BLACK ROCK FOREST

BULLETIN NO. 15

STUDIES OF THE ROOT SYSTEMS OF DECIDUOUS TREES

By

BENJAMIN B. STOUT

HARVARD BLACK ROCK FOREST
CORNWALL-ON-THE-HUDSON, NEW YORK
IN COOPERATION WITH
MARIA MOORS CABOT FOUNDATION
HARVARD UNIVERSITY
CAMBRIDGE, MASSACHUSETTS

1956

PRINTED BY HARVARD UNIVERSITY PRINTING OFFICE
CAMBRIDGE, MASSACHUSETTS, U.S.A.

CONTENTS

INTRODUCTION

Studies of species distribution as related to soils in the Harvard Forest (Stout, 1952) suggested that the root systems of the various species show characteristic patterns of distribution in the soil. The author was encouraged in this view by similar findings reported by other investigators, such as Laitakari (1927, 1934) and Pulling (1918). Furthermore, the advent of hydraulic methods for the excavation of tree root systems (Stoeckeler and Kluender, 1938; Hawboldt, 1952) bid fair to reduce materially the hitherto excessive costs of these operations.

The present paper records observations made during the excavation and study of the root systems of 25 trees in the Harvard Black Rock Forest. This material is presented on the following pages under two main headings. First is a description of the scene of the operations, and an account of the methods used. The second includes descriptions of the root systems excavated (by species), and a series of general observations and comparisons. Before these two sections is a brief review of pertinent literature; following them is a short discussion. The trees represented nine indigenous broad-leaved species. The excavations were made during 1951 and 1952.

It should be emphasized that the findings reported here are too few to form a basis for sound generalization about the structure and behavior of tree roots. Far more excavation is needed before such a basis will appear. Consequently, the "discussion" is limited to a few of the observed phenomena that seem to be reasonably well established, such as the average root-crown ratio, the response of roots to release, and the differences in the depth of root penetration that are exhibited by some of the trees.

ACKNOWLEDGMENTS

The writer is indebted to several individuals and agencies for the opportunity to complete this study: to the Maria Moors Cabot Foundation for generous financial support; to Mr. Timothy G. Stillman for the loan of water-handling equipment; to Professor Hugh M. Raup and Dr. John C. Goodlett for criticism and suggestion; and to the writer's assistants, Messrs. Herbert Tepper and Martin Brinckerhoff, who shared the idiosyncrasies of a two-cycle engine and the inevitable soaking with water. To each go special thanks and appreciation.

REVIEW OF LITERATURE

The number of published papers that deal with the morphology of the root systems of trees beyond the seedling stage and approaching maturity is rather restricted. For the most part the studies of tree root systems have dealt with four characteristics of form and behavior: depth of penetration, tendency to concentrate, areal spread, and growth in terms of bole and crown increment as it may be influenced by the roots.

With regard to the depth of penetration, Laitakari (1927, p. 358) concluded that the mean depth of the horizontal roots of Scotch pine is greater in older trees and on better sites. After completing his studies of birch he said that birch has a deeper system than pine on similar soils (1934, p. 200). Pulling (1918), working in Ontario and northern Michigan, concluded that some species are characterized by shallow and others by deep root systems. He also noted that the roots of some species are rigid (i.e., inflexible, or non-adjustable) in formation, while others are quite flexible and can cover a wide range in depth. He related the distribution of species from the arctic treeline southward to their relative rigidity or flexibility, and hence to their adaptability to varying soil depths. The soils may be shallow over perennially frozen ground or bedrock at one extreme, and deep on ground without permafrost or on glaciofluvial deposits at the other extreme. Vater (1922), working in Germany, noted that the depth to which roots penetrate is influenced by soil texture and soil humidity. Larson (1943, p. 9) expressed the opinion that "soil temperature appeared to be the factor controlling the depth of penetration of vertical roots" in 4- and 5-year-old Scotch pines.

Gaiser and Campbell (1951), who studied white oak in southeastern Ohio, discussed the concentration of roots. According to them (p. 11), "Root concentrations are influenced by the permanent wilting percentage in the A2 horizons, and it is likely that the volume weight, availability of moisture, and other soil characteristics affect concentrations in that and other horizons." Larson, working with 4- and 5-year-old Scotch pines in sandblow areas in Vermont, concluded (1943, p. 9) that "Roots showed a distinct tendency to concentrate in the A horizon . . . In all plots but one, 70 percent or more of the roots observed were concentrated within the surface foot of soil."

In discussing the areal spread of tree root systems, Laitakari (1927, p. 342) wrote that "the correspondence between the direction of the horizontal root and the crown is extremely weak." He stated also (1927, p. 344) that "differences in plant nutrients in the soil and moisture may very likely guide the direction of the horizontal root system." To illustrate the effect of differences in soil moisture upon orientation of a root system, he cited the case of a tree that was growing on a moor adjacent to a drainage ditch. According to Laitakari (1927, p. 344), "the main part of the root system tends . . . towards the ditch, or in other words towards more favorable moisture conditions." Laitakari also concluded that the area of a root system varies with soil texture — the coarser the soil the more wide-spreading the system. Garin (1942) came to a similar conclusion from studies in Connecticut, and Larson stated (1943, p. 10) that "soil composition has a marked influence upon the area of spread of root systems. In proportion to top growth, the greatest area of spread was attained by root systems in soils containing 95 percent or more of sand." McQuilkin (1935) suggested that a root system reaches a maximum spread and then proceeds to occupy more and more of the soil within the area of maximum spread. This spread, using the longest lateral as an indicator, is one and one-half times the height of the tree. His observations were based on work with pitch and shortleaf pines in the coastal plain of southern New Jersey.

The relationships between stem growth and root development were mentioned by several workers. According to McQuilkin (1935, p. 1014), the productive capacity of the root system is reflected in the crown: "Poor development of tops is associated with inferior root systems." Larson stated (1943, p. 11) that the "total height growth and annual height growth are highly associated with the volume of the root system." Greenidge (1953, p. 557), working with birch dieback on Cape Breton Island, showed a relationship between rootlet mortality and crown injury in yellow birch. On the other hand, Gaiser and Campbell concluded (1951, p. 7) that "root concentration in itself appears to have little influence on growth." They noted that root concentrations are not perceptibly different on good as opposed to poor sites, and that poorer sites may show higher concentrations of roots.

An extensive bibliography on roots has been published by Dunning (1949).

STUDY AREAS

The tree root systems described in the present paper were all located in the Harvard Black Rock Forest, which is in the towns of Cornwall and Highlands, Orange County, New York. The Forest is in the northern part of the Hudson Highlands immediately west of the Hudson River. Within the Forest the rolling upland ranges in altitude from 450 to over 1400 feet. The crystalline bedrock frequently is exposed at the higher levels, but is otherwise clothed with glacial till of Wisconsin age. At higher levels this till is thin and scattered, though on the lower northern slopes it forms a deep mantle. The thin tills of the upper slopes, and the surface layers of the thick tills, are weathered congeliturbates formed by the reworking of these materials by processes associated with a periglacial climate. (See Denny, 1938. In Denny's paper the surface materials now grouped under the term "congeliturbate" were called "warp.")

The forest cover, primarily of deciduous trees, is varied in form and species composition. Higher elevations have pitch pine-scrub oak, white oak-hickory, and chestnut oak types. Coves and lower slopes carry forests of mixed composition in which red oak, chestnut oak, sugar maple, white ash, linden and tulip trees are prominent, together making a type-complex reminiscent of the "transition hardwoods" of central New England (Raup, 1938).

The root systems studied were in five localities within the Forest. All of them are in the upland area characterized by patches of relatively thin congeliturbate scattered among bedrock outcrops.

Black Rock Brook

The surface here slopes downward at 35 to 40 percent in a west-southwesterly direction. The depth of the soil materials ranges from a few inches at points upslope near rock outcrops to at least three feet in the vicinity of tree No. 1, a chestnut oak. Four systems were studied: one each of red and chestnut oak, and two of sugar maple.

Alec Meadow

This locality is near the top of a gravelly kame terrace, and slopes downward to the south-southeast. A gravel pit nearby, on another slope of the terrace, is 40 feet deep. Four trees were excavated: one each of red maple, beech, black birch, and chestnut oak.

Beaver Swamp

Here the surface slopes at 15 to 25 percent, with a southeasterly exposure. There is an outcrop of bedrock between the locations of trees 10–18 and 19–21; yet under none of the root systems was bedrock encountered. Eleven systems were excavated: two of chestnut oak, two of red oak, three of white oak, two of red maple, one of pignut hickory, and one of sugar maple.

PLATE I. Following a single root. Cutting hose works fine material down to flushing hose. Trees are white oaks, Nos. 17 and 18.

PLATE II. General view of No. 4, a sugar maple, showing string grid in place for mapping.

Sutherland Pond

The north end of Sutherland Pond is the only locality in which bedrock was found immediately beneath the root systems studied. In the area as a whole the soil depth ranges from 0 to at least 24 inches. The surface slopes gently (20 percent gradient) to the west. Three systems were studied: one each of chestnut oak, red oak, and white ash.

Jim's Pond

The exposure here is southerly, on a 35 percent slope. Two trees were excavated: a white oak and a chestnut oak. The trees were 25 feet from the margin of the pond, eight and ten feet above it, and growing in soil material having a depth of at least 36 inches. No bedrock was encountered.

METHODS OF STUDY

The root systems were exposed for study by washing away the finer-textured soils around them, and lifting out coarser materials by hand. Such root washing requires (1) an abundant source of water, and (2) a slope of at least 20 percent with no hindrance to drainage. Heavy concentrations of boulders cause serious difficulty.

The pumping equipment used was of two types: (1) a portable pump with a two-cycle gasoline engine, and (2) a trailer-mounted fire pump with a four-cylinder gasoline engine. When the latter was used, two hoses were laid to the washing site, one for the initial cutting and the second for flushing (Plate I). When the small pump was used, only one hose could be supplied.

Before exposing the root system of a tree, the lateral extent of its crown [1] and the location of adjacent trees were mapped at a scale of 5 feet to 1 inch. The tree was then cut, and its trunk saved to be sectioned later for stem analysis. All soil material for a distance of two to four feet around the stump was washed away to a depth sufficient to expose the root crown. Then two to four roots in each quadrant were selected for detailed study. The entire root system of the first few trees was exposed. This was overly time-consuming, and the selection of roots from each quadrant seemed a fair and more efficient means of getting the information desired. Because determination of maximum spread was a primary objective, the largest roots in each quadrant were selected. The individual root was followed to

[1] This mapped representation of a tree crown will hereinafter be referred to as the "crown projection."

its end except in cases where it lay beneath a large tree or an immovable boulder.

After the individual roots had been exposed, a grid was laid out over the system using twine (Plate II). With the aid of the grid, the system was mapped at the same scale as that used for the crown projection (Appendix). The roots were not drawn to scale in cross section.

During the washing process, measurements were taken to determine maximum, minimum and mean depth figures for the lateral roots beyond the zone of rapid taper. Upon completion of the mapping, the longest root exposed was sectioned at four-foot intervals for analysis.

Ratios between the area covered by the root systems and the area covered by the crown were determined by planimetering the respective areas on the root maps (Appendix). The area for the root system was measured by drawing straight lines between the mapped root ends. In all probability this procedure gives a conservative figure. The actual periphery may be rounded rather than straight sided. Furthermore the largest root at the stump may not be the longest.

DESCRIPTIONS OF ROOT SYSTEMS EXPOSED

Twenty-five root systems, representing nine species of native deciduous trees, were excavated and studied. Twenty-one of the trees were growing in moderately well-drained, loamy till soils, and four of them in glacio-fluvial sand and gravel. All were on slopes of 20 percent or steeper. They ranged in age from 16 to 104 years, though 68 percent of them were aged 40 years or over. In nearly all cases their crowns formed a part of the closed canopy of the forest. Table 1 lists their heights, diameters, ages, areas and depths of root systems, areas of crown projection, and the ratios between the areas of their root systems and of their crown projections.

Chestnut Oak

Seven chestnut oak roots were exposed, at least one at each of the five localities. The photographs show that the larger roots are widely spaced (Plate III). The small roots (less than .25 inch in diameter) are matted near the surface. The depth of the roots at the stump covers a range of 25 inches, from 18 inches over bedrock to 43 inches in the kame terrace. The maximum depth of the laterals falls within a narrower range: between 21 and 36 inches. The 21-inch depth was found over bedrock, and the 36-inch depth was found in a thick deposit of loam. In the kame terrace the depth was 24 inches.

TABLE 1

Tree No.	Species	Age	Ht.	DBH	Root Depth at Stump	Depth of Laterals Min.	Depth of Laterals Mean	Depth of Laterals Max.	Crown Sq. Ft.	Roots Sq. Ft.	Ratio	Location
1	CO	82	57′	8.2″	20″	0″	12″	36″	123	527	4.3:1	Black Rock
8	CO	63	58	7.8	43	0	17	24	176	788	4.5:1	Alec Meadow
10	CO	17	33	3.4	26	0	15	21	15	610	40.7:1	Beaver Swamp
12	CO	17	33	3.0	30	0	16	24	23	88	3.8:1	" "
15	CO	16	27	1.8	22	0	18	22	13	65	5.0:1	" "
21	CO	37	33	4.6	18	0	12	21	23	147	6.4:1	Suth. Pond
25	CO	70	40	6.5	36	0	10	25	95	512	5.4:1	Jim's Pond
17	WO	40	33	6.5	42	0	20	36	178	608	3.4:1	Beaver Swamp
18	WO	41	33	7.2	40	0	21	40	104	496	4.8:1	" "
20	WO	19	25	3.0	36	0	18	26	21	99	4.7:1	" "
24	WO	68	39	6.4	34	0	14	34	109	635	5.8:1	Jim's Pond
2	RO	84	64	10.2	24	0	12	24	208	724	3.5:1	Black Rock
14	RO	17	23	1.5	25	0	12	18	18	147	8.7:1	Beaver Swamp
19	RO	17	22	2.5	21	0	13	19	45	211	4.7:1	" "
22	RO	73	49	6.6	22	0	8	18	77	357	4.6:1	Suth. Pond
3	SM	77	39	5.4	18	0	8	18	27	748	26.2:1	Black Rock
4	SM	104	67	9.3	28	0	8	22	206	1112	5.4:1	" "
16	SM	61+	38	5.8	27	0	7	26	172	1130	6.6:1	Beaver Swamp
6	RM	55	34	2.8	48+	0	6	17	33	408	12.2:1	Alec Meadow
9	RM	60	39	4.4	12	0	8	14	191	662	3.5:1	Beaver Swamp
11	RM	43	34	3.8	22	0	8	12	15	358	23.9:1	" "
23	WA	71	45	5.8	18	0	3	12	22	574	26.1:1	Suth. Pond
13	Hic.	42	44	3.5	36	0	12	24	36	525	14.6:1	Beaver Swamp
5	Beech	53	21	2.7	60+	0	8	20	81	312	3.9:1	Alec Meadow
7	B. Bir.	34	38	3.8	48+	0	2	7	40	244	6.1:1	" "

The root-crown ratios range from 3.8:1 (Tree No. 12) to 40.7:1 (Tree No. 10). In the ratios the relative area of the root system is given first. However, tree No. 10 is a sprout clump, and the root system is much older than the aerial portion. The stem was 17 years old, and the sectioned root was 39 years old. If this tree is eliminated, the root-crown ratios range from 3.8:1 to 6.4:1, and are commensurate with the ratios obtained for the other species studied.

