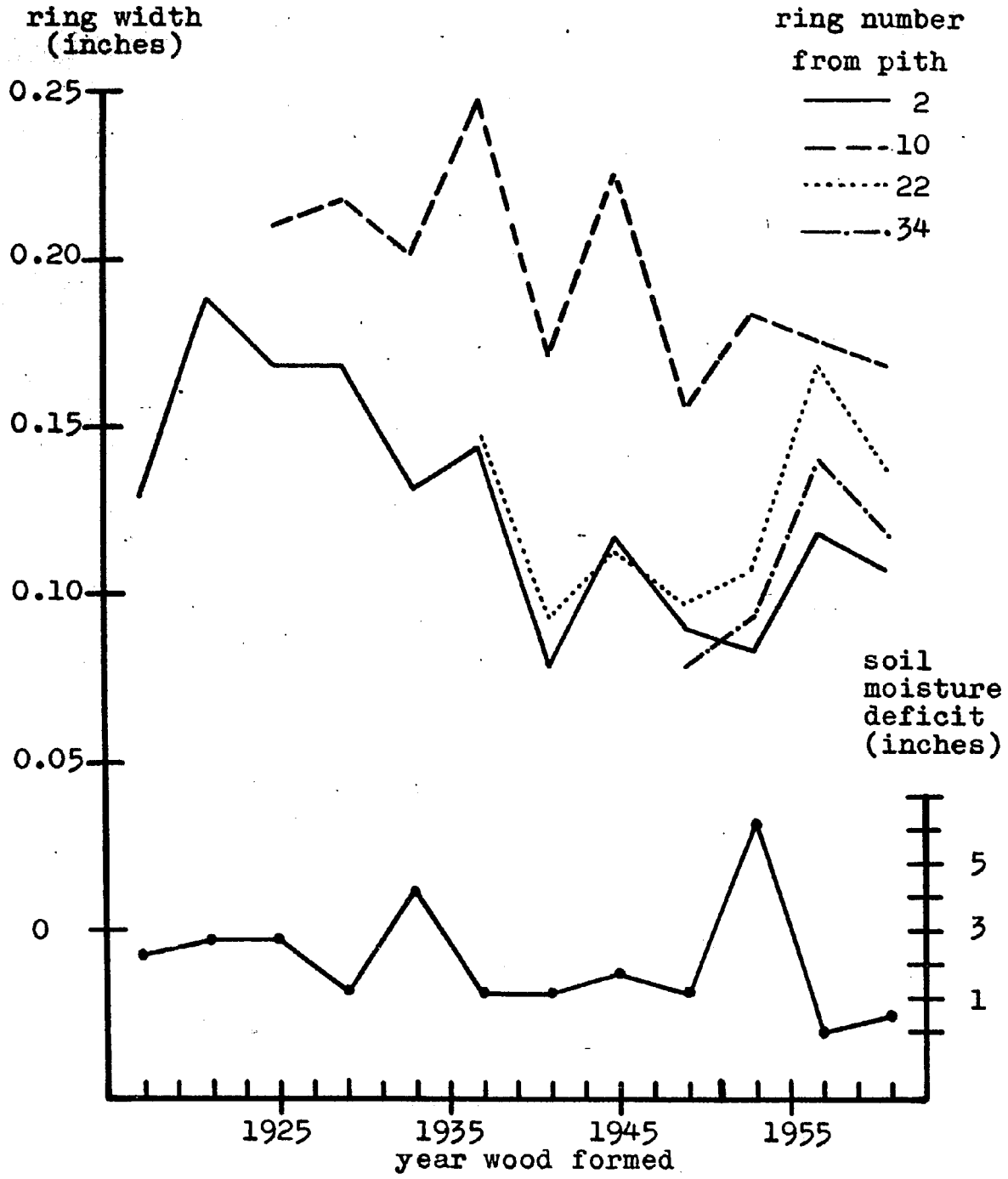


Figure 16. Vertical sequences for ring width arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

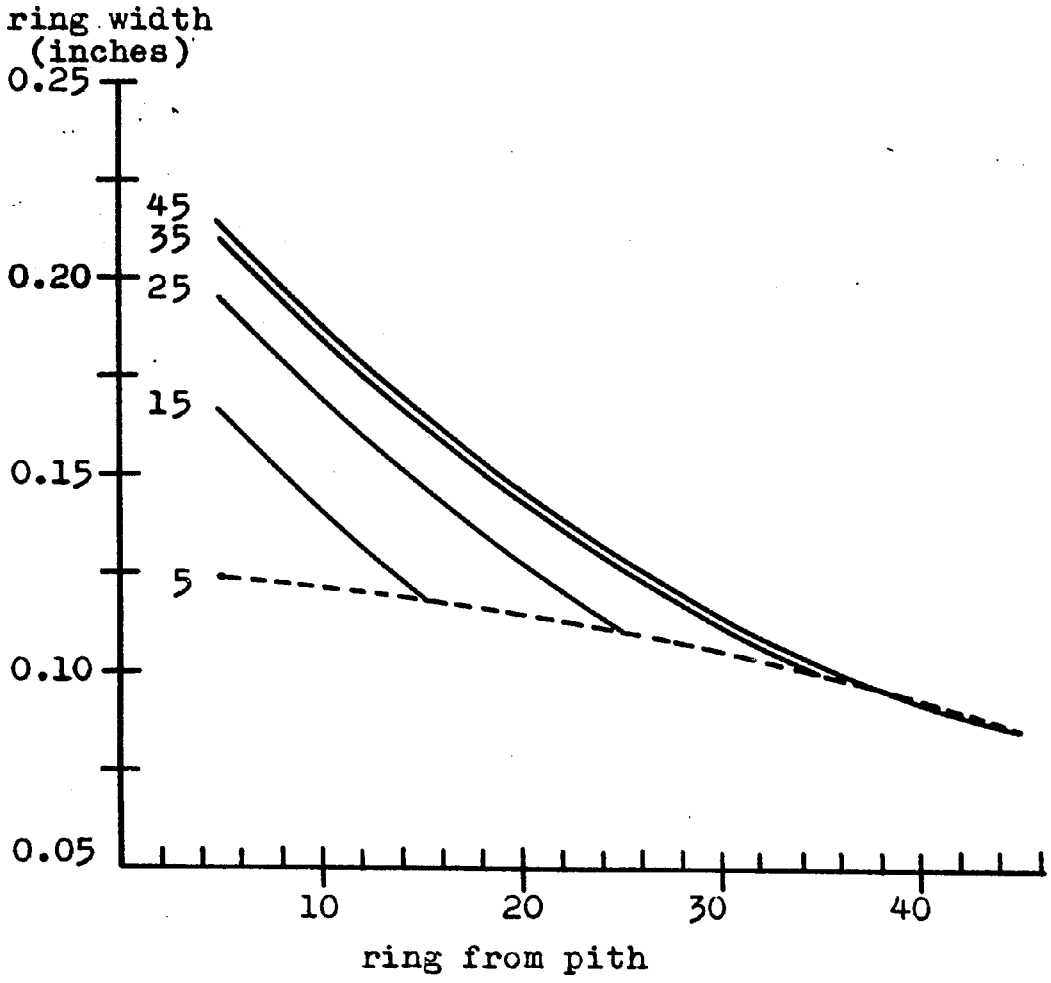


Figure 17. Calculated horizontal sequences for ring width. Numbers to left of curves indicate internode below stem apex. Broken line is oblique sequence for internodes 5 to 45 below the apex

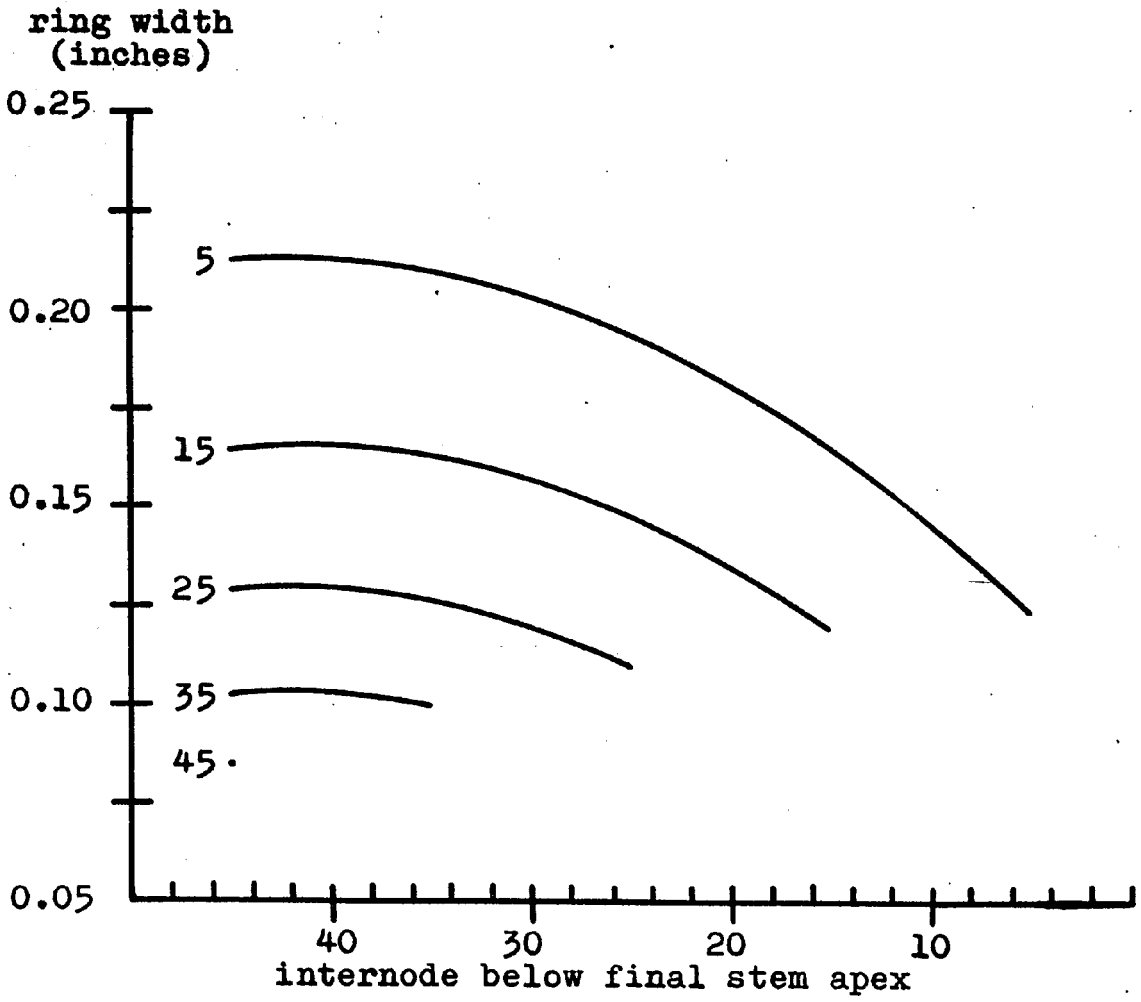


Figure 18. Calculated vertical sequences for ring width at five distances from the pith. Numbers to left of curves indicate ring from pith.

gether accounted for 42 per cent of the total variation in ring width, i.e., $R^2 = 0.423$, with a standard error of estimate of $\pm$ 0.0449 inch.

$$Y = 145.718 + 5.527X_2 - 0.0664X_3 - 5.760X_8 + 0.0515X_9 - 0.106X_{16}$$

where X_2 = internode from apex

X_3 = (internode from apex)^2

X_8 = ring from pith

X_9 = (ring from pith)^2

X_{16} = current year deficit, 1 March to 31 October.

This equation was used to derive the families of horizontal and vertical sequence curves shown in Figure 17 and 18 respectively. While the horizontal curves do not show the rise between the pith and the tenth ring, beyond this point they do portray the the decrease in width. The vertical sequences in Figure 18 show a definite positional effect towards the top of the sample tree, where ring width decreases rapidly for a given ring.

Thus, as with the earlywood cells, there is an inherent pattern of ring width formation within the stem, a major determinant of which is position relative to the current stem apex during the year of wood formation. This pattern is demonstrably altered by external factors, among them soil moisture deficit level for the period 1 March to 31 October, but within a growth sheath the positional

factor is paramount, particularly within the top eight to ten internodes.

The reasons for the progressive diminution of ring width downwards along a growth sheath are essentially those which apply to the reduction in the number of early-wood cells, and which were discussed in the previous sections. This is so for eastern white pine since the ring width shows a high correlation with the number of earlywood cells in the growth ring. The configuration of ring width basipetally in a growth sheath found in this study, i.e., increasing within the active crown, decreasing rapidly thereafter, and then more slowly towards the base, is similar to that described by Onaka (1950) for coniferous trees with crowns of medium size.

On following a given ring from the pith vertically upwards in the stem, ring width diminishes, and diminishes ever more rapidly with increasing height in the stem, particularly in rings close to the pith. It is generally true that annual height growth decreases with increasing age. Thus it is possible that, as the length of the leading shoot decreases with age, fewer needles will be produced on the leader of a 40 year old stem than on the 10 year old leader of the same tree. Assuming the needles at both ages to be equally efficient, this would result in less photosynthate being available for cellular development in the top of the older stem, giving rise to reduced ring

width in the upper levels of a given ring from the pith.

