ABSTRACT

The Development of Northern Red Oak (*Quercus rubra* L.) in Mixed Species, Even-aged Stands in Central New England

Chadwick Dearing Oliver

Yale University 1975

Northern red oak (*Quercus rubra* L.) commonly attains predominance in the main crown canopy of the mixed, stratified, deciduous forest stands that may develop on well-drained glacial tills in central New England. This predominance of red oak is manifested only after 20-30 years of stand development. Other species such as red maple (*Acer rubrum* L.) and black birch (*Betula lenta* L.), which at first dominate the main crown canopy, then lapse into the understrata.

Stands dominated by red oak can thus develop, after a major disturbance, from new, young stands in which this species is initially very low in abundance as well as in height. These stands commonly are even-aged in spite of the broad range of diameters giving them an all-aged appearance. The stands grow from understory seedlings, sprouts, and seeds after a severe disturbance to the previous forest — such as a clearcutting or a hurricane blowdown.

It may be desirable in silvicultural practices to have only 45 well-placed red oak seedlings (or seedling sprouts) per acre in the reproduction for best diameter growth on individual red oak trees, while relying on the more numerous red maple, black birch, and other species to keep the red oak pruned. The resulting wide spacing of the oaks in the ultimate main canopy produces the same rapid diameter growth that could be secured only by frequent and intensive thinning if the stands were of pure oak and started with hundreds or thousands of oak seedlings per acre.

The Development of Northern Red Oak (*Quercus rubra* L.) in Mixed Species, Even-aged Stands in Central New England

A Dissertation

Presented to the Faculty of the Graduate School

of

Yale University

in Candidacy for the Degree of

Doctor of Philosophy

by

Chadwick Dearing Oliver

June 1975

Preface

This study was undertaken primarily on the Yale Forest in Union, Connecticut, and on the Harvard Forest in Petersham, Massachusetts. It was partly financed by the Great Mountain Forest Fund.

The author is grateful to the faculty of the Yale University School of Forestry and Environmental Studies and to the staff of the Harvard Forest, Harvard University, for their assistance in this project. He appreciates the advice and encouragement of Dr. Graeme P. Berlyn, Dr. Kenneth J. Mitchell, Dr. Thomas G. Siccama, and Dr. Garth K. Voigt of the Yale School of Forestry and Environmental Studies; and Dr. Ernest M. Gould, Jr., and Mr. Walter H. Lyford of the Harvard Forest. He wishes to thank Dr. Earl P. Stephens, formerly of the Harvard Forest, for permission to supplement this research with his previously unpublished data on record at the Harvard Forest. He especially wishes to thank Professor David M. Smith of Yale University and Mr. H. R. Oliver of Forest Land Services Company of Camden, South Carolina for their interest, encouragement, and contributions without which this research would not have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Northern red oak (*Quercus rubra* L.) is an important species for commercial forestry (Smith, 1970; Core, 1971) and from an ecological standpoint. It is characteristic of the Appalachian forest (Smith, 1962b) and is distributed throughout most of the eastern United States and southeastern Canada (Fowells, 1965). Because of its often dominant position in the forest, it and other oaks help distinguish forest types of many regions (Smith, 1962b). A member of the red oak (*Erythrobalanus*) subgenus, it and other red and white oaks have been the subject of much forestry research (White and Roach, 1971). This research has often been concerned with the early growth of northern red oak or its response to silvicultural manipulations. Little work, however, has been done in tracing the pattern of development of northern red oak from seedlings (or seedling sprouts) to mature trees. A study of this growth — the subject of the present paper — should provide a background to understanding the development of the oak forest and the response of this species and its associates to various forms of silvicultural manipulation.

The deciduous forests of eastern North America are complex ecosystems containing within a small area a large number of species and a broad range of individual tree heights and diameters. This complexity has led to difficulties in describing them and understanding their patterns of development. As a result many explanations of their interaction have been put forward and are being constantly revised as new evidence emerges.

Within a single stand tree heights vary considerably, with smaller individuals existing beneath and between the canopies of the taller trees. Often segregation by species occurs, with certain species occupying the upper canopy stratum, and different ones occupying lower strata. It has frequently been assumed that these smaller trees are younger, are comprised of shade tolerant species, and will eventually replace the taller ones in the upper canopy strata (Jones, 1945; Braun, 1950; Daubenmire, 1968). By this explanation a stratified stand of mixed species is constantly recruiting new trees, thus creating an all-aged or uneven-aged condition.

The mixed stratified stands also contain a broad range of diameters which, when arranged by diameter classes, may approach a reverse-J-shaped distribution. This reverse-J-shaped distribution is especially apparent when the smaller diameter classes are not included in the sample — as is often the case in studies of forest development. The explicit or implicit assumption that tree diameter is an indication of tree age has also led to the acceptance of a forest with such a diameter distribution as being all-aged — or balanced uneven-aged — with geometrically decreasing numbers of individuals in each successively older age class (Hough, 1932; Meyer, 1943; Meyer and Stevenson, 1943; Worley and Meyer, 1951; Eyre and Zillgitt, 1953; Phillips, 1959; Piussi, 1966; Daubenmire, 1968; and Minckler, 1974b).

Recently there is increasing evidence which suggests that a mixed deciduous forest stand stratified in species composition or a reverse-J-shaped distribution of tree diameters does not necessarily depict an all-aged stand. Wilson (1953) showed a second-growth northern hardwood stand in New Hampshire — generally considered even-aged — had the reverse-J-shaped diameter distribution generally associated with all-aged stands. Putnam, Furnival, and McKnight (1960) listed diameter distributions for managed even-aged and uneven-aged southern bottomland hardwood stands. The reverse-J-shaped distribution was more apparent in the even-aged stand. Mixed species, deciduous stands in Connecticut which were examined between about 40 and 70 years after initiation followed the trend of decreasing in numbers of trees in the smaller diameter species of the understory. The species in the overstory with larger diameters were found to increase in size more rapidly than those of the understory (Olson, 1965). If such stands were all-aged, the understory would be expected to maintain a relatively constant stem number by the recruitment of new individuals while those trees present either died or increased in size to replace the senescing overstory. Also, no correlation was found between the age and diameter of trees in mixed deciduous stands in West Virginia (Gibbs, 1963).

Several students of forest development have hypothesized that a vertical stratification of tree crowns and a reverse-J-shaped diameter distribution may also be present in an even-aged stand. In these cases, stems comprising a stand begin growth after removal of the previous stand (Raup, 1964; Smith, 1971; Johnson, 1972; Drury and Nisbet, 1973). "The plants dominant in the later stages [of secondary succession] were present either from the beginning, or at least from a very early stage. Their inconspicuousness in the early stages appears to be a consequence of their slow growth and/or their suppression by other species (and to some extent, to the preoccupation of botanists with the dominant species)" (Drury and Nisbet, 1973). By the even-aged explanation the species of smaller diameters and whose crowns are beneath the main continuous canopy are of essentially the same age as their suppressors. However, the smaller trees would have been overtopped, giving the forest the characteristic conformation of an even-aged stratified mixture of species. The forest, then, would consist of a mosaic of even-aged stands, each of which originated from disturbance. Accordingly, a forest could be composed of more than one age class where there were disturbances removing only some of the standing trees and allowing new trees to initiate.

The effective stem age is dated from time of release of the advanced regeneration after overstory removal (Morris, 1948; Sprugel, 1974) by the even-aged explanation. By even-aged it is not meant that all trees start in precisely the same year, but that the range of ages is small.

The uncertainty over even-aged or all-aged stands has recently been intensified by controversy over stand manipulations on the Monongahela National Forest in West Virginia. Those who believe the forest developed in an all-aged condition, with the smaller diameter trees of the lower crown strata being younger, advocate the selection method of forest management in which older trees are continuously harvested (Minckler, 1974a). Alternatively, those who claim the forests are even-aged, stratified mixtures of species claim that the clearcutting or shelterwood method of regeneration and harvest would simulate the natural disturbances removing the overstory; these heavy cuttings would allow the seeds and seedling advanced growth near the forest floor to form a new stratified, mixed species stand (Marquis, 1974).

The role of disturbances — whether natural such as fires, landslides, hurricanes, tornadoes, or floods; or man-created such as forest cuttings — in forest succession is becoming increasingly appreciated (Bromley, 1935; Lutz, 1940; Hough and Forbes, 1943; Day, 1953; Goodlett, 1954; Stephens, 1956; Lutz, 1959; Bormann and Buell, 1964; Raup, 1964; Lyford and MacLean, 1966; Loucks, 1970; Thompson and Smith, 1970; Slaughter *et al*, 1971; Dix and Swan, 1971; Spurr and Barnes, 1973; Troedsson and Lyford, 1973; Trimble, 1973; Henry and Swan, 1974; Sprugel, 1974).

Natural and human disturbances which initiate forest succession can be divided into two broad categories (although there is in fact a gradation between these extremes) depending on whether or not seeds, seedlings, sprouts, and other forms of advanced regeneration are present within the pre-existing forest and survive after the overstory is destroyed by the disturbance which initiates succession. Clements (1916) and McKinnon *et al* (1935) recognized this influence of the advanced regeneration. Secondary succession without the presence of advanced growth occurs after such events as old field abandonment, colluvial formations on river banks, and extremely hot fires.

Succession in which the new stand is initiated from seedlings, sprouts, and advanced regeneration in the forest litter as well as from seeds introduced at disturbance occurs after many natural disturbances and heavy silvicultural cuttings.

It has been casually observed in the Yale Forest in Union, Connecticut, and the Harvard Forest in Petersham, Massachusetts, that mixed stands following pine and hardwood clearcuts and similar disturbances at first appear to be dominated by maples and birches with northern red oaks appearing as smaller and less frequent components of the stand. It is only between the second and third decades that northern red oaks seem to increase markedly in both height and diameter until they eventually form a continuous canopy above the other species.

There has been indirect evidence in New England and elsewhere that red oaks maintain rapid diameter growth at a later age than do other species. In mixed hardwood stands in Connecticut it was found by Olson (1965) that later in the life of a stand (about 40 to 70 years after initiation) the proportion of basal area contributed by northern red oak increased while the absolute number of northern red oak individuals decreased. At this time it was the individuals in smaller diameter classes which were decreasing in numbers. Karnig and Stout (1969) found that the diameter growth was much greater on *Quercus rubra* trees of larger diameter classes than smaller diameter classes in mixed forests of southern New York. Similar observations have been made of black oak (*Quercus velutina* Lam.) in Missouri (Buchanan *et al*, 1962).

Northern red oaks in Wisconsin were found by Scholz (1948) to decrease in diameter growth rate at late ages in stands of coppice origin or stands of only oak species. Alternatively, when it was in mixed even-aged stands with other hardwoods, northern red oak exhibited the latent diameter acceleration alluded to above. Scholz divided the growth of the northern red oaks of mixed stand origin into three time periods — early, middle and late (these periods each being about 20 to 50 years long) — and found the radial growth rate during the middle period to be 100-200 percent greater than during the early period and only 50 percent higher than during the late period. Baird (1967) has found that northern red oaks on the Cumberland Plateau in Tennessee display a high diameter increment at a later age than do yellow poplars (*Liriodendron tulipifera* L.). Analyses of data taken at the Harvard Forest (Yoder, 1941; Hoisington and Carr, 1949) showed similar late growth increases of northern red oak.

There has also been reference to northern red oak's latent ascension to a dominant crown position during stand growth. Northern red oak has been found to grow slower in height than its associated intolerant species during its first four or five years (Minuse, 1912; and Beck, 1970). It has also been found to be intolerant of dense shade. Scholz (1952) attributed its being found in Minnesota only in even-aged patches to this lack of shade tolerance. Tryon and Carvell (1958) found initial growth of oak regeneration beneath canopies to be closely correlated to the amount of sunlight incident on the forest floor. Seedlings of *Quercus rubra* have been observed to grow taller and with more leaves with progressive increases of light from 8-100 percent of full sunlight (McGee, 1968).

Early in stand development it appears that the oaks which later dominate must live as intermediates in the upper crown canopy. Scholz (1952) alleged that red oaks could develop into trees of sawtimber size under conditions of considerable crowding as long as they were not permanently overtopped. Ward (1964) also found the species to endure somewhat crowded conditions and devised a "crown competition index" —

a measure of the amount of shade exerted on a tree's crown by its associates — which he found related to live crown ratio.

Later in stand development — at the time of no general height increase — Stephens and Waggoner (1970) found the crown canopy of mixed hardwood stands in Connecticut to become increasingly dominated by oaks. At this time northern red oak individuals seemed either to gain dominance in the stand or to die.

While there have been several observations of the latent ascendance of northern red oak and several speculations about its cause, little direct work has been done in tracing the pattern of growth of those individuals which have gained dominance and comparing their development to that of the associated species.

GENERAL PROCEDURES

The purpose of this thesis was to test the validity of these observations of red oak ascendance and to investigate the ecological and silvicultural significance of the phenomenon if it indeed exists. In this investigation much of the effort was concentrated on tracing backwards in time a few representative stands by means of historical-development dissection of the present living and dead stems (Stephens, 1955; Swan and Henry, 1973). This method was used as an alternative to the more common practice of following the growth changes in initially young stands over a long period of time.

At first, a systematic sample of middle-aged and old unmanipulated stands on the Yale Forest — believed to be representative of hardwood forests in central New England — was studied to determine if there was in fact a consistent species stratification in the later life of the stand, with northern red oaks occupying the more dominant positions relative to red maples and black birches. It was established that in these older stands northern red oaks do occupy the upper crown positions with the red maples, black birches, and other species occupying the lower canopy positions and smaller diameters.

Next, a study was undertaken first to determine the age distribution of the trees comprising the stratified forest. Seven stands on the Yale Forest and Harvard Forest which were between the ages of 33 and 107 years and representative of the observed pattern of species stratification were selected. The age distributions of all stems in the stratified stands were determined first by aging a sample of the upper canopy red oaks — 52 in all — and then by aging all 144 other stems within a subsample of 14 plots.

Height and diameter growth analyses were made between competing oaks, maples, and birches within these plots to determine when and how northern red oaks asserted dominance with respect to red maples and black birches. A total of 66 stem analyses were performed, and the data were supplemented by 18 other stem analyses performed by Stephens (1955) in a similar stand in the Harvard Forest.

Estimates of the number of stems of each species originally present after a disturbance were made by tabulating all living and dead stems found within five plots in three of the stands. This was to determine if in fact red oak which eventually dominated the stand began from relatively few seedlings when compared to the number of red maple and black birch stems.

The procedures and results of this study are described in detail in the following two parts under two general headings: species stratification and age distribution; and growth patterns, regeneration numbers, and silvicultural significance of the findings.

Throughout this dissertation the name "red oak" will refer to the species *Quercus rubra* L., not to the subgenus *Erythrobalanus*. All numbers are expressed in the English system (inches, feet, etc.) and their metric equivalents are given in parentheses. Diameters taken at 4.5 feet (1.4 meters) will be referred to by the term "DBH" (for "diameter at breast height").

The study was undertaken over a two-year period beginning in the spring of 1972. For simplification all ages and diameters are referenced to December, 1971 unless otherwise stated. As an example, the outer annual xylem ring would be omitted from measurement in a tree cut in December of 1972. Diameter measures inside bark were converted to diameter outside bark where necessary by regression equations developed for each species studied (Appendix 7).

PART I

Species Stratification, Diameter and Age Distribution

Chapter 1

Pattern of Species Stratification

The present study was undertaken to determine the pattern of species stratification, diameter distribution, and age distribution in stands initiating after a single disturbance. It is restricted to stands initiated with advance regeneration since this seems to occur typically in nature and in silvicultural operations in the northeastern United States. The study was also confined to stands on upland New England soils which developed from sandy, bouldery, strongly acid glacial till derived principally from granite and schist. Such soils are widespread in central New England and encompass the well-drained and moderately-well-drained Gloucester, Brookfield, Paxton, Acton, and Woodbridge soils (Ilgen *et al*, 1966; Lyford, 1974). Stands growing on these sites are described by Westveld (1956) as being in the Transition Hardwoods-White Pine-Hemlock Zone.

Red oak (*Quercus rubra* L.) often forms an essentially pure upper canopy stratum on moist, well-drained sites. Crown projections of such stands were mapped in Tract "Tom Swamp II" of the Harvard Forest (Harvard Forest Records, 1974) in Petersham, Massachusetts, and observed in stands studied intensively in Compartments 31 and 97 of the Yale Forest in Union, Connecticut (Meyer and Plusnin, 1945). On dry, upper slopes, red oak occupied the upper stratum in the moister drains while black oak (*Quercus velutina* Lam.) and white oak (*Quercus alba* L.) predominated on the adjacent, drier ridges. These observations of site preferences of the oaks coincide with studies by Goodlett and Zimmermann (1973) and Goodlett (1974). White ash (*Fraxinus americana* L.) was found in the upper canopy position where microsites in the upland soils were too moist for red oak (Stout, 1952; Lyford, Goodlett, and Coates, 1963).

Red maple (*Acer rubrum* L.) and black birch (*Betula lenta* L.) occupy the lower crown strata in virtually all middle-aged or old stands. Other species, such as the aspens (*Populus* species), the hickories (*Carya* species), black cherry (*Prunus serotina* Ehrh.), eastern hemlock [*Tsuga canadensis* (L.) Carr.], and eastern white pine (*Pinus strobus* L.), were also observed in such stands. [White birch, *Betula papyrifera* Marsh., and gray birch, *Betula populifolia* Marsh., and their hybrid were not distinguished in the present study since these two birches hybridize very frequently in central New England (Remington, 1973, 1974). They are referred to herein as white-gray birch.] Sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton) become more abundant with increasing moisture.

Preliminary observations revealed northern red oak, red maple, and black birch to be principal components of the central New England upland stands. Investigation was, therefore, centered around these species, although other associated species were studied where within the sample areas. The study was confined to stands in the 7,800 acre (3,159 hectare) Yale Forest near Union, Connecticut (Meyer and Plusnin, 1945) and to the 3,500 acre (1,418 hectare) Harvard Forest in Petersham, Massachusetts.

Procedures

The consistency of the vertical stratification pattern of species within the forest was first assessed. Thirty-five permanent point-sampling plots located at random on a systematic grid (Zai, 1957) at the Yale Forest near Union, Connecticut, were re-inspected. The study was intended to determine possible patterns in vertical stratification of upland forests which had initiated where advance regeneration was present and were undergoing secondary succession. Plots or quadrants of plots were accepted if no cutting or silvicultural manipulation had occurred within the past 33 years; if the dominant canopy had initiated from disturbances which had left advanced growth seedlings, sprouts, and seeds in the soil; and if the plots were not within swamps of standing water (in June). Twenty-five of the 35 plots met these conditions.

A modification of the point-sampling inventory method (Kulow, 1965) was developed (Appendix 2). Sample trees on each plot were those trees over one inch (2.5 cm) in diameter which would ordinarily be included in a point-sampling inventory. Each sample tree was described by species, diameter, and canopy stratum. Four canopy strata were recognized, similar to those recognized by Richards (1957): Emergent (A-stratum), B-,C-, and D-strata. The following method of distinguishing between crown strata was developed to be as informative and objective as possible (Appendix 2):

A tree was assigned to the emergent or A-stratum if over one-half of its live crown vertical length was above the height of the upper continuous crown canopy of the forest. Such emergents, where present, were widely spaced and did not form a continuous canopy. They were not close enough to touch the branches of other emergent trees. A tree thus defined as being in the emergent crown class was not used in further descriptions of the interactions of other trees. A tree was assigned to the B-stratum if no tree, other than an emergent, overtopped more than one-half of any of its crown radii. The B-stratum formed a relatively smooth, continuous upper surface to the forest, with a few protruding "bumps" of A-stratum trees. A tree was assigned to the C-stratum if more than one-half of any of its crown radii was overtopped by the crown(s) of tree(s) other than emergent(s). Trees that were completely overtopped by the crowns of trees previously assigned to the B- or C- strata were assigned to the D-stratum. The C- and D-strata generally had a less smooth, continuous upper surface than the B-stratum.

A tree was defined as interacting with a sample tree if at least one-half of a radius of the crown of either tree was overtopped by the crown of the other tree. All sample trees in a plot and those trees interacting with the sample trees were defined herein as being associated with each other. Hence, two trees did not have to be visibly interacting with each other to be associated with each other.

The structure of the average forest was obtained by separating all sample trees into four relative strata. Each sample tree in each stratum was described in terms of its basal area per acre (using appropriate conversion factors from point-sampling theory), species, diameter class, and number per acre (using appropriate conversion factors). The forest was depicted both graphically and tabularly by canopy strata, species, diameter classes, number of stems per acre, and basal area per acre is shown in Figure 1 and 2 and Appendix 2. In each case in which red oaks, red maples, or black birches interacted with each other, it was noted which tree occupied the higher position with respect to the other. Each species should assume the higher position 50 percent of the time they were recorded as interacting if there were only a random pattern to the interaction of the two species. Deviations from this would indicate the probability of a more patterned interaction. Only one interaction — the interaction with the individual of the highest canopy stratum — was recorded if a sample tree interacted with more than one individual of the other species. Each tree was regarded as a separate sample where two sample trees interacted; therefore, in this case the actual interaction would be recorded twice — once under the consideration of each sample tree.

A large, dominant, ring-porous tree (usually an oak) was aged at one foot (30.5 cm) height with an increment borer in each sample plot to determine the range of ages of dominant trees in the entire sample.

Results and Discussion

Red oak was an associated species (as defined earlier) in 22 of the 25 selected upland plots (see Appendix 2, Table 2.4) on the Yale Forest. The largest trees of these plots ranged from 33 to 100 years old. Red oak occupied the B-stratum either as a single species, along with other oak species, or with maples, birches, and hemlocks where they were free of oak competition. Red maple was associated with red oak in 21 of the plots; black birch was associated with red oak in 13 of the plots; and all three species were in association in 12 of the 25 plots. This frequent concurrence of red oak with both red maple and black birch in such stands further justified concentration of the study on the interaction of these three species.

Distribution of trees by diameter (at DBH) in the sampled forest was found to be a reverse-J-shaped curve, as is shown in Figure 1 (and Table 2.2 of Appendix 2). Red oak was found in the larger diameter classes, while red maple and black birch were found with increasing frequency at smaller diameters.

Crown strata distribution by species was found by dividing the average forest (Figure 1) into canopy strata (Figure 2; and Table 2.3, Appendix 2). Trees of larger diameters were found in the B-stratum —

Figure 1. Distribution of all trees of upland forests in the Yale Forest in northern Connecticut based on point sampling of 25 plots.