The small roots that formed the mat near the surface were vertical branches of the laterals. The roots were branching in two directions, parallel to the ground surface, and normal to it. The initial impression was that the roots had reached maximum length and were no longer elongating. Closer examination showed that at the time of branching the verticals were dominant and the parallel ones grew more slowly. Near the ends of most roots, where they turned up to the surface, a smaller branch was found that continued parallel to and well below the ground surface. This rooting habit is characteristic of all the species studied.

White Oak

The root systems of four white oaks were exposed, three at Beaver Swamp and one at Jim's Pond. The white oaks showed the deepest root systems of any species studied, both at the stump and along the laterals. The depths at the stump had ranged from 34 to 42 inches. The laterals had a wider range, from 26 to 40 inches. Bedrock was not exposed under any of these systems. Like chestnut oak, the main branches of the root systems of the white oaks were rather widely spaced, presenting an open appearance. A mat of smaller roots was formed at or near the surface (Plate IV). Root-crown ratios ranged from 3.4:1 to 5.8:1.

Red Oak

The root systems of four red oaks were exposed, two at Beaver Pond and one each at Black Rock Brook and Sutherland Pond. The depth of the roots at the stumps ranged from 21 to 25 inches, the narrowest range of any of the three species of oak. The depths of the laterals, both mean and maximum, also fell within narrow ranges — four and five inches, respectively. The red oak systems appeared to have more roots per unit volume than those of the other oaks. However, the mat of small roots near the ground surface was not as pronounced as in the chestnut and white oaks. Rather, the small roots were more evenly distributed throughout the soil materials. Root crown ratios ranged from 3.5:1 to 8.7:1.

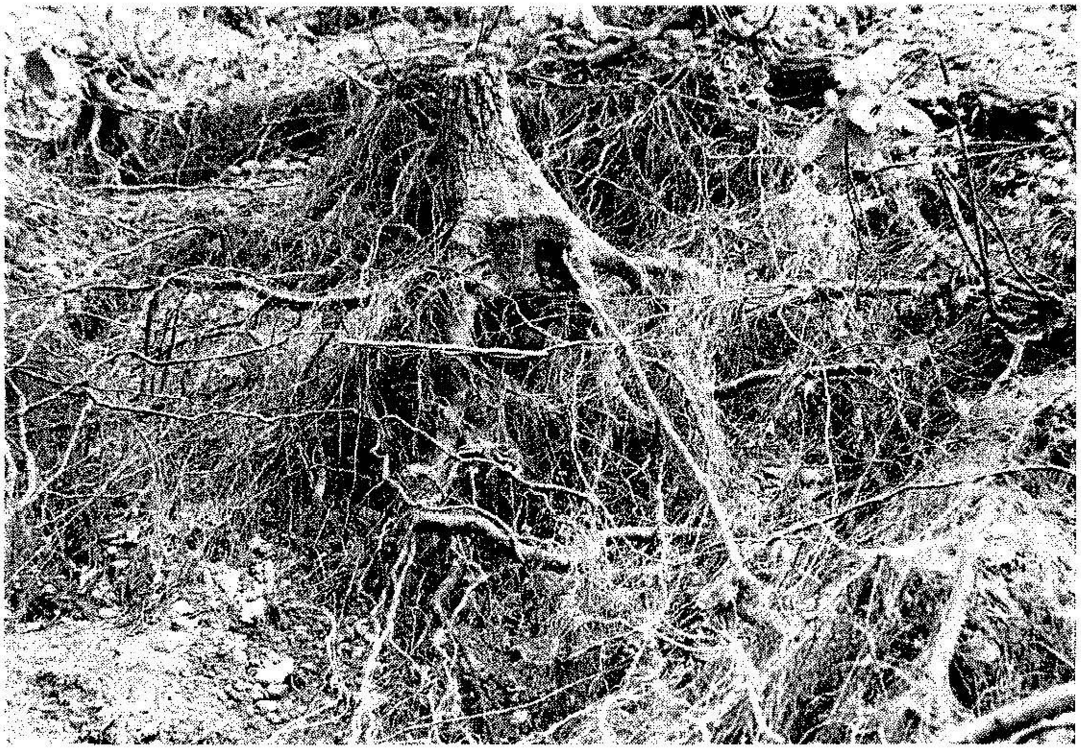


PLATE III. Chestnut oak on kame terrace.

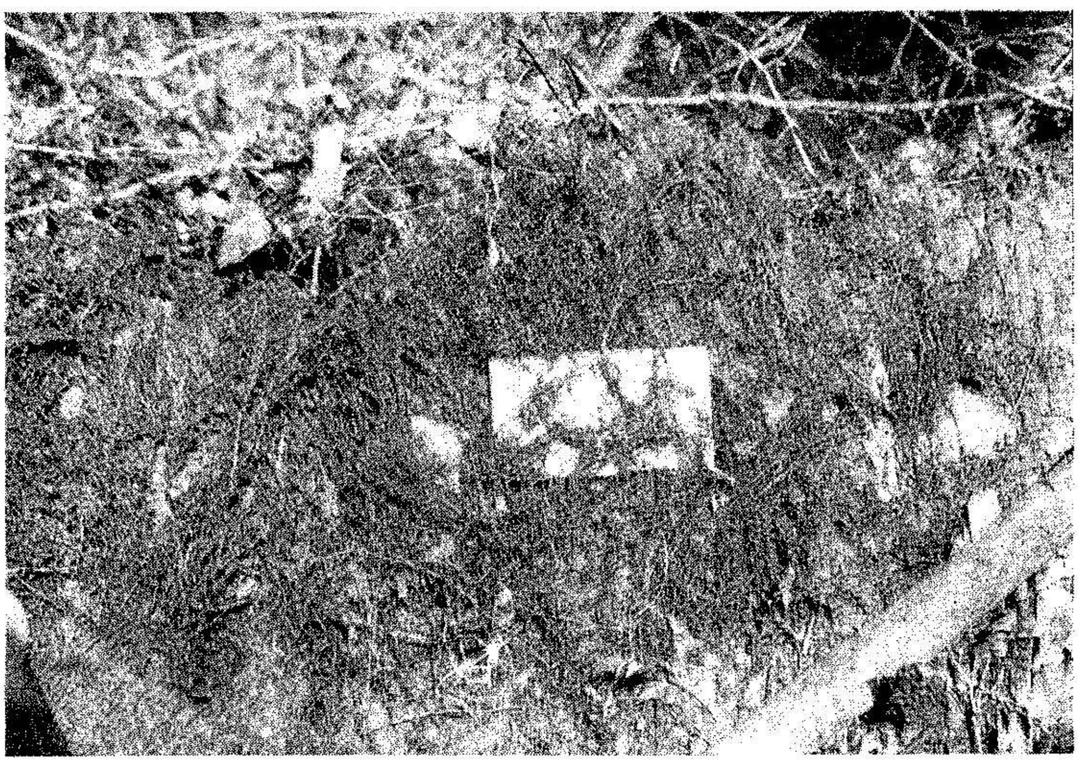


PLATE IV. Mat of small white oak roots near ground surface.

PLATE V. Hickory (No. 13). The crossed sticks at the root collar are each 24 inches long. These roots are straighter than those of other species studied.

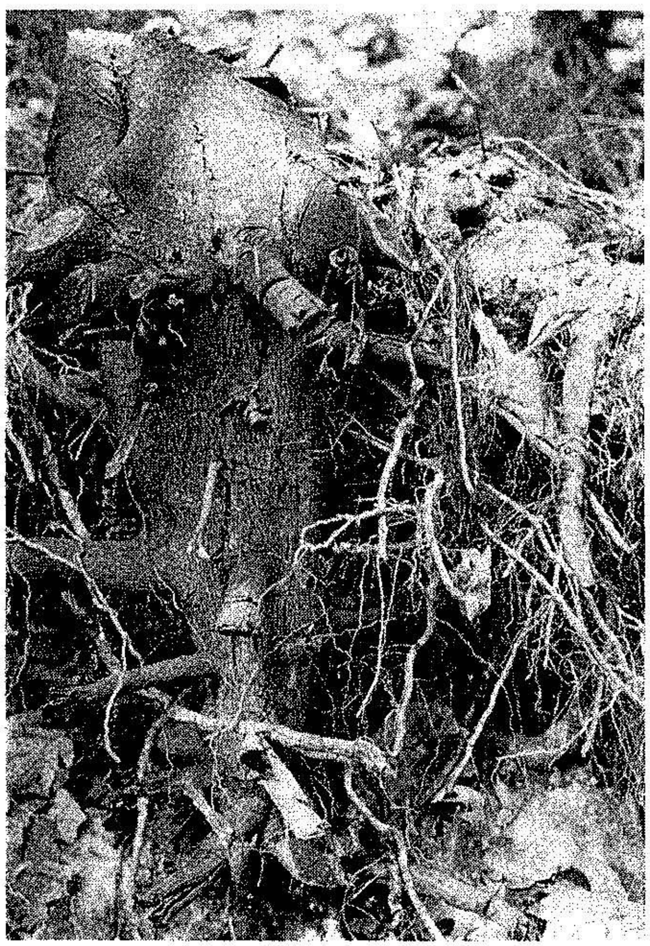


PLATE VI. Taproot of pignut hickory (No. 13).

Sugar Maple

Three sugar maple root systems were washed out, two at Black Rock Brook and one at Beaver Swamp. Roots ranged in depth from 18 to 28 inches at the stump. The shallowest system was that of a suppressed tree of sprout origin. The same sprout had the largest root-crown ratio among the sugar maples, 26.2:1. The other two sugar maples had root-crown ratios that were similar to those found for the oaks, namely, 5.4:1 and 6.6:1. The mean depth of the sugar maple laterals was quite shallow, 7 to 8 inches.

Red Maple

The root systems of three red maples were washed out, one on the kame terrace at Alec Meadow and two at Beaver Swamp. The depths of the red maple roots at the stumps, 22, 12, and more than 48 inches, had the widest range of any species studied. The mean depth of the laterals did not show a similarly wide range, and approximated that of sugar maple, 6 to 8 inches. The root-crown ratios for the systems were quite far apart. On the kame terrace the ratio was 12.2:1, and on the loam 3.5:1 and 23.9:1. The latter was a sprout that came up following a thinning in 1934.

White Ash

The white ash, located at Sutherland Pond, was growing above the red oak that was studied there. The age, height and diameter figures given in Table 1, strongly suggest that this is not an ideal site for the ash. This is further suggested by the two outsized roots that extended downhill to the bottom of the slope just above the level of the pond and within 75 feet of it.

Pignut Hickory

The hickory at Beaver Swamp showed a taproot which extended downward 36 inches to a compact horizon. The lateral roots grew in nearly straight lines (Plate V, and Tree No. 13, Appendix) as compared to the roots of the other species. Further, the laterals originated along the entire length of the taproot. The taproot itself was without severe distortion, except at the points of origin of the lateral roots, and resembled an inverted cone (Plate VI).

Beech and Black Birch

The root systems of one beech and one black birch that grew on the kame terrace at Alec Meadow were exposed. The depth of the beech roots at the stump was more than 60 inches; the depth of the birch roots at the stump was more than 48 inches. These depths are as great as or greater than those recorded for a chestnut oak (No. 8) and a red maple (No. 6), that were excavated on the same kame terrace. Although all four species showed similar root depths at the stump, the lateral branches grew in different levels. The mean depths of the lateral roots were as follows: black birch, 2 inches; beech, 8 inches; chestnut oak, 17 inches; and red maple, 7 inches. The root-crown ratios of the birch and beech were 6.1:1 and 3.9:1 respectively. The root system of the beech showed the only root sucker that was found. The beech that was studied may have originated as a sucker. Nearby was a beech 12 inches DBH that could well have been the mother tree for all the beech in the vicinity.

GENERAL CHARACTERISTICS OF ROOT SYSTEMS STUDIED

Variations in Numbers and Dimensions of Roots

The number of roots in each root system varied widely among the 25 that were studied. Tree No. 8, a chestnut oak, had 34 roots over one inch in diameter 6 inches from the stump; Tree No. 9, a red maple, had 14 of similar size.

Near their points of origin roots have a region of pronounced taper. In the root systems examined, pronounced taper did not continue more than three or four feet away from the stumps. Beyond this distance the roots usually maintained relatively uniform diameters for many feet. However, in some instances roots were larger at 20 feet from the stump than at 10 feet.

When a living tree is overturned, the roots usually break where the pronounced taper diminishes. This observation is based upon the examination of trees overturned by high winds in the period between 1950 and 1954. Root sections showed that the pith in the pronounced taper areas was well off center, and located near the bottom of the root. Beyond the area of pronounced taper the cross sections showed the pith to be at or near the center of the root.

Depth of Root Penetration

In the root systems of chestnut oak, red oak, white oak, and sugar maple on the loamy till soils, the distance from the ground surface to the deepest point of root penetration at the stump varied with the species. The mid-points between the shallowest and deepest penetrations for each species can be arranged in a rough series: sugar maple, 23 inches; red oak, 23 inches; chestnut oak, 27 inches; and white oak, 38 inches. Sugar maple is placed before red oak because its shallowest depth was 18 inches as compared to 21 inches for the red oak. The chestnut oak follows red oak because the 18-inch penetration of the chestnut oak was in thin soil over bedrock at Sutherland Pond.

The roots of the four trees, beech, black birch, chestnut oak and red maple, growing on the kame terrace, reached depths that were not possible on the loamy till soils, because no bedrock or impervious layer exists in the terrace. The red maples, which showed the widest range of depth penetration under the stump, 12 to over 48 inches, had their greatest depth on the terrace.

The main branches of the root systems, away from the stump, were generally found nearer the ground surface, both in till and glacio-fluvial soil materials, than the deepest roots at the point of origin. They showed a characteristic range in depth, according to species, similar to the sequence of depths at their points of origin: sugar maple, 7 to 8 inches; red oak, 8 to 13 inches; chestnut oak, 10 to 18 inches; and white oak, 14 to 21 inches.

The only taproot was found in the hickory system. If the other species had developed taproots in youth, these had lost their identity as taproots by the time the washing occurred.

Root Grafts

Root grafts between roots of the same species were common in those parts of the systems that were crowded. Usually the root grafts were found within 3 or 4 feet of the stumps. At least six grafts are visible in the two root systems (Trees 17 and 18) shown in Plate VIII. One count made on these two systems gave a total of 24 grafts; there may have been more. A root from tree No. 22, a red oak, had grafted to a root from a neighboring red oak at a point 12 feet from its point of origin. Bedrock was only three inches below the surface at this point and the crowding was equal to that near the points of origin.