Percentage of Latewood

Percentage of latewood is the width of the latewood band in a growth ring expressed as a percentage of the entire ring width. With the small number of latewood cells existing in eastern white pine one might wonder what is served by an examination of percentage of latewood. As has been noted, the number of latewood cells tends to increase slightly with increasing distance from the current stem apex along any growth sheath, while the number of earlywood cells beyond the eighth internode from the apex decreases quite rapidly and then more gradually. Thus, though there is little change in the number of latewood cells, due to the decrease in number of earlywood cells the latewood band occupies a progressively greater portion of the growth ring with an increasing number of internodes from the current stem apex, becoming a more potent factor in the characteristics of the ring as an entity.

There is a constant trend of increasing percentage of latewood with a greater number of internodes from the apex, though this pattern may be heavily overlain by external effects. As discussed previously, the confounding effect of annual weather changes can be removed by plotting values for individual growth sheaths while obtaining variation due to position in the stem. The oblique

sequence curves for percentage of latewood in Figure 19 display clearly the increase in latewood percentage with increasing distance from the apex along a given growth sheath, the rate of increase rising with successively greater distances from the current stem apex. Variation in association with soil moisture deficit is not particularly evident.

Four horizontal sequences are shown in Figure 20 and, as with earlywood cells and ring width, display greater variation within each sequence while adhering to the general ever-steepening form of the oblique sequences. On plotting the horizontal sequences over year of formmation, Figure 21, the curves can be matched with the 1 June to 31 August soil moisture deficits current at the time of wood formation. Thus, unlike earlywood and ring width, percentage of latewood is associated most closely with moisture deficit in the latter part of the growing season. As with the two previous variables, the effect of soil moisture level appears throughout the sequence, beginning at the second ring from the pith. However, there remains a strong positional influence exerted over the entire curves which generally ascend with increasing physiologic distance from the pith.

Soil moisture levels are shown in association with vertical sequences in Figure 22, and indicate that while percentage of latewood fluctuates seasonally, it remains

Figure 19. Oblique sequences for percentage of latewood. Soil moisture deficit is for current 1 June to 31 August.

Fig. 19

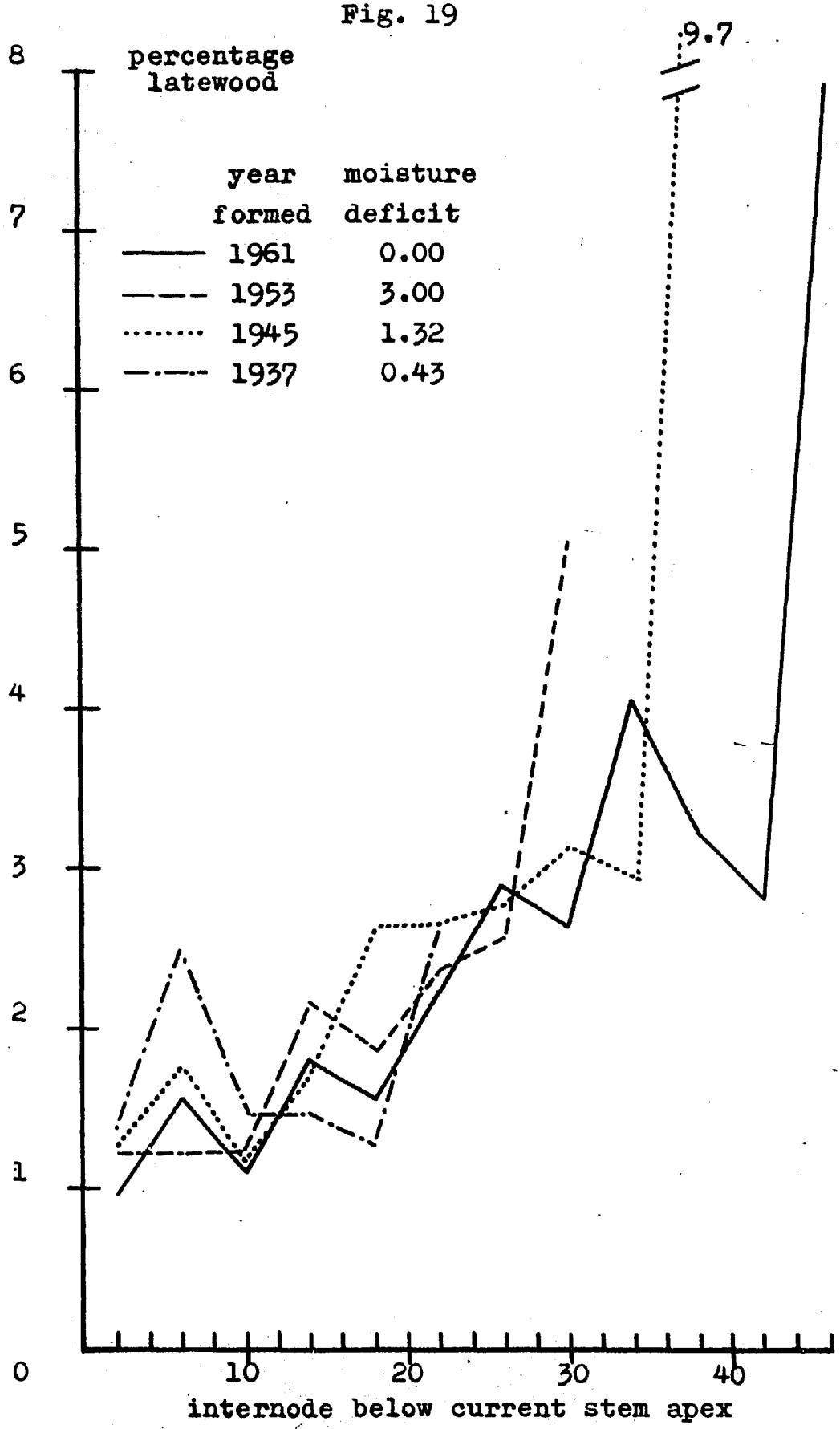

percentage latewood
year formed
moisture deficit
1961 0.00
1953 3.00
1945 1.32
1937 0.43
9.7
8
7
6
5
4
3
2
1
0
10
20
30
40
internode below current stem apex

Figure 20. Horizontal sequences for percentage of latewood.

Fig. 20

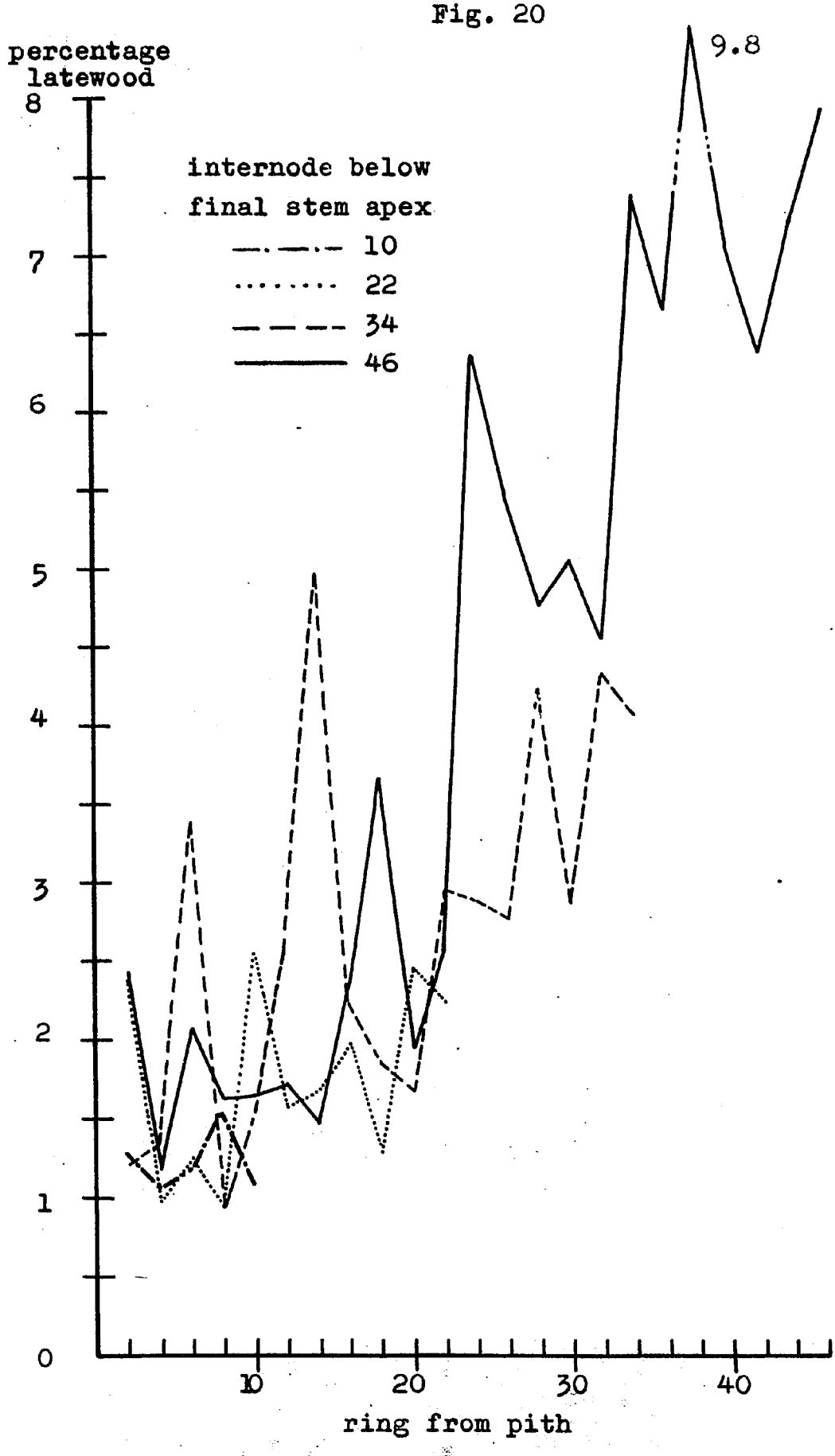

percentage latewood
8
7
6
5
4
3
2
1
0
internode below final stem apex
10
22
34
46
9.8
10
20
30
40
ring from pith

Figure 21. Horizontal sequences for percentage of latewood arranged over year of wood formation and current 1 June to 31 August soil moisture deficit.