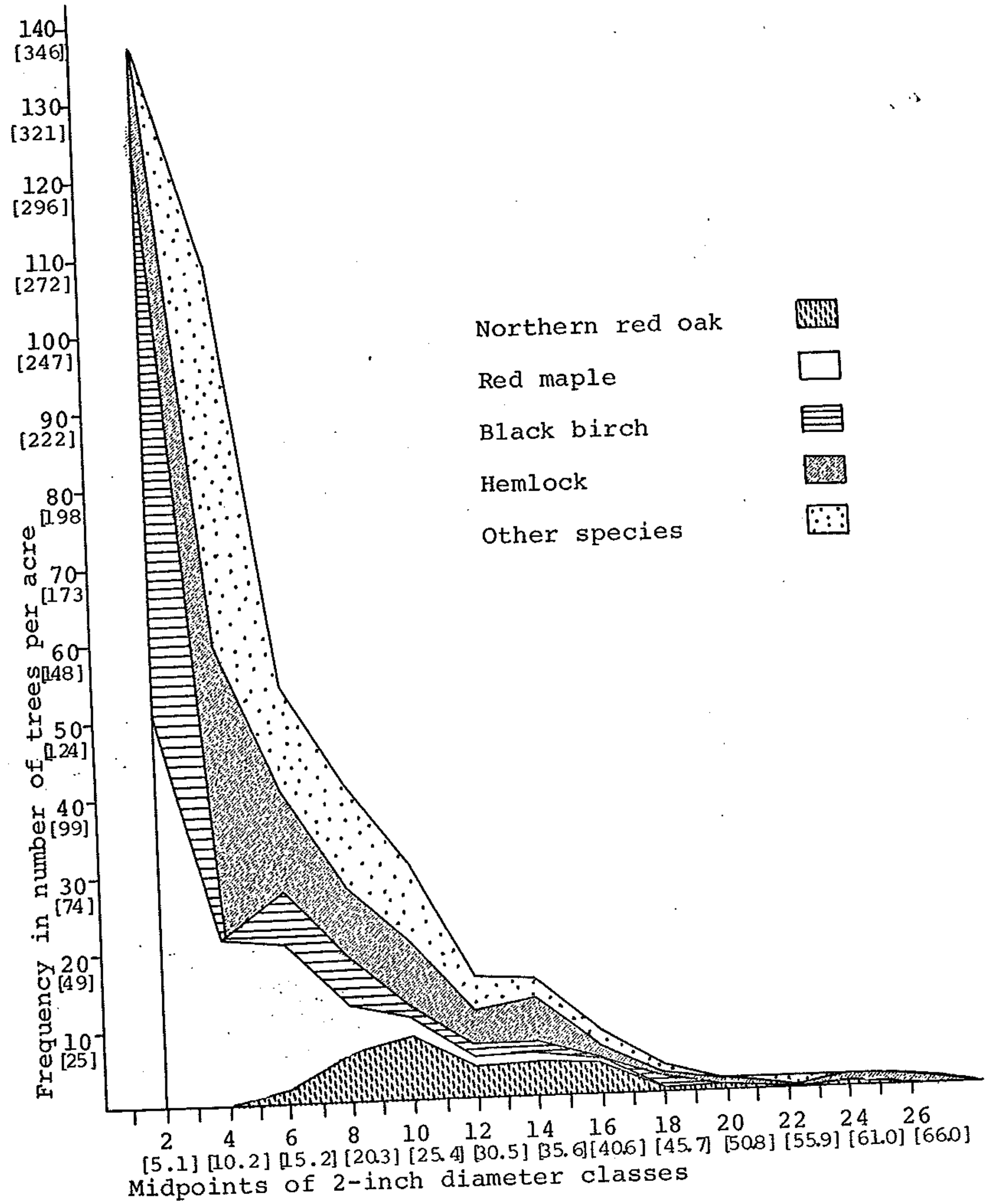
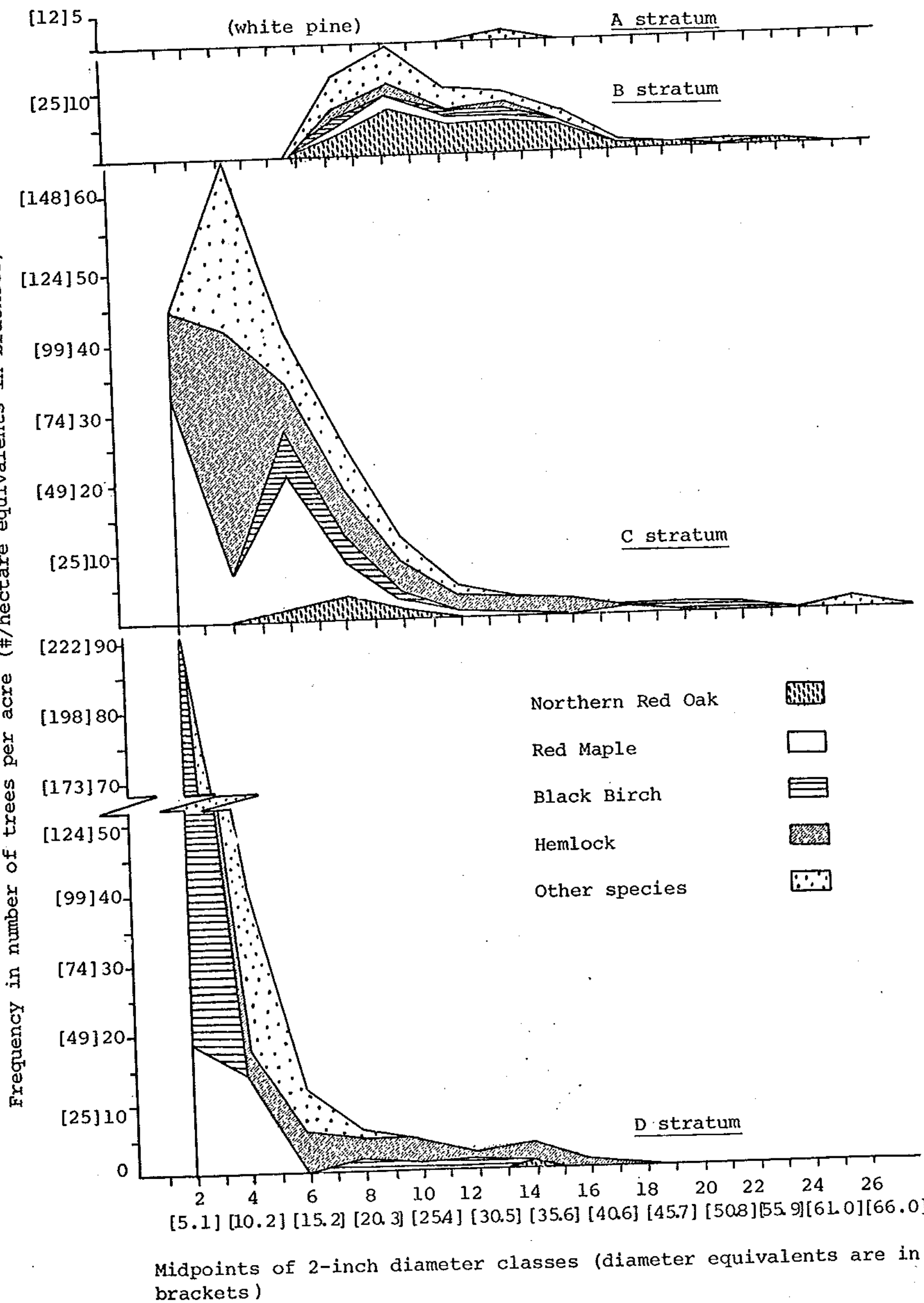

Frequency in number of trees per acre
140 [346]
130 [321]
120 [296]
110 [272]
100 [247]
90 [222]
80 [198]
70 [173]
60 [148]
50 [124]
40 [99]
30 [74]
20 [49]
10 [25]
Northern red oak
Red maple
Black birch
Hemlock
Other species
2 [5.1]
4 [10.2]
6 [15.2]
8 [20.3]
10 [25.4]
12 [30.5]
14 [35.6]
16 [40.6]
18 [45.7]
20 [50.8]
22 [55.9]
24 [61.0]
26 [66.0]
Midpoints of 2-inch diameter classes

Figure 2: Vertical stratification of trees of forest of Figure 1.


(white pine)
A stratum
B stratum
C stratum
D stratum
[12]5
[25]10
[148]60
[124]50
[99]40
[74]30
[49]20
[25]10
[222]90
[198]80
[173]70
[124]50
[99]40
[74]30
[49]20
[25]10
0
Frequency in number of trees per acre (#/hectare equivalents in brackets)
Northern Red Oak
Red Maple
Black Birch
Hemlock
Other species
2 4 6 8 10 12 14 16 18 20 22 24 26
[5.1] [10.2] [15.2] [20.3] [25.4] [30.5] [35.6] [40.6] [45.7] [50.8] [55.9] [61.0] [66.0]
Midpoints of 2-inch diameter classes (diameter equivalents are in brackets)

or upper continuous canopy — with the exception of hemlock. Progressively smaller trees were relegated to lower canopy strata. Red oak accounted for over 40 percent of the stems in the upper continuous canopy (B-stratum) although it comprised less than 8 percent of all stems. Red maple and black birch, on the other hand, were found primarily in the lower (C- and D-) strata of the forest. Those red oaks found in the lower two strata were subordinate to other red oak trees (and not to other species) 75 percent of the time.

A definite pattern was found in the interaction of red oak with red maple or black birch. Red oak and red maple interacted on 16 plots with a total of 50 interactions (Table 2.4, Appendix 2). Red oak subordinated or overtopped the red maple in all 50 interactions. Red oak dominated black birch in 30 of 31 interactions. The probability that the red oak might be above the red maple in all 50 instances or above the black birch in 30 instances as a matter of chance is infintesimally small. Therefore, red oak can be expected to be in a canopy stratum equal to or higher than red maple or black birch where red oak between 33 and 100 years is found with either of these species on such upland sites.

The observed diameter distribution and canopy strata patterns could conceivably be interpreted as evidence of either even-aged or all-aged stands. According to the even-aged interpretation, red maples and black birches had already been relegated to lesser crown positions than red oaks in the stands. If the stands were all-aged, it would be presumed that the red maples and black birches had not yet surpassed the oaks even in the oldest stand with trees of 100 years.

Chapter 2

Age and Diameter Distributions in Stratified Stands

Introduction

Selection and Dating of Stands

Age Distribution of B-stratum Red Oaks

Diameter and Age Distributions of Substrata Associates

60-Year-Old Stands

33-, 45-, 74-, and 107-Year-Old Stands

Discussion

A Forest as an Aggregate of Even-aged Stands

It was established that forests arising from disturbances on uplands in central New England often become dominated by red oaks. Further study was limited to forests which had begun after a single disturbance which removed all trees of the previous stand and which were not followed by smaller, intervening disturbances — such as fire or cuttings — removing only part of the new tree population. The types of disturbances involved in this study — clearcuttings of old field white pine, blowing down of a stand by a hurricane, and clearcutting of a deciduous stand — and the methods of their detection are discussed below. The more complicated variation manifested by a forest with a history of several smaller disturbances was at first avoided. Portions of the stands chosen in this study, however, did contain intervening disturbances created by the 1938 hurricane in addition to their initiating one. The relation of these to the single disturbance that initiated the stand is later considered.

Selection and Dating of Stands

Much of central New England, once farmed fields and pastures, grew into stands of white pine when the farms were abandoned. Such old field white pine stands were very numerous (Sargent, 1884). Between 1890 and 1920, many of them were clearcut for boxboards, matchsticks, lumber, and similar products (McKinnon, 1935; Bromley, 1935). These clearcuts can become forests of red oak in the dominant canopy and red maple, black birch, and other species in the understory despite efforts to re-establish the white pine by weeding out the hardwoods (Lutz and Cline, 1947).

The cause and approximate time of an initiating disturbance and evidence of other disturbances within a stand can be documented by studying natural history evidence through the historical-development method (Stephens, 1955; Henry and Swan, 1974). In the present study, remnants of many closely spaced white pine stumps which had been cut approximately six to twelve inches above the ground in an area surrounded by a stone wall gave evidence of stand origin as clearcutting of old-field white pine. Many advanced growth understory seedlings beneath the white pine were mowed, pushed over, or damaged at the root collar by the pine cutting (Patton, 1922; McKinnon *et al*, 1935). Remnants of white pine logs in the A-horizon were frequently found in the present study at a point of early damage to presently living stems. The pine remnants indicated that these stems had been advanced regeneration, and that pine cutting was the cause of damage. Growth ring analyses indicated the time of the clearcutting. Previous clearcutting of deciduous woodlots was indicated by a high frequency of multiple-sprout (coppice) stems initiated at the same time (Frothingham, 1912).

Disturbance by the 1938 hurricane — either a complete or partial stand blowdown — was detected by the time of release of trees, by windthrow mounds (Lutz, 1940; Stephens, 1956), and by the presence of remains of trees blown by southeast winds. Complete stand blowdown was obvious by the large numbers of windthrow mounds and parallel, blown-over stems (in the cases of this study the downed trees had not been salvaged). Where only occasional trees were blown over, adjacent trees had expanded to close the canopy, leaving little evidence of the hurricane. Windthrow mounds (with trees generally having blown to the northwest) and diameter accelerations shortly after 1938 of the remaining nearby trees revealed hurricane disturbances in five of the studied stands (Stands I, II, III, IV, and VII) and in many other areas observed in the Yale and Harvard Forests.

Seven stands on the Yale Forest and Harvard Forest were selected for the more detailed study of their historical development (Table 1). Five of these arose after clearcutting old-field white pine — three (Stands I, II, and III) which had initiated approximately 60 years earlier; one (Stand IV), approximately 74 years earlier; and another (Stand V), approximately 45 years earlier. After the pattern of growth of the red oak and the interactions of the species were determined in stands following pine clearcutting, the study was extended to two stands which had originated from other forms of heavy disturbance. One of these (Stand VI), on the Yale Forest, had developed beginning 33 years ago after the blowdown of an old field white pine stand in the 1938 hurricane. The other (Stand VII), at the Harvard Forest, had started approximately 107 years earlier after a very heavy fuelwood cutting of a woodlot in about 1864.

Age Distribution of B-stratum Red Oaks

The question of whether the selected stands were even-aged or all-aged was investigated. Initially the ages of only B-stratum red oaks were determined. Three stands approximately 60 years of age were studied first (Stands I, II, and III). They contained B-strata composed largely of red oaks, with lower strata of red maples, black birches, and many of the other species found in the initial 25 plot inventory of upland stands. A sample of 16 B-stratum red oaks was selected from Stand I. This was estimated to be a 2.7 percent sample

Table 1. Stands studied intensively, plots used within the stands, and average age and diameter characteristics of B-stratum red oaks of stands studied.

Stand Number	Approximate years since initiating disturbance	Range of heights of selected trees at 50 years	Data for B-stratum red oaks at DBH: Number sampled	Mean age	Standard deviation	Mean diameter	Standard deviation	Plots selected in each stand
I	60*	59	16	59.7 yr.	3.2	11.3 in. [28.7 cm]	1.9 [4.8]	I-1a, b, & c** I-2a, b, & c
II	undocumented	63 - 66	13	58.3 yr.	1.6	11.6 in. [29.5 cm]	2.2 [5.6]	II-1, II-2
III	60*	63 - 65	6	58.2 yr.	1.3	12.0 in. [30.5 cm]	1.4 [3.6]	III-1, III-2, III-3
IV	74*	56 - 66	3	70.3 yr.	1.3	14.0 in. [35.6 cm]	0.7 [1.8]	IV-1, IV-2, IV-3
V	undocumented	—	7	42.7 yr.	2.2	6.4 in. [16.3 cm]	1.9 [4.8]	V-1, V-2
VI	33*	—	5	26.8 yr.	3.1	3.9 in. [9.9 cm]	1.4 [3.6]	VI-1
VII	undocumented	—	5	106.6 yr.	5.6	18.3 in. [46.5 cm]	1.6 [4.1]	VII-1

* Dated from natural history evidence; ages may be slightly less than true time of stand initiation.

** Plots I-1 and I-2 were enlarged to three different sizes for three different intensities of study. These different sizes are referred to as a, b, c.

of the B-stratum trees of that stand (Appendix 3). Each selected red oak was cored at breast height (4.5 feet; 1.4 meters) with an increment corer to determine its age and diameter growth pattern. Less intensive samples of the dominant red oaks of Stand II and III were taken — 13 trees (1.4 percent sample) and six trees (0.7 percent sample), respectively, as patterns of the red oak growth were established.

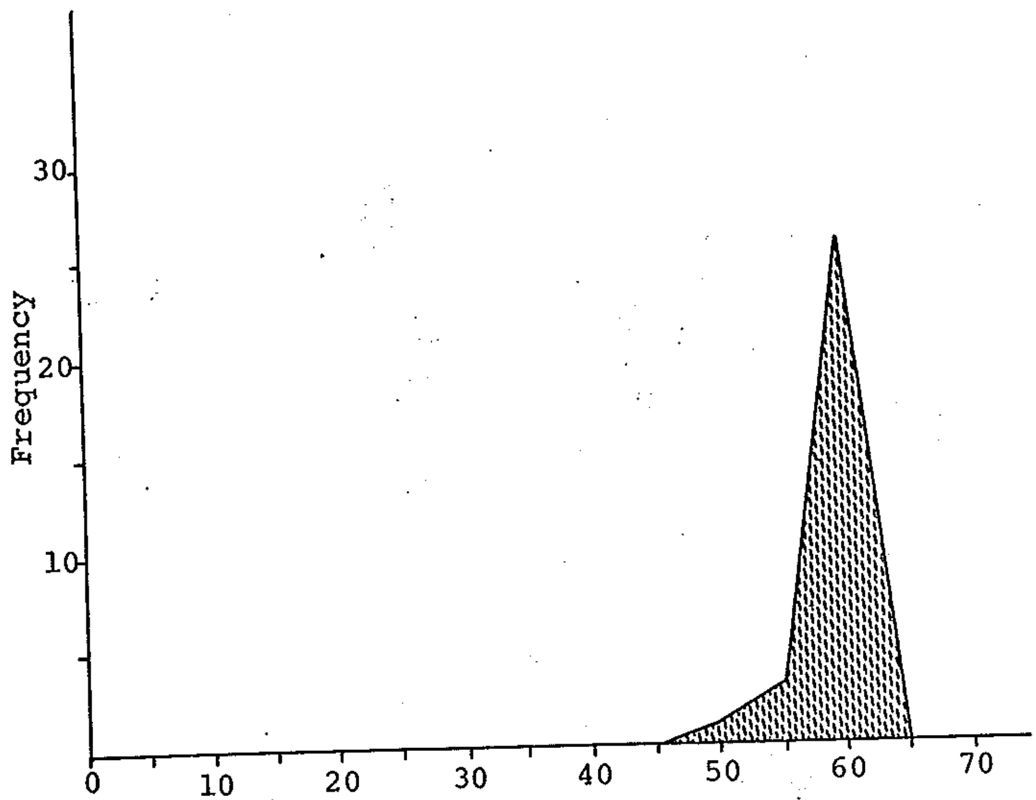
Analysis of variance of the samples taken showed that Stands I, II, and III contained B-stratum red oaks which had diameters and ages whose means were not significantly different (5 percent level of significance). This proved convenient for studying the relation of B-stratum oaks to sub-strata stems since, for the rest of this study, these three stands were all considered part of the same population.

A histogram of age class versus frequency for the aged B-stratum red oaks in Stand I, II, and III is shown in Figure 3. The ages at 4.5 feet (1.4 meters) of these red oaks all proved to be slightly less than the time of the stand-initiating disturbance; therefore, these oak B-strata were essentially even-aged.

To determine if this pattern was true for older and younger stands, less intensive samples of the B-stratum red oaks were taken in Stands IV, V, VI, and VII. Three selected red oaks were aged in Stand IV; a total of seven oaks in two randomly placed, circular one-fiftieth-acre (0.008 hectare) plots were aged in Stand V; five oaks in a randomly placed, circular one-fiftieth-acre (0.008 hectare) plot were aged in Stand VI; and five selected oaks were aged in Stand VII (four of these oaks in Stand VII had been previously aged by Harvard Forest scientists; Harvard Forest Records, 1974).

The four additional stands represented a wide range of times since stand initiation — 33 to 107 years — and three forms of stand-initiating

Figure 3: Distribution of ages of B-stratum northern red oaks sampled from Stands I, II, and III.



Midpoints of 5-year age classes of B-stratum red oaks aged at 4.5 feet.

disturbances — old field white pine clearcutting, hurricane blowdown, and deciduous forest clearcutting. They, too, had the essentially even-aged condition of the B-stratum red oaks.

The number of red oaks sampled, their mean age, and the standard deviation of the mean age of each stand are shown in Table 1 (and Appendix 3A). [More detailed measures of each tree sampled are given in Appendix 3.] Within each of the seven stands the age distribution of the B-stratum oaks was extremely narrow, the standard deviation never exceeding six years. As in the 60-year-old stands, mean age at 4.5 feet (1.4 meters) of the sample oaks in each stand was slightly less than the time of the initiating disturbance. The oaks in each case, therefore, began growth soon after the overstory was removed and — between 33 and 107 years — formed an even-aged B-stratum.

<u>Diameter and Age Distributions of Substrata Associates</u>

It was desirable to determine how even-aged red oaks which formed the B-stratum grew in relation to those trees which, at some time in the past, could have influenced or been influenced by the overstory oaks and were presently in the lower crown strata. Substratum associates of selected red oaks from each of the seven stands of the previous sample were studies more intensively. The plot size used and the method of selection varied with the age of the stand investigated. The sizes and shapes of these selected stand will be discussed later.

A total of 14 plots were chosen. All 152 living trees within these plots were cut; cross-sectional disks were taken at one foot (0.3 meters) and 4.5 feet (1.4 meters) for age and diameter growth determinations. Disks were taken from selected trees every four feet (1.2 meters) up the stem (beginning at eight feet; 2.4 meters) to the top, to be used for more accurate determination of age (Appendix 4).

The disks were prepared (Appendix 4B), the number of rings in each was counted, and the individual widths were measured with an Addo-X tree ring counter. Some of the rings of the understory trees were very small and possibly missing, as was found by Larson (1956) and Bormann (1965) in suppressed trees. A method was developed whereby ages of basipetal disks could be determined by tracing growth patterns downward through consecutive disks at four-foot (1.2 meter) intervals from the top (where the rings are wider) to the base for those trees sectioned for the length of their stem. [This method is described more fully in Appendix 4B.] The ring patterns were compared between the two disks for those stems sectioned only at one foot (0.3 meter) and four and one half feet (1.4 meters). In these ways trees were aged and annual radial growth patterns at 4.5 feet (1.4 meters) were recorded (Appendix 5). If a tree was hollow at the point of measurement, radial growth measurements were taken on solid disks close above or beneath the desired location.

60-Year-Old Stands

Plots were first chosen beneath seven B-stratum red oaks of the sample from Stands I, II, and III. These were labelled Plots I-1a, I-2a, II-1, II-2, III-1, III-2, and III-3, and are listed in Table 1. Height range at 50 years (Table 1) was obtained from stem analysis of the B-stratum red oak in each plot. Plots were selected as those having mostly red maple and black birch beneath the red oak since these species occurred frequently together (Chapter 1). The seven oaks chosen all had age (at 4.5 feet; 1.4 meters) and diameter values determined to be within a central range containing 80 percent ($z = 1.28$) of the values of the population of B-stratum red oaks taken from Stands I, II, and III based on the sample of 35 trees (Appendix 3C).

Initially, plot size was established as the area beneath each chosen B-stratum red oak's canopy; this was determined as the area described by vertical projection of the periphery of the crown of this oak to a horizontal plane. (Plots I-1a and I-2a were later enlarged to two other sizes for more detailed study; these enlargements, described in detail later, are referred to as I-1b, I-2b, I-1c, and I-2c.) The sample area beneath the dominant red oak canopy was determined for each of the seven selected plots. Species, diameter at 4.5 feet (1.4 meters), and positions of all living trees which had their bases within the plot area were noted. Sections of these stems were analyzed as described earlier for age and diameter analyses.

Frequency distributions by diameter and age classes of the combined seven plots are shown in Figure 4 (A and B). [Table 4.1 of Appendix 4C shows a list of all trees sectioned on the seven plots, their ages, diameters, and the total height of trees on which height-age analyses were performed.] As can be seen in these figures selected trees of an even-aged red oak B-stratum and trees in the lower strata beneath them show the reverse-J-shaped diameter distribution associated with all-aged stands. Age distribution, however, shows all trees initiated soon after a disturbance (in this case the clearcutting of old field white pine stands); and hence arose in an essentially even-aged condition.

All trees studied in these seven plots had their root collars beneath an oak canopy — a vertical projection of the crown periphery of a B-stratum red oak. Plots I-1a and I-2a were then enlarged to determine if trees with root collars beyond the oak canopies showed a

Figure 4: Distribution of diameters (Figure A) and ages (Figure B) of all trees in seven selected plots dominated by northern red oak in stands (Stands I, II, and III) initiating after clearcutting old field white pine approximately 60 years ago.

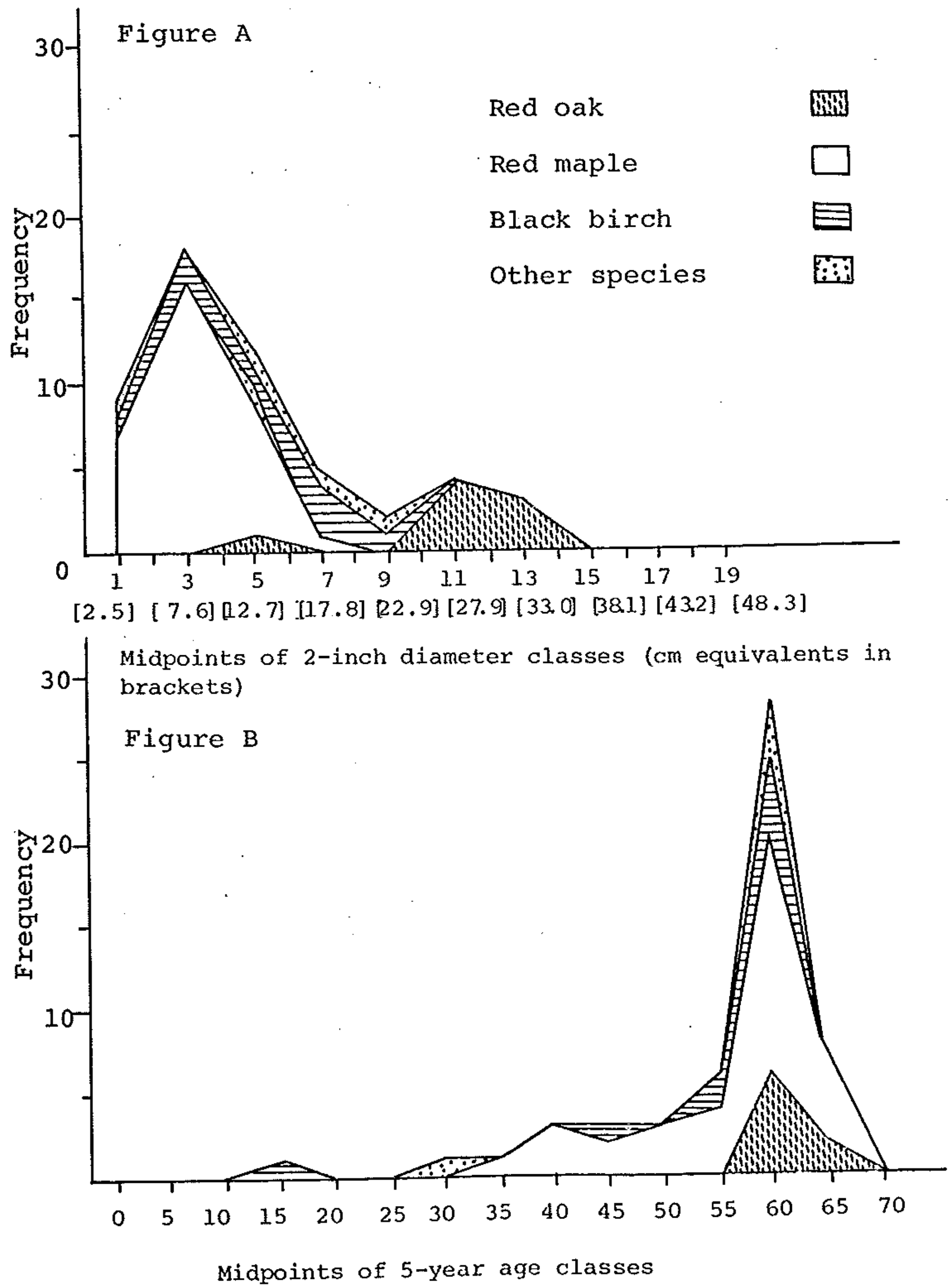


Figure A
Red oak
Red maple
Black birch
Other species
Frequency
0
10
20
30
1 3 5 7 9 11 13 15 17 19
[2.5] [7.6] [12.7] [17.8] [22.9] [27.9] [33.0] [38.1] [43.2] [48.3]
Midpoints of 2-inch diameter classes (cm equivalents in brackets)
Figure B
Frequency
10
20
30
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Midpoints of 5-year age classes

different age distribution. These enlargements to well beneath the crowns of the surrounding B-stratum trees are referred to as Plots I-1b and I-2b. Vertical crown projections were mapped of the surrounding B-stratum trees (all were red oaks) and the central B-stratum tree of each of the two plots (Appendix 6). That part of the forest floor which lay outside of the B-stratum canopy projections could be distinguished by use of these maps.