Morphology of a Root System

A root system has three rather distinct parts: 1) the root crown, 2) that portion of the roots that has pronounced taper, and 3) the area beyond the pronounced taper where the roots meander and intermingle (Fig. 1).

The root crown, which here includes the bases of all the laterals and the concentration of small roots immediately beneath the root crown, is the point of origin for all the lateral roots. The figures in Table 1 for depth at the stump are the distances from the ground line to the point of deepest penetration of the small roots at the base of the spheroid root crown. The spherical shape of the root crown can best be observed when old stumps are overturned.

The pronounced taper section provides the lateral support or anchorage for the tree. The roots, elliptical in cross section, give maximum resistance to a force that would tend to push the bole and crown from the vertical. As a whole, the area of pronounced taper resembles a low, wide-based cone with the root collar at the apex.

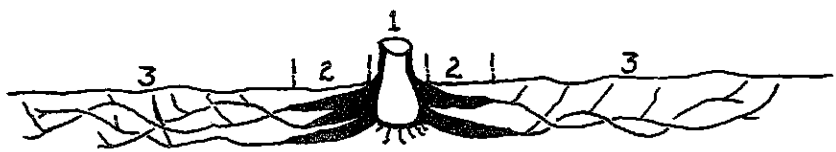


Fig. 1. Diagrammatic sketch of the root system of a typical non-taprooted tree. 1 Root crown section. 2 Rapid taper section. 3 Terminal section.

Lateral roots arising from the taproot of the hickory (No. 13) did not have the pronounced taper found in the other species. The laterals originated all along the taproot from the ground level to the tip (Plate VI).

The third part of the typical root system consists of the laterals beyond the zone of pronounced taper. The roots are usually round in cross section with the pith in the center. If this part of the root system serves any purpose in keeping the tree standing, it would be to tie down the pronounced taper section. The individual roots are found at varying levels, now deep, now close to the soil surface, within the limits described earlier for the several species. The horizontal meanderings are shown in the root maps in the Appendix.

Areal Patterns of Root Systems

Root systems viewed from above may be either round or elliptical in general outline. They may be more or less symmetrically arranged around the stump, or mostly upslope or downslope from the stump, or to one side or the other. The most nearly circular systems were in trees 2, 5, 10, 11, 12, 13, 15, 17, 18, 19, and 24. This list includes at least one each of the following species: red oak, chestnut oak, white oak, red maple and hickory. One chestnut oak (No. 1) and one red maple (No. 6) had elliptical systems. Trees with root systems mostly upslope from the stump were Nos. 4, 7, 14, 21, and 25. The species, in order, were: sugar maple, black birch, red oak and two chestnut oaks. A chestnut oak (No. 8), a red maple (No.

9), and a white oak (No. 20), had most of their root systems downslope from the stump. The trees with root systems to one side, but above and below the stump, were two sugar maples (No. 3 and No. 16), a red oak, (No. 22), and a white ash (No. 23).

Because the general outlines of the root systems are the sum total of the growth patterns of the individual roots, the following notes on the behavior of single roots may have some significance. The direction in which a root departs from the stump is not always indicative of its later course. At least one root in each system exposed had some abrupt directional change. Tree No. 6, a red maple, and tree No. 17, a white oak, had the most elaborately looped roots. One of the red maple roots changed direction three times and then followed a course along the contour of the slope.

The direction of root growth away from the stump appears quite unpredictable from the data at hand. The systems are variable in the extreme, and the erratic behavior of the individual roots is not easily interpreted. The red maple described above (Tree No. 6, Appendix) grew on a kame terrace, and in view of the fact that roots on the gravel bank side of the terrace have been found mostly in lenses of fine materials, it is entirely possible that the long root grew in a layer of fine material. The presence of a body of water nearby may have influenced three of the elliptical systems. The two chestnut oaks that had most of the roots upslope from the stump were growing near ponds. The form of the white ash system is the result of two roots that extend downslope toward the level of a pond. Some roots were found following the courses of decayed roots. Bark remnants of the old roots formed tubes through which the younger roots occasionally had grown. One tube was 11 inches in length, but whether the new root followed the old for a greater distance could not be determined.

The sectioned root of tree No. 3, a sugar maple, extended to the foot of a rock outcrop where there was a heavy accumulation of partially decomposed organic material, consisting mostly of leaves and twigs. Throughout this mass, a single root from the tree had put out thousands of tiny rootlets, mostly 1/64 of an inch or less in diameter. It was impossible to separate the living from the dead material in this tangled mass. The stream of water used to wash the systems only made dents in the mass, and did not effect a separation.

Frequently roots terminate in a mass of fine rootlets surrounding and lying beneath the base of a neighboring tree. One root of tree No. 4 doubled back on itself and terminated under the parent stump.

The roots ramify generally throughout the upper parts of the soil materials. Small vertical branches of the main laterals, generally less than

0.25 inches in diameter, further subdivide near the ground surface. In the white and chestnut oaks dense mats of these rootlets are formed.

ROOT-CROWN RATIOS

The ratio between the area of the root system and the area of the crown ranged, in the 25 trees, between 3.4:1 and 40.7:1. Eighteen of the 25 trees ranged from 3.4:1 to 6.6:1. A rough average for these 18 trees is a ratio of 4.5:1.

The photographs and maps show that the root systems of the individual trees do not have individual growing spaces in the comparatively thin soils of this forest (Plate VII, Tree Nos. 10, 11, 14, 15, 19, and 20, Appendix). Plate VIII shows a red oak root that crossed the root system of a white oak (No. 18). There is another red oak root, even larger, that enters the upper side of the washed area, runs directly under no. 18, and then continues downslope to points unknown.

ROOT-STEM ANALYSES

Growth ring counts were made of cross sections removed at four foot intervals from the stems and from the longest mapped roots. The sections were polished with progressively finer grades of sandpaper until the growth rings were clearly discernible under a low-power microscope. Nevertheless, errors of two or three years could have been made, and should be allowed for when considering the root development curves. A chronological arrangement of the growth ring data for both the stem and the longest root of each tree is presented in a single graph (Appendix).

The growth curves show a relationship to stand history as revealed by the Harvard Black Rock Forest records. Chestnut, formerly abundant in the Forest, was killed about 1915. At the Black Rock Brook locality, the sectioned roots of all four systems studied — chestnut oak (No. 1), red oak (No. 2), and two sugar maples (Nos. 3 and 4) — either emerged from the root crown or showed a definite increase in elongation rate at the time of the death of the chestnut. At the Alec Meadow locality the stems of the beech (No. 5) and the chestnut oak (No. 8) were released by the death of the chestnut. The longest mapped root of the beech emerged from the root crown at that time. At the Beaver Swamp locality the sectioned root of the sugar maple (No. 16) emerged from the root crown at the time of the death of the chestnut. However, at Sutherland and Jim's Pond the sectioned roots showed no change in growth characteristics that could be so dated.

The stand at the Black Rock Brook locality was thinned in 1931. The

PLATE VII. Red oak (No. 2) on right with sugar maple (No. 3) in background.

PLATE VIII. Two white oaks (Nos. 17 and 18). Rule is extended to 24 inches. Root across system on right belongs to a red oak sprout clump 26 feet away.

root of a sugar maple (No. 4) showed an increase in elongation rate coincident with this date. The stand at the Beaver Swamp locality was thinned in 1934, and the sectioned roots of trees that were present in the stand prior to the thinning all show releases that seem to be related to this operation. An example of the release of a root is shown on the graph for Tree No. 18, a white oak (Appendix). The root was 40 years old. During its first 23 years it grew a total of 4 feet. After 1934, the year the stand was thinned, it grew 4 feet during the ensuing five years. This increased rate was maintained until the time of excavation. The stem showed a similar increase in height growth. Other trees at this locality showing releases following the 1934 thinning were Nos. 9, 10, 11, 13, 16, and 17. This list excludes Nos. 12, 14, 15, 19, and 20, all of which became established immediately following the 1934 thinning.

Rarely did the sectioned roots prove to be of the same age as the stem. Furthermore, the main branches of the root systems often showed a wide variation in age. For example, the eight roots of No. 4, a sugar maple, showed the following ages at the stump, proceeding clockwise around the stump from the sectioned root: 55, 47, 25, 41, 42, 94, 89, and 86 years. The base section of the stem indicated an age of 104 years (Table 1). Generally a root was several years younger than the stem. However, the sectioned roots of a red maple (No. 9) and a chestnut oak (No. 10) at the Beaver Swamp were older than the stem, indicating sprout origin. This was also apparent from features above ground.

DISCUSSION

It is clear from the material presented above that the present study affords but little from which to draw generalizations on the form and behavior of tree root systems. There is so much variation within species and sites that many more individual trees will have to be excavated and studied before any broad statements can be made. Rather, the 25 trees described here should be looked upon for the most part as "cases" that suggest characteristics and trends which are worthy of further observation and study. One of these is the average root-crown ratio. Another is the fact that in many of the root systems clear evidence of release was obtained that could be correlated with similar releases in the stem, and at the same time with known thinnings or other openings in the aerial portions of the stands. The direction of growth and the space relations of single roots give rise to speculation and question. And, lastly, differences among the species in the depth of root penetration are as yet more suggestive than factual, but they are perhaps worthy of some consideration.

It has been noted that the mean root-crown ratio for 18 of the excavated trees is 4.5:1. This indicates that the total area of the root systems in a unit area within a closed stand is four and one-half times the area of the ground surface. It follows that under each square foot of ground surface in the closed stands, where these systems were excavated, at least four trees probably are competing for the available space, water, and nutrients. This is the present situation in spite of the fact that the stands had been thinned at least once by the death of the chestnut about 1915, and some of them again by light cultural treatment in the early 1930's.

The response of the roots to openings in the crown canopy is striking. The roots appear to respond to release just as rapidly as the stems. The increased elongation rate is maintained for about the same length of time as in the stem (Appendix). Thirteen of the 25 sectioned roots had grown very slowly for 10 to 45 years before starting to elongate at a rate that eventually made them the longest mapped roots. The cross sections showed that the annual ring pattern was similar to that of a stem section that had been suppressed and then released — the rings were narrow and then, upon release, were considerably thicker.

The course followed by the roots is probably closely allied to response to release. It would seem, theoretically, that given a uniform soil medium in which tree roots could develop, there would be no reason for the root to elongate along anything save a straight line. If this theory is tenable, then each of the loopings and directional changes seen is the result of some difference between one part of the soil and another. Obviously, in the rocky soils here, the roots could not penetrate the rocks. This does not explain all the directional changes and terminations, however. Still to be explained are such things as the root on No. 3, a sugar maple, that had completely infiltrated with rootlets an accumulation of leaves and twigs some distance from the stump; or the loops of No. 6, a red maple, which grew along the contour of the slope on what may have been a lens of fine material in the kame terrace; or the pronounced upslope trend of the root systems of the two chestnut oaks (Nos. 21 and 25) that were growing near ponds; or the almost total absence of roots in the right, upslope quadrant of No. 16, a sugar maple; or the two outsized roots on the white ash (No. 23) that extended downslope to moist soil near a pond.

The foregoing lists only a few of the many directional changes, apparent abnormalities, and terminations that were observed during the washing process. A cause of difficulty in the interpretation of these things is in the washing process itself. By the time a change in direction is found, the soil materials in which the change took place have been washed away.

After observing 25 root systems, only tentative suggestions as to their maximum extent may be offered. Tree No. 4, a sugar maple, had a bole

104 years old. The graph showing the development of its longest root (Appendix) suggests that the root is still elongating. The graph also shows, however, that the root is not as old as the tree. This example — and the other 24 systems seemed to show substantially the same phenomena — suggests two trends that may be operating in the development of tree root systems. One of these is indicated by the many-aged nature of the roots, which suggests that throughout the life of a root system there is a continuous process in which old roots die off and new roots emerge. If this is the case, then there would be coming from the stump and major laterals waves of new roots that would occupy and reoccupy the soil. For example, the mapped root of No. 16, a sugar maple, had originated on the side of a major lateral some 12 inches from the stump. Second, if the first process exists, the rough average root-crown ratio of 4.5:1 might actually represent a maximum lateral extent for the root systems even though individual roots are still elongating.

Preston (1942) suggests that roots are found around and beneath the root crowns of other trees because of organic materials and moisture that collect on the bole and gravitate downward. In view of the many roots that were traced to the base of another tree in the present study, this seems a reasonable conclusion.

Among the trees growing on till soils, four seem to be in a roughly defined series, from lesser to greater depths at the stump. These are sugar maple, red oak, chestnut oak, and white oak. The depths of the main laterals, away from the immediate vicinity of the stump, show the same series. These depth ranges, in spite of the small sample, are believed to be a good indication of the general growth pattern. White oak will serve as an example. From the study of glacial geology mentioned earlier, the location of the deeper soil deposits is known. The forest type maps show that the distribution of white oak coincides with the distribution of the deep, well-drained soils. In the areas of till and bedrock outcrops, white oak is commonly found on spots that could well have soil accumulations deeper than the surrounding areas.

The inclination to write of the roots of trees as though they possessed powers of thought and reason is strong. The white ash sends roots to a pond level; the chestnut oak grows away from ponds; and a sugar maple sends a mat of fine roots into a mass of organic material. This inclination will probably continue to be strong until there is more understanding of the structure and behavior of tree roots. It carries, in itself, clear evidence of the need for further exploration in this field, for it lays bare our primitive human tendency to personify and make mysterious the natural phenomena we do not understand.

LITERATURE CITED

DENNY, C. S., 1938. Glacial Geology of the Black Rock Forest. Black Rock Forest Bull. No. 8.

DUNNING, D., 1949. Roots of forest trees: A selected list of references. Calif. Forest and Range Exp. Sta. Forest Research Notes, No. 52.

GAISER, R. N. and J. R. CAMPBELL, 1951. The concentration of roots in the white oak forests of southeastern Ohio. Central States Forest Exp. Sta., Tech. Paper No. 120.

GARIN, G. I., 1942. Distribution of roots of certain tree species in two Connecticut soils. Conn. Agr. Exp. Sta., Bull. 454, pp. 97–167.

GREENIDGE, K. N. H., 1953. Further studies of birch dieback in Nova Scotia. Canadian Journal of Botany, 31:548–559.

HAWBOLDT, L. S., 1952. Climate and birch "dieback." Dept. of Lands and Forests, Prov. of Nova Scotia, Bull. No. 6.

LAITAKARI, E., 1927. Mannyn juuristo morfologinem tutkimus. (The root system of pine, *Pinus silvestris*, a morphological investigation.) Acta Forest. Fenn., 33:1–380. (In Finnish. English Summary, p. 305–380.)

———, 1934. Koivun juuristo. (The root system of birch.) Acta Forest. Fenn., 41:1–217. (In Finnish. English Summary, p. 169–216.)