Fig. 21

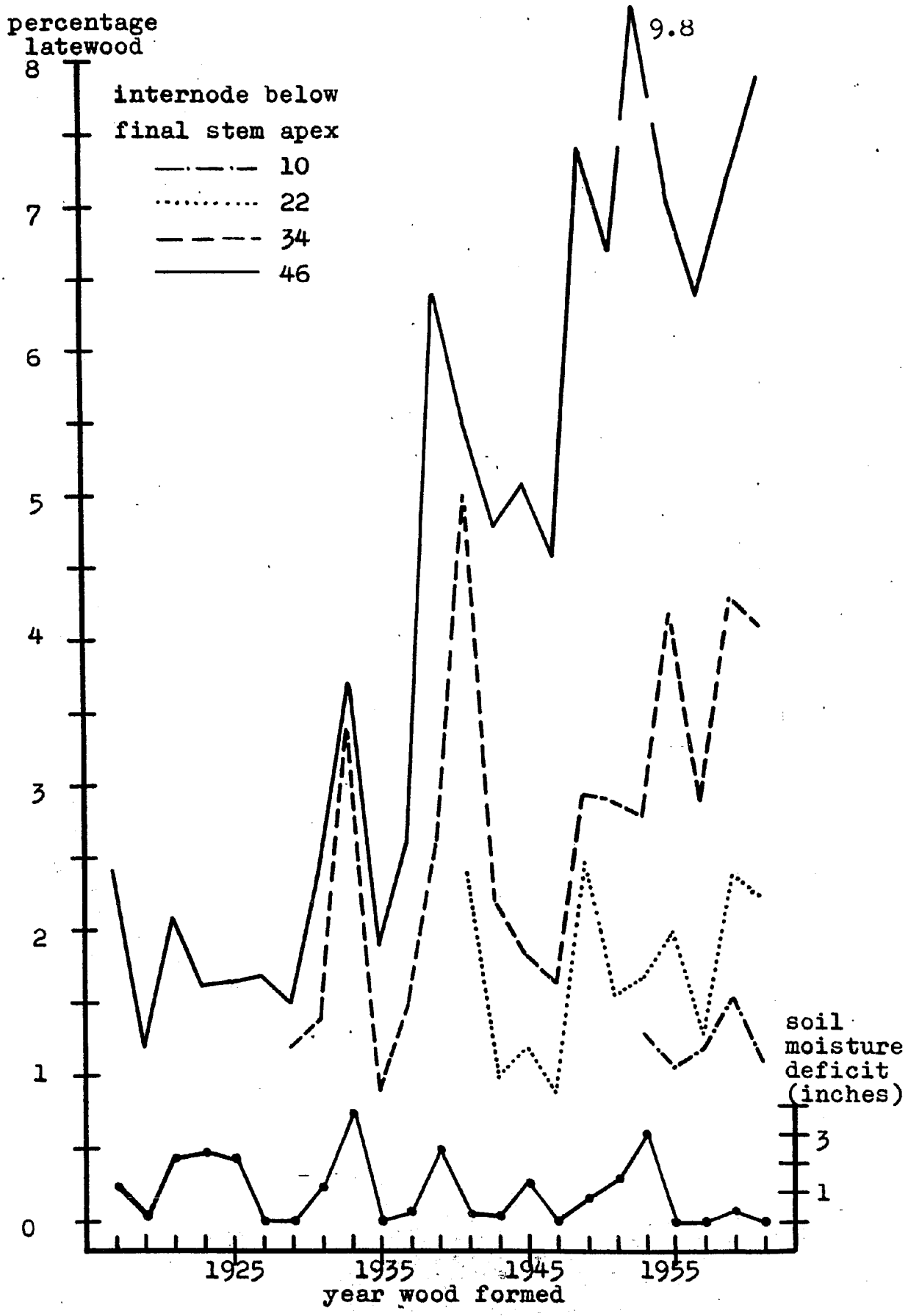
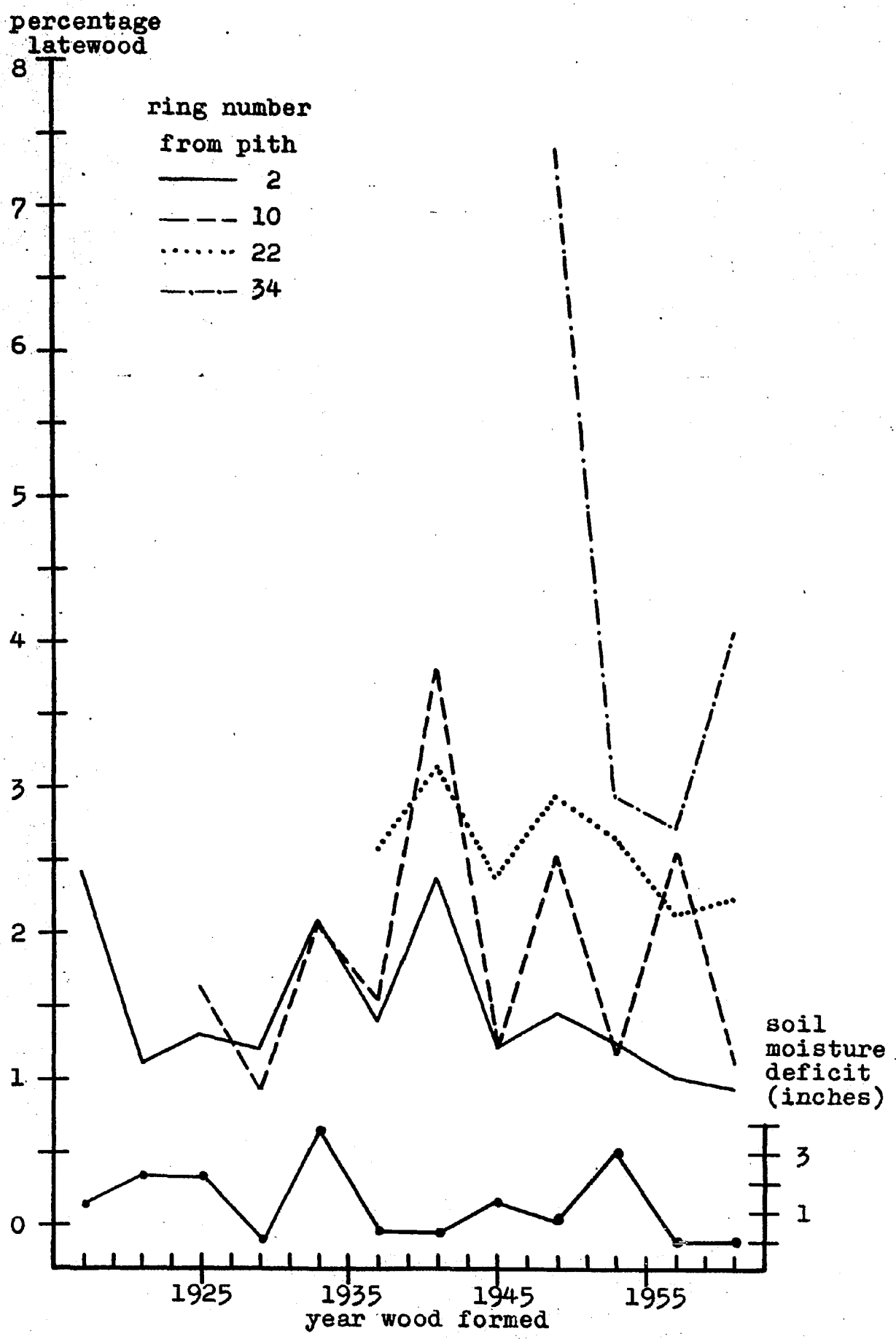

percentage latewood
8
7
6
5
4
3
2
1
0
internode below final stem apex
10
22
34
46
9.8
soil moisture deficit (inches)
3
1
1925
1935
1945
1955
year wood formed

Figure 22. Vertical sequences for percentage of latewood arranged over year of wood formation and current 1 June to 31 August soil moisture deficit.

Fig. 22


percentage latewood
8
7
6
5
4
3
2
1
0
ring number from pith
2
10
22
34
soil moisture deficit (inches)
3
1
1925
1935
1945
1955
year wood formed

relatively constant as a given ring from the pith is followed upwards in the stem. The vertical curves illustrate also the increase in percentage of latewood with increasing number of rings from the pith at a specified level in the stem.

Of the regression equations tested, the following gave an R^2 value of 0.257 and a standard error of estimate of ± 2.015. Even at this low level the equation was superior to the others tested, and was significant at the one percent level.

$$Y = 1.509 - 0.0789X_{17} + 0.00160X_2 + 0.0567X_4 + 0.000895X_8 - + 0.00345X_{10}$$

where X_2 = internode from apex

X_4 = (internode from apex)^2

X_8 = ring from pith

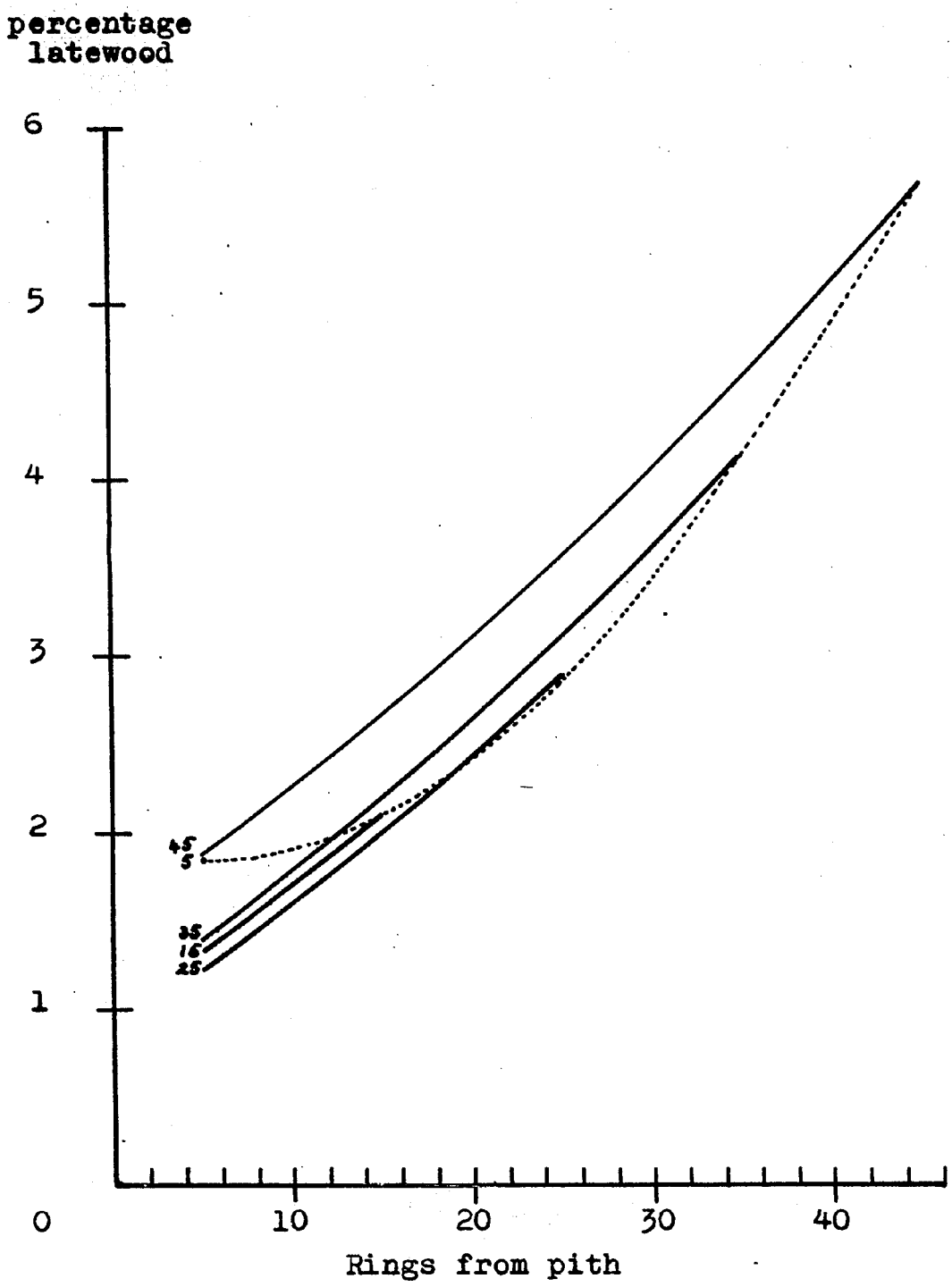
X_{10} = (ring from pith)^2

X_{17} = current year deficit, 1 June to 31 August

Horizontal sequences were calculated from this equation and these comprise Figure 23, illustrating the persistent rise of latewood percentage from pith to circumference. In Figure 24 the vertical sequences decrease, then increase with height in the stem. Despite the full-bellied form of these curves it should be noted that this variation amounts to less than 0.7 percent latewood along a single curve, and represents negligible variation vertic-

Figure 23. Calculated horizontal sequences for percentage of latewood. Numbers to left of curves indicate internode below stem apex. Broken line is oblique sequence for internodes 5 to 45 below the apex.

Fig. 23


percentage latewood
6
5
4
3
2
1
0
10
20
30
40
Rings from pith
45
5
35
16
25

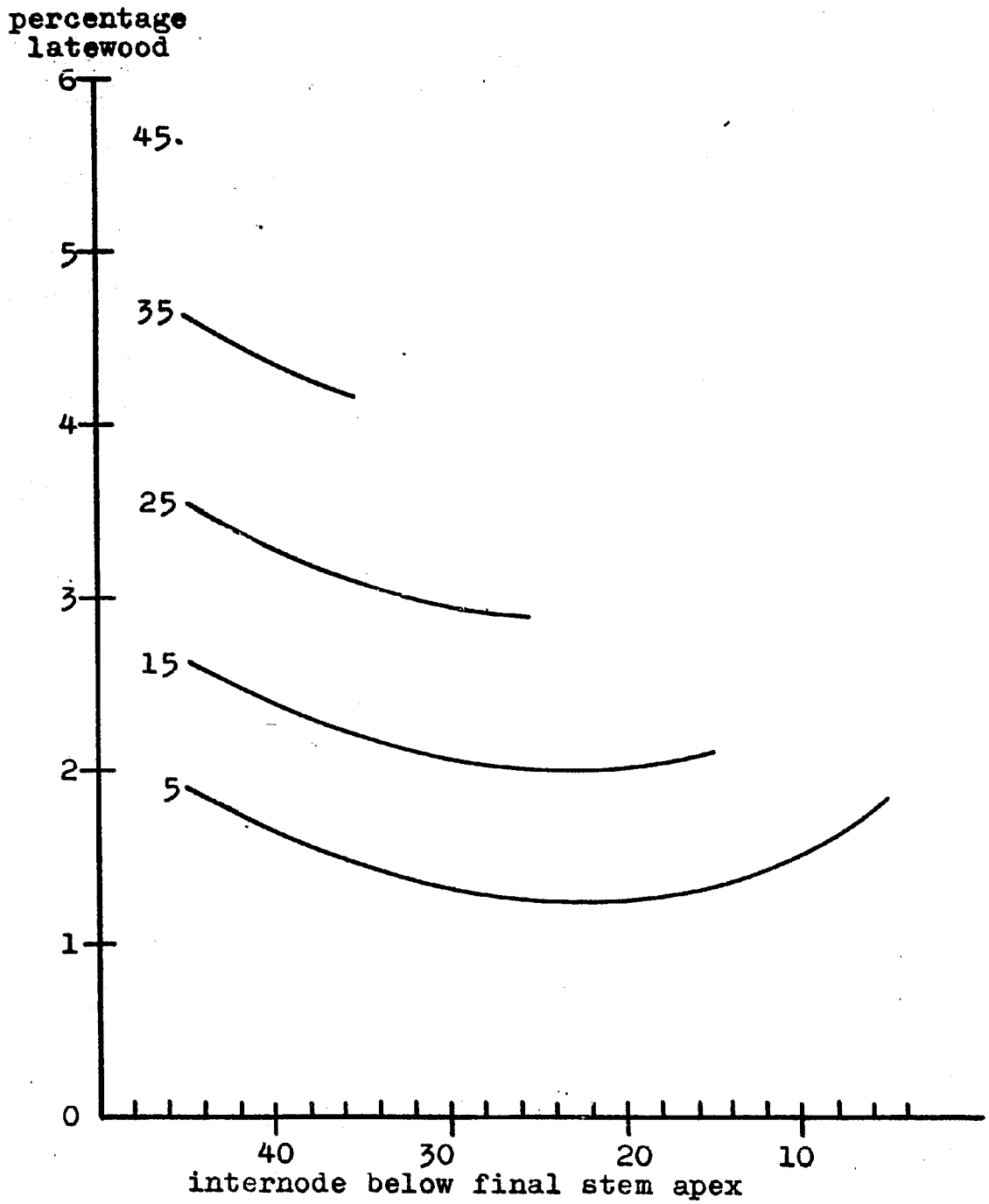


Figure 24. Calculated vertical sequences for percentage of latewood at five distances from the pith. Numbers to the left of the curves indicate ring number from pith.

ally within a given ring from the pith.