Locations of root collars of all living trees were mapped in Plots I-1b and I-2b. Within each of these enlarged plots stem analyses were then done on all trees which had not already been analyzed for the study of Plots I-1a and I-2a. The studied trees were divided into two groups: those whose stems originated outside the canopy of any B-stratum tree, and those trees within these areas. Student's t-distribution analysis showed no significant difference (at the five percent level) between the ages of trees growing beneath and outside of B-stratum oak canopies in Plots I-1b and I-2b.

These 60-year-old stands with vertically stratified canopies and reverse-J-shaped diameter distributions proved to be essentially even-aged since the B-stratum red oaks showed a very narrow range of ages (Figure 3) and those trees occupying the C- and D-strata both within and between B-stratum oaks showed a similar narrow range of ages. Therefore, the reverse-J-shaped distribution of diameters does not necessarily depict an all-aged forest and the stratification of species into crown classes does not necessarily mean those in the understory are indicative of a younger, later stage of succession.

Diameter and age distributions of the living stems per unit area for these three stands were estimated. Use of the plots delimited by vertical projections of crown peripheries would have introduced a bias in favor of the B-stratum red oaks. Alternatively, the entire stand area could conceivably be divided into a number of unbiased, unequal size plots with each plot consisting of the area within the vertical projection of the canopy of a B-stratum tree and extending outward from this for half the distance to the vertical projection of the periphery of the surrounding B-stratum trees (as can be seen in Appendix 6).

Plots I-1 and I-2 were thus adjusted to a third size, referred to as Plots I-1c and I-2c. [The species, diameters, and ages of the trees found within Plots I-1c and I-2c are shown in Tables 6.1 and 6.4 of Appendix 6.] Figure 5 shows that on a per-unit-area basis the diameters are broadly distributed although here, too, there is a narrow range of ages of the trees.

33-, 45-, 74-, and 107-Year-Old Stands

To determine if older and younger stands containing red oak, red maple, and black birch also showed the even-aged patterns, older and younger stands whose age distributions of B-stratum red oaks had been studied as mentioned earlier were examined more intensively. These stands were sampled in different ways because of variations of age and hence degree of canopy stratification. [The diameters and ages of the sampled trees in each stand are shown in Table 4.1 of Appendix 4C.]

The oldest stand (VII) resulted from a heavy cutting, presumably for hardwood fuelwood. Six B-stratum red oaks had been previously found to be approximately 107 years old [by increment corings at 4.5 feet (1.4 meters); Harvard Forest Records, 1974]. A black birch and a sugar maple dominated by a B-stratum oak were cut and aged. No attempt was made to analyze all trees existing beneath the crown of the dominant oak.

Figure 5: Distribution of diameters (Figure A) and ages (Figure B) of trees per acre based on two plots in Stand I where stand was partitioned into areas closest to each B-stratum tree. The plots were 0.016 acres (0.006 hectares) and 0.013 acres (0.005 hectares) in size and both dominated by red oaks.

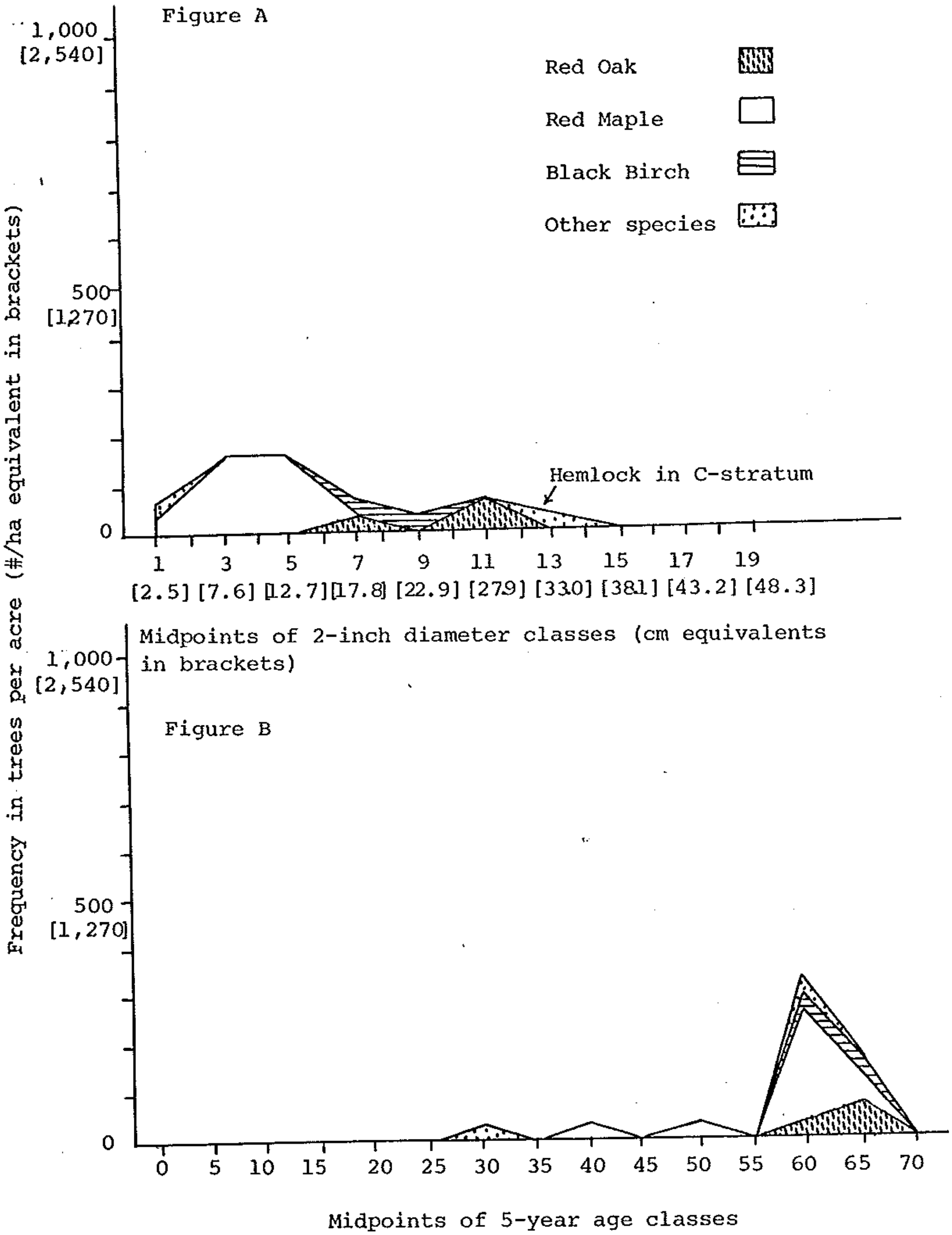


Figure A
Red Oak
Red Maple
Black Birch
Other species
Hemlock in C-stratum
1,000
[2,540]
500
[1,270]
0
1 3 5 7 9 11 13 15 17 19
[2.5] [7.6] [12.7] [17.8] [22.9] [27.9] [33.0] [38.1] [43.2] [48.3]
Midpoints of 2-inch diameter classes (cm equivalents in brackets)
Frequency in trees per acre (#/ha equivalent in brackets)
Figure B
1,000
[2,540]
500
[1,270]
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Midpoints of 5-year age classes

All three trees were the same age (106 years at one foot) although the red oak was 19.2 inches (48.8 centimeters) in diameter at 4.5 feet (1.4 meters); the black birch, 7.9 inches (20.1 centimeters); and the sugar maple, 6.1 inches (15.5 centimeters).

Three B-stratum red oaks with red maple and black birch beneath them were selected from the stand (Stand IV) which arose from clearcutting old field white pine approximately 74 years ago. All trees within the vertical projection of the canopy periphery of each B-stratum red oak were aged as in the seven 60-year-old plots. The diameters, species, and age distributions of these trees (Figure 6 and Table 4.1 of Appendix 4C) verify existence of the even-aged condition.

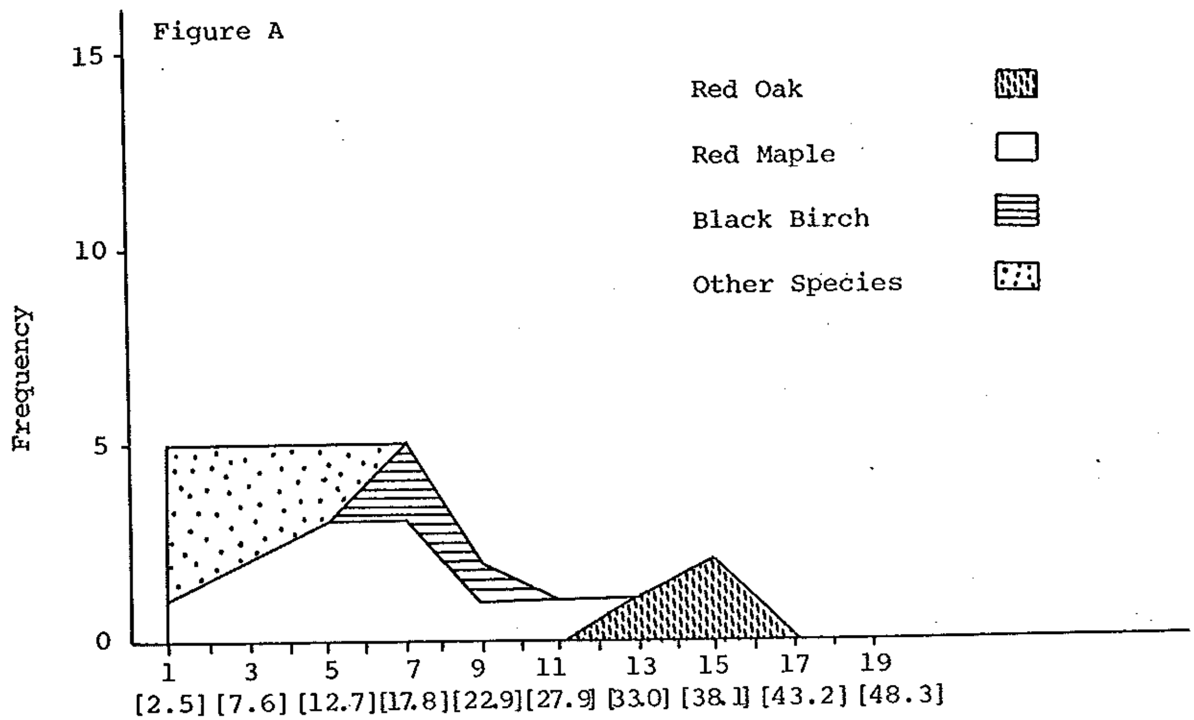
Two circular one-fiftieth-acre (0.008 hectare) plots were randomly chosen within the stand (Stand V) resulting from clearcutting old field white pine approximately 45 years previously. All trees within the plots were cut, measured, and aged. Diameter, age, and species distributions of trees within this clearly even-aged stand can be seen in Figure 7 (and Table 4.1 of Appendix 4C).

A single one-fiftieth-acre (0.008 hectare) plot was randomly placed within the stand (Stand VI) resulting from the 1938 hurricane blowdown of old field white pine (33 years prior to 1971). All trees within the plot were cut, measured, and aged. As in all the older stands the even-aged condition was found. Diameter and age distributions by species within this plot on a per-unit-area basis can be seen in Figure 8 (and Table 4.1 of Appendix 4C).

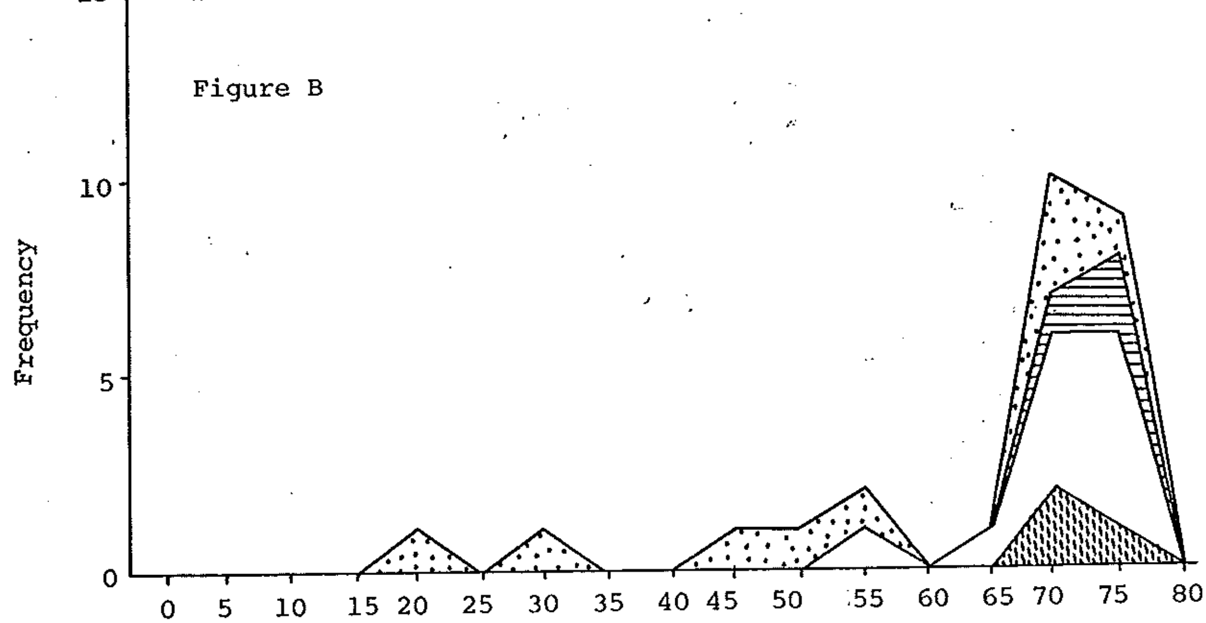
Discussion

All of these mixed species, even-aged stands had a vertical stratification of crown canopies by species and all approached the

Figure 6: Distribution of diameters (Figure A) and ages (Figure B) of all trees in three selected plots with red oaks in the B-stratum in Stand IV. The stand resulted from clearcutting of an old-field-white pine stand approximately 74 years ago.



Midpoints of 2-inch diameter classes (cm equivalents in brackets



Midpoints of 5-year age classes

Figure 7: Distribution of diameters (Figure A) and ages (Figure B) of trees per acre resulting from clearcutting of white pine stand approximately 45 years ago. Based on two 50th-acre plots in Stand V.

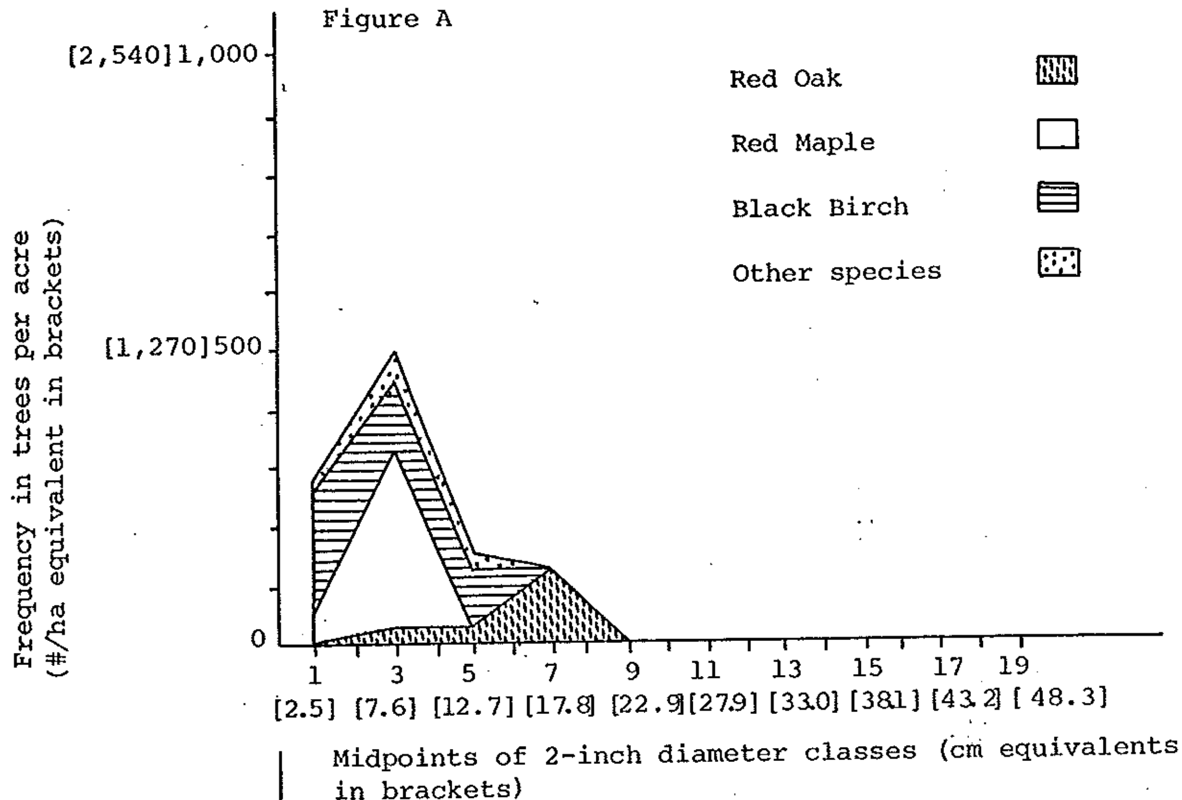


Figure A
Red Oak
Red Maple
Black Birch
Other species
Frequency in trees per acre
(#/ha equivalent in brackets)
[2,540]1,000
[1,270]500
0
1
3
5
7
9
11
13
15
17
19
[2.5]
[7.6]
[12.7]
[17.8]
[22.9]
[27.9]
[33.0]
[38.1]
[43.2]
[48.3]
Midpoints of 2-inch diameter classes (cm equivalents
in brackets)

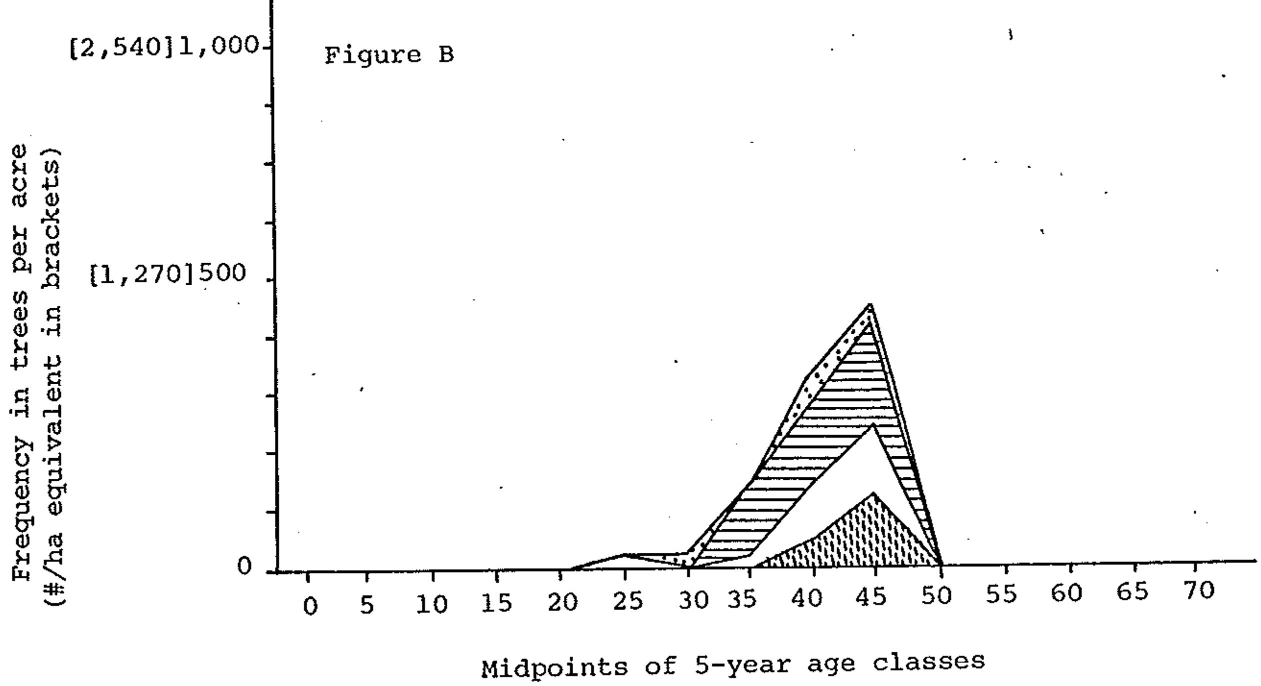


Figure B
Frequency in trees per acre
(#/ha equivalent in brackets)
[2,540]1,000
[1,270]500
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Midpoints of 5-year age classes

Figure 8: Distribution of diameters (Figure A) and ages (Figure B) of trees per acre resulting from hurricane blowdown of white pine stand 33 years ago. Based on one 50th-acre plot in Stand VI.

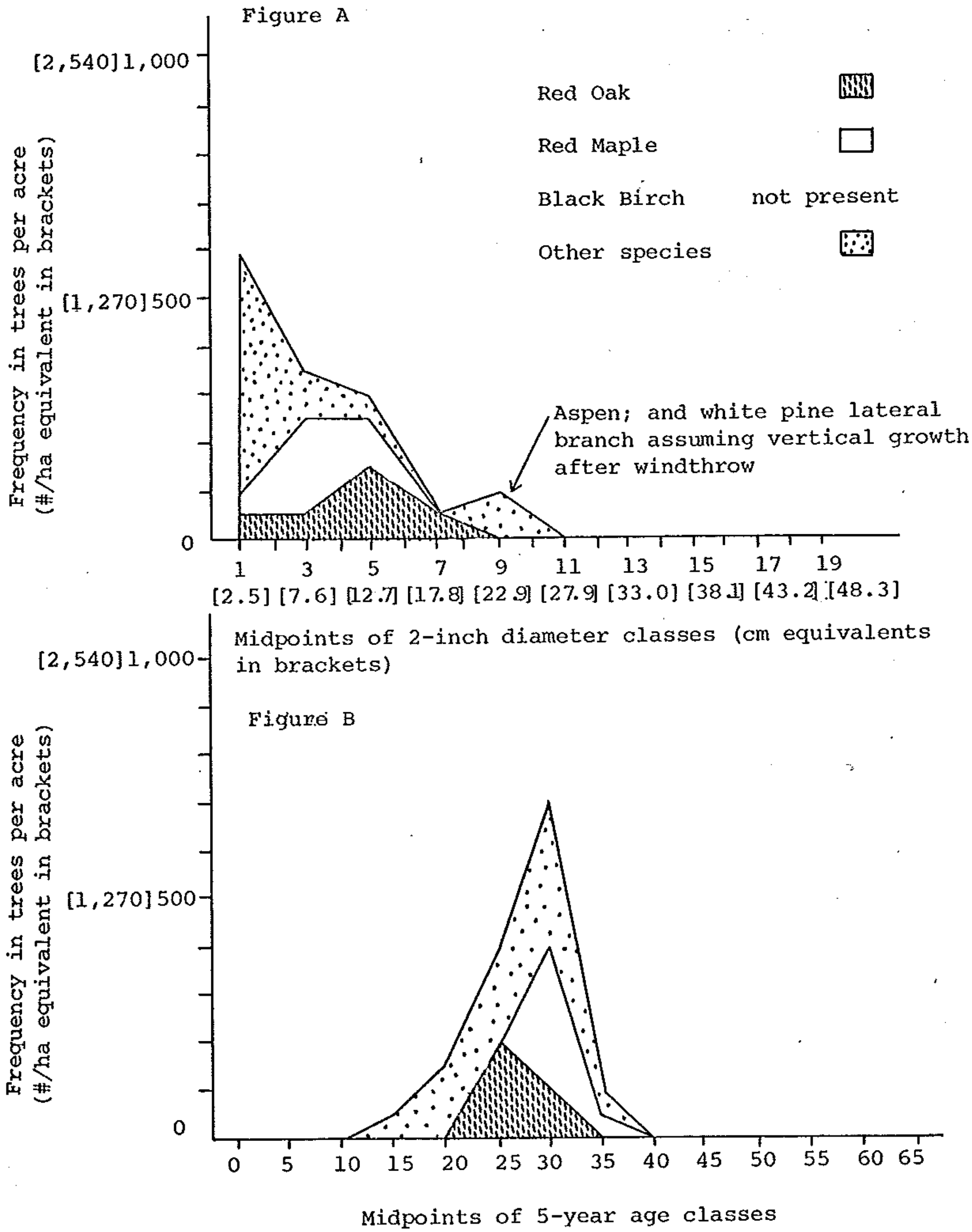


Figure A
Frequency in trees per acre
(#/ha equivalent in brackets)
[2,540]1,000
[1,270]500
0
Red Oak
Red Maple
Black Birch not present
Other species
Aspen; and white pine lateral branch assuming vertical growth after windthrow
1 3 5 7 9 11 13 15 17 19
[2.5] [7.6] [12.7] [17.8] [22.9] [27.9] [33.0] [38.1] [43.2] [48.3]
Midpoints of 2-inch diameter classes (cm equivalents in brackets)
Figure B
Frequency in trees per acre
(#/ha equivalent in brackets)
[2,540]1,000
[1,270]500
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65
Midpoints of 5-year age classes

reverse-J-shaped *diameter* distribution so often assumed to be indicative of all-aged stands. However, the *ages* were narrowly distributed about a mean age slightly younger than that of the time of initial disturbance rather than being distributed in the reverse-J-shaped manner. The total number of trees became fewer as the stands became older, but each stand still maintained its essentially even-aged condition.