LARSON, C. C., 1943. The relationship of height growth to root development in Scotch pine (*Pinus sylvestris* L.). Thesis. Univ. of Vermont and State Agricultural College.

MCQUILKIN, W. E., 1935. Root development of pitch pine, with some comparative observations on short-leaf pine. Journal of Agr. Research, 51:983–1016.

PRESTON, R. J., JR., 1942. Roots of juvenile lodgepole pine. Jour. Forestry, 40:966–967. Dec.

PULLING, H. E., 1918. Root habit and plant distribution in the far North. Plant World, 21:223–233.

RAUP, H. M., 1938. Botanical studies in the Black Rock Forest. Black Rock Forest Bull. No. 7.

STOECKELER, J. H. and W. A. KLUENDER, 1938. Hydraulic excavation of roots. Ecology, 19(3):355–369.

STOUT, B. B., 1952. Species distribution and soils in the Harvard Forest. Harvard Forest Bull. No. 24.

VATER, H., 1927. Die Bewurzelung der Kiefer, Fichte und Buche. (The root system of Pine, Spruce and Beech.) Tharandter Forstliches Jahrbuch 78(3):65–85. (USFS Translation No. 301.)

LIST OF SPECIES STUDIED

Pignut hickory	— Carya glabra (Mill.) Sweet
Black birch	— Betula lenta L.
Beech	— Fagus grandifolia Ehrh.
White oak	— Quercus alba L.
Chestnut oak	— Quercus Prinus L.
Red oak	— Quercus rubra L.
Sugar maple	— Acer saccharum Marsh.
Red maple	— Acer rubrum L.
White ash	— Fraxinus americana L.

APPENDIX

LEGEND

ROOT MAPS

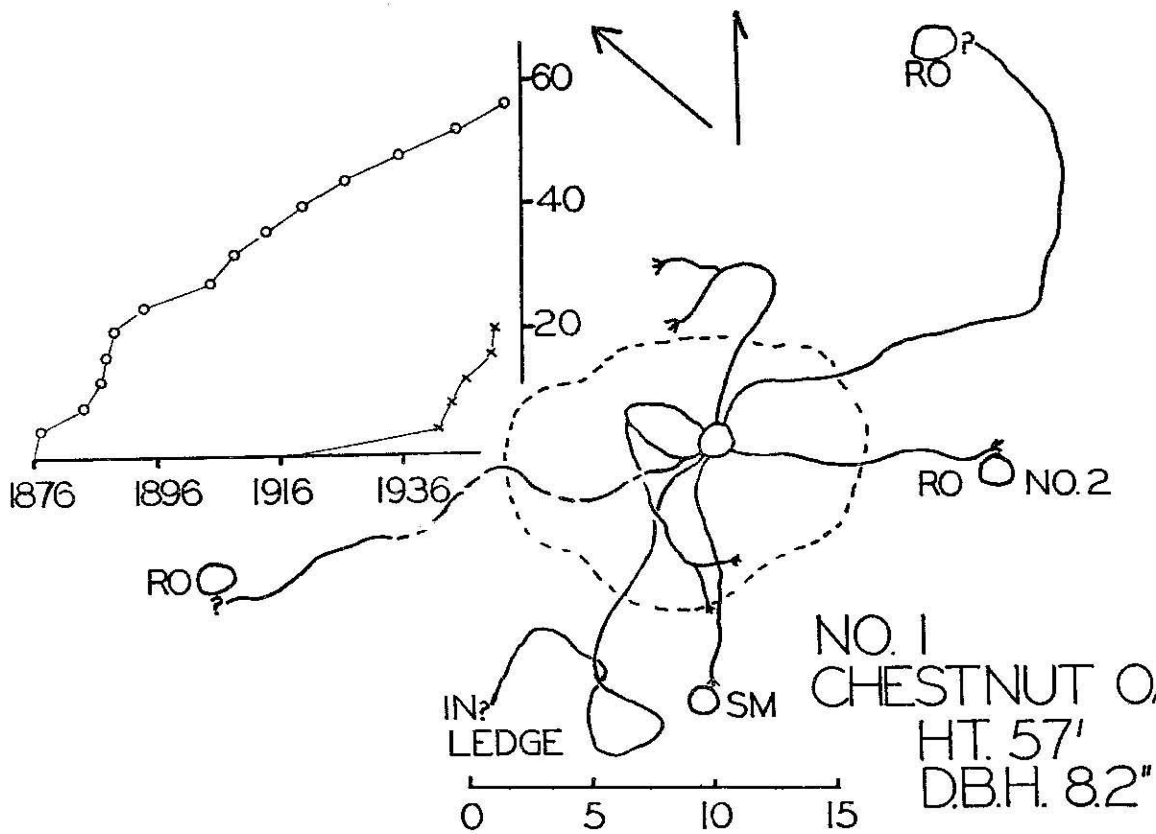
O	Tree Location
	Root
	Sectioned Root
	Root End
	Root End Not Reached
	Crown Periphery
	Direction of Slope (Up)
	True North
	Scale — In Feet

STEM-ROOT ANALYSIS GRAPHS

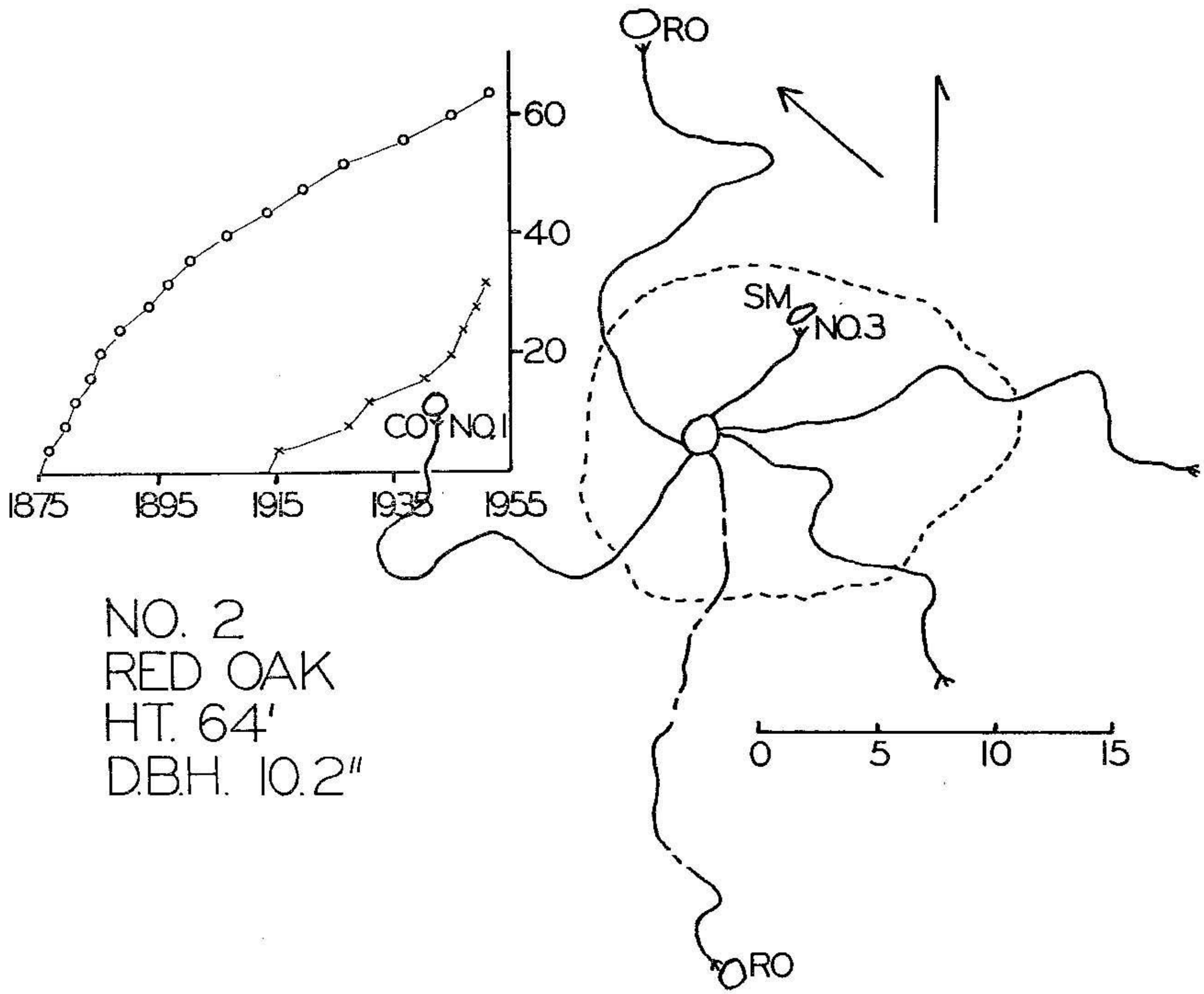
Ordinate	Height of Stem or Length of Root in Feet
Abscissa	Age — Actual Year
— o —	Stem
— × —	Root

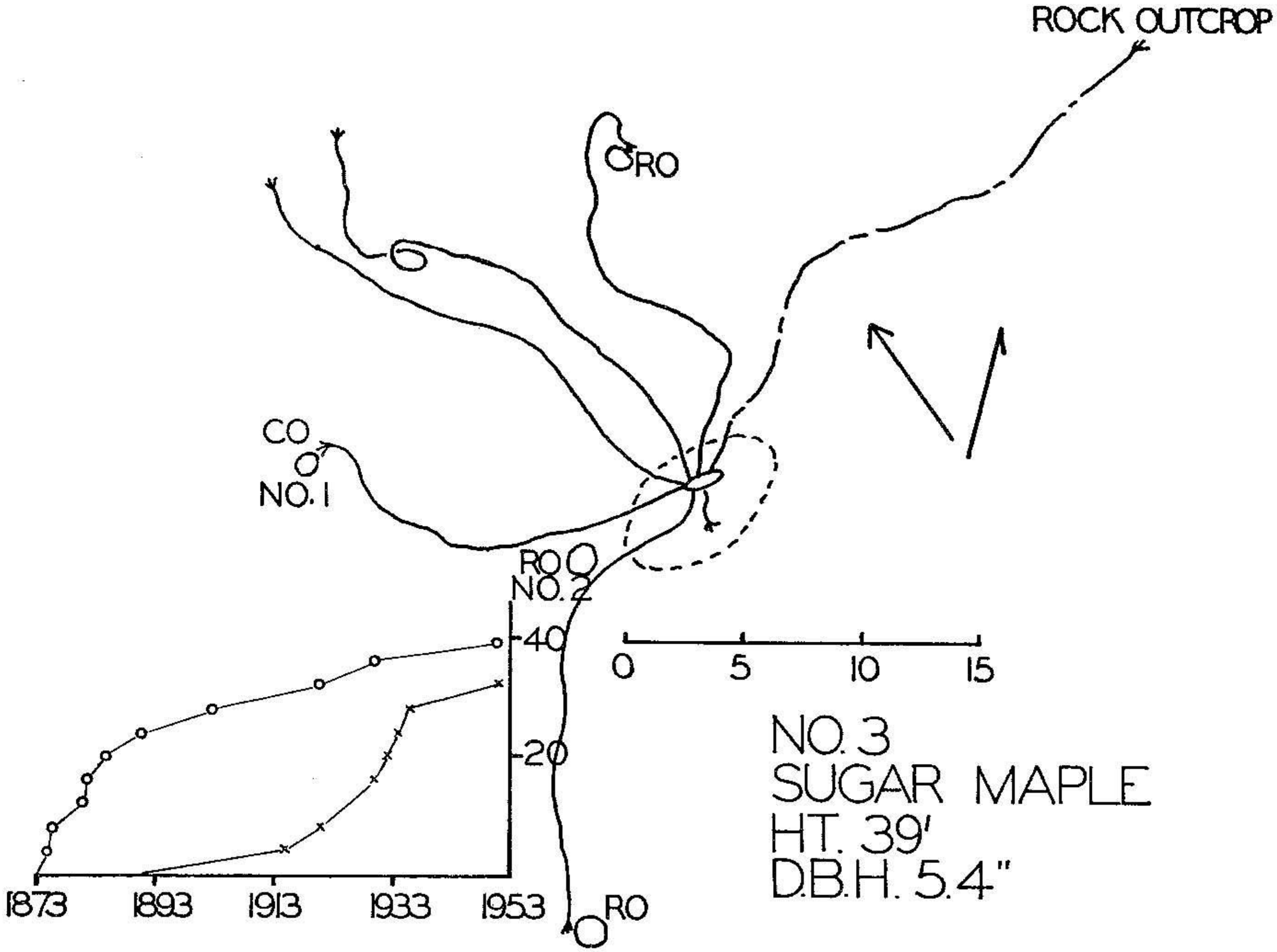
SPECIES ABBREVIATIONS

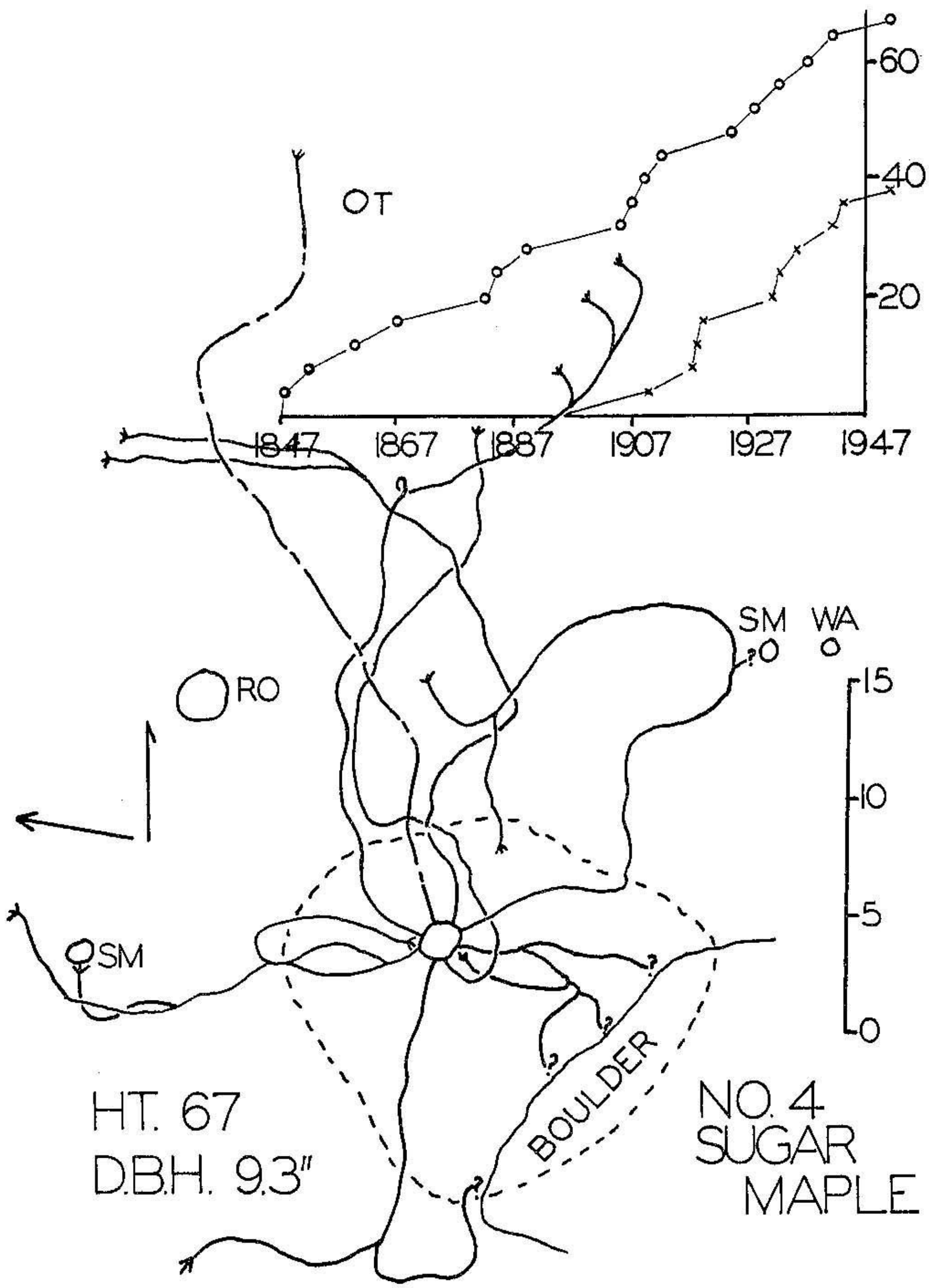
RO	Red Oak
WO	White Oak
CO	Chestnut Oak
SM	Sugar Maple
RM	Red Maple
T	Eastern Hemlock
WA	White Ash