Number of earlywood cells, and ring width as a result, both changed in association with soil moisture deficit for the period 1 March to 31 October of the current growing season. Number of latewood cells, however, showed little direct relationship with soil moisture availability, though percentage of latewood fluctuated in accord with soil moisture deficits for the current 1 June to 31 August. All four characteristics displayed patterns of behavior apparently dependent on the number of internodes which the active cambium is removed from the upper crown, and current stem apex, along a given growth sheath.

Some of the factors affecting numbers of cells formed and ring width have been discussed in preceding sections. An examination of oblique sequences for cell numbers, ring width, and percentage of latewood, i.e., Figures 7, 13, and 19, show clearly that the basipetal increase of the last variable is due to a pronounced decrease in earlywood cells, not to marked increased latewood formation. The amount of latewood does vary but only to the extent of emphasizing the earlywood-determined pattern.

The observations reported here agree with the findings of Smith and Wilsie (1961) for loblolly pine in Arkansas, to the extent that percentage of latewood formed varies in association with soil-moisture deficit in the latter part of the year in which the wood is formed.

However, low soil moisture deficit in Arkansas resulted in a basipetal increase in percentage of latewood, while higher deficits reduced the difference between the top and bottom of the growth sheath. In extreme drought the pattern was reversed, the highest percentage of latewood being formed in the uppermost part of the growth sheath. In the white pine examined conditions were opposite, percentage of latewood increasing with increasing distance from the current stem apex in all instances. Indeed this pattern was accentuated in years of high soil moisture deficit due to the greater decrease in earlywood, especially in the lower portion of the growth sheath. Thus though percentage of latewood is associated with late season soil moisture deficits in both species, a high deficit is associated with high latewood percentage in the top of loblolly pine, but with high latewood percentage at the base of eastern white pine.

The importance of percentage of latewood will be apparent in subsequent discussion of longitudinal shrinkage and specific gravity. A correlation coefficient of +.40 was obtained between specific gravity and percentage of latewood, higher specific gravity being associated with higher latewood percentage. With longitudinal shrinkage, per cent latewood gave a correlation of -.16, per cent shrinkage decreasing with increasing percentage of latewood. Both of these relationships were significant

at the one percent level. Thus though the latewood band is narrow and relatively uniform in width in eastern white pine, its proportional variation in regard to total ring width, expressed as percentage of latewood, has a statistically significant effect on longitudinal shrinkage and specific gravity.

Longitudinal Shrinkage.

Longitudinal shrinkage is expressed throughout in terms of the difference between green and oven-dry length parallel to the grain as a percentage of oven-dry length. Pooled data from the three trees were used to obtain the oblique sequence curves shown in Figure 25. These show a precipitous drop in longitudinal shrinkage between the second and sixth internodes in each growth sheath, from values of 0.7 or 0.8 percent to 0.2 percent. Thereafter in each sequence there is fluctuation, but seldom more than $\pm$ 0.05 about 0.2 percent. There is no visible difference between the sheaths laid down in different growing seasons, variation in the lower portions of the curves being essentially random. This pattern is repeated in the horizontal curves shown in Figure 26.

When the horizontal curves were plotted over year of formation and soil moisture deficit for the current 1 March to 31 October, Figure 27, there was little relationship between the peaks and valleys of the several sequences, or between these and the moisture deficits.

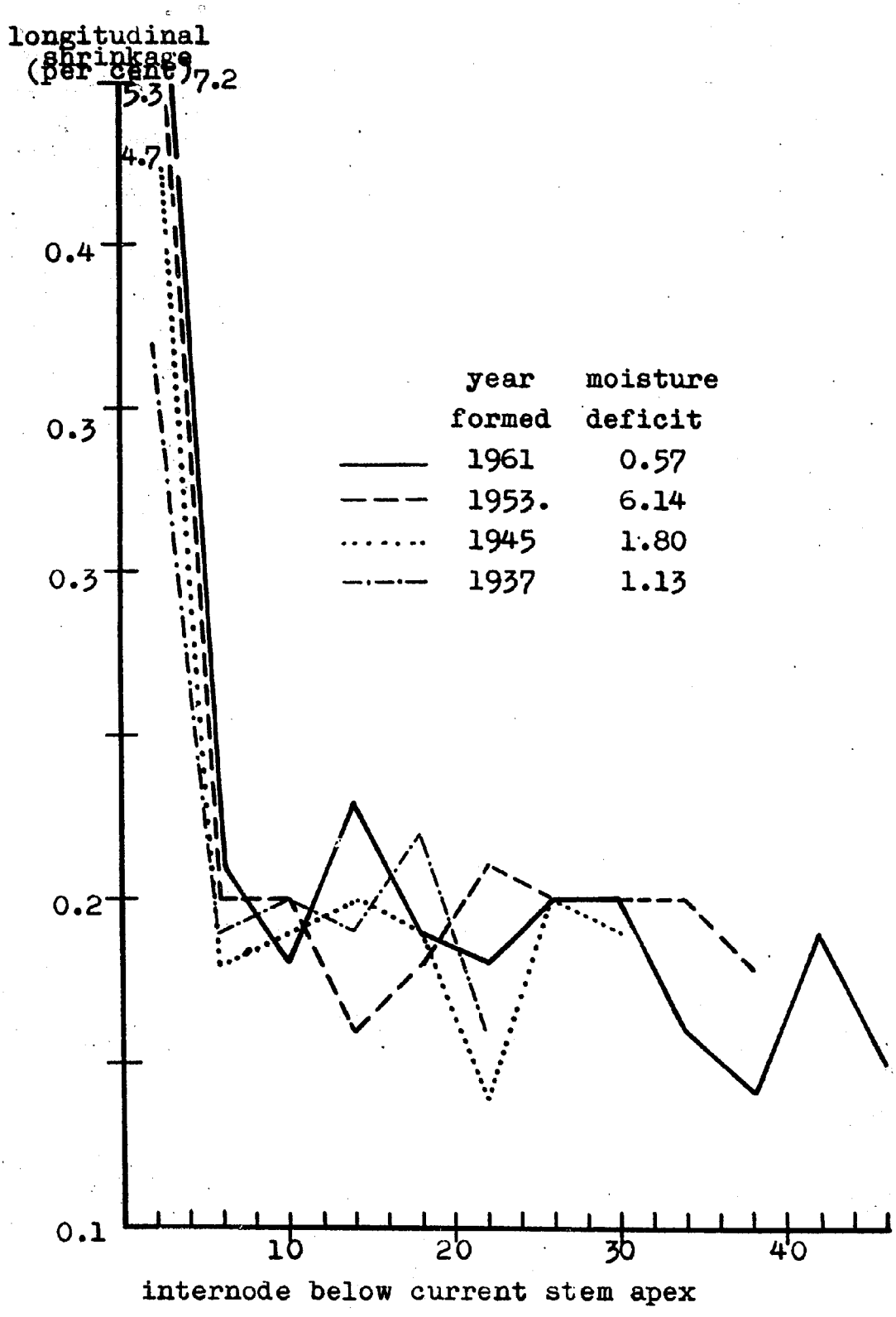


Figure 25. Oblique sequences for longitudinal shrinkage

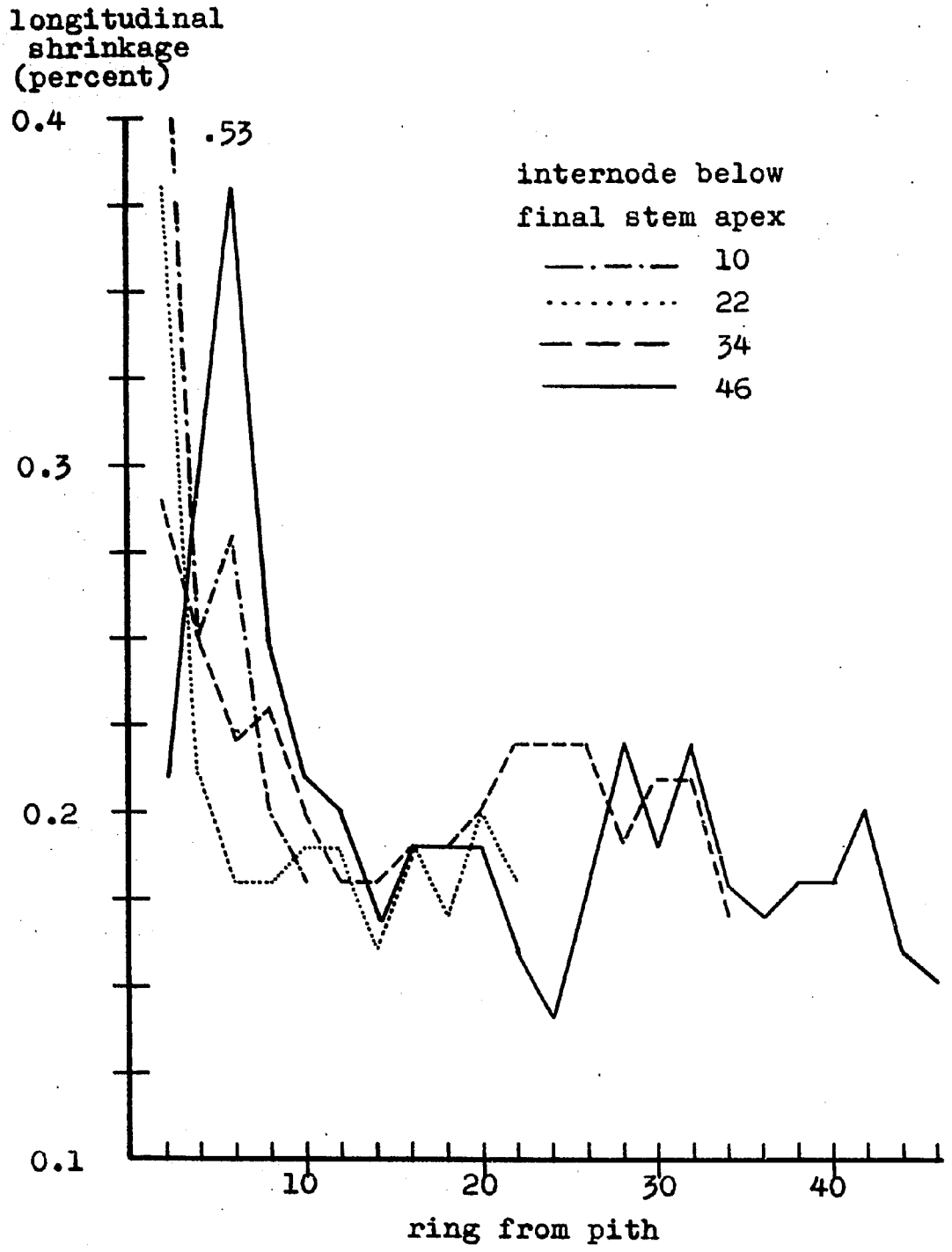
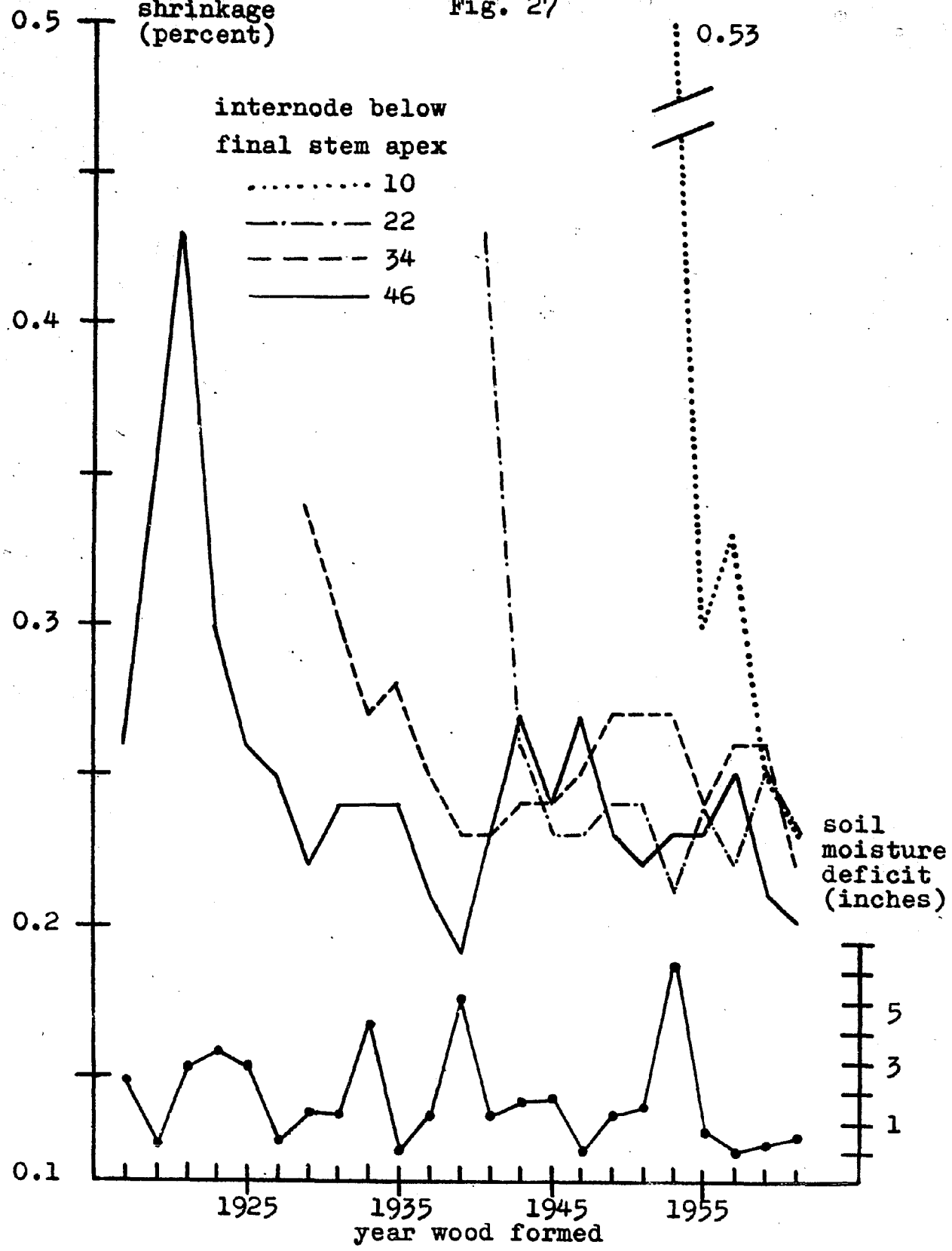