There was a narrow range of ages found in each stand when based on the time of release (for understory advanced regeneration) and aged at one foot height. The ages at one foot height of the trees in all plots (except the initially cored B-stratum red oaks) were distributed around their respective means and combined (as shown in Figure 9) to determine how broad the range of ages was. It was found that 61 percent of all trees studied were within five years on either side (a ten-year span) of the mean ages of the respective plots; and 87 percent were within ten years on either side (a twenty-year span) of the mean ages.

The relation of diameter to age of all trees in the three 60-year-old stands were compared by species to determine the relation of age to diameter. The trees plotted included the B-stratum oaks first studied, as well as all species in the seven plots (and extended plots) of Stands I, II, and III. The relation is shown in Figure 10. As can be seen, the oaks were generally the largest in diameter (and also occupied the B-stratum, as described earlier). There seems to be no meaningful relation between age and diameter of these trees ($r^2 = 0.28$; $n = 96$). No meaningful relation was found between diameters and ages when comparing all stems of the present study ($r^2 = 0.44$; $n = 193$). This is contrary to assertions of Phillips (1959) and the common and seemingly plausible assumption that diameter and age should be closely related.

Figure 9: Age (at one foot height; 0.3 meter) distribution about mean age of plot for all trees studied (except for B-stratum oaks first sampled in Stands I, II, and III).

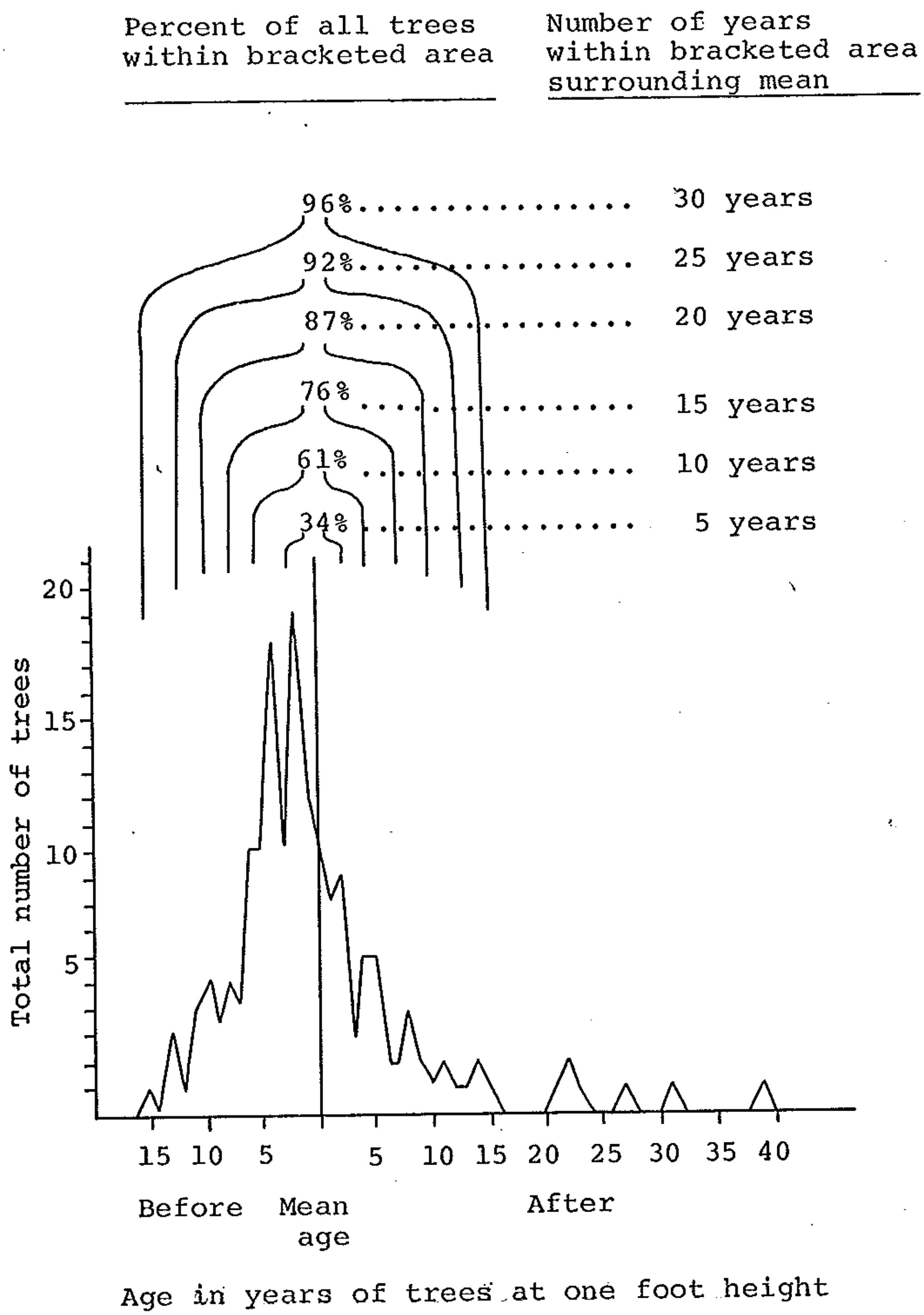
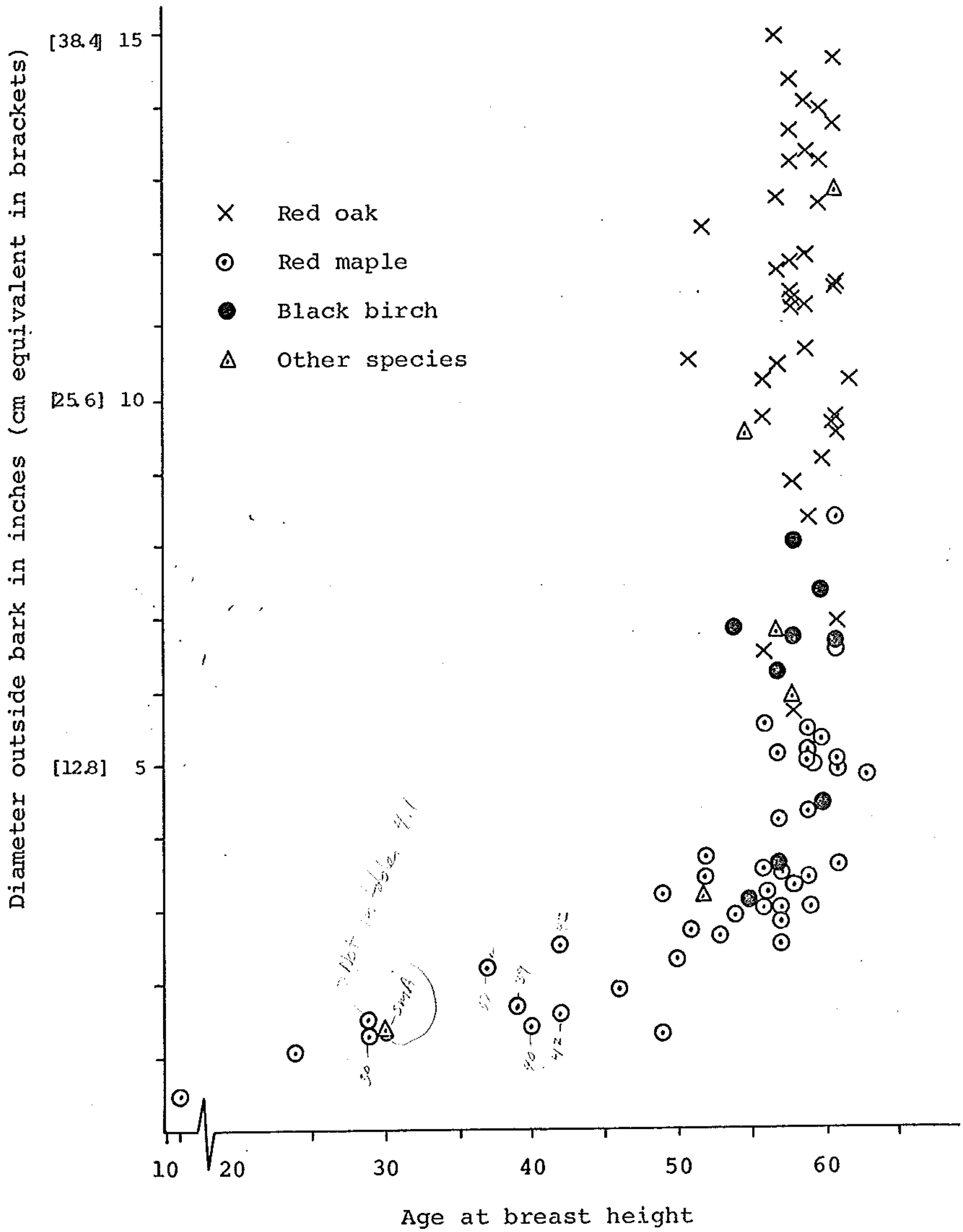

Percent of all trees within bracketed area
Number of years within bracketed area surrounding mean
96%
30 years
92%
25 years
87%
20 years
76%
15 years
61%
10 years
34%
5 years
Total number of trees
20
15
10
5
15 10 5 5 10 15 20 25 30 35 40
Before
Mean age
After
Age in years of trees at one foot height

Figure 10: Relation of age and diameter at breast height (4.5 feet; 1.4 meters) of trees studied in 60-year-old stands.



Diameter outside bark in inches (cm equivalent in brackets)
[38.4] 15
[25.6] 10
[12.8] 5
Red oak
Red maple
Black birch
Other species
10
20
30
40
50
60
Age at breast height

In general, the largest of those trees of each species which attained breast height much later than the mean age grew less in diameter than could be explained solely on the basis of their fewer rings. The disadvantage of competing with earlier established vegetation for limited soil and light growth factors may explain why more of these slightly younger trees did not exhibit as rapid diameter growth as their older associates. Similarly, the competitive disadvantages of younger vegetation may explain why there was not a continuous growth of new trees into the stand, as it was assumed occurs in an all-aged forest.

There were three plots affected by partial disturbances caused by the 1938 hurricane. A blowdown of an oak near Plot IV-3 resulted in accelerated diameter growth in a remaing B-stratum oak and in many of the understory trees. The blowdown of a red oak and a hemlock within Plot I-2b did not result in diameter acceleration of the B-stratum oak but caused slight diameter acceleration in an adjacent hemlock. A red oak blown over near Plot VII-1 caused diameter acceleration of a nearby sugar maple, black birch, and B-stratum red oak. This pattern of diameter growth following release will be discussed later; however, it is significant to note that none of the 18 living trees studied in these three plots can be dated from immediately after the 1938 disturbance. In these cases small disturbances within a forest did not create a new age class as a permanent component of the stand, but only increased the growth rate of the remaining older trees.

A Forest as an Aggregate of Even-aged Stands

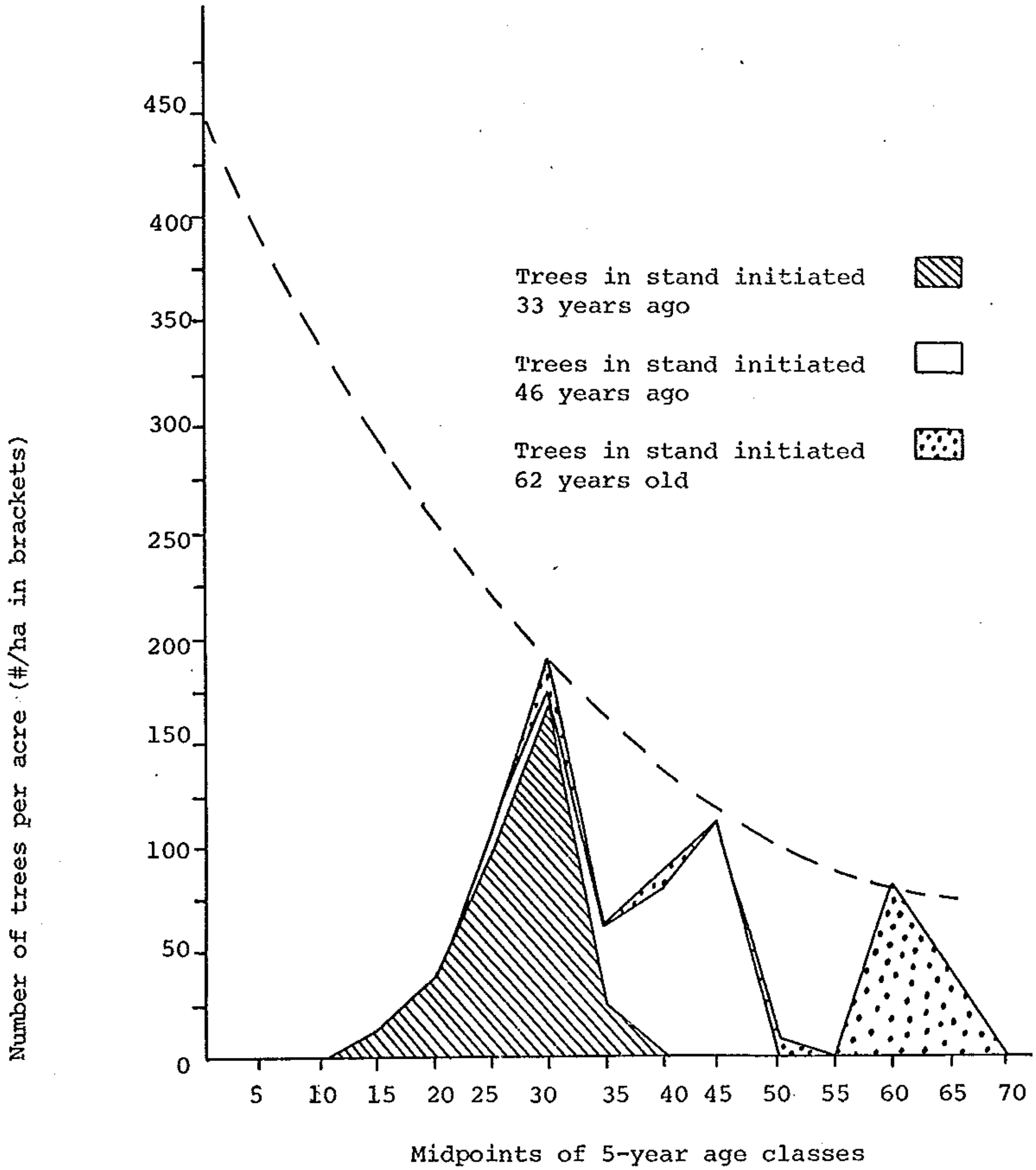
Red oak occupied more of the dominant canopy of the forest studied than any other species, as was found in Chapter 1. In some instances it occurred as the only species in the B-stratum.

In central New England and probably elsewhere such red oaks commonly develop in even-aged stands with red maples, black birches, and other species and assert a dominance over them. Such stratification of the forest gives a reverse-J-shaped appearance to their diameter distributions—one of the alleged attributes of balanced uneven-aged (or all-aged) stands. The stratified even-aged stands arise after severe disturbance, with many of the trees developing from advanced reproduction in the understory of the pre-existing stand. The size of the even-aged stand is dependent on the extent of the disturbance creating it.

The forest developing in each area of disturbance may be an even-aged stratified mixture of species. However, a large forest covering many disturbances occurring at equally distributed times may show reverse-J-shaped aggregate diameter and age distributions. As an example, it may be assumed that a sampled upland forest is the mosaic of three stands. Each stand initiated after a disturbance of approximately 33, 45, or 60 years prior and is represented by the stands taken from Figures 5, 7, or 8, respectively. All stands are equally represented in area and the forest is sampled for age; the resulting age distribution would appear as in Figure 11. The dashed line in Figure 11 shows that, if more different age classes were represented, the result might well approximate the reverse-J-shaped age distribution. The all-aged forest as a combination of even-aged stands has been previously proposed by Hough (1932).

In fact, the probability of disturbance to a stand increases with age; therefore, it would be expected that more stands of younger ages

Figure 11: Age distribution per acre expected if sampled forest were mosaic of even-aged stands with equal areas initiated after disturbances approximately 33, 45, and 60 years ago.


Number of trees per acre (#/ha in brackets)
450
400
350
300
250
200
150
100
50
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70
Midpoints of 5-year age classes
Trees in stand initiated 33 years ago
Trees in stand initiated 46 years ago
Trees in stand initiated 62 years old

would appear, giving an even larger number of young stands and hence an even greater skew to the reverse-J-shaped curve. Such a forest would appear in aggregate to be all-aged. The mistaken concept that diameter is necessarily indicative of age in a given stand may lead to the belief that each small area within the forest is all-aged. In reality a large, all-aged forest may be composed of mosaics of even-aged stands with each stand caused by a release of growing space following a disturbance (Raup, 1964; Smith, 1971; Johnson, 1972; Drury and Nisbet, 1973).

PART II

Silvics of Mixed Red Oak-Red Maple-Black Birch Stands

Chapter 3

Physiognomic Development of Mixed Species Stands

Stratified, mixed species, oak-dominated forests were found in Part I to have arisen after clearcuttings or similar disturbances in an essentially even-aged condition. Therefore, clearcutting and even-aged management are compatible with the development of such forests.

There have, however, appeared to be problems obtaining new oak-dominated stands (Smith, 1970) where forests with oak overstories have been clearcut as part of even-aged management. In new stands there usually appear to be too few oaks relative to the other species (Clark and Watt, 1971; Roach, 1971). Clark and Watt (1971) reviewed a number of preharvest thinning regimes designed to ensure adequate oak regeneration; Russell (1973) investigated a method of planting northern red oak at close spacing; and Marquis (1973) suggested planting 1,000 oak acorns per acre (2,470 per hectare) to obtain an oak forest. Trimble (1972, 1973) reviewed the effect of various sites and silvicultural treatments on mixed deciduous forests with oaks previously in the overstory in West Virginia; he found other species more numerous than red oak on all sites five years following clearcutting.

Procedures

Growth histories of the stratified, mixed species, oak-dominated stands of this study were further investigated to determine their pattern of development and to shed some light on the concern about oak regeneration. The tracing backwards in time of representative stands was accomplished through stem analyses and the historical development methods used by

Stephens (1955) and Henry and Swan (1974).

All 14 plots in the seven stands studied contained either red maple, black birch, or both species as well as others in the C- and D-strata, as described in Chapter 2. All stems in the 107-year, 74-year, and 60-year old plots were mapped and sectioned at one foot (0.3 meters) and 4.5 feet (1.4 meters) for age and diameter growth analyses. The tallest red maple and black birch present, the B-stratum red oak, and other selected individuals were analyzed for height growth. This was done by sectioning each tree at one foot (0.3 meter) and 4.5 feet (1.4 meters), and every four feet (1.2 meters) beginning at eight feet (2.4 meters) except for the red oak in Plot VII-1, which was sampled by climbing the tree and coring it at four foot intervals to 16 feet (4.9 meters). The sections were then aged (see Appendix 4B). The positions of all forks, breaks, and major branches were recorded. By this method height-age curves were constructed for the stems (Appendix 5). Less detailed height-age curves were obtained for trees in the 45- and 33-year old plots by aging each tree at one foot (0.3 meter) and 4.5 feet (1.4 meters) and finding its total height.

Diameter growth patterns for all stems were obtained as described in Chapter 2. Diameter growth was converted from inside- to outside-bark measurements by means of formulas empirically developed for each species measured (Appendix 7).

Development of Species Stratification

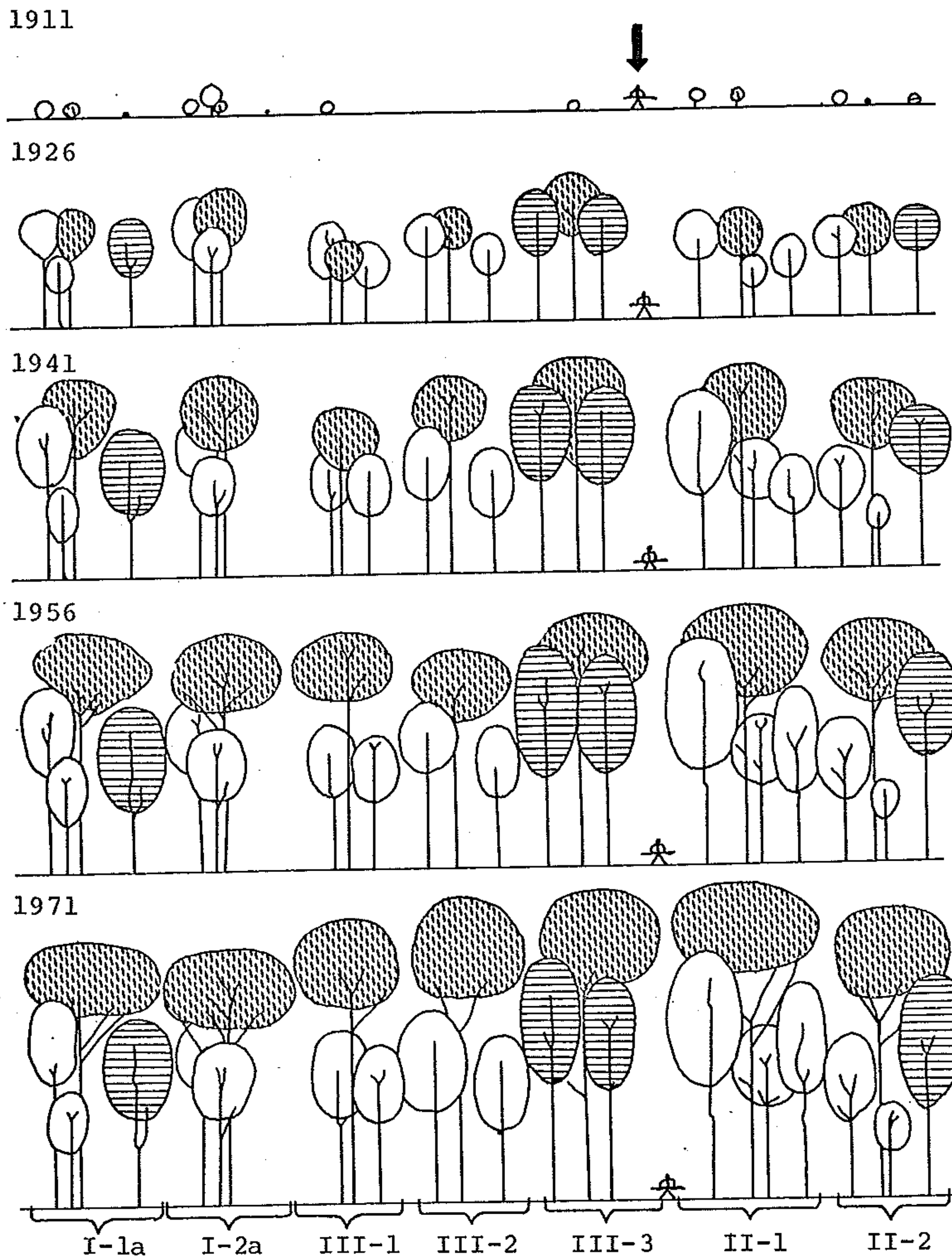
Development of a Composite Forest

A schematic forest was constructed from the height-age curves, plot maps, and data on stem branching and breaks (Appendix 5); this consisted of the B-stratum oaks of the seven 60-year-old plots (Plots I-1a, I-2a, II-1, II-2, III-1, III-2, III-3) and the tallest associated red maples and black birches as well as other red maples and black birches. It is shown in Figure 12, with the development at each 15-year stage beginning 1911. Height growth; relative spacing of trees within each plot; and positions of branches, forks, and breaks in the trunks *are all to scale and based on direct measurements*. The plots were not all contiguous as is implied in this figure. However, the figure may be considered as a condensed, schematic representation of the interaction of red oak, red maple, and black birch during the development of upland hardwood stands since the stands from which the plots were taken contained primarily even-aged red oaks in the B-stratum. Not all stems living within each plot are shown; other living red maples and black birches and other species were present. In addition, many trees and species (such as gray birches and aspens) which died before the forest was 60 years old are not shown.

Detailed Development of a Red Oak and Its Associates

More intensive study was then undertaken on a typical individual red oak and its substratum associates (Plot I-2b, an enlargement of Plot I-2a shown in Figure 12, was used for this purpose). All living stems within an area surrounding the oak tree and extending beyond a vertical projection of the periphery of its canopy were mapped as described in Chapter 2. Stems that died since the clearcutting of the old field white pine (to be discussed in more detail later) and stumps of the previous pines themselves were mapped and identified by species after removal of the L and F soil horizons (Appendix 6). The locations of specific forks and other relocatable positions of the

Figure 12: Growth of even-aged composite forest consisting of seven B-stratum red oaks (with dotted crowns) and tallest red maple (with plain crowns) and/or black birch (with striped crowns) and other red maples and black birches with stem beneath vertical projection of crown of B-stratum red oak. Person (see arrow) is six feet (1.8 meters) tall and holds a stick ten feet (3.1 meters) long.



PLOT NUMBER

central red oak living branches were mapped in three dimensional space by means of triangulation with surveyors' transits. This oak was then cut down and sections were taken every four feet (1.2 meters) along its stem and major branches to determine the ages of the previously located branches, forks, and other positions. The red maples, black birches, and other species within the plot were similarly analyzed.

Figures 13A through 13H show a reconstruction of the development of the trees on this area as viewed from the south at each 10-year interval from 1901 to 1971. The stems shown in Figure 13H were living in 1971 and are depicted in their measured dimensions. The additional trees shown in Figures 13B and 13G represent the probably growth patterns of the stems for which only a root collor and possibly a fallen or standing dead stem were found. The size obtained by these stems and the time of their death is estimated from height-age curves of similar living trees analyzed throughout this study, as well as from the size and extent of decay of the dead stem remnants. Figure 13A shows what the previous old field white pine stand probably looked like prior to clearcutting.