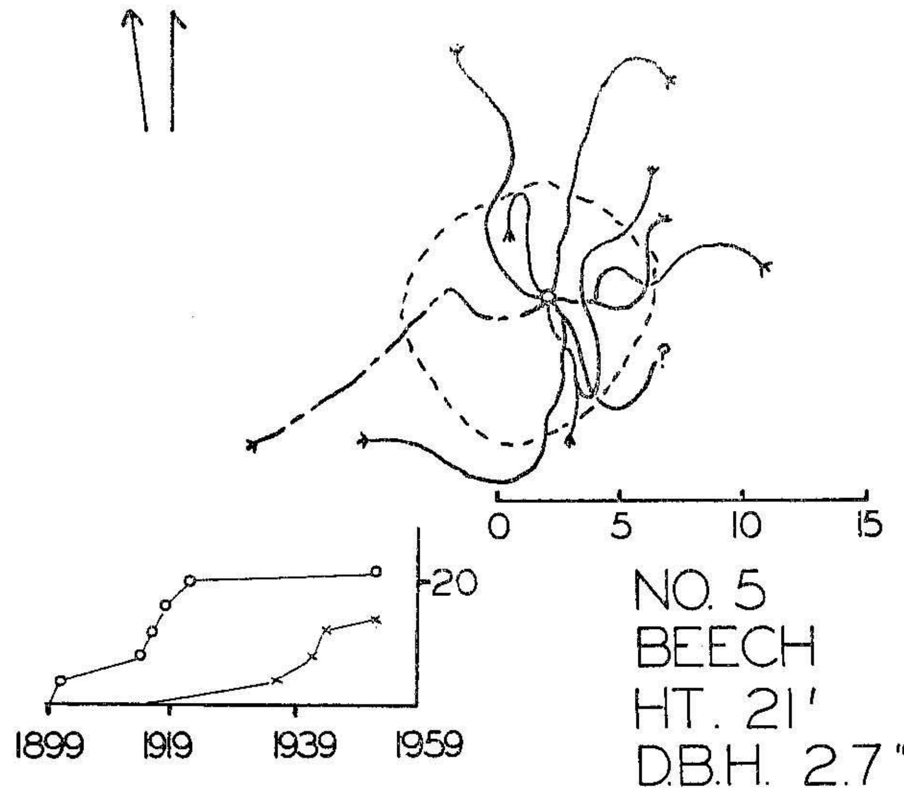
NO. 1
CHESTNUT OAK
HT. 57′
D.B.H. 8.2″

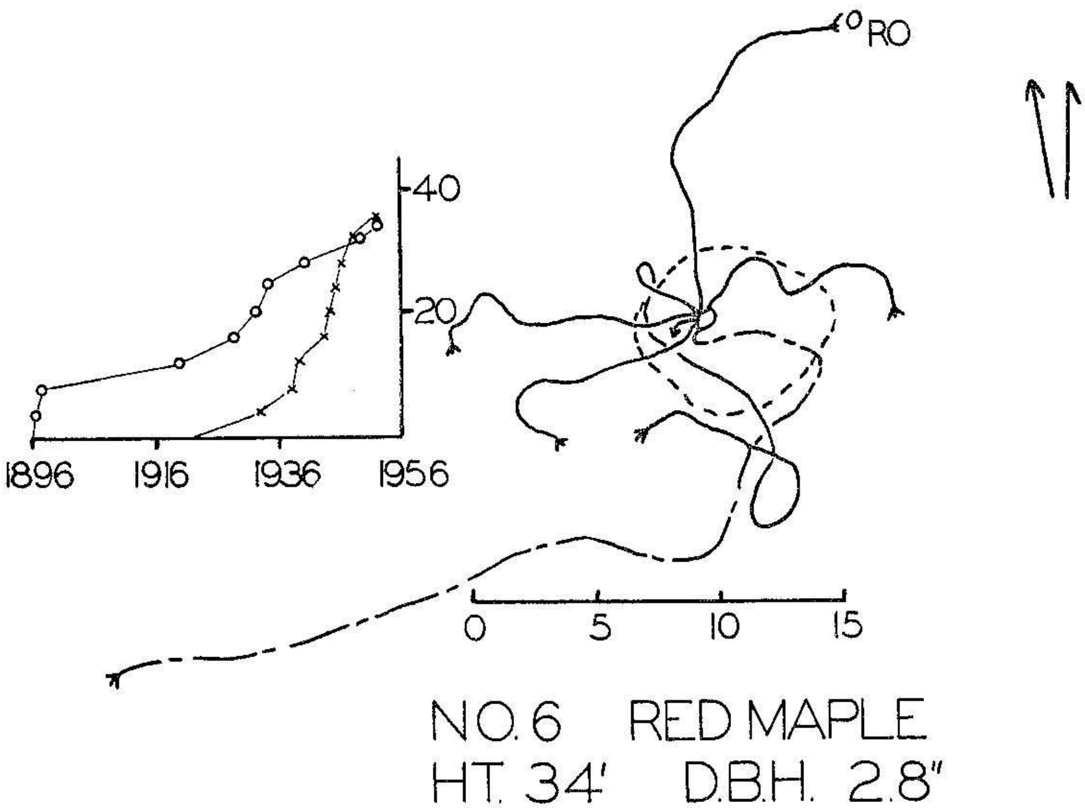

RO
60
40
20
1875
1895
1915
1935
1955
CO
NO.1
SM
NO.3
NO. 2
RED OAK
HT. 64'
D.B.H. 10.2"
0
5
10
15
RO


ROCK OUTCROP
RO
CO
NO. 1
RO
NO. 2
40
20
1873
1893
1913
1933
1953
RO
0
5
10
15
NO. 3
SUGAR MAPLE
HT. 39'
D.B.H. 5.4"

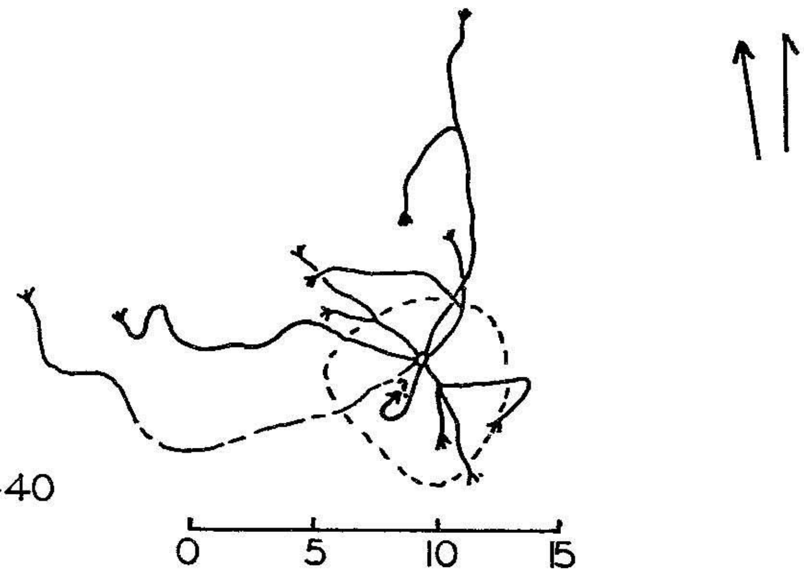


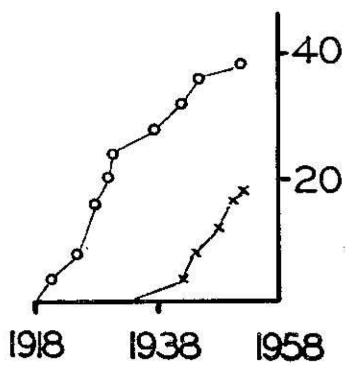
OT
60
40
20
1847
1867
1887
1907
1927
1947
SM
WA
RO
15
10
5
0
SM
BOULDER
HT. 67
D.B.H. 9.3"
NO. 4
SUGAR
MAPLE