Figure 26. Horizontal sequences for longitudinal shrinkage

Figure 27. Horizontal sequences for longitudinal shrinkage arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Fig. 27

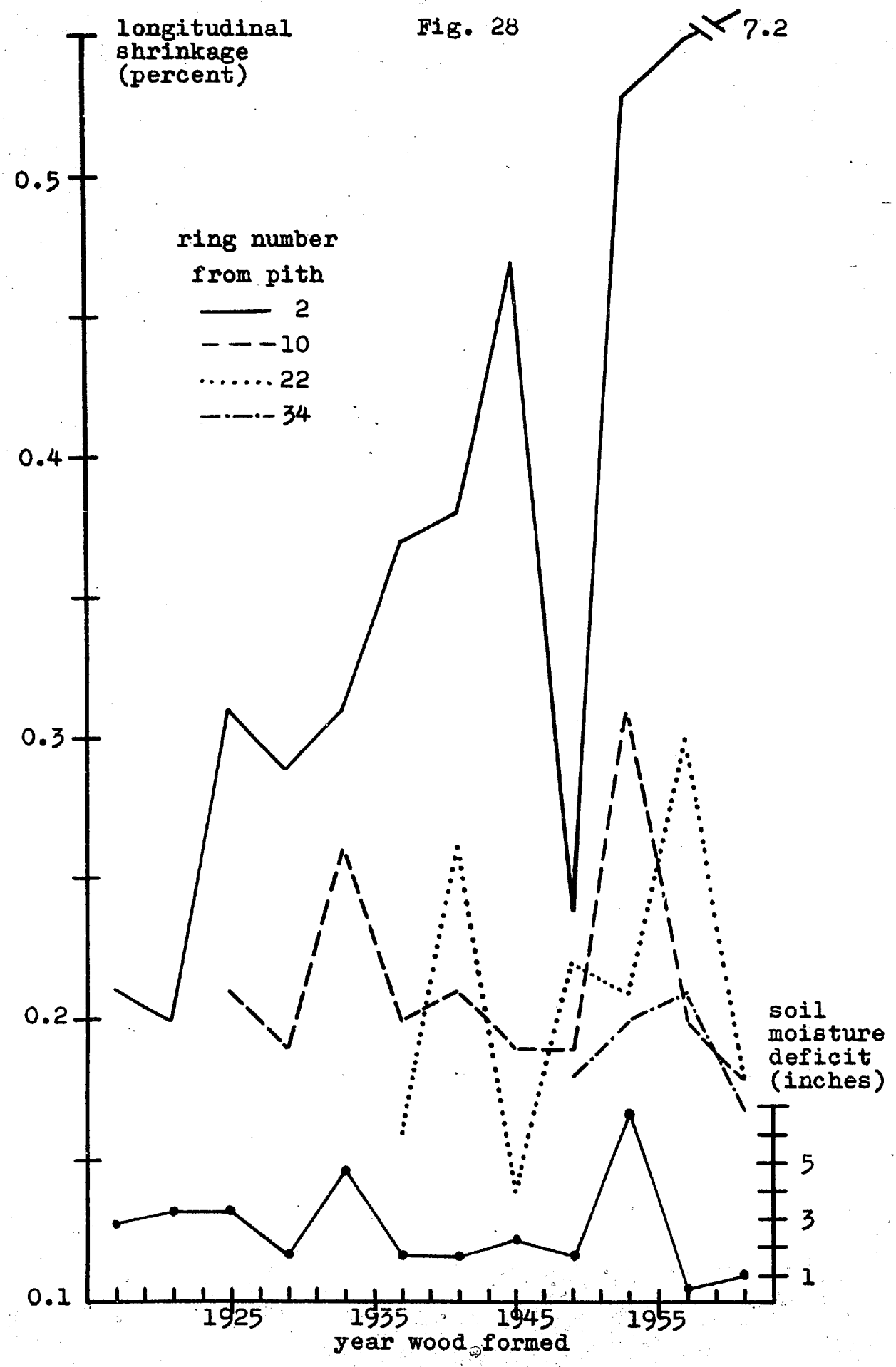

longitudinal shrinkage (percent)
0.5
0.4
0.3
0.2
0.1
0.53
internode below final stem apex
10
22
34
46
soil moisture deficit (inches)
5
3
1
1925
1935
1945
1955
year wood formed

This agrees with the regression analysis which indicated that longitudinal shrinkage was not significantly associated with any of the five soil moisture deficits tested. Of the five deficits, that illustrated in Figure 27 might be expected to have the closest relationship with longitudinal shrinkage since it affects the number of earlywood cells formed in a growth ring. Earlywood cell number showed the highest correlation coefficient with longitudinal shrinkage, +.21, i.e., greater longitudinal shrinkage was associated with higher numbers of earlywood tracheids in the growth ring.

On plotting the vertical sequences, Figure 28, there was no discernible pattern associated with soil moisture deficit. Nor was there any tendency for longitudinal shrinkage to increase or decrease within a specific growth ring from the pith with increasing height in the stem. An exception was the second ring from the pith which showed an upward trend with increasing height in the stem. The pattern for a ring close to the pith, as compared to one more than ten rings from the pith, is shown with greater clarity in the smoothed series of vertical curves which appear as Figure 29. These were derived from a regression equation giving $R^2 = 0.237$, with a standard error of the mean of $\pm$ 0.106. Highly significant F values were obtained with X_4 and X_{10}, but on inclusion of X_1, X_2, and X_8, the F value ceased to be significant.

Figure 28. Vertical sequences for longitudinal shrinkage arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Fig. 28


longitudinal shrinkage (percent)
7.2
0.5
0.4
0.3
0.2
0.1
ring number from pith
2
10
22
34
soil moisture deficit (inches)
5
3
1
1925
1935
1945
1955
year wood formed

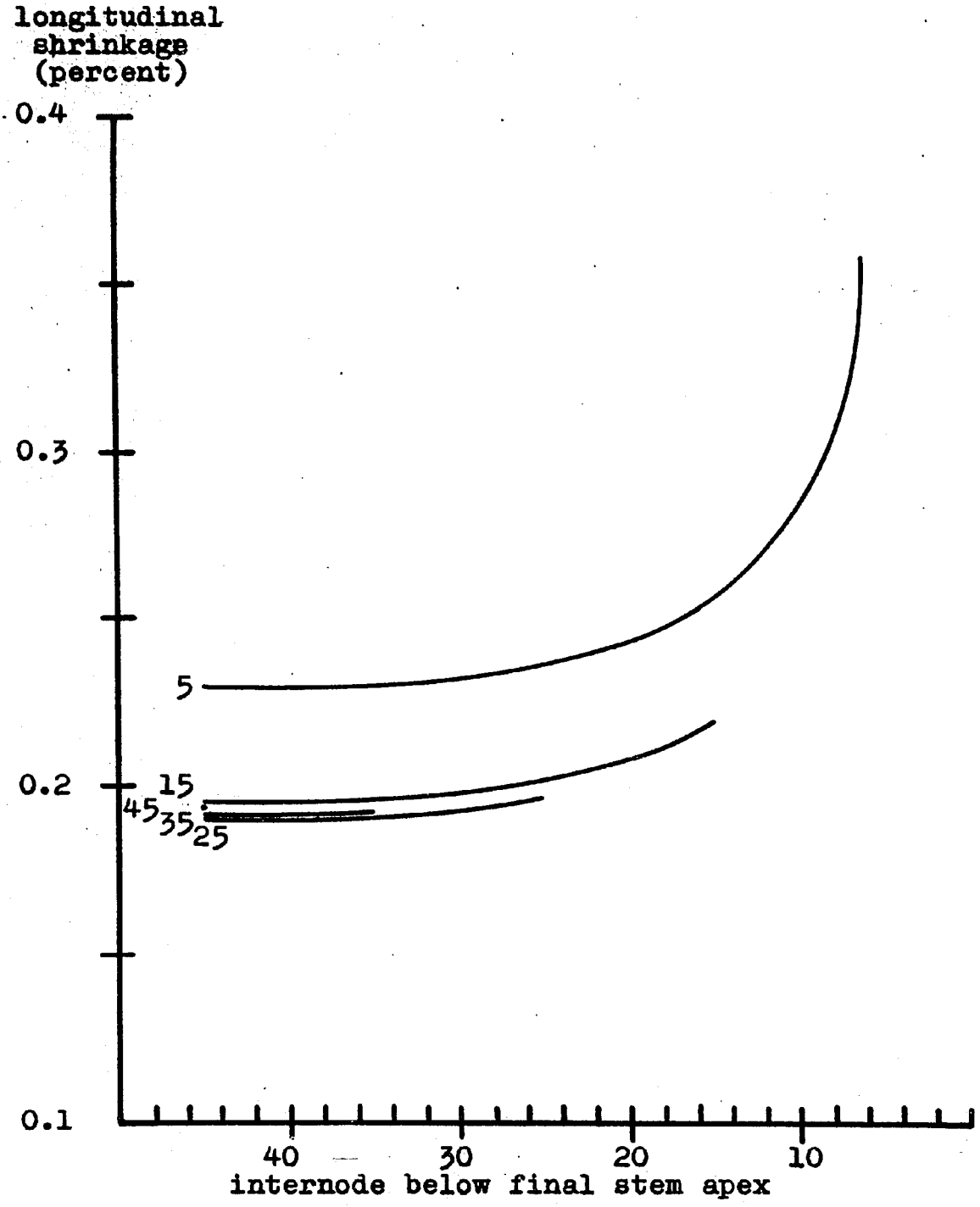


Figure 29. Calculated vertical sequences for longitudinal shrinkage at five distances from the pith. Numbers to the left of curves indicate ring from pith.

$$Y = 0.116 + 0.00922X_1 + 0.00042X_2 + 0.815X_4 + 0.00044X_8 + 0.306X_{10}$$

where X_1 = aspect

X_2 = internode from apex

X_4 = (internode from apex)$^{-1}$

X_8 = ring from pith

X_{10} = (ring from pith)$^{-1}$

As previously noted, addition of soil moisture deficits added nothing to the regression analysis in this instance, therefore none are included in the equation used to derive the horizontal sequences making up Figure 30. These curves illustrate a decline to about the 12th ring from the pith with virtually no change in shrinkage from thence to the circumference. The curves show a strong effect of proximity to the pith and stem apex, the latter statement being equally true for the fifth ring from the pith in the vertical sequences forming Figure 29. The overall impression is that, except for the eight to ten rings closest to the pith, longitudinal shrinkage in white pine is relatively constant irrespective of position in the stem.