Red Oak Crown Development as Viewed From Above

Figure 14 shows the development as seen from the top of the central red oak of Figure 13H, the red oaks which eventually became contiguous to it in the B-stratum, and the remnants of dead red oaks found within the area. The only branches analyzed were those living in 1971; it is possible that branches dead before then may have made the crowns wider and deeper than shown here during the early years.

Figure 13 (A - H): Reconstruction of upland New England forest growth following old field white pine clearcutting. The following diagrams show the development of Plot I-2b as if seen from approximately due South. It is the typical development of an upland forest stand after the clearcutting of an old field white pine stand. Numbers in Figure 13 A and B correspond to those in Appendix 6, Figures 6.4 and 6.6.
[Note that tree #7 is the red oak which ultimately predominated and is the central tree of Plot I-2.]

Legend:

Hemlock 

White Pine 

Birches 

Maples 

Oaks 

Not identifiable

Figure 13 A:

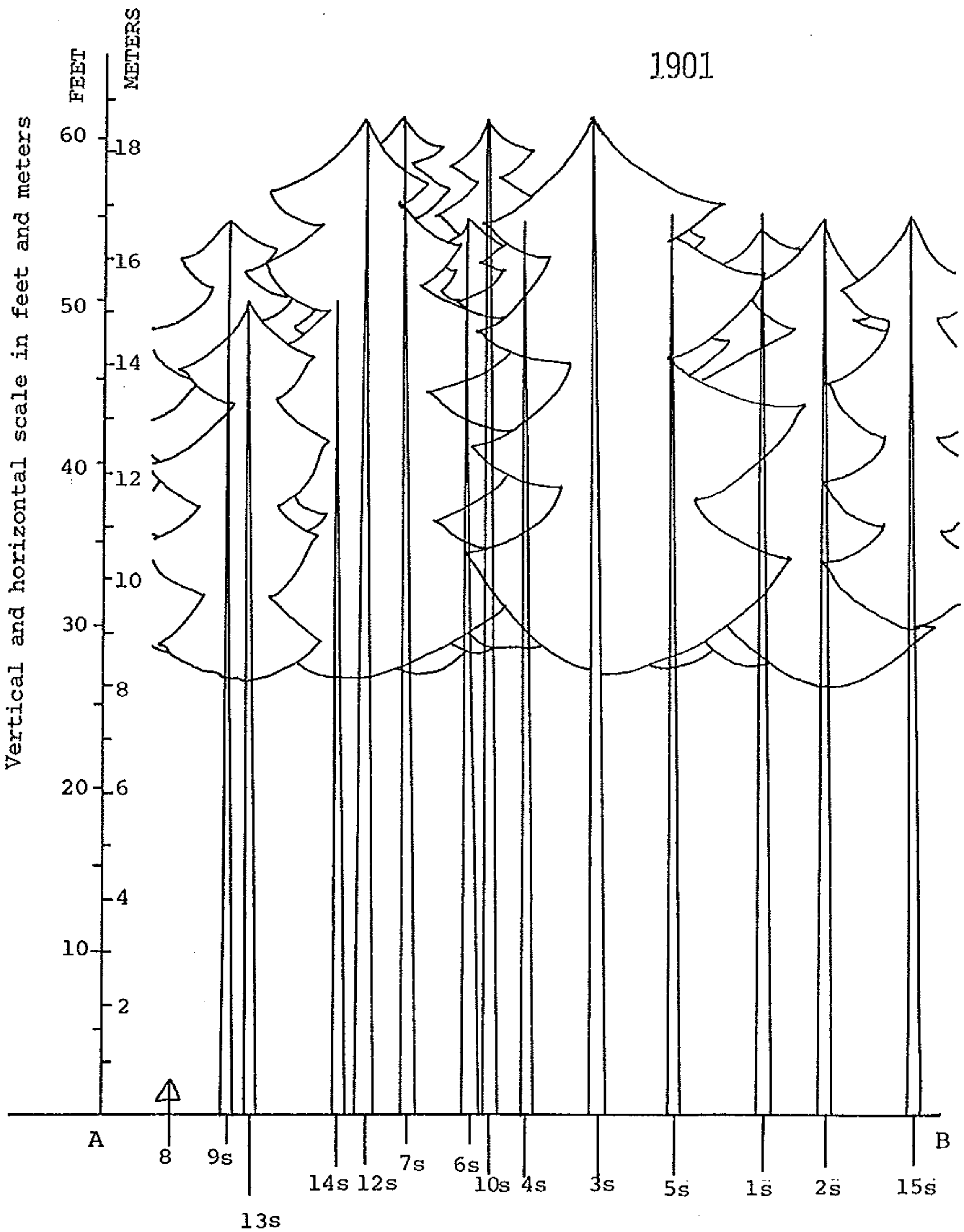

1901
FEET
METERS
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
A
B
8
9s
13s
14s
12s
7s
6s
10s
4s
3s
5s
1s
2s
15s

Figure 13 B:

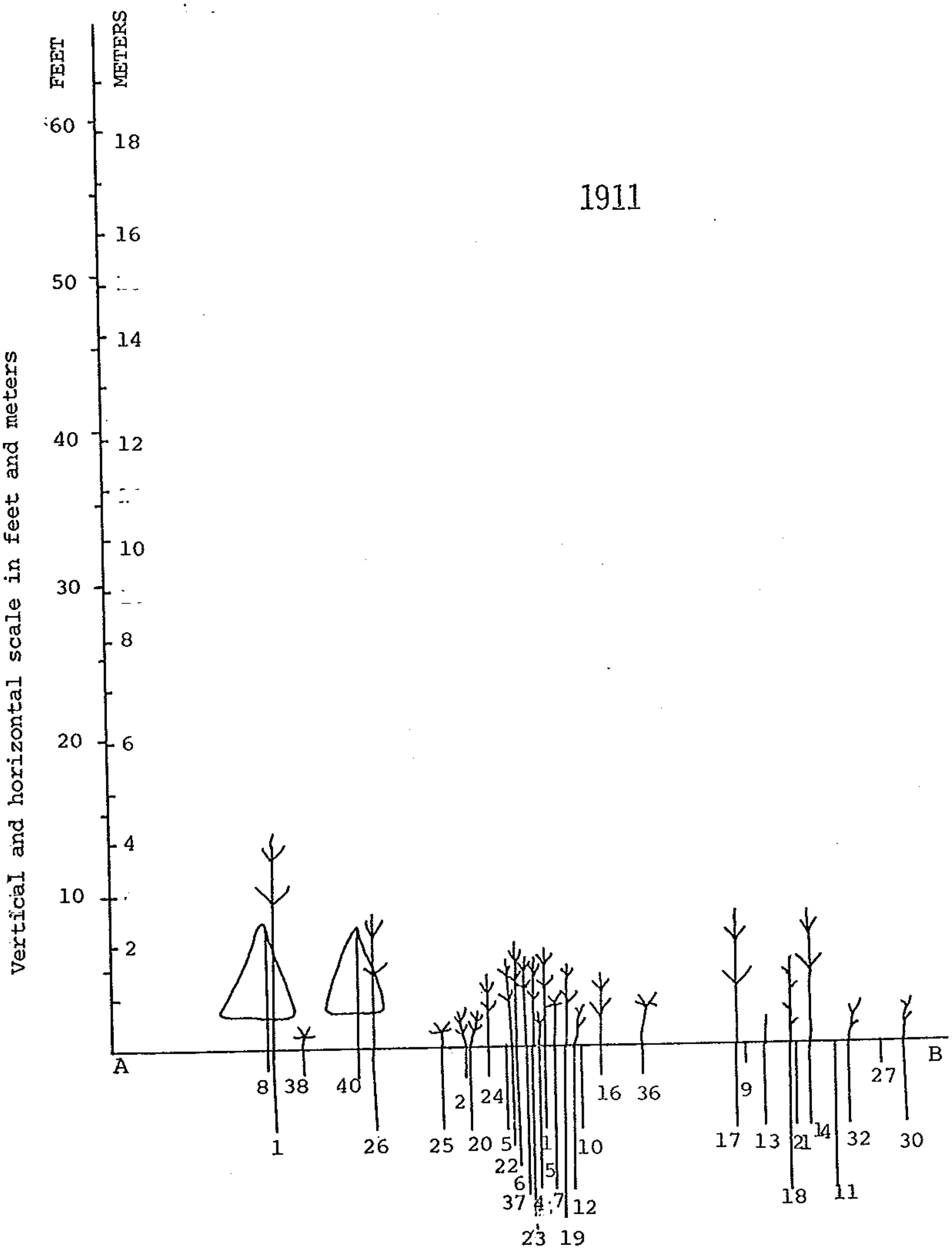

FEET
METERS
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
1911
A
B
8 38 40
1
26
25 20 5
2 24
22
6
37
23 19
12
10
16 36
17 13 21 14 32 30
9
27
18 11

Figure 13 C:

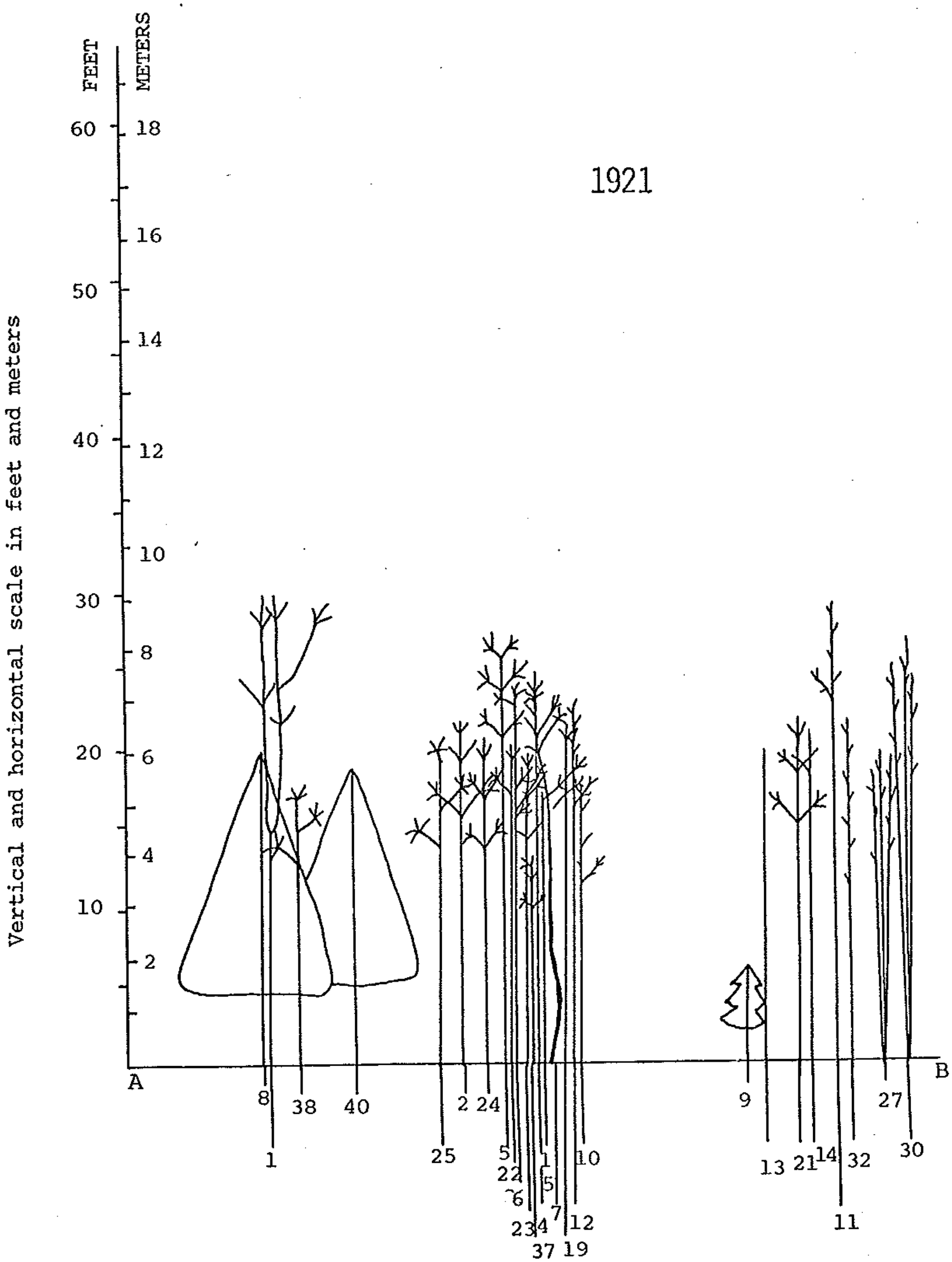

FEET
METERS
60
18
16
50
14
40
12
10
30
8
20
6
4
10
2
Vertical and horizontal scale in feet and meters
1921
A
B
8
1
38
40
25
2
24
5
22
6
23
4
37
1
5
7
12
19
10
9
13
21
14
11
32
27
30

Figure 13 D:

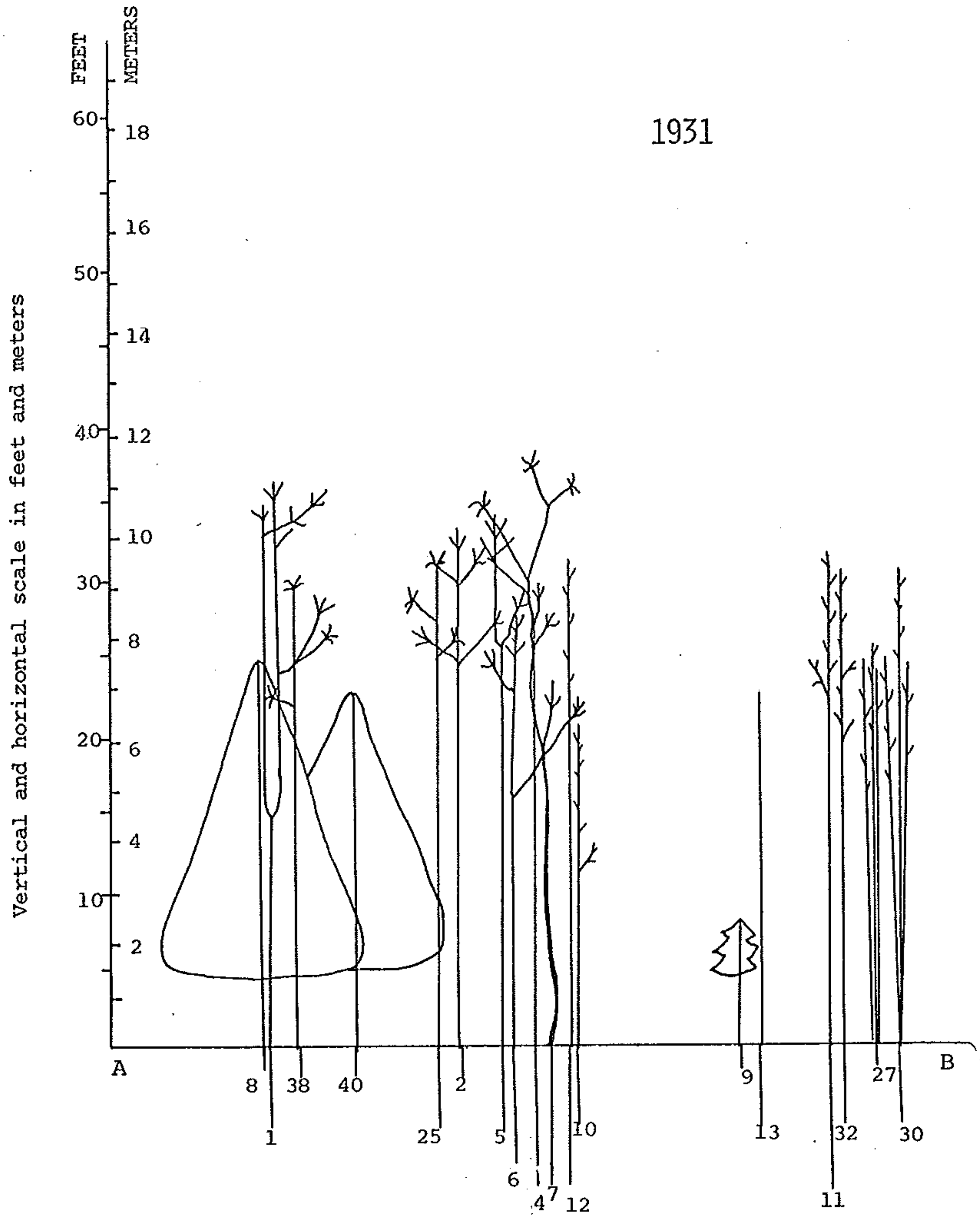

Vertical and horizontal scale in feet and meters
FEET
METERS
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
1931
A
B
8
38
40
2
1
25
5
6
4
7
12
10
9
13
11
32
27
30

Figure 13 E:

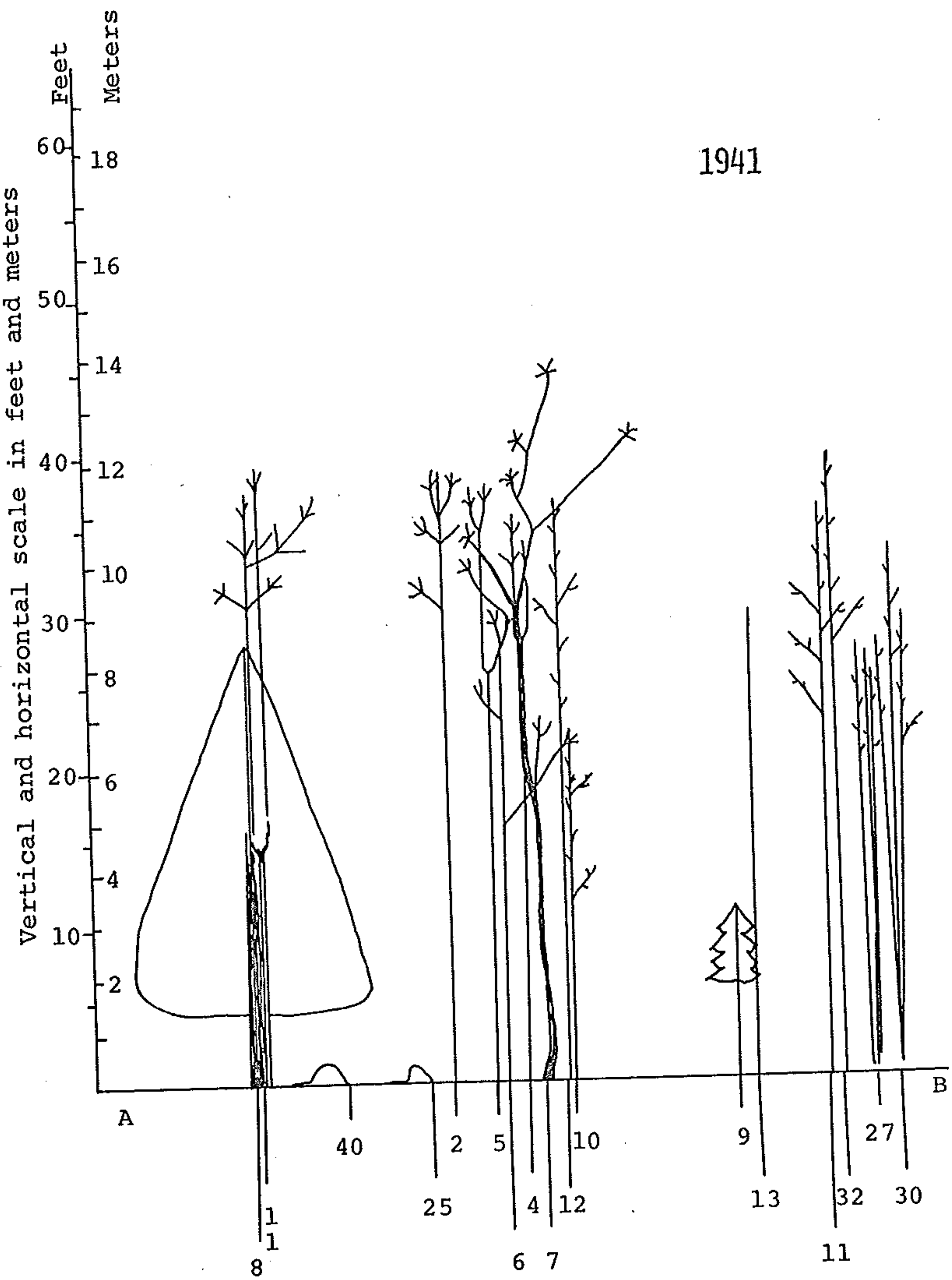

Feet
Meters
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
1941
A
B
40
2
5
10
9
27
1
1
8
25
4
12
13
32
30
6
7
11

Figure 13 F:

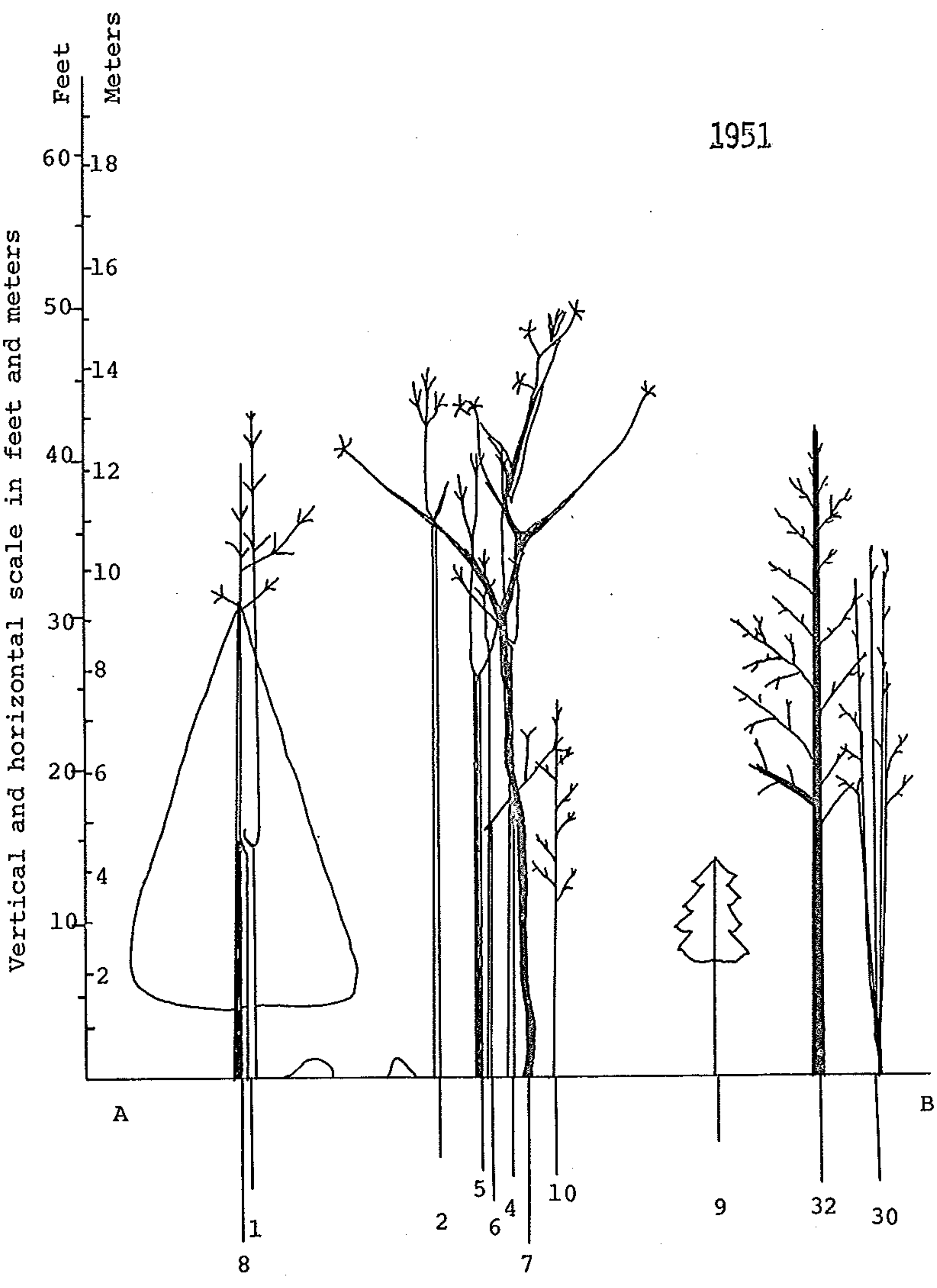

Feet
Meters
1951
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
A
B
8
1
2
5
6
4
7
10
9
32
30

Figure 13 G:

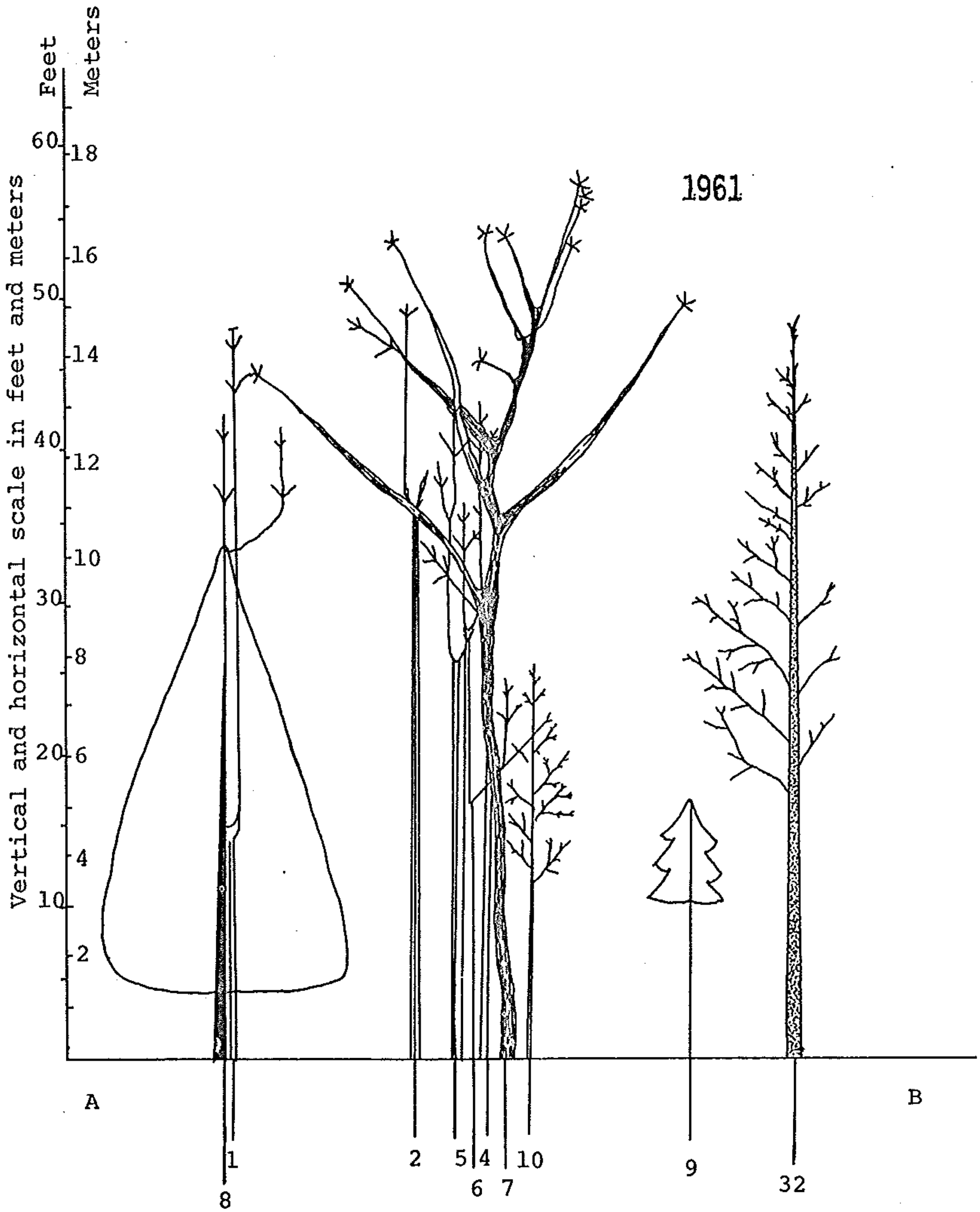

Feet
Meters
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
1961
A
B
1
8
2
5
6
4
7
10
9
32

Figure 13 H:

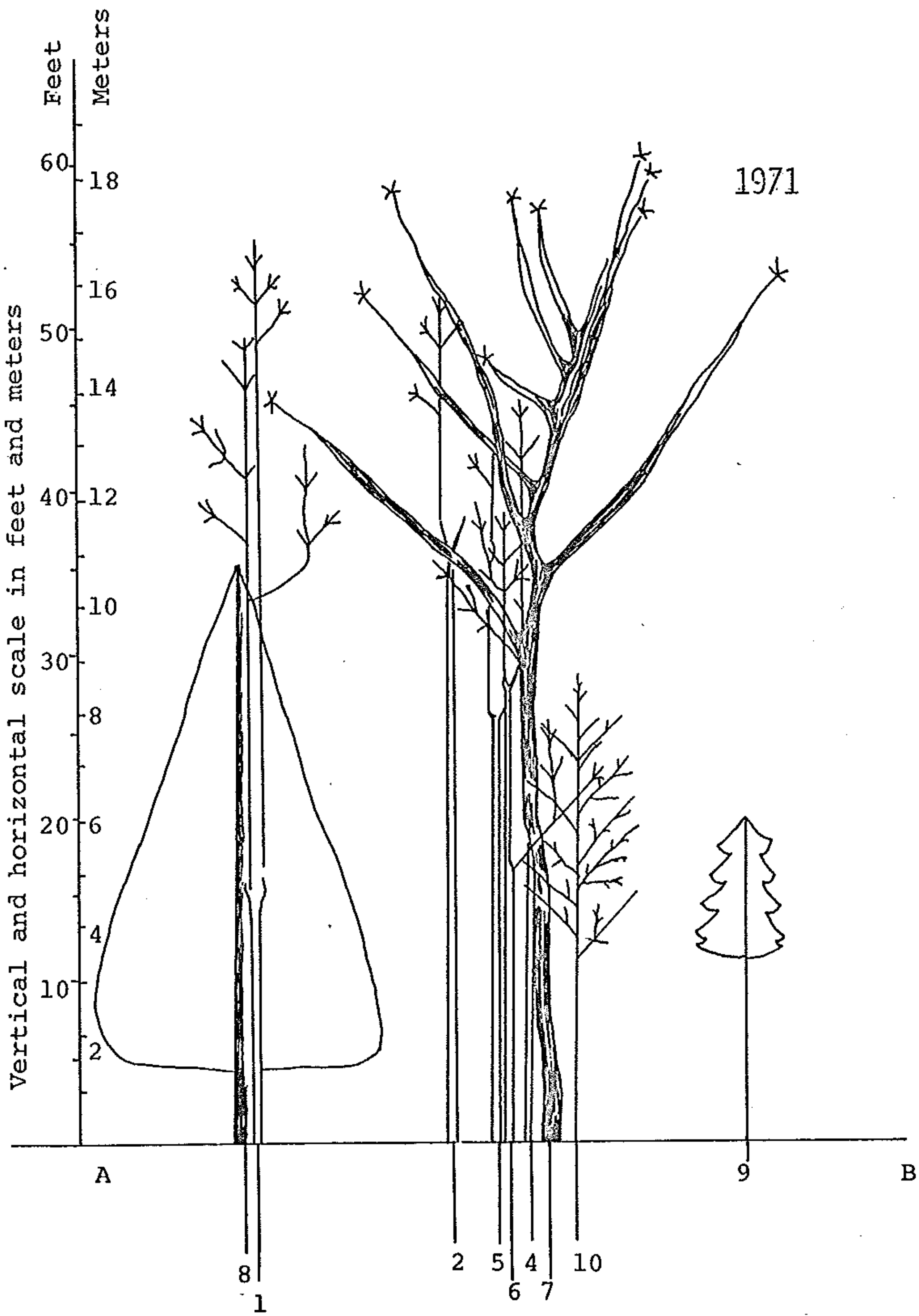

Feet
Meters
Vertical and horizontal scale in feet and meters
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
1971
A
B
8
1
2
5
6
4
7
10
9

Figure 14: Reconstruction of growth between 1931 and 1971 of crown of central northern red oak in Plot I-2 and crown growth of surrounding northern red oaks as viewed from the top. These oaks are widely spaced with red maple, black birch, and other species (not shown) in between. Note competition within B-stratum for closely spaced oaks in southwest quadrant.

Legend:

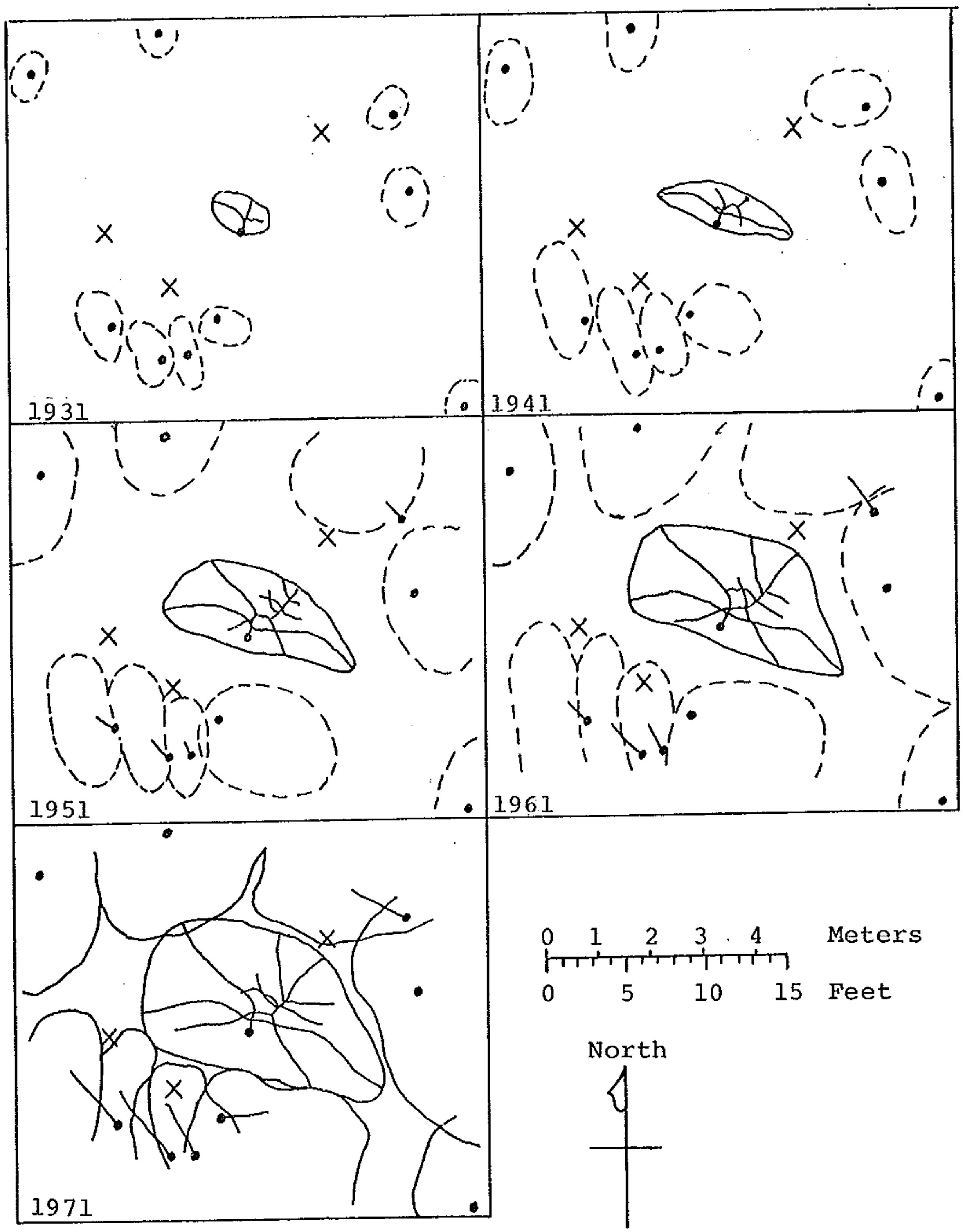
Root collars of northern red oaks living as of 1971: •

Dead northern red oak stump positions: X

Estimates of crown projections of B-stratum red oaks: 

Crown size and branch positions of B-stratum red oak of Plot I-2 based on stem analysis: 

Known crown projections of B-stratum red oaks: 


1931
1941
1951
1961
1971
0 1 2 3 4 Meters
0 5 10 15 Feet
North

Discussion

The stands shown growing in Figures 12, 13, and 14 originated after old field white pine clearcutting of about 1910. Many of the trees initiating growth after the cutting arose from new seeds or from seedlings existing beneath the previous white pine stand. Not all trees started immediately after the clearcutting, but most did so within a short time (as described in Chapter 2).

What eventually became a stand with red oaks in the upper stratum and more numerous red maples and black birches in the lower strata began as an even-aged stand after a disturbance. In the present study the oaks ascended to dominant positions without any disturbance by cutting, fire, or grazing. This result is not what would be anticipated based on such findings as those of Clark and Watt (1971) and Roach (1971). Their observations of development and their proposed management were based on studies of early developmental stages.

If these stands had been examined during the first 25 years as they appeared in the stages shown in Figures 13B and 13C, it would have seemed very unlikely that the limited numbers of red oaks would ever dominate the main canopy as shown in Figure 13H. Not only were they vastly outnumbered by red maples, black birches, and other species, but their comparatively low stature would also lead one to infer that they were more likely to be suppressed than to ascend to positions of dominance.

The lowest lateral branch still alive at 60 years (Figure 13H) appeared to have initiated just as the red oak began to emerge. The lowest living branches on seven 60-year-old B-stratum red oaks (in Plots I-1, I-2, II-1, II-2, III-1, III-2, and III-3) in similar stands varied from 30 to 41 feet (9.2 to 12.5 meters) above the ground and averaged

36 feet (11.0 meters). The long lateral (or "scaffolding") branches seen also in Figures 13 and 14 produced the broad, flat-topped, irregular shape of the typical red-oak crown. They may also have been instrumental in suppressing the lower trees by wind-whipping terminals of maples and birches protruding into these crowns.

The hurricane of September 21, 1938, blew down a hemlock (#40) and a red oak (#25) shown in Figure 13. These trees were adjacent to large rocks which did not permit adequate root anchorage on the windward sides. The effect of such thinnings will be discussed in more detail later.

When viewed from above (Figure 14), the crowns of the widely spaced oaks are at first isolated among other species but eventually are consolidated in a pure upper canopy stratum. Where red oaks grew in close proximity to each other, it was observed that they began to segregate into the conventionally recognized dominant, codominant, and intermediate positions *within* the same canopy stratum. [Note the oaks in the southwest quadrant of Figure 14.] This expression of dominance in the upper stratum oaks appears to be a slow process. Closely growing oaks each occupied a part of the canopy space with virtually no overlap of foliage between crowns. Where red oaks were more widely spaced, there was more room for the crowns of an individual tree to spread. Where oaks were in lower strata it was mainly because other oaks had excluded them from the B-stratum. The exclusion of oaks primarily by other oaks is supported by the observation made during the Yale Forest stratification study (Chapter 1) that 75 percent of the red oaks not found in the upper canopy were beneath the canopies of other red oaks.

Few red oaks survived suppression. Only seven per acre (17 per hectare) were found alive below the upper continuous canopy stratum in the Yale Forest stratification study (Chapter 1 and Appendix 2) compared to 23 per acre (57 per hectare) in the upper continuous stratum. This intolerance of the older oaks has also been observed by Scholz (1952), as mentioned earlier.

In the stand illustrated in Figure 14 there were three oaks which had died. The 1938 hurricane blew over one (#25 in Figure 13), another (not shown in Figure 13) was apparently suppressed in the competition with the closely growing oaks to its southwest, and there is no clear explanation for the death of the third (#38 in Figure 13).

It is probably silviculturally better to grow norther red oaks, and perhaps other oaks, in mixture with other hardwood species than to attempt to create pure oak stands. The other species keep the oak stems well pruned and probably keep them straight. The emergence of the red oaks into the upper stratum and the submergence of the other species, coupled with the initial paucity of oak regeneration, induces a natural thinning effect. If one could create a pure oak stand with hundreds of oaks per acre, very intensive artificial thinnings would be required to produce a similarly beneficial result.

Chapter 4

Height and Growth and Species Stratification

Introduction

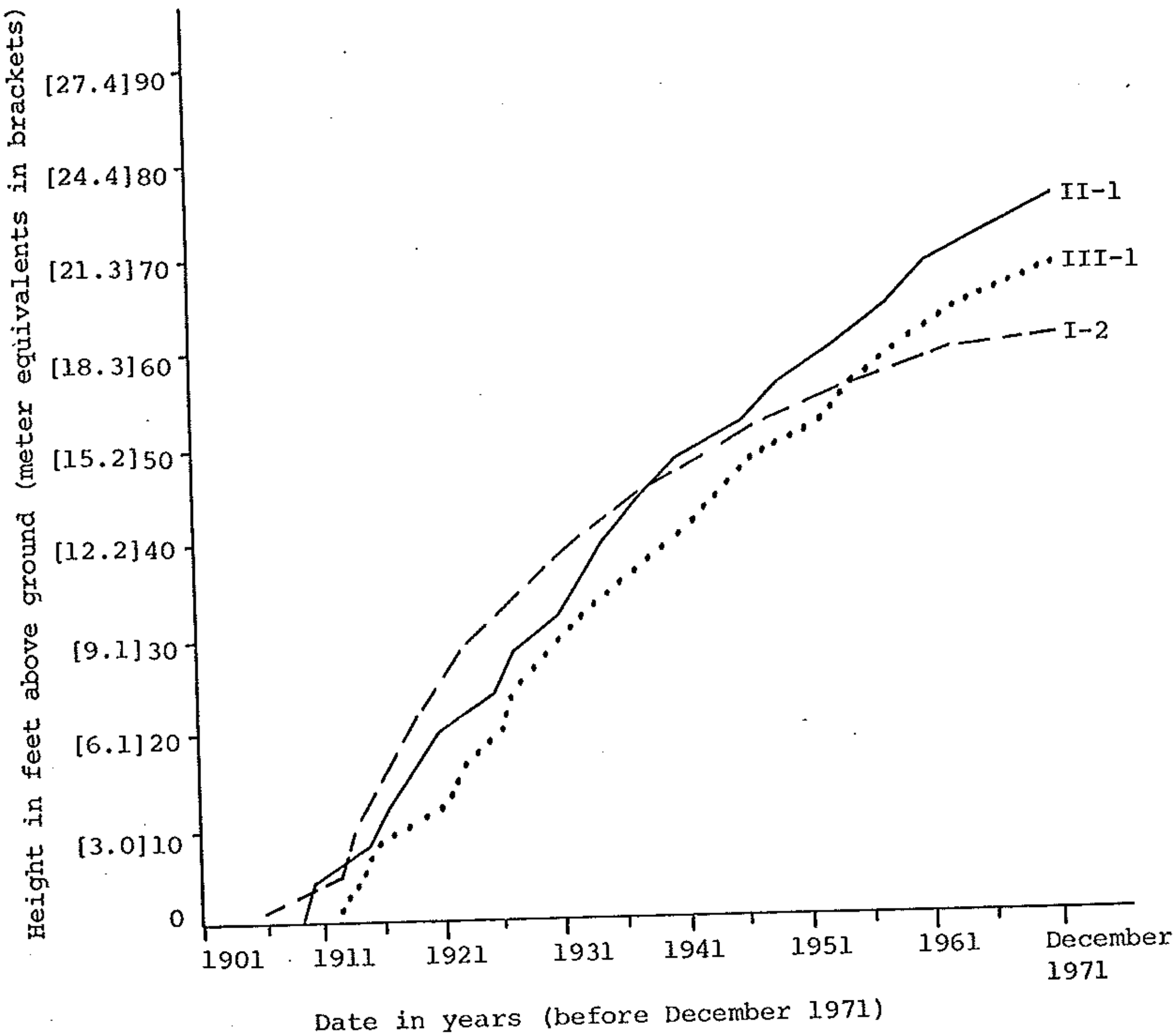
Procedures

Results and Discussion

Early height growth of red oak has been found to be governed by the age (and hence physiological condition) of the root system from which it developed (Sandor, 1971). Height-age curves of this species, therefore, would be expected to follow a variety of patterns. Dominant red oaks of the seven plots of the 60-year-old stands were studied as described previously to attempt to determine height-age patterns. Figure 15 shows three of these red oak trees with widely varying patterns of growth. The tree with the greatest early height growth did not maintain this fast rate while another whose early growth was slow maintained a more constant height increase and becaem a taller tree by 60 years.

Early height growth of red maple (and probably other species) varies between long shoots of seedlings and sprouts. Sprout elongation is further governed by the time at which the stem is severed and the extent of release of the sprouts from competition (Wilson, 1968). It is very difficult, therefore, to predict which species in a young oak-maple-birch stand will gain dominance based solely on the studies of early height growth. As is shown in Figures 12 and 13, red oaks, red maples, and black birches grew as competitors within a single crown stratum during youth. Later, the red oaks began to assert dominance until eventually they formed a continuous canopy stratum above the other species.

Figure 15: Cumulative height growth patterns of three B-stratum red oaks in 60-year-old plots (Plots identified by numbers on right). [Note wide variation in height growth patterns.]


Height in feet above ground (meter equivalents in brackets)
[27.4]90
[24.4]80
[21.3]70
[18.3]60
[15.2]50
[12.2]40
[9.1]30
[6.1]20
[3.0]10
0
II-1
III-1
I-2
1901
1911
1921
1931
1941
1951
1961
December 1971
Date in years (before December 1971)

Procedures

Height-age analyses of stems on the seven plots in 60-year-old stands (Plots I-1a, I-2a, II-1, II-2, III-1, III-2, and III-3) and two of the plots of 74-years (Plots IV-1 and IV-2) were examined to determine the height growth and age pattern of the tallest red maples and black birches compared to the B-stratum oaks in the forest stratification. [The third plot (IV-3) in the 74-year-old stand was rejected because the trees were released in 1938.]

Additional information on the relative height growth of competing red oaks, red maples, and black birches was obtained from unpublished data collected by E. P. Stephens (Stephens, 1955) at the Harvard Forest between 1951 and 1955. His study was undertaken on a 0.89 acre (0.36 hectare) plot of forest with species and soils similar to the others of this study. The causes and times of natural and man-made disturbances — loggings, hurricanes, fuelwood cuttings, chestnut blight and salvage, and a gypsy moth attack — which created several age classes had been documented for the area by careful study of cut stumps, times of tree release, soil profiles, and written records (Stephens, 1955). These disturbances, as those of the present study, had not destroyed advanced growth seedlings and seeds in the soil. All living trees on the plot had been mapped, sectioned, and aged at one foot (0.3 meter), 4.5 feet (1.4 meters), and every four feet (1.2 meters) thereafter.

Red oaks from Stephens' data which were considered in the present study were those growing in competition with red maples and/or black birches that originated after the same disturbances as did the oaks.

All red oaks originally described as "dominant" and "codominant" (as opposed to "intermediate" and "suppressed") were selected. Any tree within a 15 foot (4.6 meter) radius of this stem was regarded as competing with it. The relative height-age relations of the tallest individuals of each of the three species were studied whenever a red maple or black birch was found to be of the same age as the red oak and within 15 feet of it. Four of 14 dominant and co dominant red oaks in the area were found competing with red maples and five were competing with black birches. These were between 63 and 98 years old at the time they were analyzed. There were no instances in Stephens' study in which a single red oak competed with both red maples ans black birches.

These height-age data from Stephens' study were used to supplement the height-age data of the present study. Unfortunately, diameter growth trends at 4.5 feet (1.4 meters) were not recorded by Stephens and could not be determined for the present study.

For each of the nine plots selected from the present study and the nine plots from Stephens' study, height of the red oak at each five-year interval following stand initiation was compared with the simultaneous height of the presently tallest red maple and/or black birch. There were 12 comparisons between red oak and red maple, and 10 between red oak and black birch. A paired variates test (Student's t-distribution) was used to compare height at each five-year interval of red oak with red maple and/or black birch within the same plot.

Mean height growth of 18 red oaks, 12 red maples, and 10 black birches representing the tallest tree of each species found on each plot are shown in Figure 16A. The t-statistic of differences between paired variates (red oak-red maple and red oak-black birch) are shown in Figure 16B.

Figure 16A: Cumulative height-age growth patterns of northern red oak, red maple, and black birch for 60 years after stand initiation. Red oak (NRO) growth is mean growth every five years based on 18 upper canopy trees. Each of these red oaks had red maple, black birch, or both species growing beneath it. Red maple (RM) growth curve shows mean of 12 trees, representing tallest red maple (where any were present) beneath each red oak. Black birch (BB) growth curve shows mean of ten trees, representing tallest black birch (where any were present) beneath each red oak.

Figure 16B: T-statistic (Student's t-test) of paired variants for mean height of red oak and red maple (dotted line) and red oak and red maple (dashed line) for each five years between stand initiation and 60 years. For red oak-red maple comparison (in feet), $t_{.95} = 2.201$; $t_{.99} = 3.106$ (df = 11). For red oak-black birch comparison, $t_{.95} = 2.262$; $t_{.99} = 3.250$ (df = 9). T-statistic positive when red oak is taller.