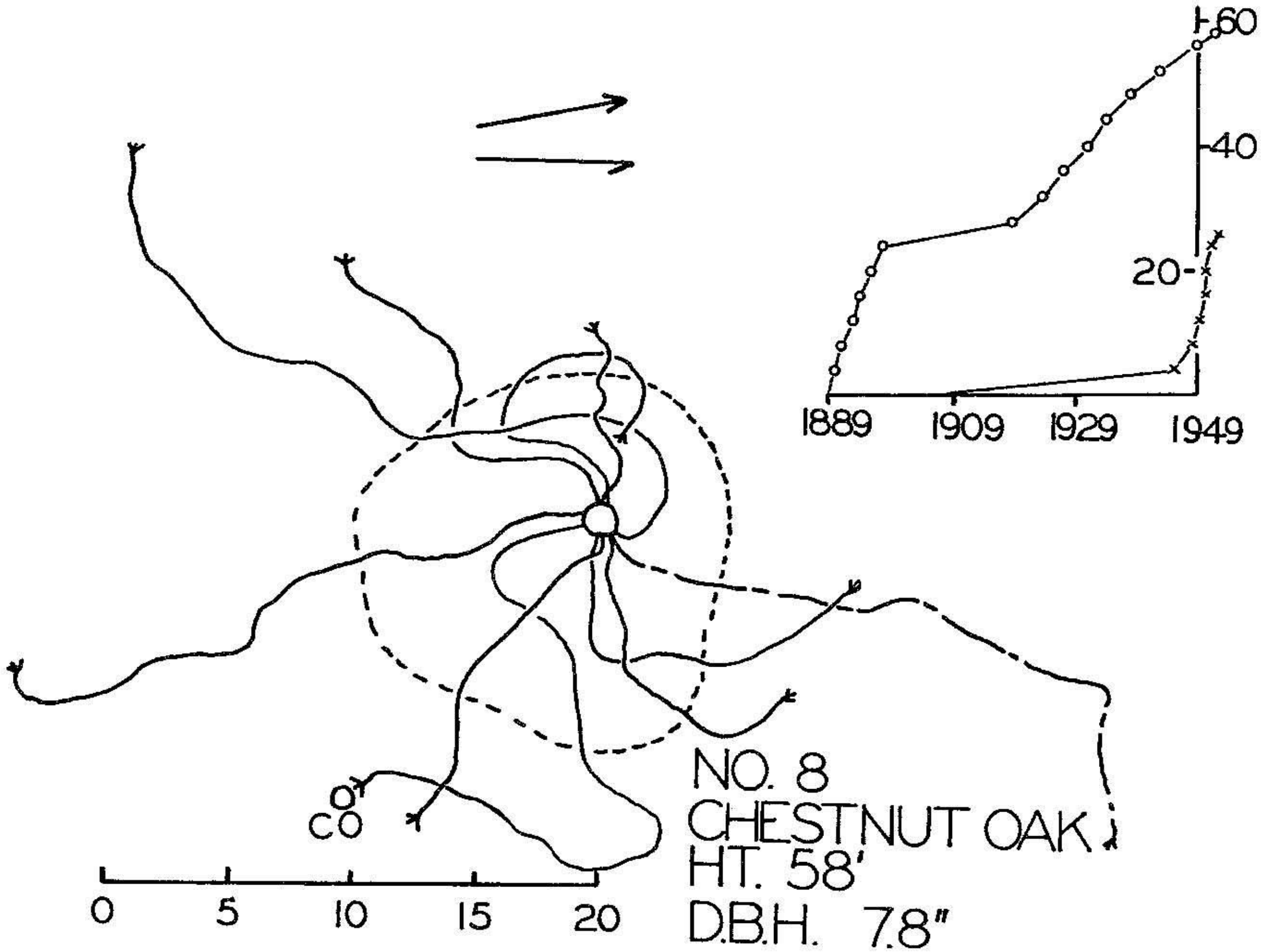


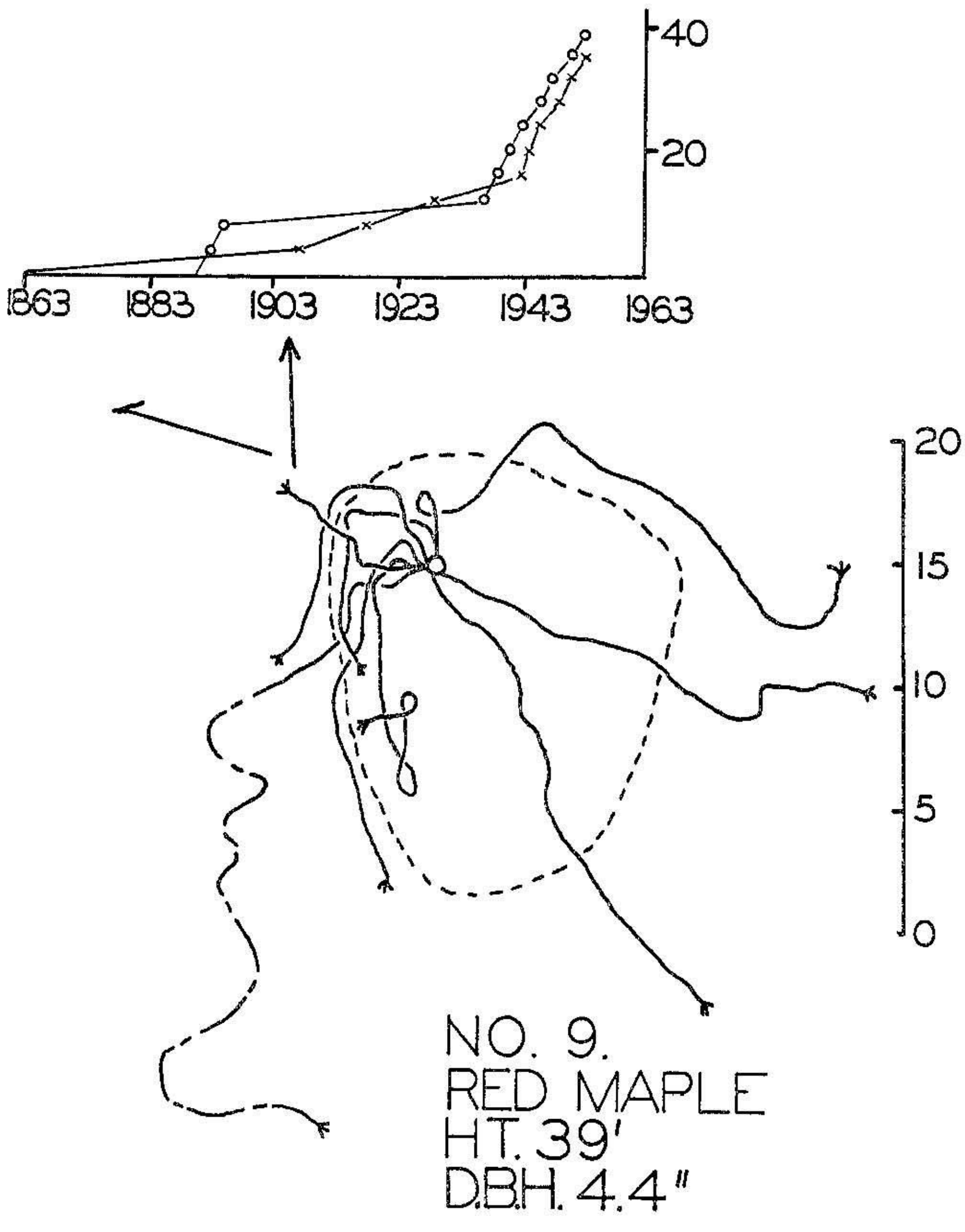
NO. 6 RED MAPLE
HT. 34' D.B.H. 2.8"

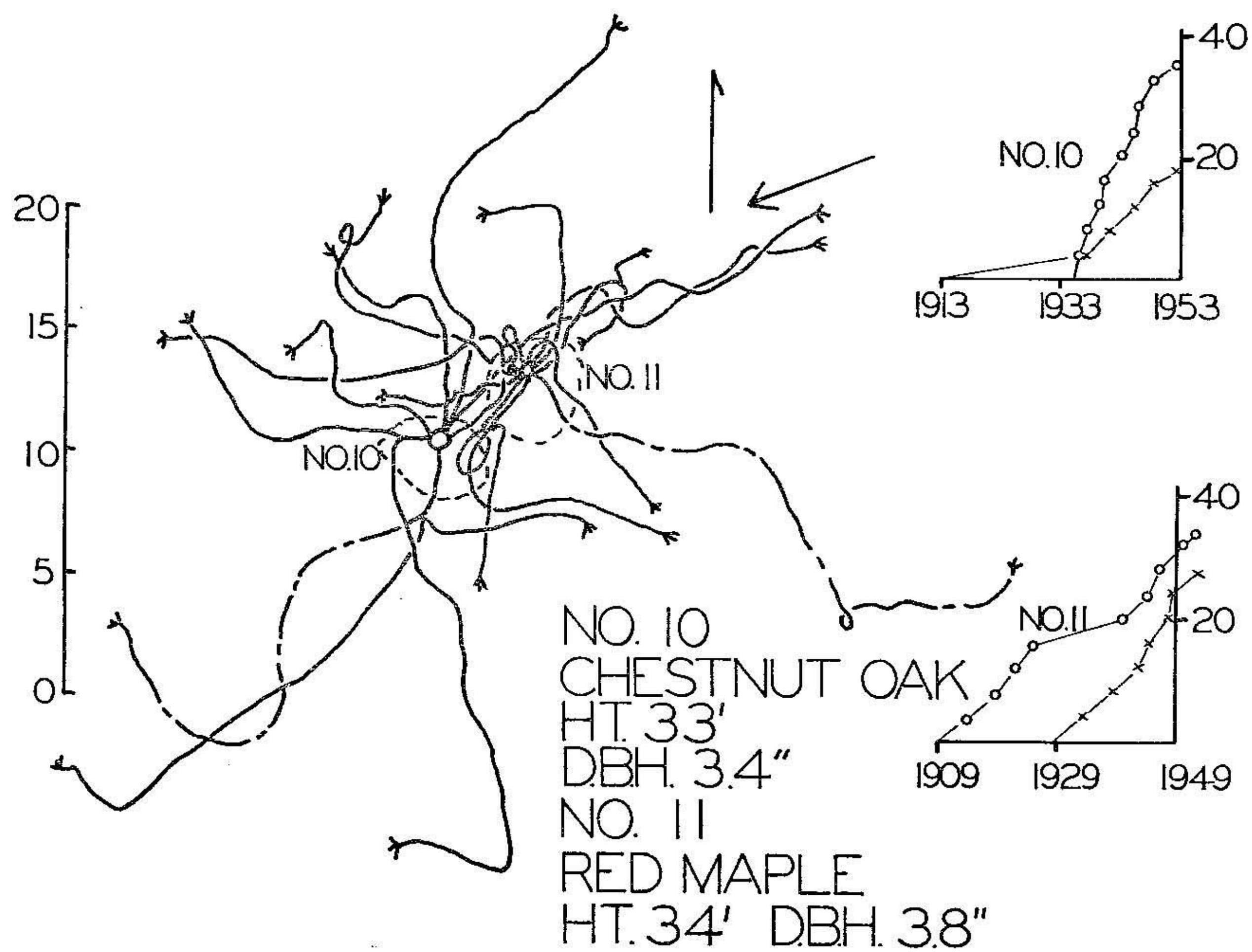


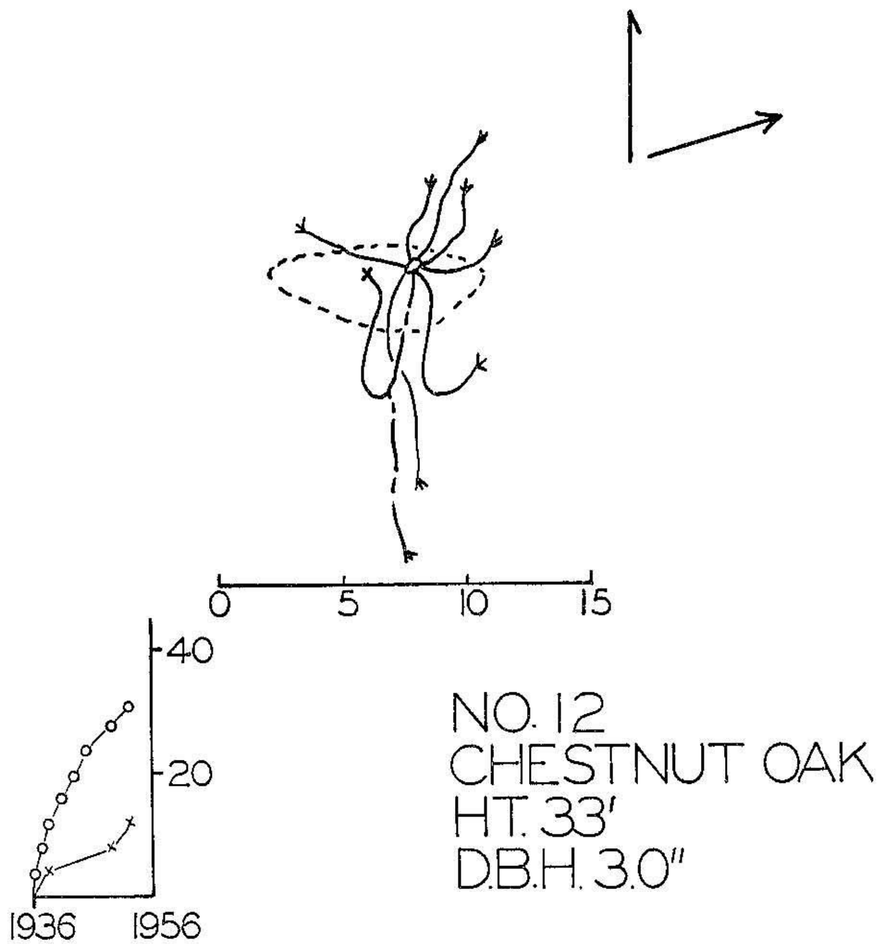


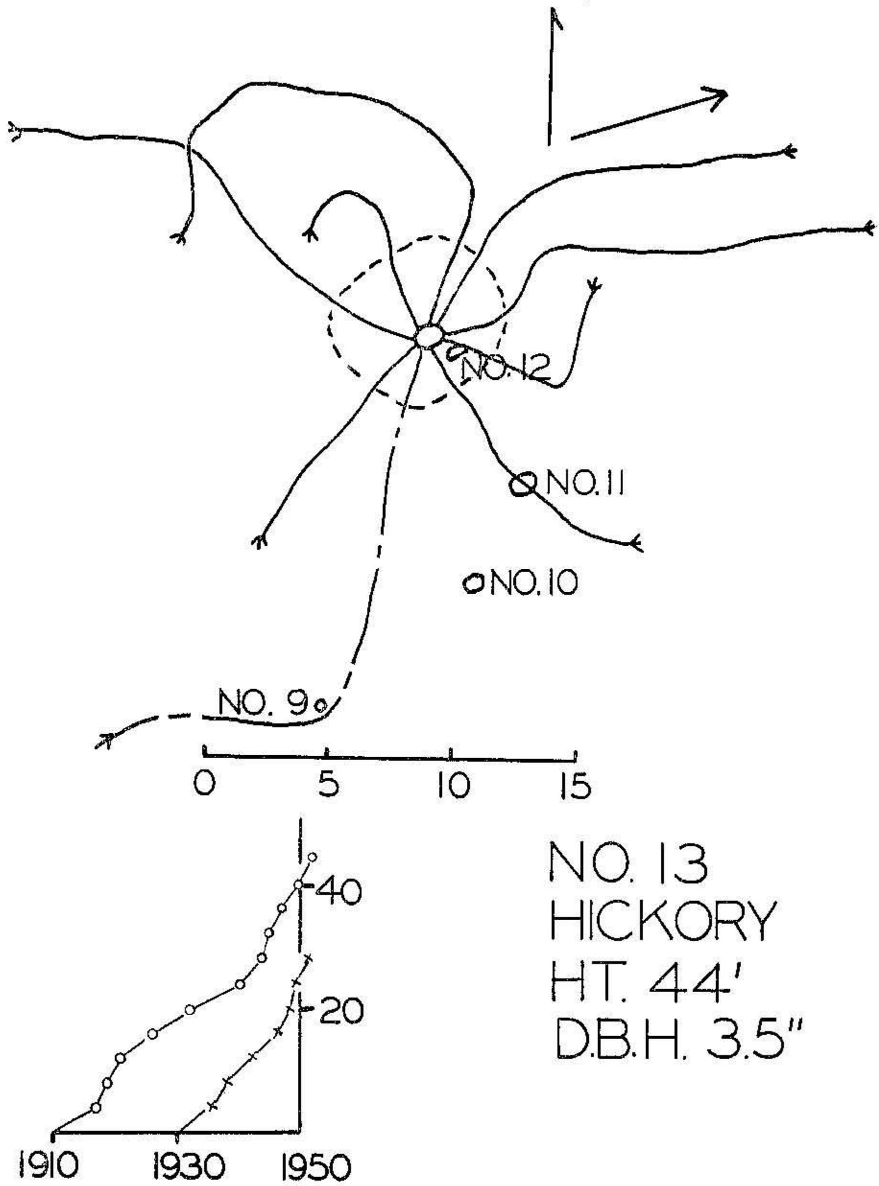
NO. 7 BLACK BIRCH
HT. 38' D.B.H. 3.8"


60
40
20
1889
1909
1929
1949
O
CO
0
5
10
15
20
NO. 8
CHESTNUT OAK
HT. 58'
D.B.H. 7.8"

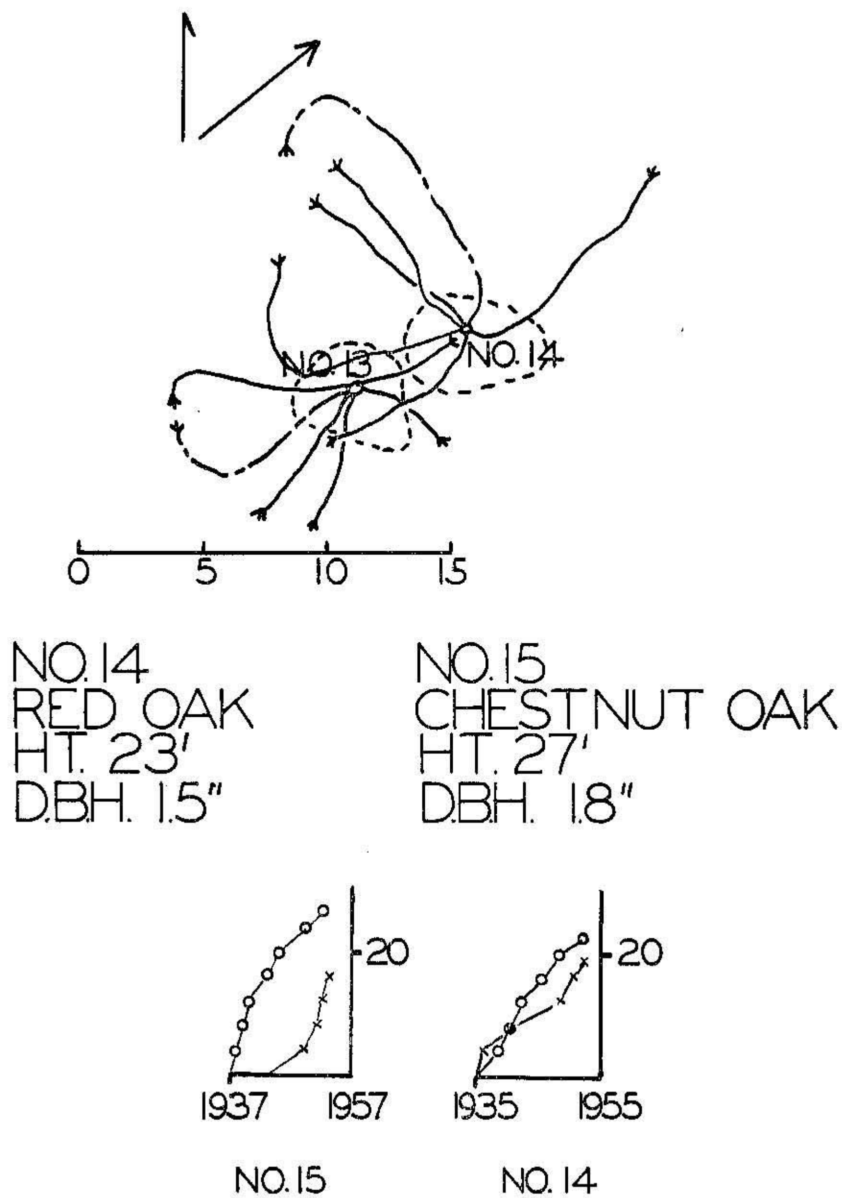

40
20
1863
1883
1903
1923
1943
1963
20
15
10
5
0
NO. 9.
RED MAPLE
HT. 39'
D.B.H. 4.4"