High longitudinal shrinkage in the top internodes of a growth sheath or close to the pith of the entire tree is due certainly to a combination of factors (Spurr and Hyvarinen, 1954). First, percentage of latewood is minimal in this part of the stem (Figures 19 and 20) and

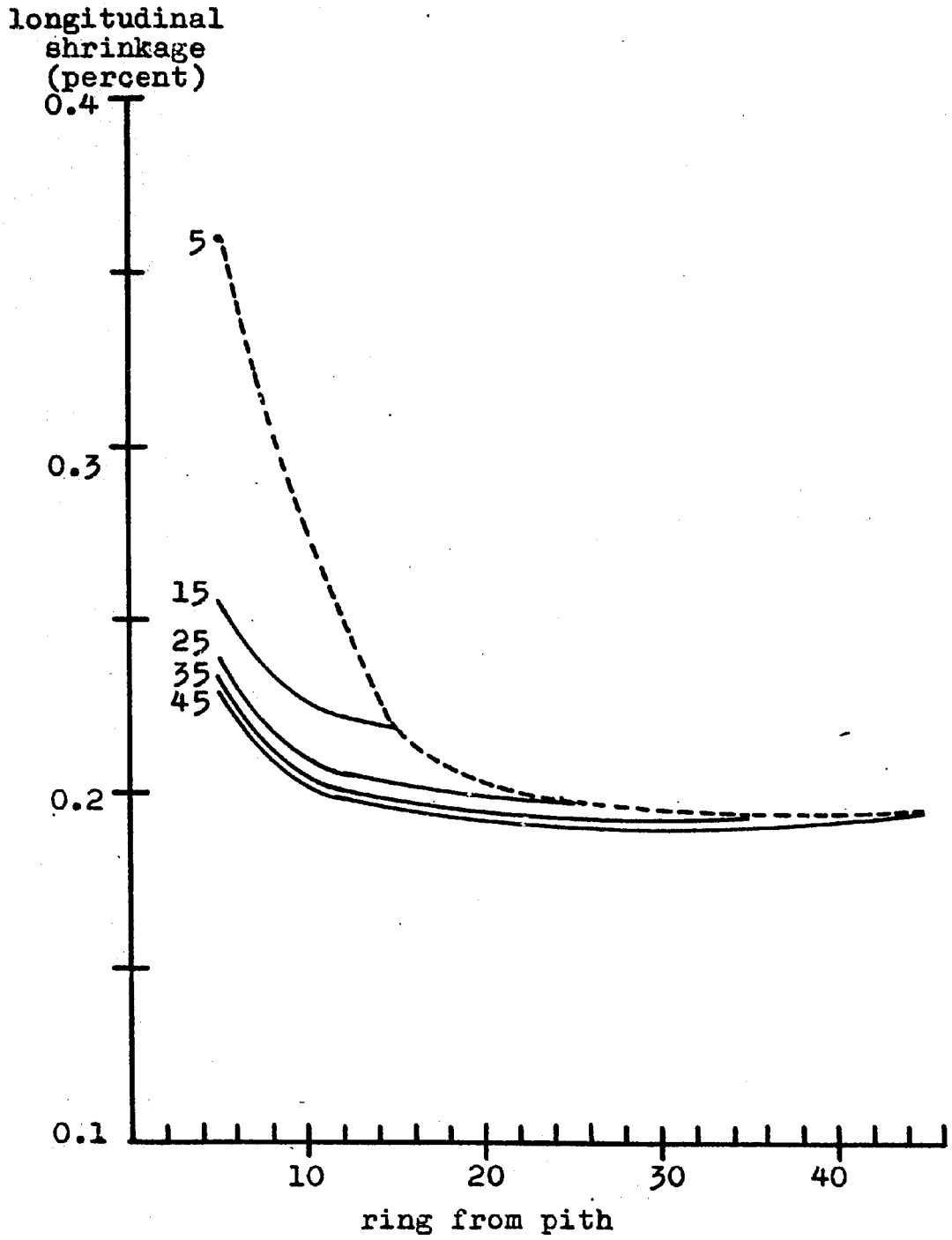


Figure 30. Calculated horizontal sequences for longitudinal shrinkage. Numbers to the left of curves indicate internode below stem apex. Broken line is oblique sequence for internodes 5 to 45 below the apex.

both Koehler (1931) and Cockrell (1947) noted that the earlywood component of the growth ring tends to shrink more longitudinally than the latewood portion. With the low percentage of latewood present, there is a tendency for greater shrinkage close to the apex. As latewood percentage begins to rise steeply at about the tenth internode from the current stem apex, longitudinal shrinkage begins to level off, cf. Figures 19 and 25. This is the area where number of earlywood cells in the growth ring, and hence total ring width, begin to diminish from the maximum values, Figures 7 and 13. The coincidence of the major inflexion of the four series of curves suggests that, above a certain value, percentage of latewood in the growth ring may exert a restraining influence on the longitudinal shrinkage of the entire ring. This agrees with Cockrell (1949) who showed that, in several conifers, latewood expanded longitudinally on drying from the green to air-dry state. When an entire ring was oven-dried, the latewood exerted a restraint on the shrinkage of the whole ring.

Yet percentage of latewood can not wholly account for the high shrinkage percentage found in the topmost six to ten internodes of a growth sheath, or in the first ten rings from the pith in a horizontal sequence. This latter zone comprises the so-called "juvenile" wood wherein tracheids are rather shorter, have greater fibril angle, lower tensile strength, and higher specific gravity, than

in growth rings laid down subsequently (Dadswell, 1960). These properties are similar to those ascribed to compression wood by Wardrop and Dadswell (1952). While juvenile wood may not be compression wood in the truest sense, it has many of the same properties, of which fibril angle in the secondary cell wall is possibly the most influential of longitudinal shrinkage. This is so since removal of water from the cell wall results in the fibrils being drawn closer together normal to their long axis. When the fibrils make a small angle with the long axis of the cell there is little shrinkage in the longitudinal direction. Given a large fibril angle, a greater part of the shrinkage force acts in this plane, with a resultant increase in longitudinal shrinkage. Compression wood, generally, is characterized by a large fibril angle and high longitudinal shrinkage (Pillow and Luxford, 1937).

Development of juvenile, or compression, wood in the top internodes may be caused in part by the high auxin concentrations found in this region. Formation of compression wood in seedlings following high auxin applications was reported by Wershing and Bailey (1942). More recently, Wardrop and Davies (1964) found compression wood formation to be induced in Pinus radiata by the application of 3-indoleacetic acid and gibberellic acid, either separately or together. In addition to chemical stimulus, compression wood development may be influenced

by mechanical stresses imposed on the stem by buffeting winds. Sinnott (1952) stimulated compression wood formation by bending stems out of the vertical, and it is conceivable that wind force may accomplish the same end.

If the degree of longitudinal shrinkage is associated with the amount of compression wood present, and this in turn is affected by mechanical bending, it is interesting to note that longitudinal shrinkage of wood formed close to the apex increases with height in the stem. This is illustrated in the vertical sequence for the fifth ring from the pith in Figure 29. The increase may be due to a progressively greater exposure to sway of the topmost internodes of the tree with increasing age and height, particularly for dominant and codominant trees such as those used in this study. The top six internodes of the young tree, possibly protected by brush and at the end of a relatively short stem, would be less liable to bending from the vertical than the top six internodes of a 50 year old stem, where they are subject to "whiplash" action at the end of a 75 foot cantilever beam. As a corollary, it would be of interest to trace the longitudinal shrinkage pattern in a suppressed stem, progressively more protected from wind sway within the stand. One would expect little or no increase in following upwards the vertical sequence of a ring close to the pith.

There appears to be a complex of factors affecting longitudinal shrinkage along a growth sheath. At lower levels in the stem,where the plant is less pliable, longitudinal shrinkage is associated with a limiting value for percentage latewood. In the upper portion of the sheath, the preponderance of earlywood cells in the ring, high auxin levels, and mechanical bending stresses, may be more important. Longitudinal shrinkage does appear to be independent of growth rate and of position in the stem beyond the first ten rings from the pith.

Specific Gravity.

That specific gravity is possibly the most studied and most discussed property of wood is evident from the numerous references appearing in reviews on the subject, (Spurr and Hsiung, 1954; Larson, 1957; Tappi, 1962; Paul, 1963). It is a utilitarian property, lending itself to interpretation in terms of mechanical strength characteristics of wood both as a structural material (Brown, Panshin, Forsaith, 1952) and as a source of wood fiber (Curran, 1936; Dadswell et al., 1959).

Since it has widely applicable diagnostic qualities, there has been much effort to determine which growth factor, or factors, influence specific gravity. Both percentage of latewood and ring width have their protagonists who suggest that these two properties, either separately or in concert, determine specific

gravity. Certainly in species with substantial, and varying, amounts of latewood in the growth ring, as in the southern pines or Douglas fir, one might expect that this would affect the specific gravity of the growth ring as has been described by Larson (1957) and Smith (1955). Fegel (1941) working with eastern white pine has suggested that width of the earlywood band is the determining variable, with the latewood band having relatively unchanging width. Data from the present study agree with Fegel's observations, except that these conditions, i.e., constant latewood and varying earlywood widths do result in changes of latewood percentage, which are associated with changes in specific gravity. Ring width measurements in the present study likewise are associated with changes in specific gravity, but it is believed that the observations indicate a predominating effect of physiologic position relative to the active crown. Thus specific gravity, in all growth sheaths, decreases to approximately the tenth internode below the current stem apex, then increases gradually to the base of the sheath. Number of earlywood cells, ring width, and percentage of latewood, are all contributory factors, as doubtless are others not examined here, but the dominant influence is that of cambial age in years, and hence of distance from the top of the stem. This agrees in substance with Turnbull's (1947) thesis that wood density is a function of age rather than of ring width.

This is partially illustrated by the oblique sequences shown in Figure 31, where high specific gravity close to the stem apex declines to a minimum about the eighth internode, and thereafter increases gradually to the base of the sheath. Moisture deficits for the period 1 March to 31 October in the year the wood was formed are shown in the figure. There is no typical difference between sequences for the wettest and the driest years. The form of the oblique sequences is repeated in the horizontal sequences, comprising Figure 32, which decline to ring eight or ten and then increase towards the periphery.

The same horizontal sequences are shown in Figure 33, plotted over year of formation and total soil moisture deficit for the current growing season. There is poor correlation between specific gravity and variation in moisture availability. The correlation is slightly better in the case of the vertical sequences plotted in Figure 34, but here too the correspondence is not close. There is apparent in the vertical sequences a trend of increasing specific gravity within a given ring from the pith with increasing height in the stem, and of an increase in specific gravity with a mounting number of rings from the pith. The high specific gravity close to the pith is reflected in the high level of ring 2 throughout.

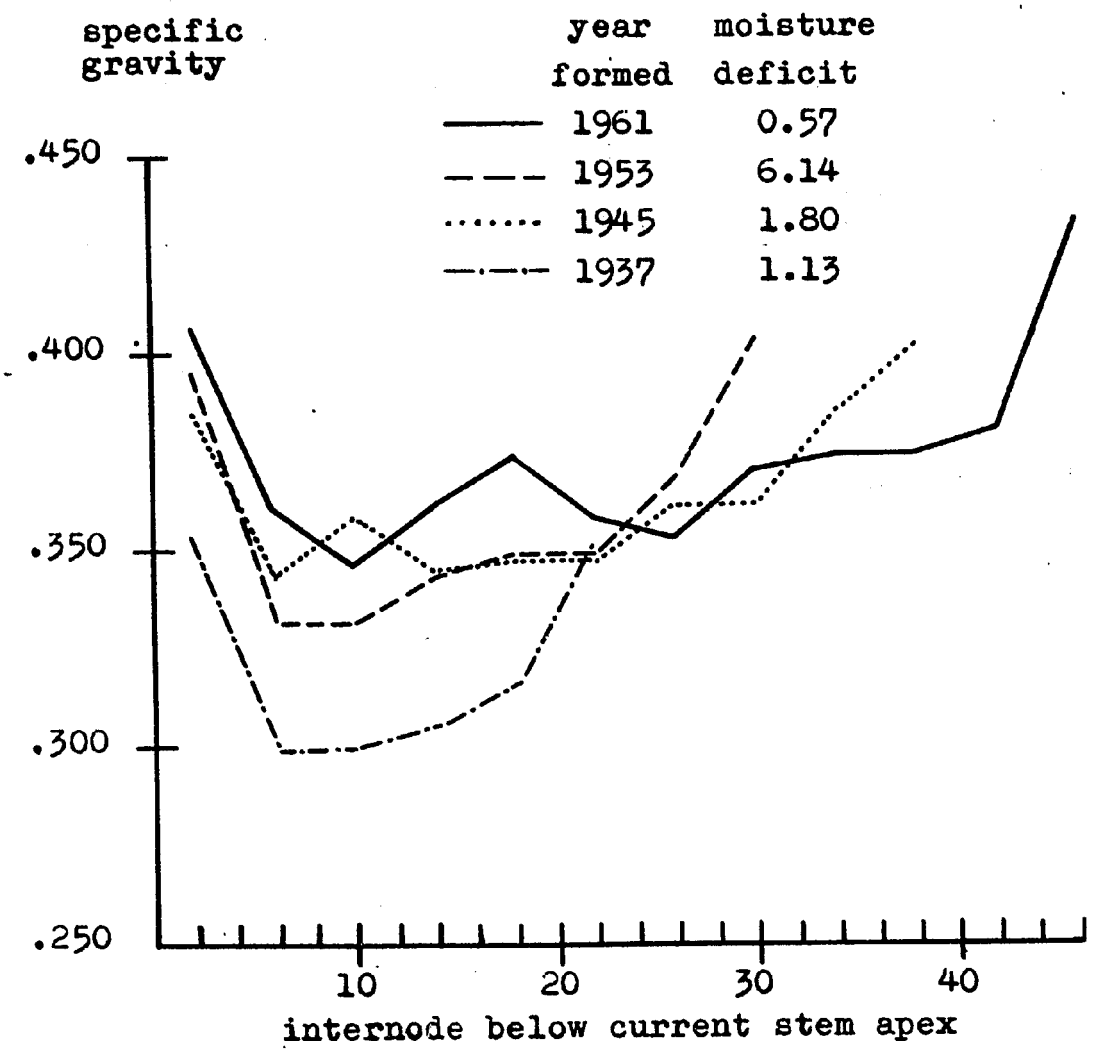


Figure 31. Oblique sequences for specific gravity. Soil moisture deficit in inches is for current 1 March to 31 October.