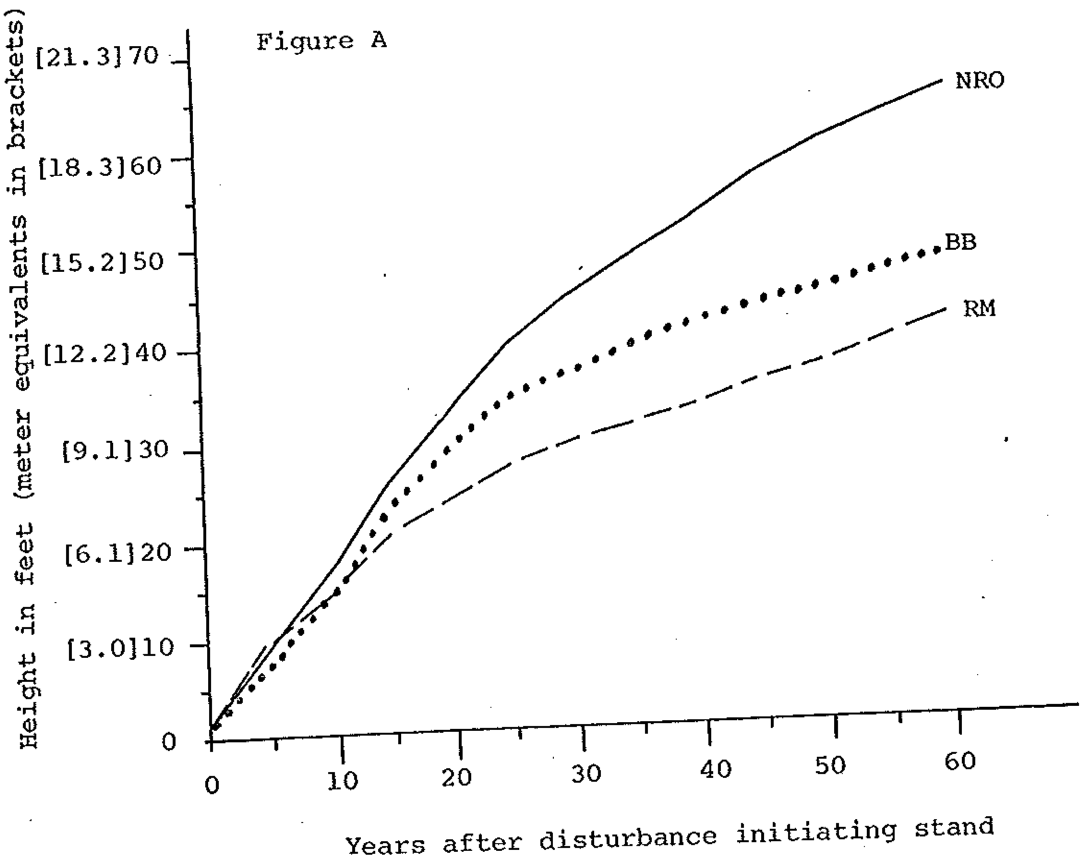


Figure A
Height in feet (meter equivalents in brackets)
[21.3] 70
[18.3] 60
[15.2] 50
[12.2] 40
[9.1] 30
[6.1] 20
[3.0] 10
0
NRO
BB
RM
0
10
20
30
40
50
60
Years after disturbance initiating stand

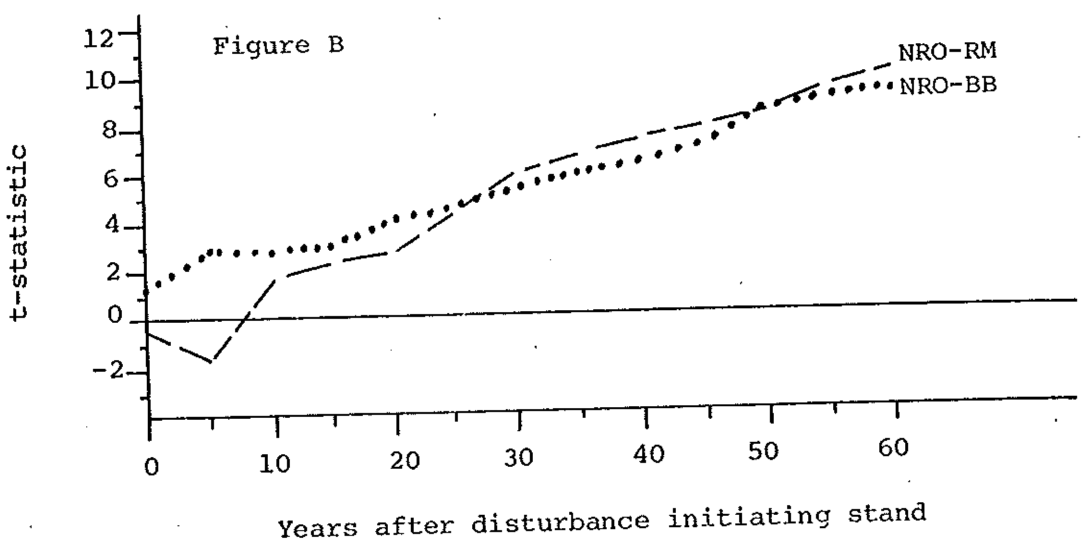


Figure B
t-statistic
12
10
8
6
4
2
0
-2
NRO-RM
NRO-BB
0
10
20
30
40
50
60
Years after disturbance initiating stand

Results and Discussion

The red maple stems may actually have been taller than the red oaks for the first ten years of growth, as may be seen in Figures 16A and 16B. [Note the t-statistics of Figure 16B for red oak-red maple comparisons are negative until the tenth year.] The same relationship was observed for other red maples of the present study as well. Arend and Scholz (1969) similarly found red oak regeneration to be shorter than their associated species immediately following cutting in southern Wisconsin. These early years before crown stratification have been referred to by Gingrich (1971) as the "brushy" stage. The slow early height growth of oaks during this stage has sometimes led silviculturists examining only young stands to infer that oaks in such mixed stands following cuttings would not survive. Between the ages of 20 and 25, the tallest red maples decelerated in growth, becoming highly significantly (one percent level of significance) shorter than the associated red oaks by 25 years. After this they tended to grow relatively little in height, becoming relegated to the lower canopy strata.

Black birches did not assume a rapid early height growth compared to the red maples but maintained a steady rate for a longer period (Figures 16A and 16B). The tallest black birches eventually reached a height plateau slightly higher than the red maples.

Similar patterns of relative height-growth were found for these three species in the younger and older plots, where it was not unusual to find either red maples or black birches taller than red oaks during the first 25 years. As observed in Chapter 1, the ultimate ascendancy of red oaks over red maples and black birches seems to be highly consistent on the broad range of central New England glacial till sites.

Chapter 5

Diameter Growth and Response to Release

A study of the diameter growth rates (at 4.5 feet; 1.4 meters) of 63 upper canopy red oaks from three 60-year-old stands (Stands I, II, and III) revealed two patterns of growth (Appendix 3): (1) an essentially linear rate of quite even growth with slight acceleration or, more often, slight deceleration with increasing age; and (2) an abrupt increase in growth during or shortly after 1939. The remains of trees blown down by the 1938 hurricane were found beside all but one of the 15 trees that showed the abrupt diameter increase after1938. Upper canopy oaks of the older and younger stands studied (33, 45, 74, and 107 years since initiation) similarly revealed the two diameter growth patterns.

Patterns of Growth of Released Red Oaks

The 15 trees released in the stands now averaging 60 years maintained, with two exceptions, an accelerated average growth since the hurricane. A period of one to several years was observed immediately after 1938 during which the annual diameter growth of the released trees was less than the mean growth of the tree from 1943 to 1971. This was probably caused by a temporarily unfavorable situation resulting from sudden exposure; it is also possible that the crown(s) were damaged temporarily by the hurricane. The average duration of this growth lag was 1.3 years.

Growth rate was proportional to the diameter at the time of release ($r^2 = 0.95$) for the first 10 years following release, as may be seen in Figure 17. After this (Figure 17), competition from surrounding red oaks

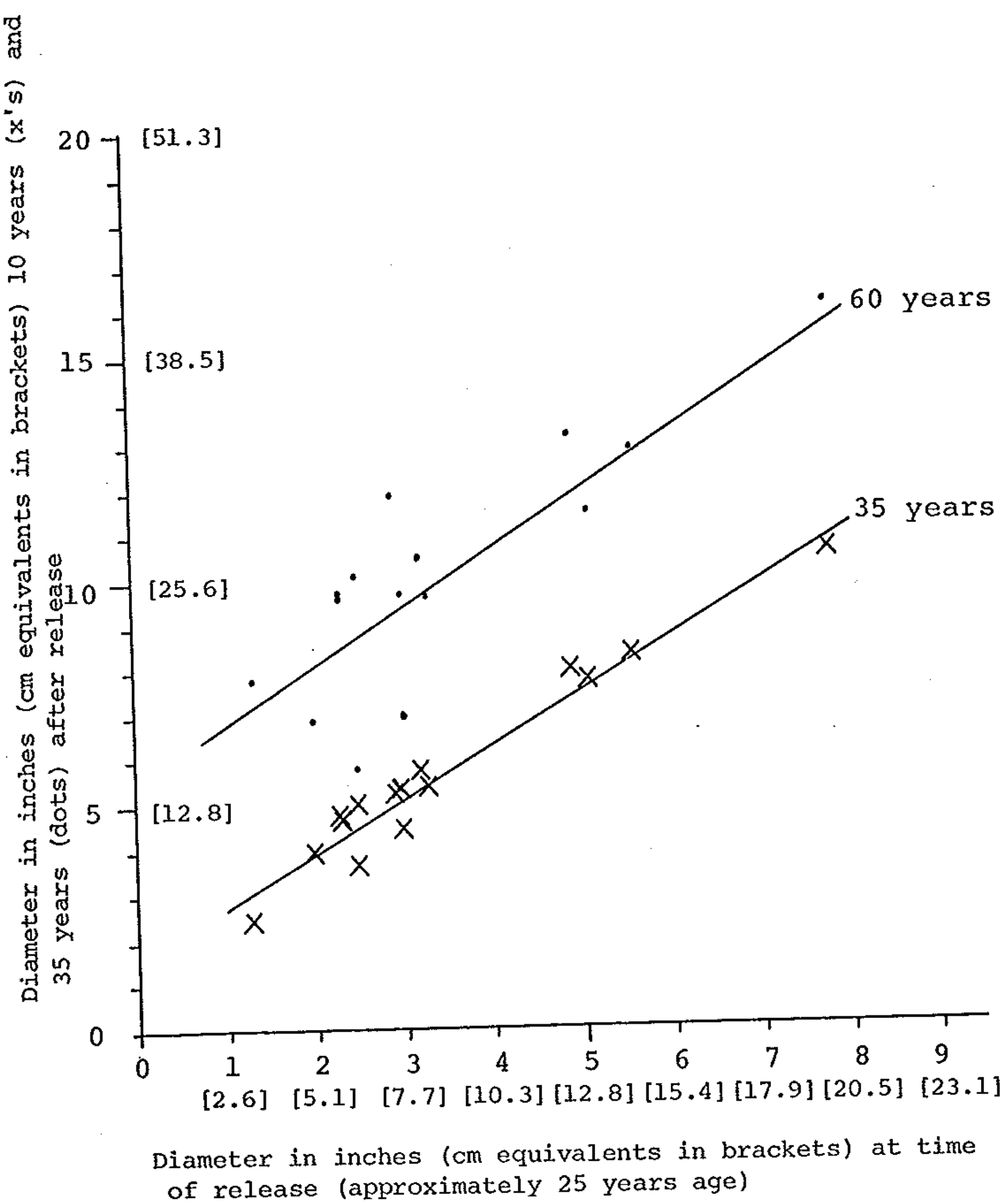
Figure 17: Relation between DBH of northern red oak trees when released at 25 years and DBH at 35 and 60 years. The relation between diameter at time of release (D_r) and ten years later (D_{r10}) is:

$$D_{r10} = 1.2D_r + 1.5 \qquad (r^2 = .95)$$

This is shown on lower line. The relation between diameter at time of release (D_r) and at 60 years (D_{r35}) is:

$$D_{r35} = 1.3D_r + 5.5 \qquad (r^2 = .70)$$

This is shown on upper line.


Diameter in inches (cm equivalents in brackets) 10 years (x's) and
35 years (dots) after release
20
[51.3]
15
[38.5]
10
[25.6]
5
[12.8]
0
60 years
35 years
0
1
2
3
4
5
6
7
8
9
[2.6]
[5.1]
[7.7]
[10.3]
[12.8]
[15.4]
[17.9]
[20.5]
[23.1]
Diameter in inches (cm equivalents in brackets) at time
of release (approximately 25 years age)

apparently decreased the growth rate of many trees, reducing the correlation between diameter and growth rate ($r^2 = 0.70$) 30 years after release.

Red oaks in the dominant canopy of even-aged stands responding to release by the 1938 hurricane were also found in the 74- and 107-year old stands (Stands IV and VIII). In all, red oaks showing a growth acceleration were found between two and 13.5 inches (5.1 and 34.3 centimeters) in diameter at the time of release and between 20 and 71 years old. These responses of red oak to thinning agree with observations of Gingrich (1971) and Carvell (1971).

Not all dominant red oaks which had proximal disturbances created by the 1938 hurricane showed growth increases. The central, dominant red oak of Plot I-2 (shown in Figures 13 and 14) showed no diameter growth increase after blowdown of adjacent hemlock and oak trees. There is evidence (Harvard Forest Records, 1974) that on fairly moist sites red oak shows diameter response to release only if the tree is released from crown competition, allowing more room for light to be available to the tree. Low thinnings or their equivalent seem to release growing space which is refilled by understory trees or by herbs or low shrubs.

Response to Release of Associated Species

The B-stratum red oak of Plot IV-3 in the 74-year-old stand had been released by the 1938 hurricane. It and its substratum associates were studied. Release caused an acceleration of diameter growth of several substratum trees — red maples and sugar maples — as well as the dominant oak. Figure 18 shows a comparison of diameter growth of substratum red and sugar maples beneath a B-stratum red oak (Plot IV-3)

Figure 18: Cumulative DBH growth of representative trees of an area where a tree had been blown over by a hurricane (Plot IV-3; Figure A) and an undisturbed area (Plot IV-2; Figure B). Note increased diameter of certain trees in disturbed plot as remaining trees expanded to growing space released from overturned tree.

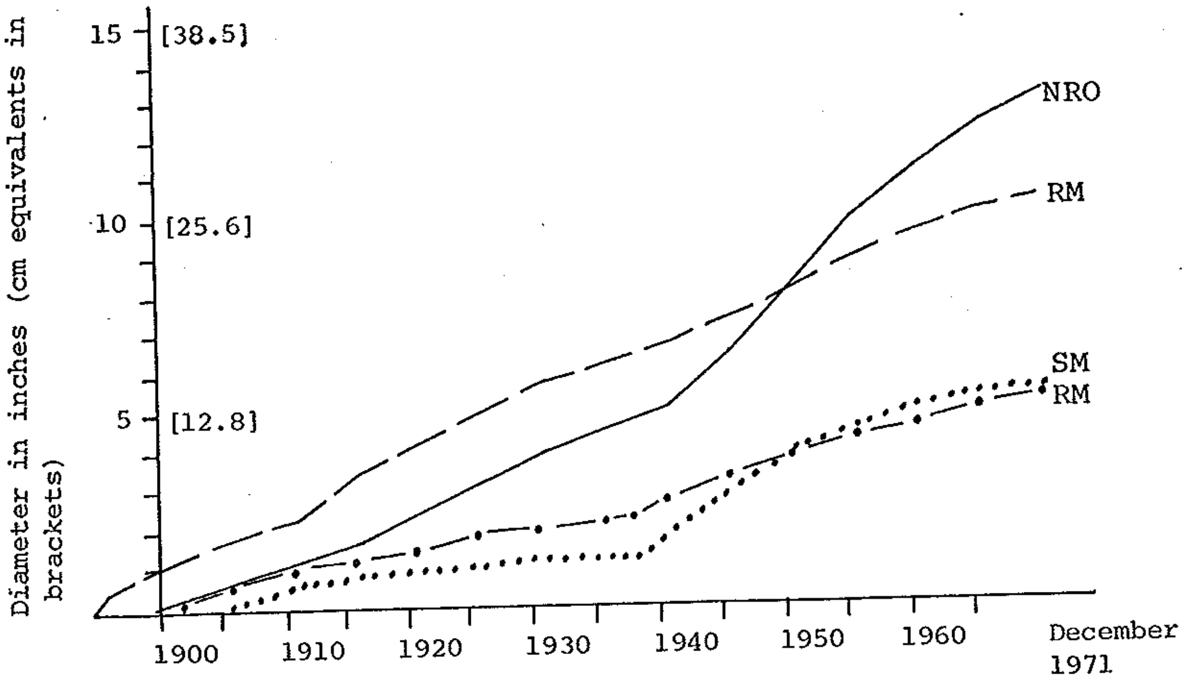
NRO = northern red oak

RM = red maple

BB = black birch

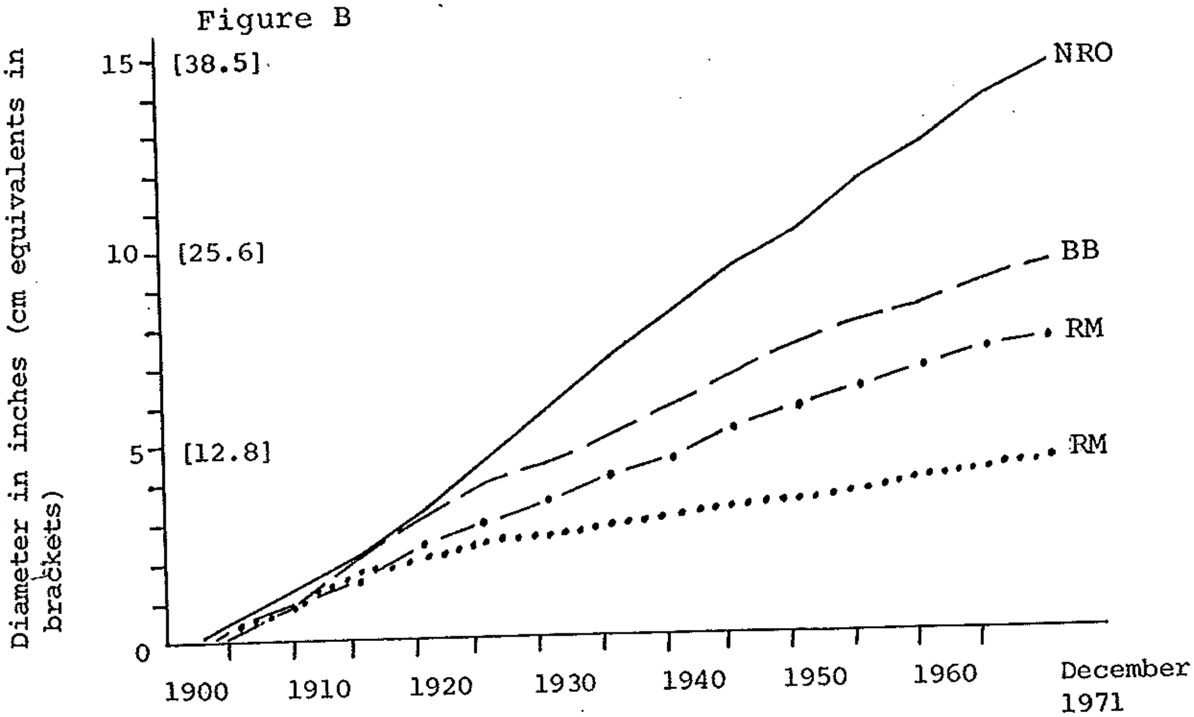
SM = sugar maple

Figure A



Date in years (ending December 1971)

Figure B



Date in years (ending December 1971)

released in 1938 and similar substratum red and sugar maples within the same stand beneath a red oak which was not released (Plot IV-2). Eventually released substrata trees again declined to nearly negligible growth. The 1938 hurricane blowdown of an oak in the 107-year-old stand caused an acceleration of growth of a nearby substratum black birch and sugar maple (at the time these trees were 73 years old) as well as a B-stratum red oak. These observations indicate that not only do red oaks respond by accelerated diameter growth to sudden release of growing space, but substratum red maples, sugar maples, and black birches may also respond. Such responses of both the B-stratum oaks and their substrata associates imply that silvicultural thinnings may be feasible in manipulating both oaks and their understory contemporaries.

Growth Patterns of Non-released Red Oaks, Red Maples, and Black Birches

The sustained rapid uniform diameter growth of unreleased oaks in these mixed stands probably resulted from the pattern of emergence of oaks from surrounding competition. Early in their lives, the eventually dominating oaks were subjected to intense crown competition, which in turn should restrict photosynthetic surface and hence diameter growth rate. The oak crowns expanded as they emerged above other species, enabling a higher later diameter growth rate (Holsoe, 1948) which, when put on over larger surface areas in the outer rings, probably caused the annual rings of approximately equal radial thickness.

Five-year diameter growths for the seven intensively studied red oaks in the plots of 60 years (Plots I-1a, I-2a, II-1, II-2, III-1, III-2, and III-3), the two oaks in the 74-year plots (Plots IV-1 and IV-2; Plot IV-3 was excluded), and the one in the 107-year plot (Plot VII-1) were compared with the red maples and/or black birches present of largest diameter within each of the ten plots. These red oaks showed no signs of release after 1938 or at any other time. They all had growth and age patterns representative of the upper-canopy oaks of the even-aged, stratified, mixed species forest of central New England (Chapter 2). The diameter comparisons were made with a paired variates test (Student's t-distribution) as in the height-growth comparisons.

Mean diameter growths of the ten red oaks, eight red maples, and six black birches studied are shown in Figure 19A. The best estimates of the standard deviations of the populations of differences between paired variates are shown in Figure 19B.

Red maples generally remained smaller in diameter than their competing oaks (as may be seen in Figures 17A and 17B), although the maples may have been taller (Figure 16A) for the first few years. Red oaks were highly significantly (one percent level of significance) larger in diameter than the red maples by the time the stands were approximately 15 years old. Black birches were at first smaller in diameter than both the red maples and red oaks. They soon grew larger than the red maples and maintained a high diameter growth rate for about 45 years. Similar diameter growth patterns were found in the older and younger stands studied. Here, as with early height growth, it was not unusual for either red maples or black birches to be larger in diameter than the red oaks during the first 25 years.

Red oaks did not emerge to a dominating position in the stand until approximately 25 years after stand initiation. At this time red oaks were 30 to 45 feet (9.2 to 13.7 meters) tall and four to six inches (10.2 to 15.2 centimeters) in diameter. Before this stage, it would have been easy to conclude that the young (0 to 25 year old) stands would not develop a red oak B-stratum without knowledge that stands presently

Figure 19 A: Cumulative diameter-age growth patterns of northern red oak, red maple, and black birch for 60 years after stand initiation. Red oak (NRO) growth is mean growth every five years based on ten upper canopy trees. Each of these red oaks had red maple, black birch, or both species growing beneath it. Red maple (RM) growth curve shows mean of eight trees, representing largest diameter red maple (where any present) beneath each red oak. Black birch (BB) growth curve shows mean of six trees, representing largest diameter black birch (where any were present) beneath each red oak.

Figure 19 B: T-statistic (Student's t-test) of paired variates for mean diameter growth of red oak and black birch (dotted line); and red oak and red maple (dashed line) for each five years between stand initiation and 60 years. For red oak-red maple comparison (in inches), $t_{.95} = 2.365$; $t_{.99} = 3.499$ (df = 7). For red oak-black birch comparison, $t_{.95} = 2.571$; $t_{.99} = 4.032$ (df = 5). T-statistic is positive when red oak is taller.

Figure A

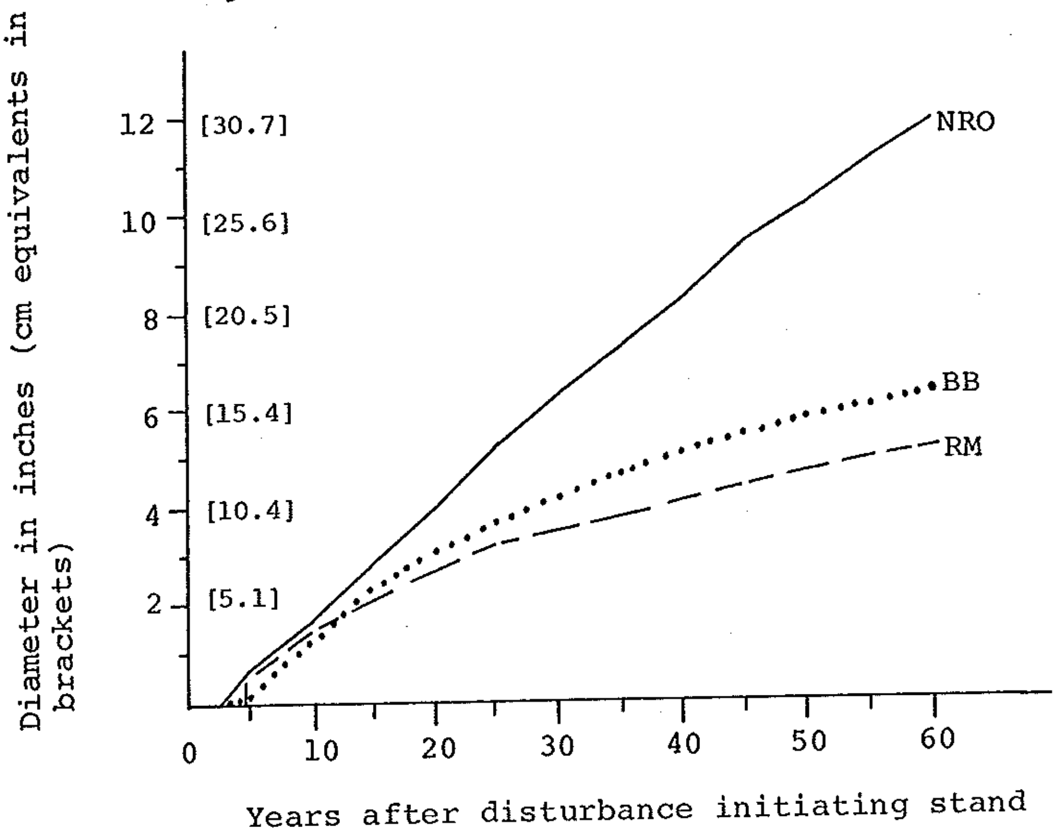
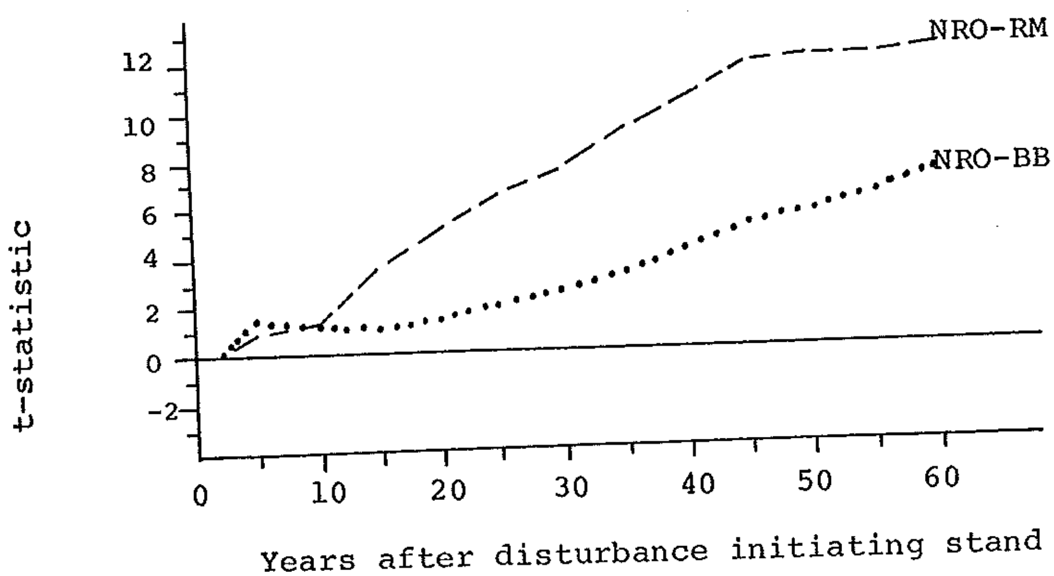


Figure B



containing a pure upper continuous canopy of red oaks went through a stage where the maples and birches appeared to overwhelm the oaks.