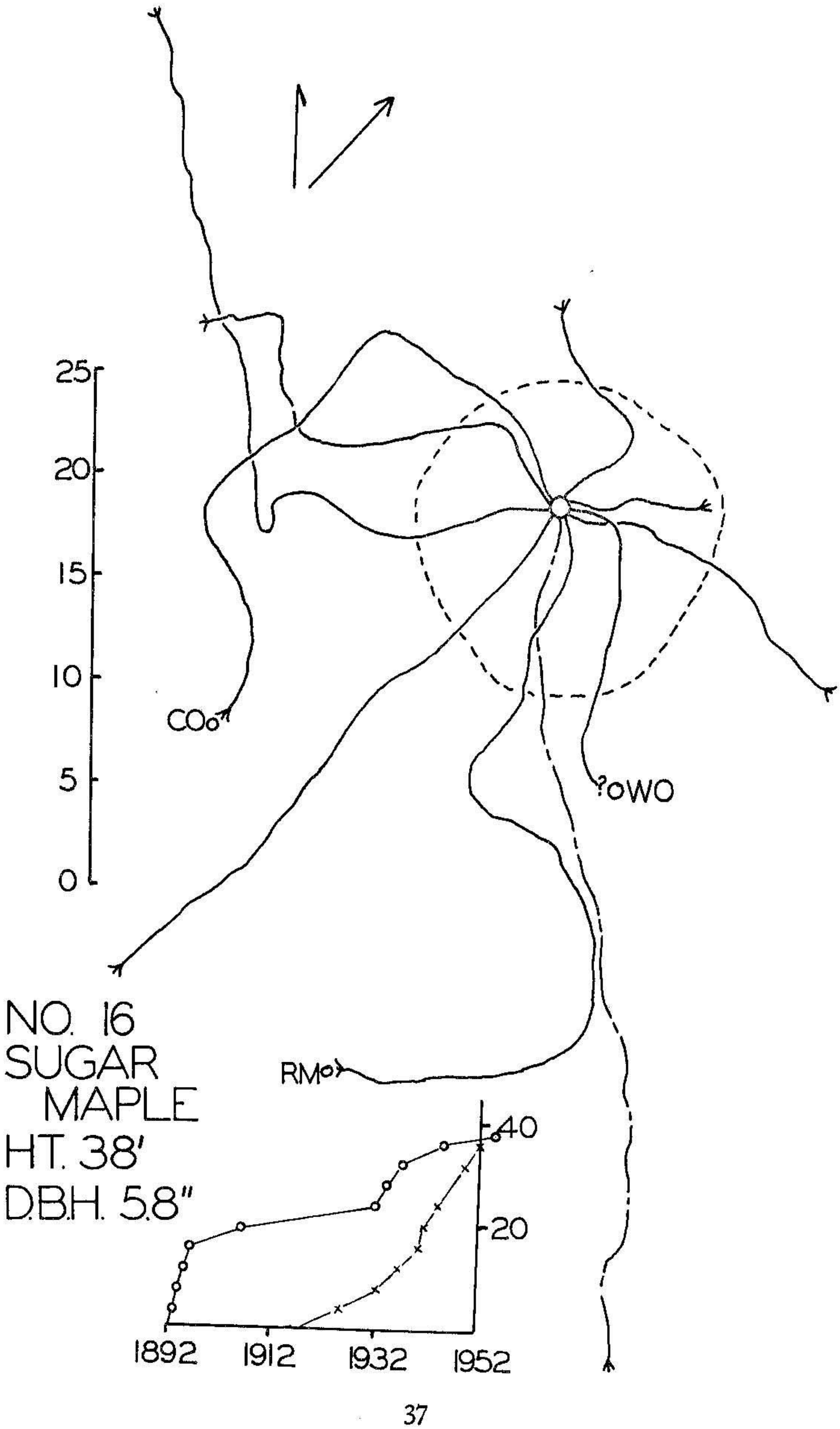

20
15
10
5
0
NO.10
NO. 11
NO. 10
CHESTNUT OAK
HT. 33'
D.B.H. 3.4"
NO. 11
RED MAPLE
HT. 34' D.B.H. 3.8"
NO.10
40
20
1913
1933
1953
NO.11
40
20
1909
1929
1949

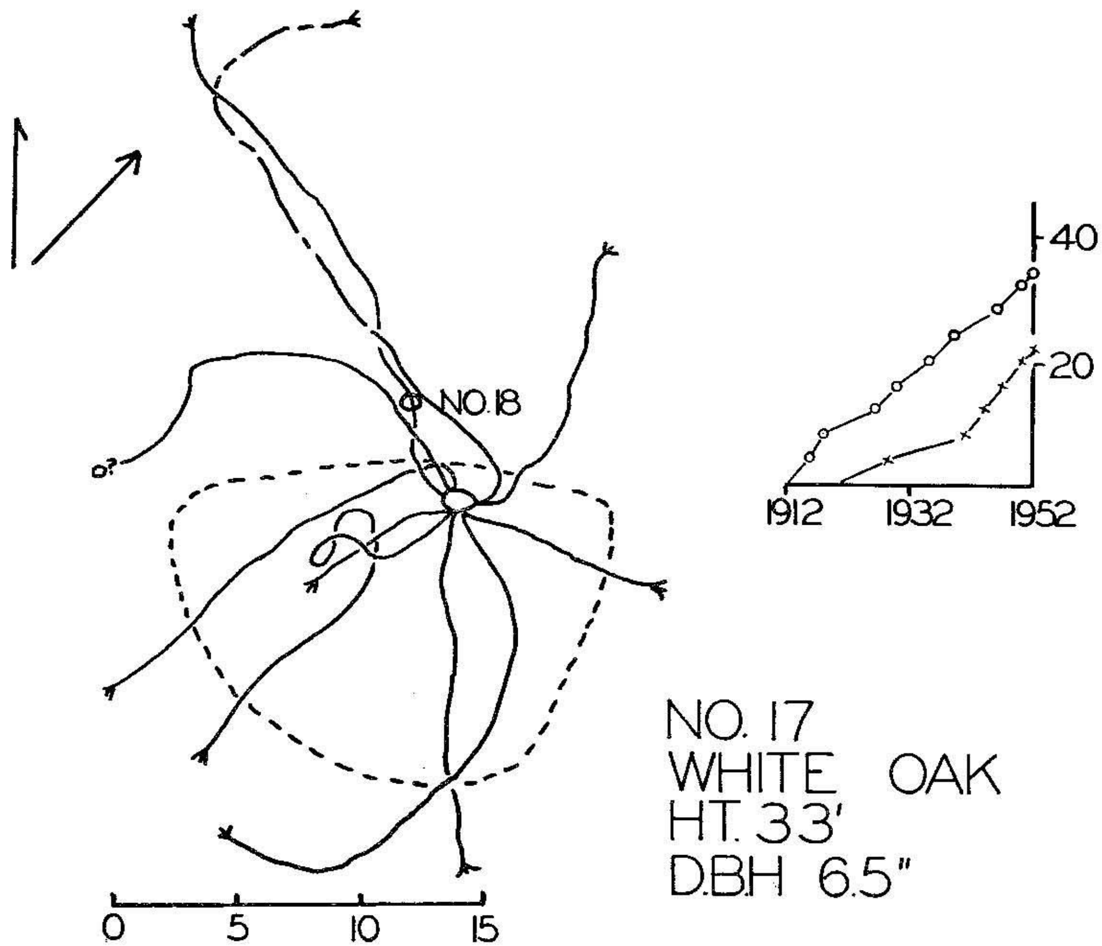

0
5
10
15
40
20
1936
1956
NO. 12
CHESTNUT OAK
HT. 33'
D.B.H. 3.0"

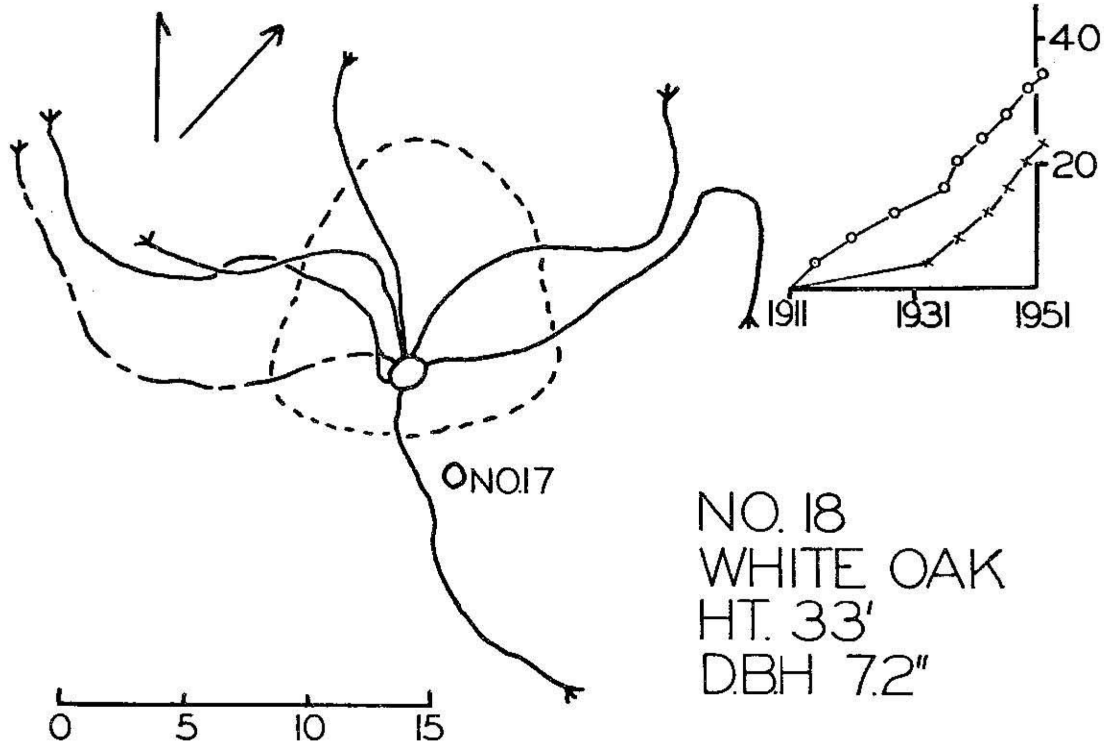


NO. 13
HICKORY
HT. 44′
D.B.H. 3.5″

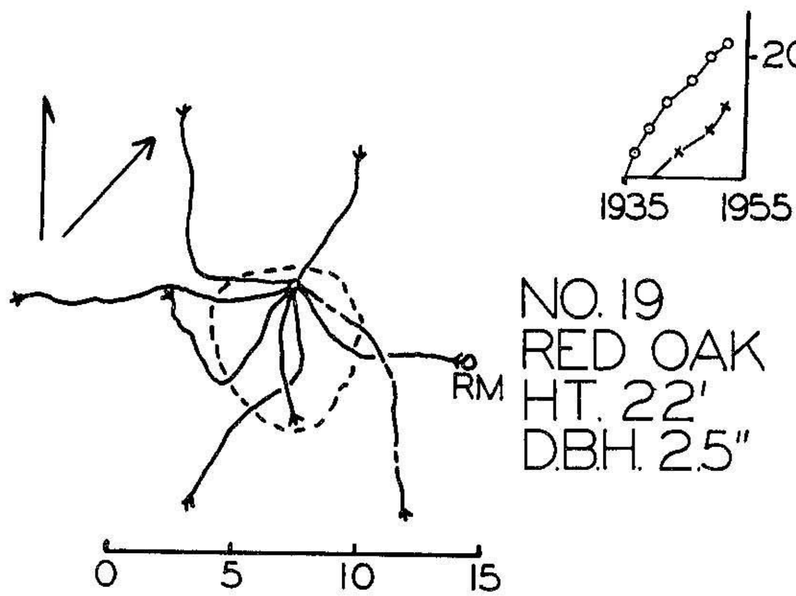

NO.13
NO.14
0
5
10
15
NO.14
RED OAK
HT. 23'
D.B.H. 1.5"
NO.15
CHESTNUT OAK
HT. 27'
D.B.H. 1.8"
20
1937
1957
NO.15
20
1935
1955
NO.14

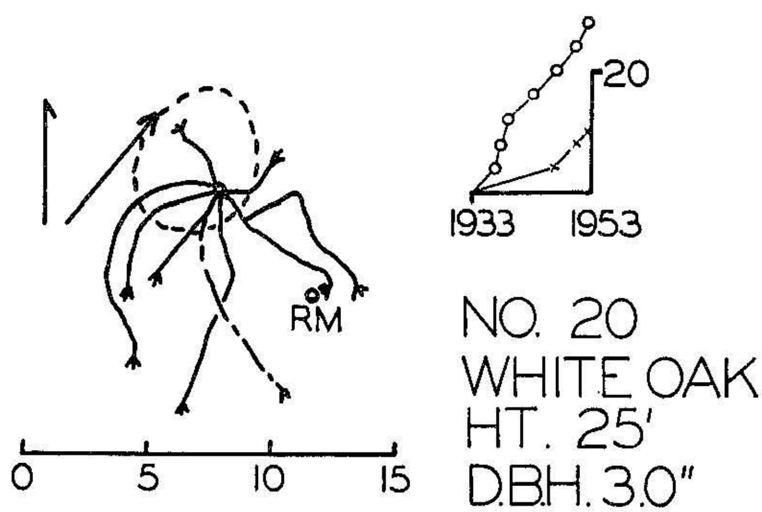

25
20
15
10
5
0
CO
?OWO
RM
NO. 16
SUGAR
MAPLE
HT. 38'
D.B.H. 5.8"
40
20
1892
1912
1932
1952

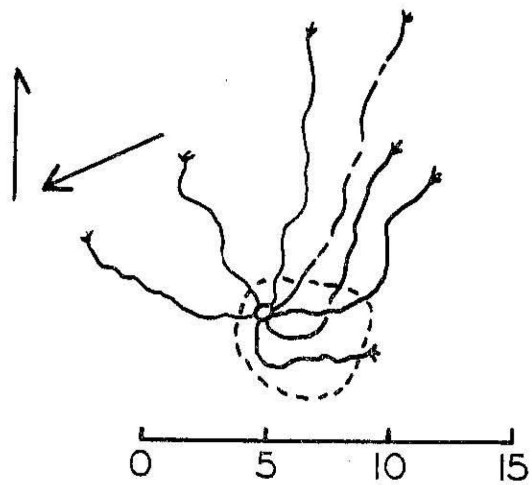

NO.18
40
20
1912
1932
1952
NO. 17
WHITE OAK
HT. 33'
D.B.H 6.5"
0
5
10
15

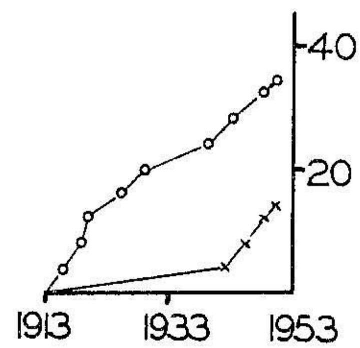


40
20
1911
1931
1951
NO.17
0
5
10
15
NO. 18
WHITE OAK
HT. 33'
D.B.H 7.2"