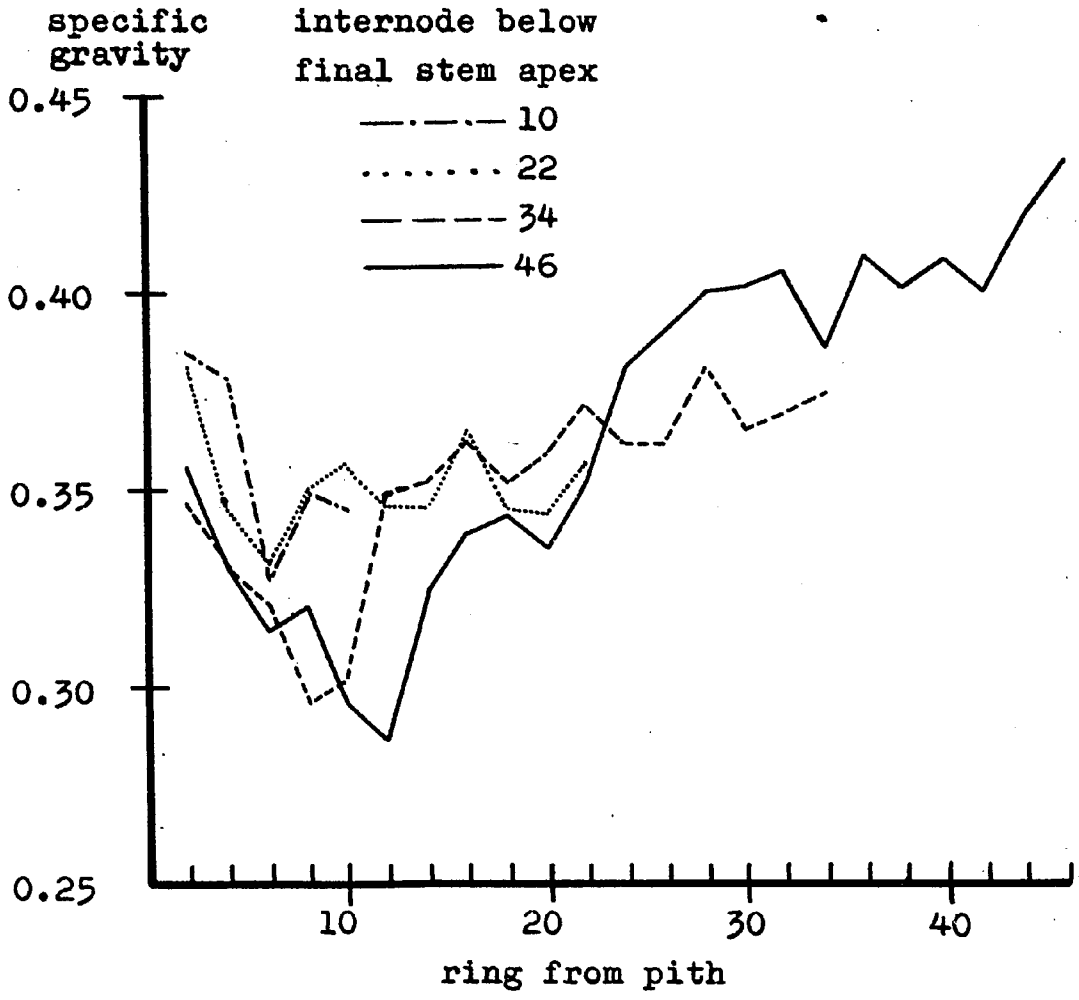


Figure 32. Horizontal sequences for specific gravity.

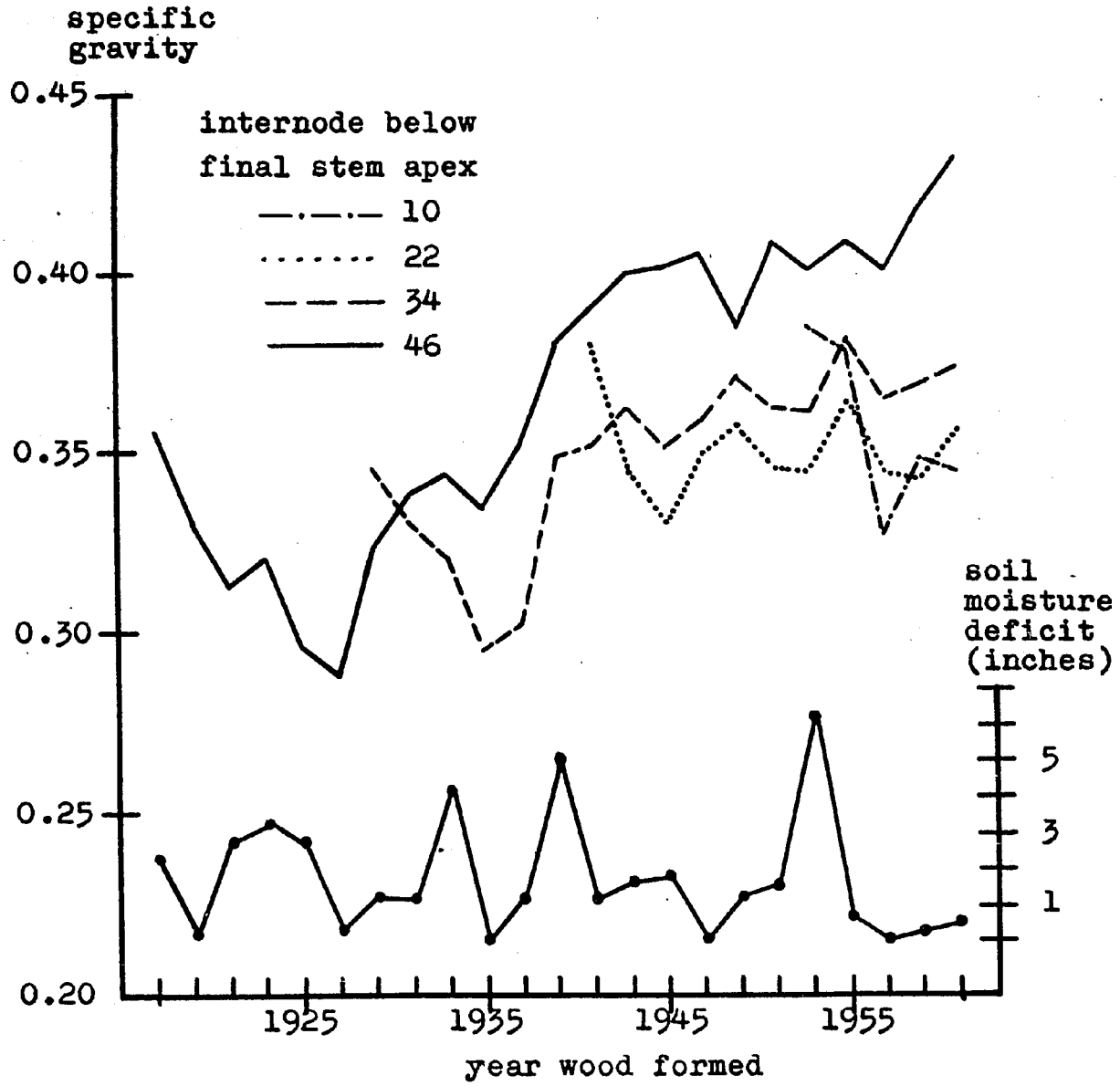


Figure 33. Horizontal sequences for specific gravity arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

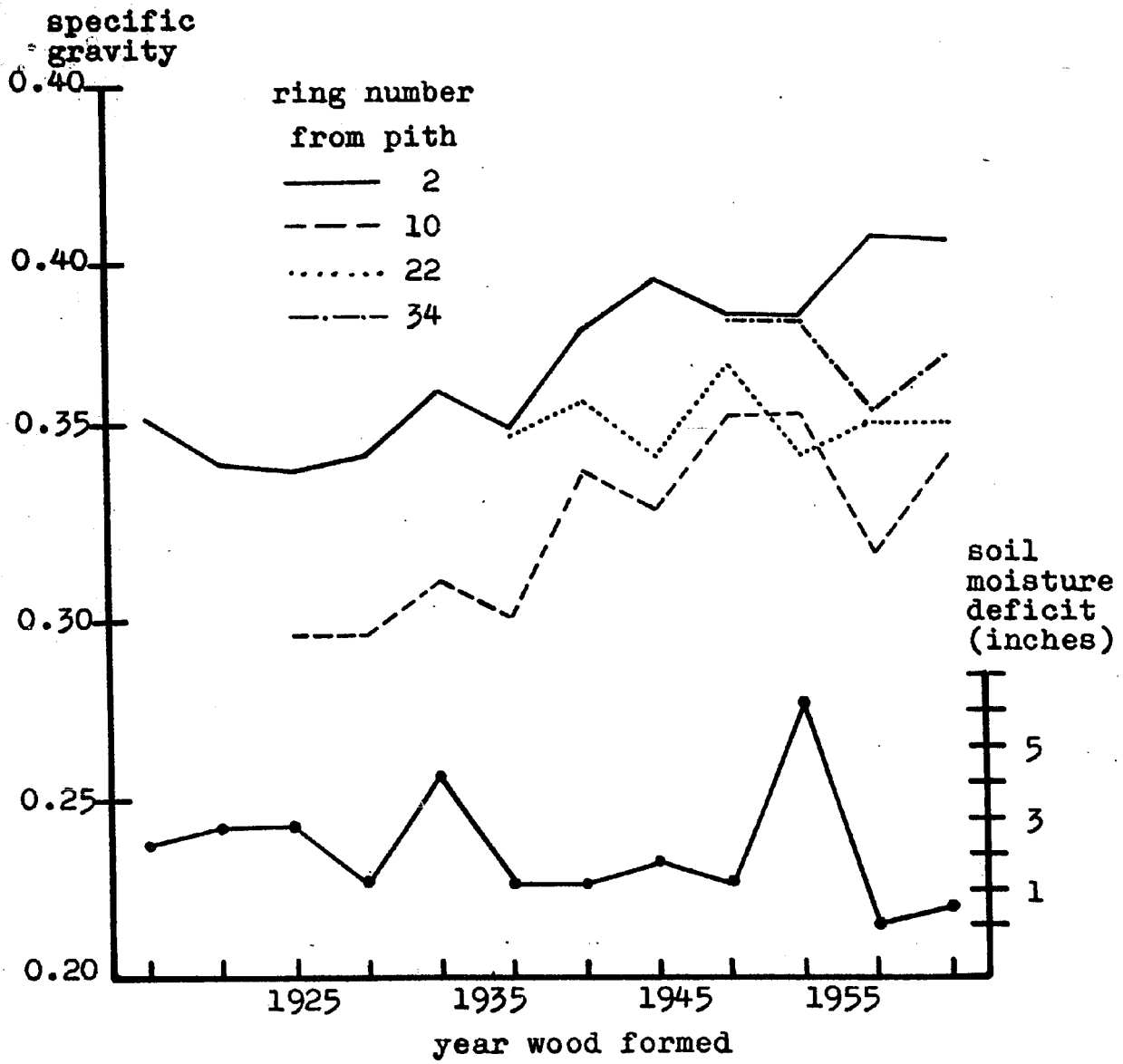


Figure 34. Vertical sequences for specific gravity arranged over year of wood formation and current 1 March to 31 October soil moisture deficit.

Horizontal sequence curves were derived from the regression equation:

$$Y = 0.321 - 0.00537X_1 - 0.00104X_2 + 0.0458X_4 + 0.00317X_8 + 0.145X_{10}$$

where X_1 = aspect

X_2 = internode from apex

X_3 = (internode from apex)$^{-1}$

X_8 = ring from pith

X_{10} = (ring from pith)$^{-1}$

This equation gave a coefficient of determination of 0.429 and a standard error of $\pm$ 0.028. None of the soil moisture variables tested added significantly to the value of R^2, and therefore are not included. The horizontal sequences are shown in Figure 35 and illustrate the continuing influence of position to the stem circumference. The vertical sequences in Figure 36 show with greater clarity the pattern, described in Figure 34, of gradually increasing specific gravity with increasing height in the stem for a given ring number from the pith.