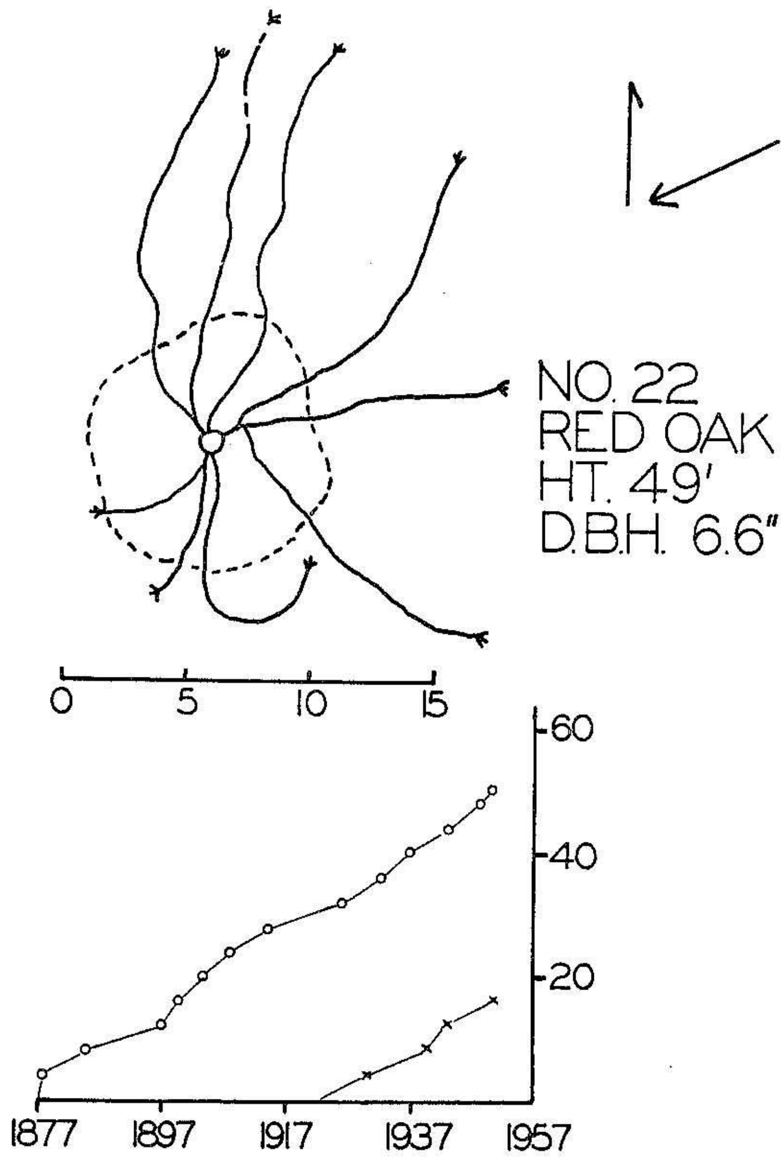

20
1935
1955
RM
NO. 19
RED OAK
HT. 22'
D.B.H. 2.5"
0
5
10
15

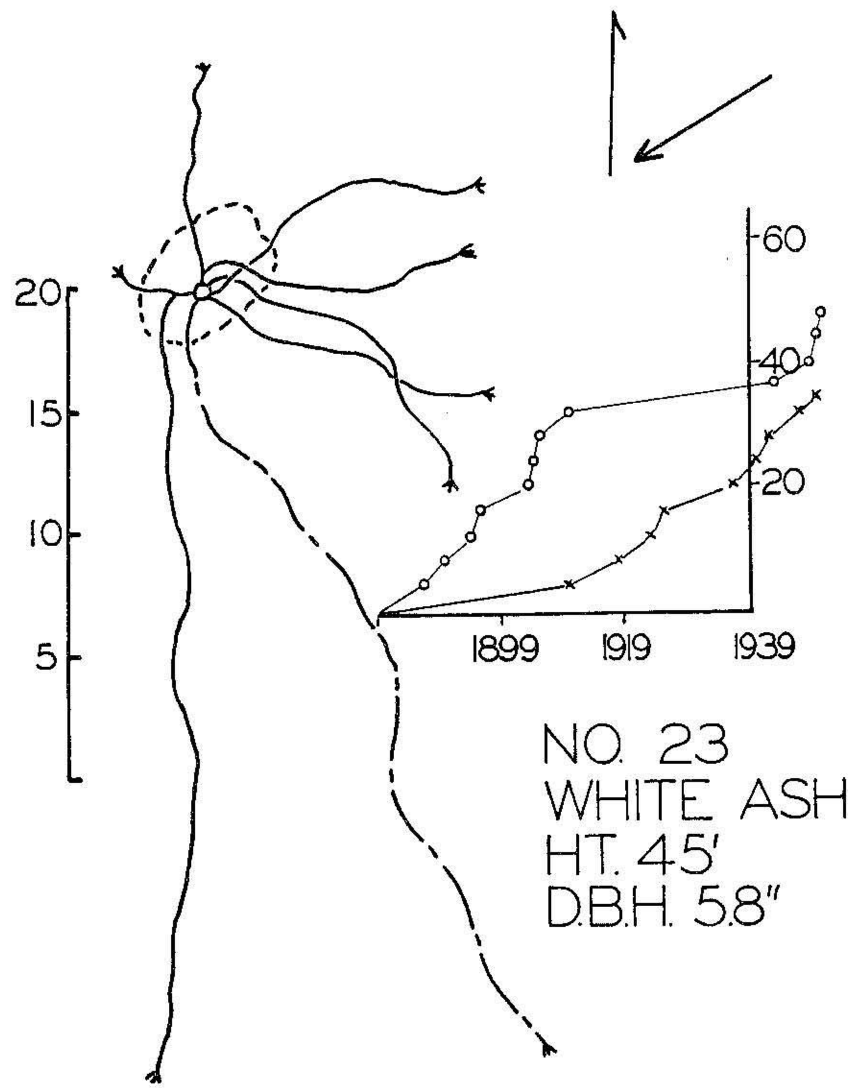

20
1933
1953
RM
NO. 20
WHITE OAK
HT. 25'
D.B.H. 3.0"
0
5
10
15

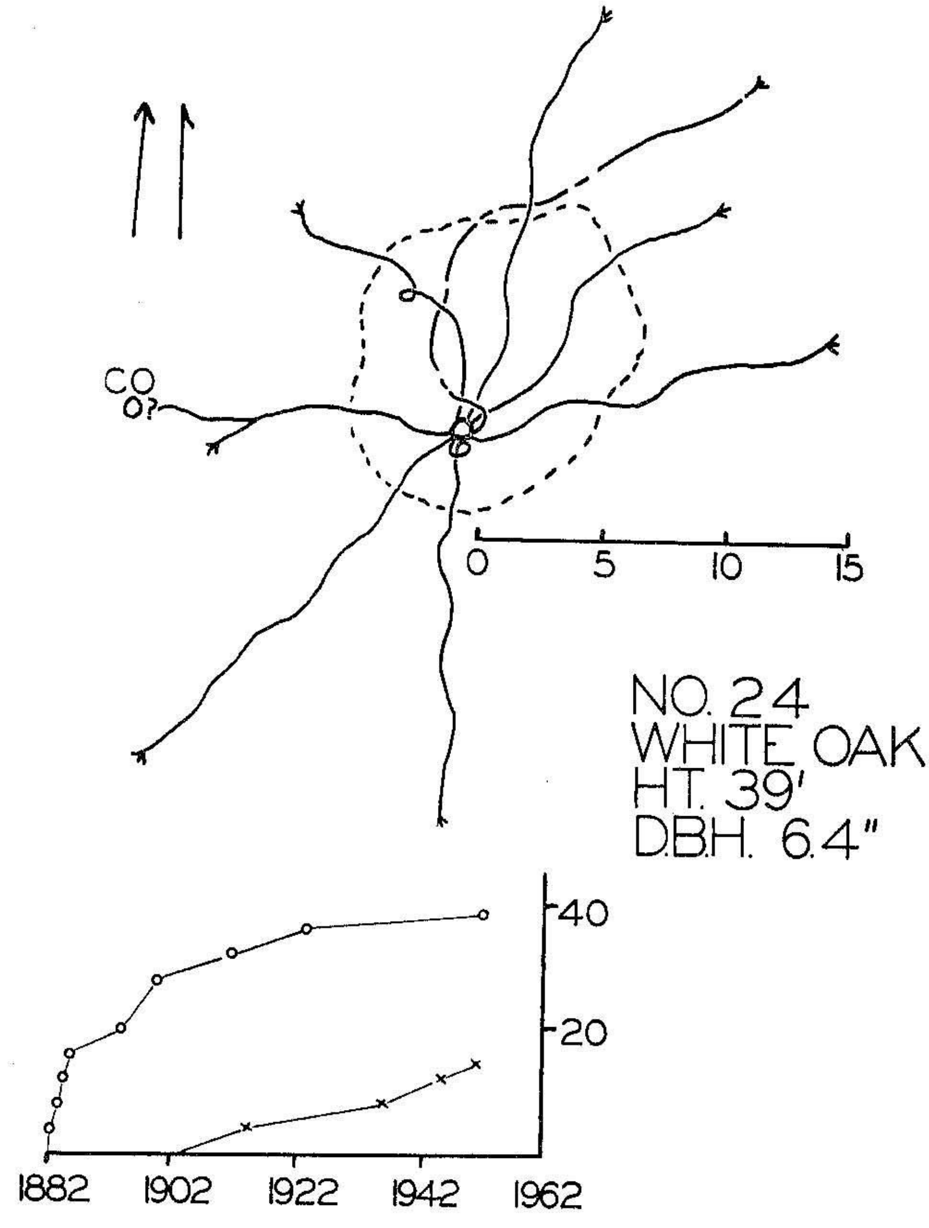


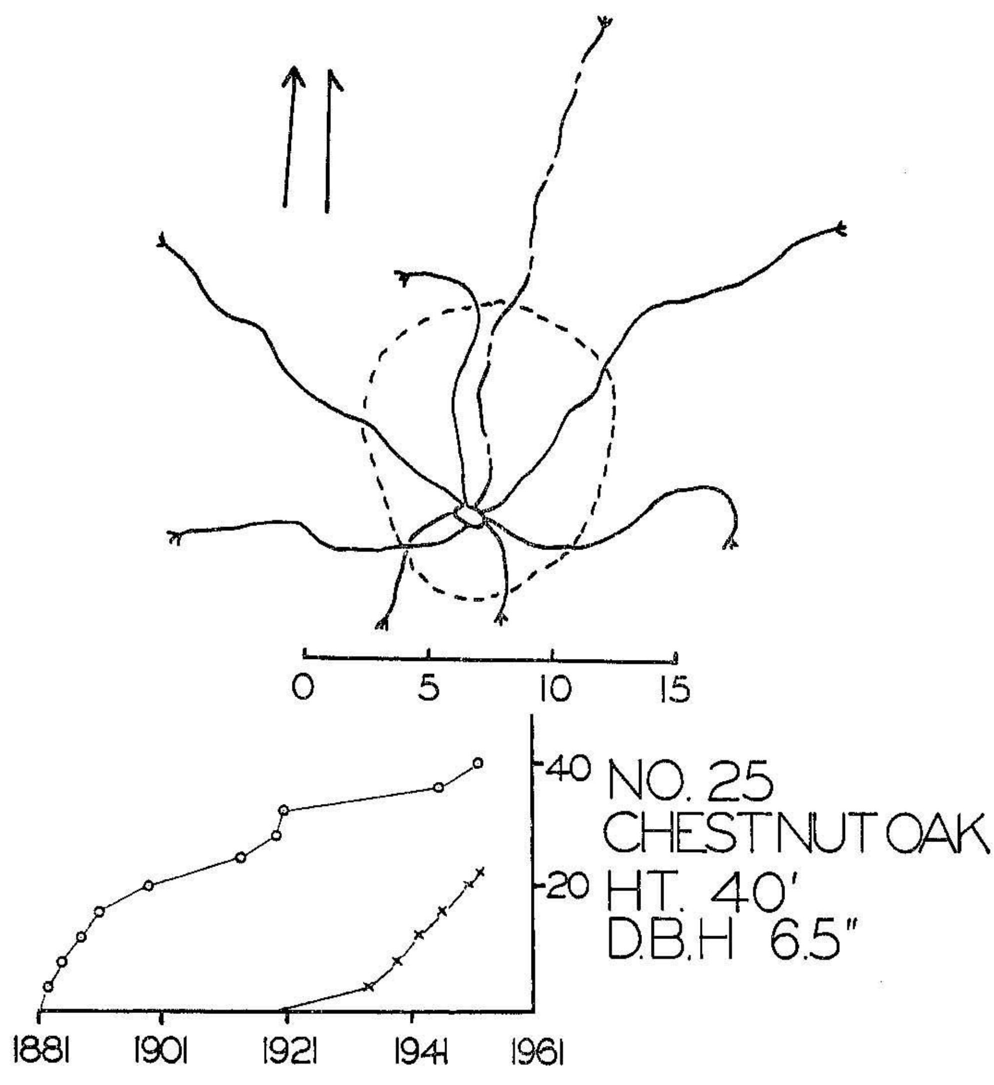


NO. 21
CHESTNUT OAK
HT. 33'
D.B.H 4.6"


NO. 22
RED OAK
HT. 49'
D.B.H. 6.6"
0
5
10
15
60
40
20
1877
1897
1917
1937
1957


20
15
10
5
60
40
20
1899
1919
1939
NO. 23
WHITE ASH
HT. 45'
D.B.H. 5.8"


CO
O?
0
5
10
15
NO. 24
WHITE OAK
HT. 39'
D.B.H. 6.4"
40
20
1882
1902
1922
1942
1962


0
5
10
15
40
20
1881
1901
1921
1941
1961
NO. 25
CHESTNUT OAK
HT. 40'
D.B.H 6.5"