While the present study by no means accounted for all of the variables affecting specific gravity of eastern white pine, since $R^2 = 0.429$, the data do indicate a repetitive annual pattern in the growth sheaths. The nature of this pattern is such that when horizontal sequences at given levels in the stem are examined, there emerges a curve showing a decrease in specific gravity

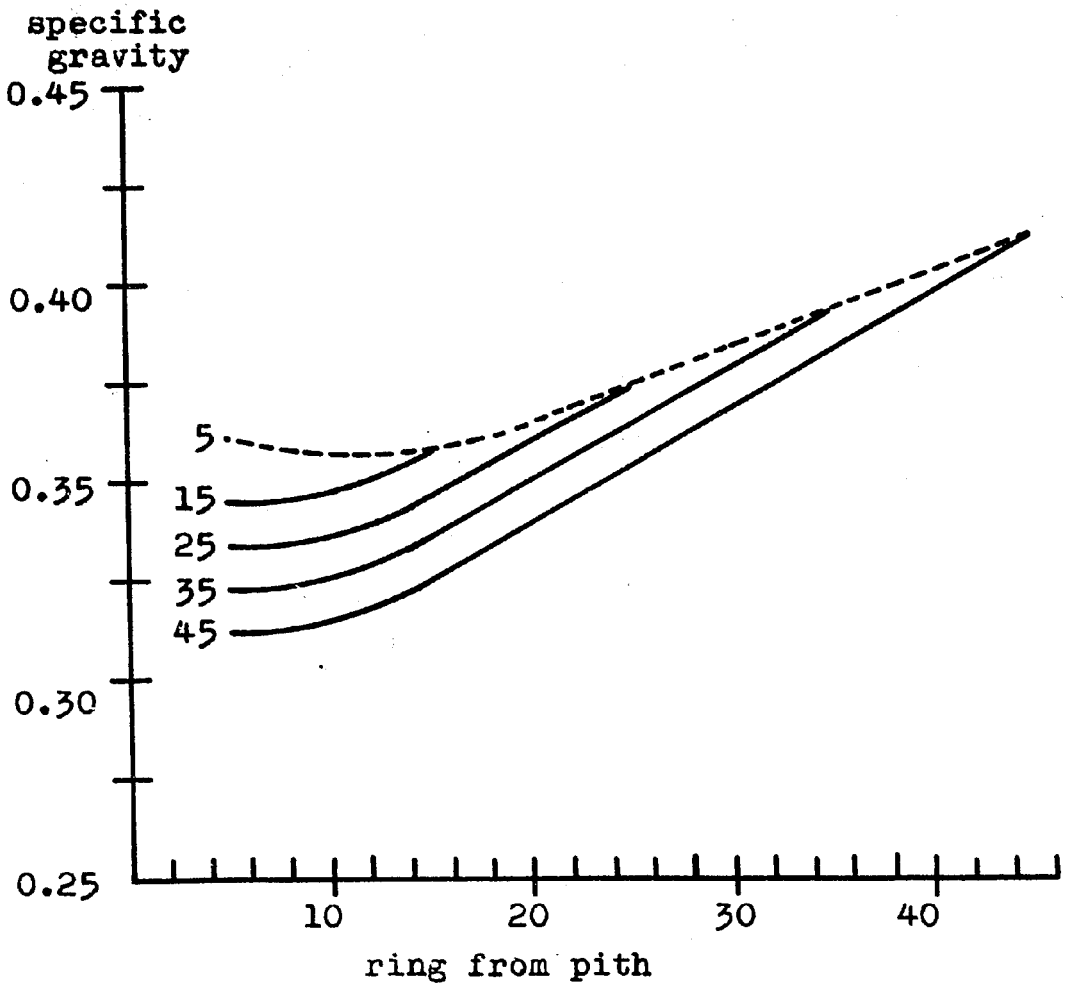


Figure 35. Calculated horizontal sequences for specific gravity. Numbers to the left of the curves indicate internode below stem apex. Broken line indicates oblique sequence for internodes 5 to 45 below the apex.

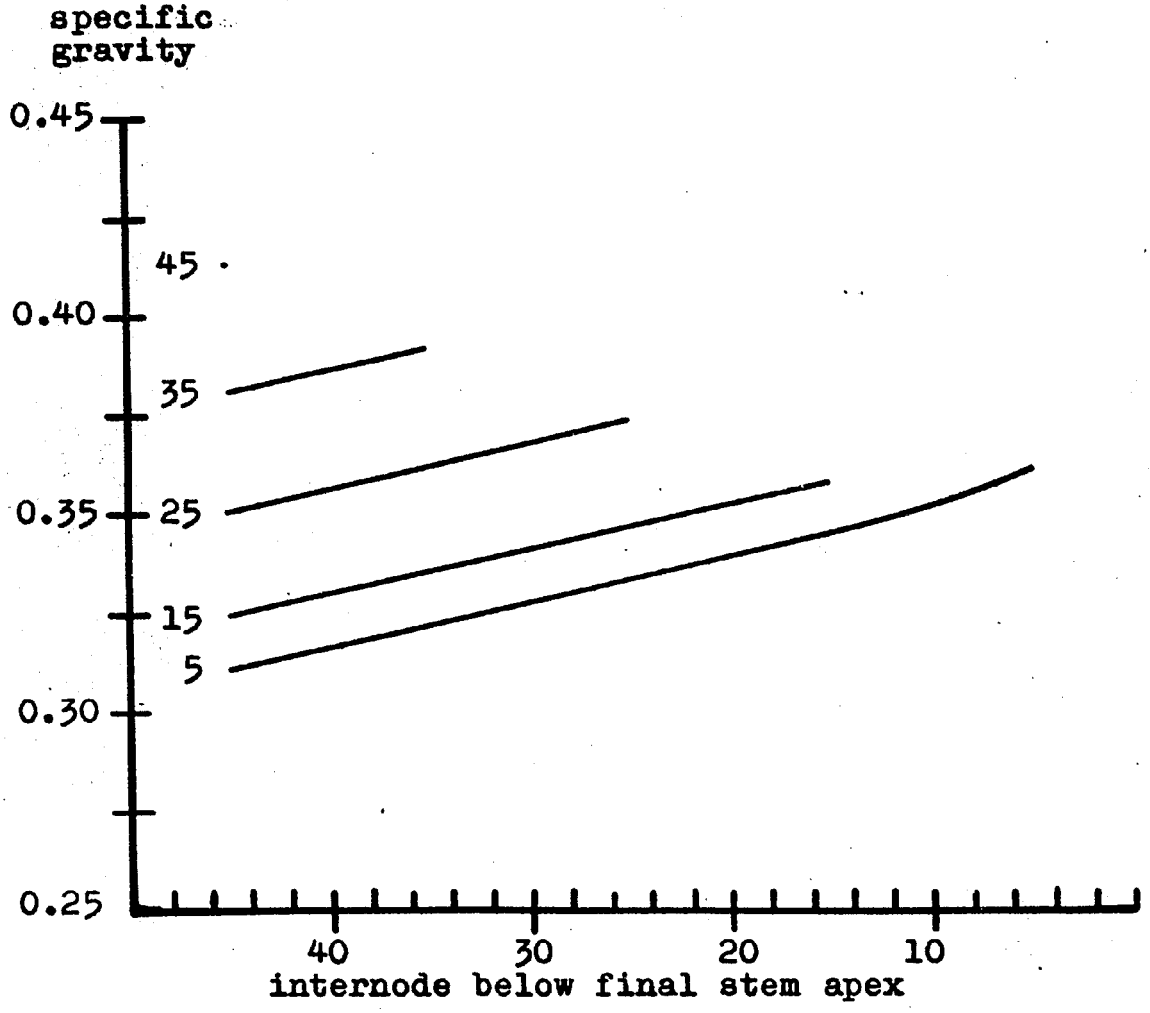


Figure 36. Calculated vertical sequences for specific gravity at five distances from the pith. Numbers to left of curves indicate ring from pith.

from the pith to ring eight, followed by a gradual increase from this point to the circumference. The specific gravity at the circumference is frequently as high as, or higher than, that found at the pith. Fluctuations accompanying changes in ring width or percentage of latewood, while consistent in direction, are slight in size. This is in substantial agreement with Paul's (1963) statement that eastern white pine shows little change in specific gravity with change in growth rate. The view of Fry and Chalk (1957) with reference to Pinus patula, that distance from the pith and ring width operate together in affecting specific gravity, appears applicable to eastern white pine, when the distance is measured in terms of annual rings. This pattern has been noted previously (Turnbull, 1947; Spurr and Hsiung, 1954) and generally ascribed to ageing of the cambium, which is indeed the case. However, ageing of the cambium at any level in a tree stem is accompanied by a concurrent increase in physiologic distance between the cambium and the upper whorls of the crown and the stem apex. It is this combination which primarily controls specific gravity.

There are no simple, complete answers as to what "controls" specific gravity. Indeed, the fact that it is so descriptive of the properties of the wood cell indicate that it is a reflection of many influences. In eastern white pine, specific gravity is affected by

fluctuation in ring width and percentage of latewood. Generally, specific gravity shows an inverse relationship with ring width, -.56, and a direct relationship with percentage of latewood, +.40, both correlations being significant at the one percent level. Thus, on following a growth sheath downward in the stem, the increasing ring volume occupied by cells with marked secondary thickening is associated with increased specific gravity of the entire ring. As noted in this study, both ring width and percentage of latewood are influenced strongly by the number of earlywood cells in the growth ring. Therefore, an obvious determinant of specific gravity is the number of earlywood cells in the growth ring. However, this structural characteristic is but the final result of an imperfectly understood complex of factors, both within and without the tree. In the final analysis, it is these factors which control specific gravity.

Summary of Results

Data from the three eastern white pine measured, indicated that the major structural characteristic of the three stems was the predominance of earlywood tracheids in the growth ring, and their resultant effect on the physical properties. The pattern of earlywood cell formation downward along a growth sheath showed a consistant increase in the number of tracheids from the second to the eighth internode below the stem apex, followed by a decrease in the number of cells from this point to the base of the sheath. The number of latewood cells in the growth ring was small and showed only a slight increase basipetally. While percentage of latewood rose consistently on moving down a growth sheath, the salient point is that this increase was due to a marked decline in the width of the earlywood component of the growth ring, emphasized by a modest increase in latewood width.

Regression analysis showed that number of earlywood cells and ring width fluctuated in association with soil moisture deficit for the period 1 March to 31 October of the year in which the ring was formed, wider rings being correlated with lower soil moisture deficits. While the number of latewood cells formed showed no statistical relationship with any of the soil moisture deficits tested, percentage of latewood varied with moisture availability between 1 June and 31 August of the current growing season.

The relationship was direct, higher latewood percentages being associated with higher soil moisture deficits.

Both the plotted observations and regression analyses showed that while the number of earlywood tracheids, ring width, and percentage of latewood fluctuate in association with soil moisture deficit levels, these are variations superimposed upon a more rigid pattern determined by position in the growth sheath relative to the uppermost portion of the crown and elongating shoots, both terminal and lateral. All three of these characteristics, and to a lesser extent number of latewood cells also, display a discernible repetitive pattern in which the relative value of one internode to another within a given growth sheath is largely predictable. The actual values within the growth sheaths will vary with fluctuations in the external factors.

Position within the stem is paramount in the longitudinal shrinkage and specific gravity patterns, as neither property showed a statistically significant association with any of the five soil moisture deficits. That an indirect association must exist between the latter and the two physical properties is apparent from the highly significant correlations of specific gravity with ring width and percentage of latewood, both of which vary with moisture availability. Further evidence of inter-relationships among the several dependent variables is apparent on

comparing the oblique sequence curves, the major downward inflexion in earlywood cell number and ring width curves occurring at approximately the same number of internodes below the current stem apex as does the primary upward inflexion in percentage of latewood and specific gravity, and the leveling of longitudinal shrinkage.

In all instances the primary controlling factor appears to be the number of internodes along a given sheath between the cambium and the most photosynthetically active part of the crown and the terminal meristem. While there may be superimposed annual changes in the levels of the curves, their basic form is constant. The data suggest that the major influence governing the patterns evident in the oblique sequence is the translocation of carbohydrate and growth regulators, or precursors of the latter, from the needles and apices of the uppermost branch whorls. The association ofwood property variation and soil moisture availability reflects, a) the indirect effect of increased internal water stresses as reflected in reduced rates of photosynthesis and translocation and, b) the direct effect of reduced cell turgor at the cambium with a slowing down of cambial metabolism and increased opportunity for secondary thickening to develop in the maturing tracheids.

Since specific gravity and longitudinal shrinkage are less pervious to environmental influences, the horizontal sequences give a reasonable approximation of varia-

tion along an oblique growth sheath, e.g. Figures 32 and 31, 26 and 25. Therefore, it would seem possible to predict these properties from a limited sampling base if desired, using the horizontal sequences derived from increment cores. Further, realizing that a pattern of variation does occur, one would agree with Richardson (1961) that the sampling point in a stem must be defined precisely in physiologic, rather than linear, terms if conclusions as to wood properties are to be made from such increment cores or a few wood samples. All data presented here indicate a relationship between property and the number of internodes which the sample site lies below the apex of the main stem. Therefore, sampling should be done not only between nodes, to avoid the effects of branch whorls immediately below a node, but on the basis of the number of internodes from the tree tip rather than height above ground.

As stated earlier in this paper, the pattern developed for three trees on a single site is only the first step in establishing a family of "behavior patterns" for eastern white pine. It should be possible to develop curves for other sites based on judiciously placed increment cores. These norms should provide a reliable basis for the comparison of wood properties among stems of different genetic composition, or between identical gene patterns grown on different sites. In addition, the in-

formation should contribute to the intelligent utilization of plantation grown white pine, much of which is harvested at a relatively young age and includes material in the zone of major change close to the pith.

Conclusion

All of the properties examined showed a definite pattern of variation relative to the stem apex. For number of earlywood cells and ring width, variation due to position in the stem was large, with an additional effect of current soil moisture deficit. Longitudinal shrinkage and specific gravity appeared virtually independent of moisture availability, and though the pattern due to position was well defined, the amount of variation was small. Thus the wood of eastern white pine is characterized by relative uniformity of longitudinal shrinkage and specific gravity beyond the tenth ring from the pith, at all heights in the stem and under varied soil moisture availability conditions.

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