Chapter 6

Initial Species Stocking and Changes with Time

Substratum species were more numerous than red oaks of the same age and higher canopy stratum in all stands studied. The younger these even-aged stands, the greater the preponderance of red maples, black birches, and similar species over the oaks. To understand more fully the development of such even-aged stands the total number of stems of each species which had been present since stand initiation was estimated from five plots in three stands of 60, 45, and 33 years (Stands I, V, and VI).

Procedures

Plots I-1c and I-2c (Chapter 2 and Appendix 6), first established to obtain an unbiased estimate of the number of living stems per acre, were used. These enlarged plots each included the area within the vertical projection of the crown periphery of a B-stratum red oak and extended outward from this for one-half the distance to the vertical projections of the crown peripheries of the immediately surrounding B-stratum trees.

The L and F horizons on these two plots were carefully removed. Stumps, stump holes, dead stems, and other evidence of where a tree had previously grown were marked. These locations were later mapped; the species were identified by comparing wood or bark samples of the dead stems to living trees; the diameters and extents of decay of these stumps were noted. The disturbance removing the previous stand — the clearcutting of old field white pine — had been very destructive, as observed elsewhere by McKinnon *et al* (1935). Except for the large stumps of the cut white pine, it is very probable that all stem remnants found indicated trees which had grown since the clearcutting. Essentially all living stems of similar origin in seven even-aged stands, ranging from 33 to 107 years of age, were found to have begun soon after a stand-initiating disturbance (Chapter 2); it is probable, therefore, that the dead stems found in this study had been released or had germinated soon after the clearcut and had died in the ensuing competition.

The remains of dead stems found were in all stages of decay, of many species, and as small as 2.2 inches (5.6 centimeters) in diameter at the root collar. It is probable that remnants of most stems larger than three inches (7.6 centimeters) basal diameter were found. In this way an approximation of all trees having reached sapling size and a minimum estimate of the total number of trees per acre was obtained.

Three more plots were examined to provide supplementary evidence of the total number of stems of each species which initiated on an area. Circular one-fifth acre (0.08 hectare) plots concentric to the two randomly placed one-fiftieth acre (0.008 hectare) plots (Plots V-1 and V-2) were established in the 45-year-old stand and one one-tenth acre (0.04 hectare) plot was established in the 33-year-old stand (concentric to Plot VI-1). All living and dead stems in these plots were identified by species and whether living or dead.

Stem numbers for all plots within each of the three stands were combined to obtain an average estimate for stand. There were, therefore, estimates of the total number of presently living stems and all those having reached three inches (7.6 centimeters) basal diameter (about sapling size) since the last disturbance from three separate stands of differing ages.

Results

The estimated total number of living and dead stems in each stand and of each species are shown in Table 2. The greatest number of red oaks found to have existed in any stand at any past time was 152 per acre (375 per hectare), although there was a maximum of between 1,323 and 1,860 saplings per acre (2,268 and 4,594 per hectare) of all species soon after stand initiation. Less than ten percent of the saplings in each stand had been the ultimately dominant red oaks. Red maples had been more numerous, comprising 21 to 49 percent of the total saplings; and black birches had varied from 8 to 35 percent of the total. At 60 years old, red oaks forming a pure B-stratum averaged only 97 stems per acre (242 per hectare) — 17 percent of the total number of living stems.

Discussion

McKinnon *et al* (1935) studied hardwood reproduction following old field white pine clearcuttings in central New England. They found an average of 689 "crop trees" per acre (1,702 per hectare) — excluding red maples and aspens — on the better till soils five years after the clearcut (slightly fewer on the poorer soils). Red oaks averaged 241 trees per acre (595 per hectare) on better soils and 139 per acre (343 per hectare) on poorer soils immediately after clearcutting. Here, too, they observed oaks dominating as the stands became older. Patton (1922) estimated as many as 3,800 hardwood stems per acre (9,386 per hectare) 13 years after a white pine clearcutting in central New England [based on a single twelfth-acre (0.35 hectare) plot]; only eight percent of these were red oaks. Trimble and Hart (1961) observed several

Table 2. Estimates of the minimum numbers of trees, living and dead, per acre since stand initiation based on analyses of stumps and other evidences in stands now of three different ages.

Species	60-year-old stand [2 plots, total 0.031 acres (0.012 hectares)]		45-year-old stand [2 plots, total 0.40 acres (0.162 hectares)]		33-year-old stand [1 plot, total 0.10 acres (0.040 hectares)]	
	#/acre	#/hectare	#/acre	#/hectare	#/acre	#/hectare
Northern red oak						
-total	129	319	152	375	150	370
-living (1971)	97	240	134	331	130	321
Red maple						
-total	645	1593	565	1396	390	963
-living (1971)	355	877	377	931	360	889
Black birch						
-total	323	798	578	1428	150	370
-living (1971)	65	161	270	667	40	99
Other						
-total	226	558	336	830	1170	2890
-living (1971)	64	158	258	637	790	1951
All species						
-total	1323	3268	1631	4029	1860	4594
-living (1971)	581	1435	1039	2566	1320	3260

thousand stems per acre arising after clearcutting northern Appalachian hardwood stands; here, too, only a small fraction of all stems were northern red oaks.

An estimated initial stocking of 130 to 150 red oak stems per acre (321 to 371 per hectare) out of a total of at least 1,300 to 1,900 stems (per acre; 3,210 to 4,693 per hectare) of all species eventually formed a B-stratum over virtually all of these other species. Initially the red oaks were as low in both numbers and height as in the young stands where observers such as Clark and Watt (1971) and Roach (1971) have been led to doubt whether red oaks would ever become prominent. It seems clear from the cases examined in this study that northern red oaks do have the capacity to assume ultimate dominance over many other species after "clearcutting" or similar disturbances *provided it is initially present as advance growth*. This will occur even though it remains in a subordinate position for two decades or more.

Red oak saplings appear to have a low mortality rate compared with many other species. Seventy-five percent of all red oak stems found initiating in the stand (Stand I) were alive after 60 years, compared with 55 percent for red maples; 20 percent for black birches, and 44 percent for all species. Red oaks with their large seeds, seem to have evolved a mechanism by which their reproductive effort is concentrated on fewer seedlings, each with a higher probability of success, compared with the many seedlings of red maples. Such varying reproductive adaptations have been hypothesized by Janzen (1969).

Chapter 7

Silvicultural Considerations of Stocking and Volume Growth

Red oaks have relatively broad, flat-topped crowns with a thin layer of foliage along their upper surfaces and essentially no lower layers of foliage. Therefore, the surface area of a vertical projection of a crown periphery on a horizontal plane was taken to be a good approximate index of a red oak's photosynthetic surface area.

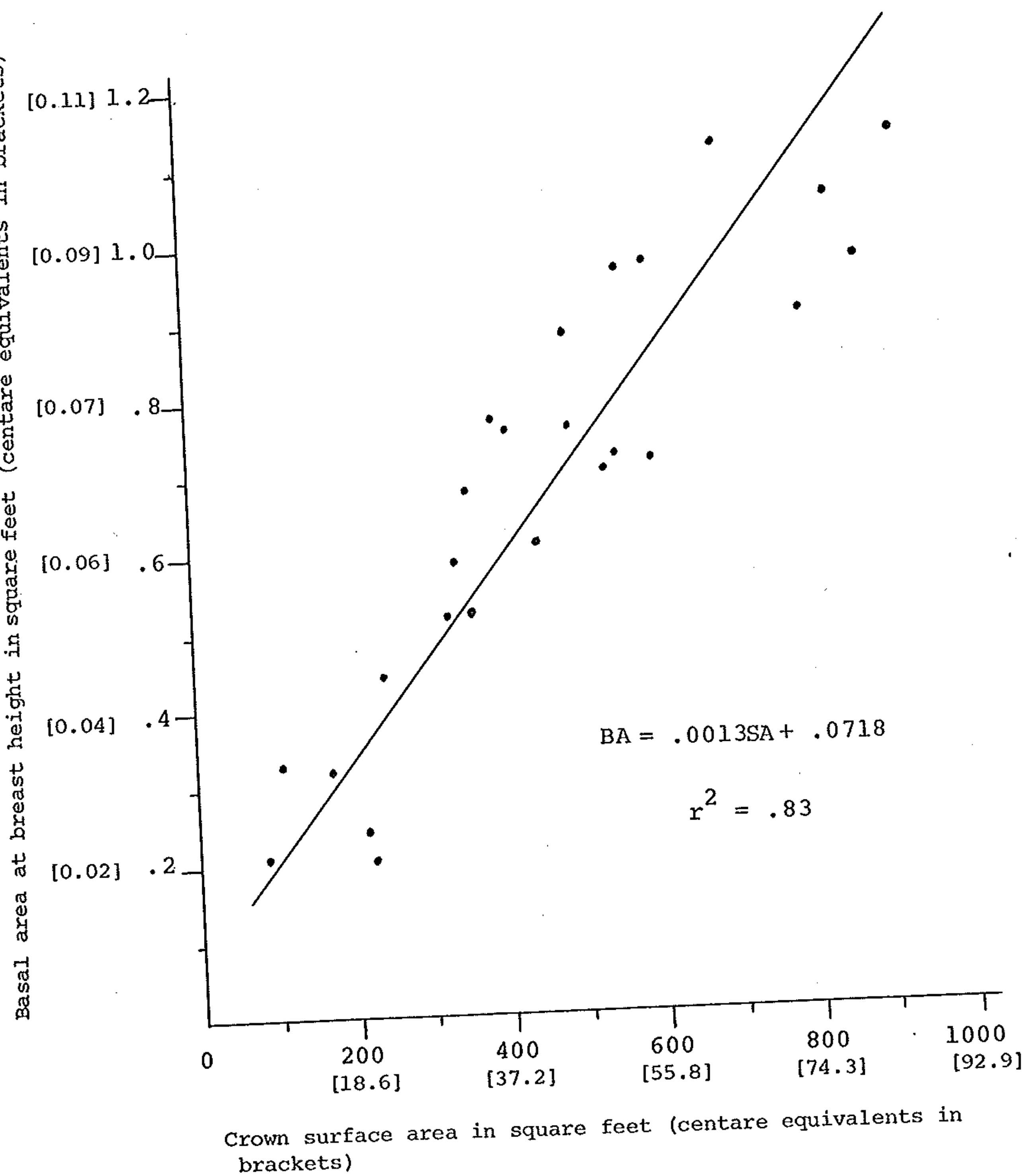
This index of photosynthetic surface area would be expected to be closely related to the accumulated basal area of the tree stem where there had been relatively little disturbance. Holsoe (1948) found a close relation between basal-area growth and both crown diameter and crown surface area in red oaks and white ashes. Berlyn (1962) similarly found a close relation between basal area and crown surface area in eastern cottonwoods (*Populus deltoides* Bartr.).

Basal areas and areas of crown projections of 25 trees in the three stands (Stands I, II, and III) of approximately 60 years of age were measured. There was no evidence of disturbance to the stands except for the 1938 hurricane, which had caused acceleration in diameter growth of some trees. As anticipated from Holsoe's studies, there was a close correlation ($r^2 = 0.83$) between basal area and crown surface area for these trees shown in Figure 20 and expressed by the equation:

$$BA = (0.0013 \times SA) + 0.0718$$

where BA - basal area per red oak in the upper canopy stratum at 60 years age; and SA = surface area of vertical projection of the red oak crown on a horizontal plane at the same age. A very similar relation was found by Patton (1922) for 70-year-old oak trees.

Figure 20: Relation of basal area (BA) at DBH to surface area (SA) of crown projection of red oak on a horizontal plane.


Basal area at breast height in square feet (centare equivalents in brackets)
[0.11] 1.2
[0.09] 1.0
[0.07] .8
[0.06] .6
[0.04] .4
[0.02] .2
0
200 [18.6]
400 [37.2]
600 [55.8]
800 [74.3]
1000 [92.9]
BA = .0013SA + .0718
r2 = .83
Crown surface area in square feet (centare equivalents in brackets)

A highly significant correlation (one percent level of significance) was also found in comparing 63 red oak trees in a 70-year-old stand at the Harvard Forest which had been thinned often. The correlation was not as close ($r^2 = 0.54$) as in the 25 trees sampled from the virtually unthinned stand:

$$BA = (0.0009 \times SA) + 0.228$$

On a crown map of a stand with a B-stratum of red oaks, the area between adjacent B-stratum crowns was bisected parallel to the edges of the crowns. This enabled estimates of the area outside each crown but ascribed to it. No meaningful correlation ($r^2 = 0.335$) was found between crown size and amount of ascribed intercanopy area; this area averaged 60.2 square feet (5.6 centares) per tree, regardless of crown size.

By adding this 60.2 square feet (5.6 centares) of intercanopy area to the horizontally projected surface area of each upper canopy tree, the number of trees of any given diameter which can be grown on an acre can be approximated. Figure 21 shows graphically the estimated change in basal area (BA) per tree and diameter at 4.5 feet (1.4 meters) of each B-stratum red oak with the change in number of individuals on a uniform, square (i.e. not equilateral) spacing.

Figure 22 shows the board foot volume per red oak for all red oaks per acre forming a pure B-stratum. These values are based on Figures 20 and 21 and the International ¼-inch scale (Form Class 78; Forbes, 1955). It also assumes two logs (32 feet; 9.8 meters) of merchantable timber per tree — an assumption derived from the observation in Chapter 3 that the height of the lowest living branch of the seven sampled 60-year-old red oaks averaged 36 feet (11.0 meters).

Figure 21: Diameter and basal area expected from northern red oak at 60 years when forming a pure B-stratum if thinned to given spacing (or number per acre or hectare) at no later than 25 years. Based on relations of Figure 19.

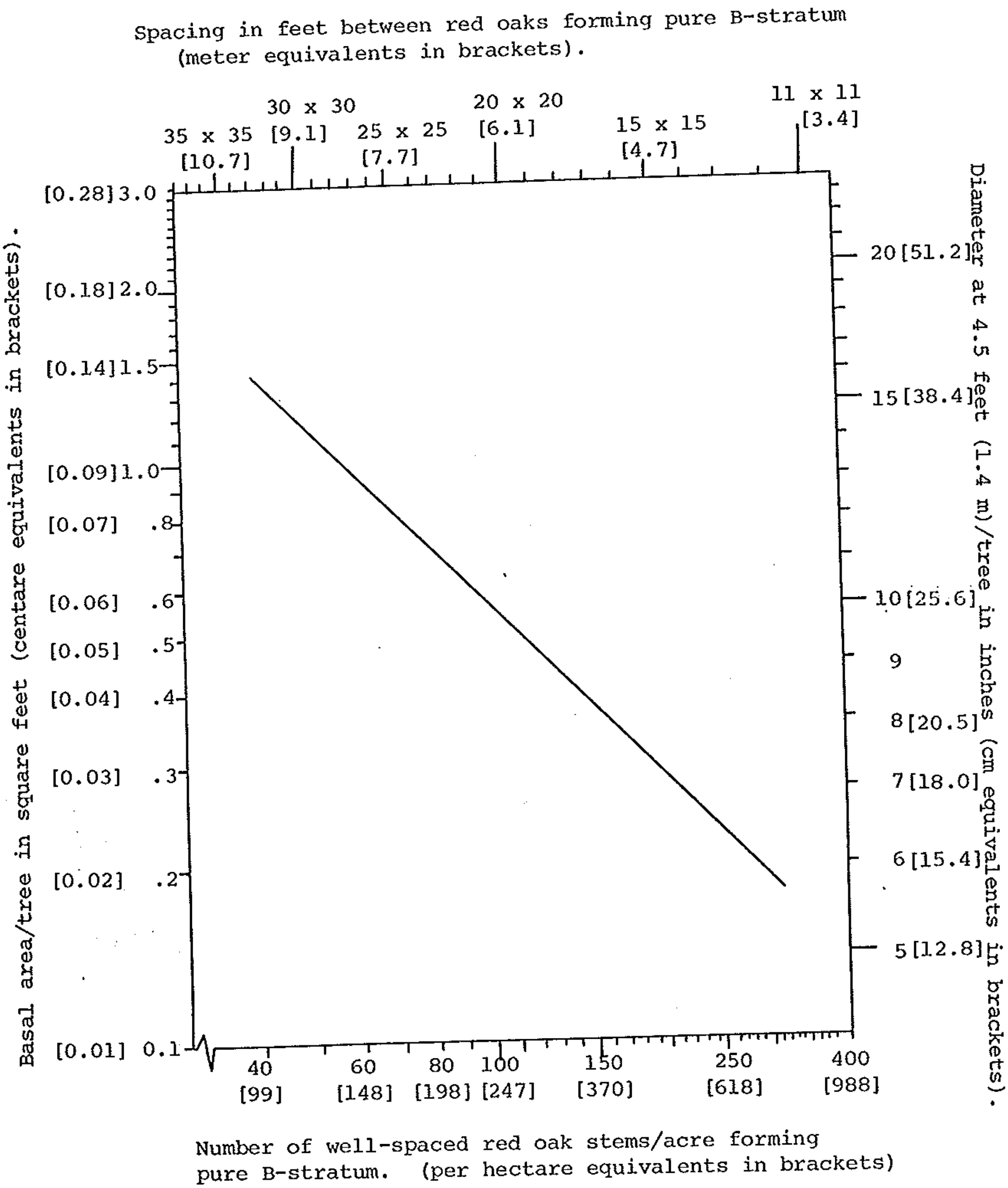
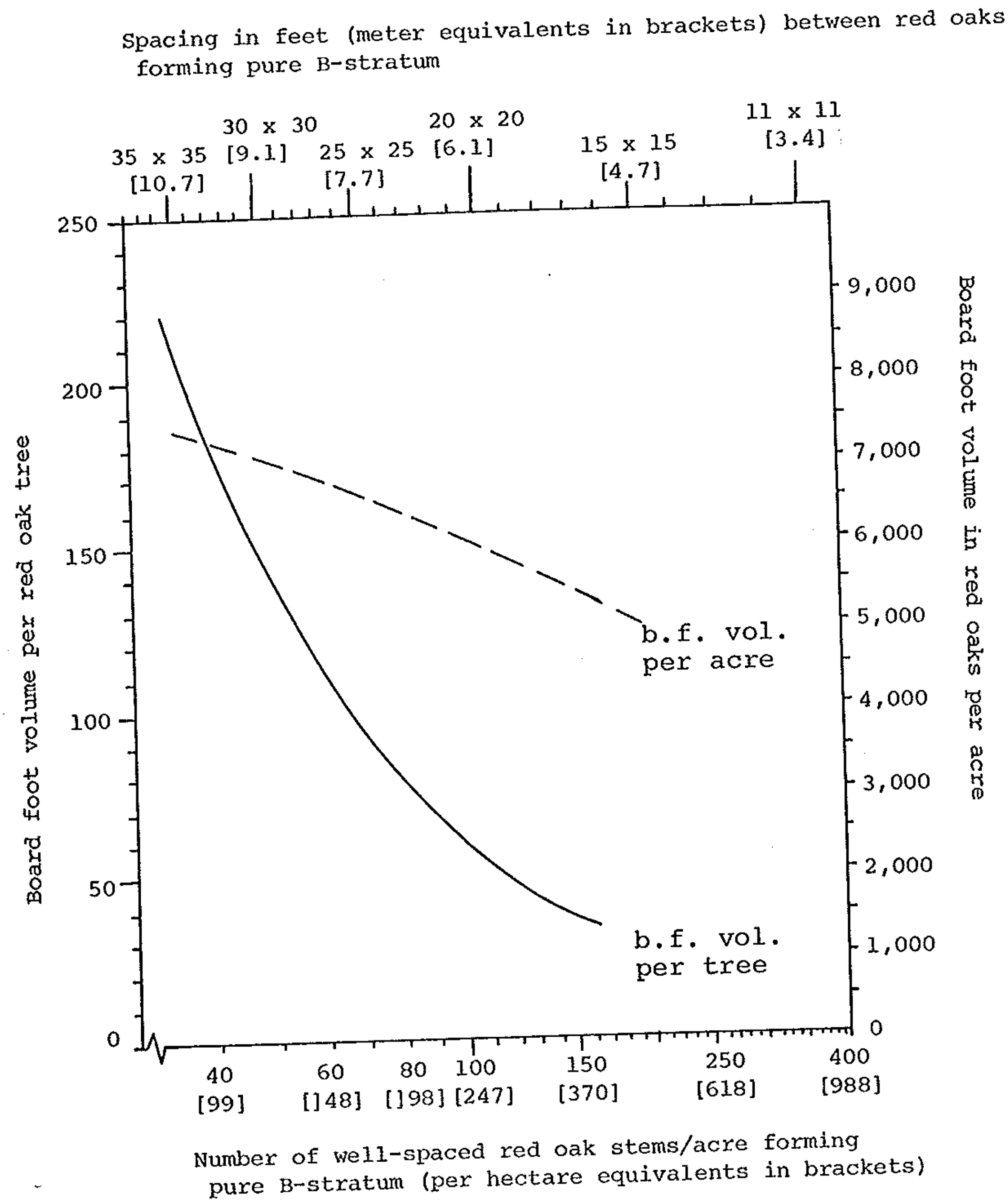

Spacing in feet between red oaks forming pure B-stratum
(meter equivalents in brackets).
35 x 35
[10.7]
30 x 30
[9.1]
25 x 25
[7.7]
20 x 20
[6.1]
15 x 15
[4.7]
11 x 11
[3.4]
Basal area/tree in square feet (centare equivalents in brackets).
[0.28] 3.0
[0.18] 2.0
[0.14] 1.5
[0.09] 1.0
[0.07] .8
[0.06] .6
[0.05] .5
[0.04] .4
[0.03] .3
[0.02] .2
[0.01] 0.1
Diameter at 4.5 feet (1.4 m)/tree in inches (cm equivalents in brackets).
20 [51.2]
15 [38.4]
10 [25.6]
9
8 [20.5]
7 [18.0]
6 [15.4]
5 [12.8]
40
[99]
60
[148]
80
[198]
100
[247]
150
[370]
250
[618]
400
[988]
Number of well-spaced red oak stems/acre forming
pure B-stratum. (per hectare equivalents in brackets)

Figure 22: Board foot volume (International 1/4-inch rule, Form Class 78) per tree (solid line and scale on left) and per acre (dashed line and scale on right) of varying numbers of well-spaced red oaks in pure B-stratum when not thinned since 25 years. Based on Figures 19 and 20.



Spacing in feet (meter equivalents in brackets) between red oaks forming pure B-stratum
35 x 35 [10.7]
30 x 30 [9.1]
25 x 25 [7.7]
20 x 20 [6.1]
15 x 15 [4.7]
11 x 11 [3.4]
Board foot volume per red oak tree
0
50
100
150
200
250
Board foot volume in red oaks per acre
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
b.f. vol. per acre
b.f. vol. per tree
40 [99]
60 []48]
80 []98]
100 [247]
150 [370]
250 [618]
400 [988]
Number of well-spaced red oak stems/acre forming pure B-stratum (per hectare equivalents in brackets)

Maximum board foot volume per tree and per stand can be obtained with as few as 45 upper canopy red oak stems per acre (111 per hectare) [based on these figures] if the oak stand is not thinned after age 30. There would be more stems per acre, but the others would be of other species and relegated to the understory. In fact, the board foot volume figures are slightly biased in favor of fewer stems per acre, since at narrower spacings competition with other oaks would cause higher pruning and hence longer merchantable boles (Patton, 1922; Gevorkiantz and Hosley, 1929).

This study shows that it is not only unnecessary but even undesirable to have large numbers of red oaks in mixed stands in which this species is destined to predominate. The capacity of the red oaks to emerge at middle age above most associated species results in the same effect as thinning, provided that the red oaks are not so close together that they compete with each other. The optimum number of red oaks is indeed so small that they are not readily obvious to casual observation amidst the more numerous associated species during the early stages of stand development.

Chapter 8

General Discussion and Conclusions

In summer the stratified forest, when viewed from beneath, seems like one of maples and birches; the oak crowns with their thin layer of foliage along their relatively flat tops are almost hidden by the more dense, lower strata of birches and maples. The red oaks are visually most evident from their large, widely spaced trunks. The seeming lack of oaks may add to the stratified appearance of the forest. Oaks remained in the lower strata mainly where other oaks had excluded them from the B-stratum (Chapter 3). It was observed in this study and by Scholz (1952) that large red oaks are quite intolerant of shade; this intolerance may also accentuate the forest stratification.

Possible Causes of Oak Dominance

Possible causes of the slow early growth and later emergence of red oaks over red maples and black birches may include a variety of physiological and environmental factors such as larger xylem vessels relative to the other two species studied, the oak's deep root system, and its terminal growth form and the abrasion resistance of its small branches.

Relative Shade Tolerance of Associated Species

The observation that species such as red maple are tolerant of shade and red oak is intolerant may suggest that red oak leaves must photosynthesize less at lower light intensities than do red maples. This is not necessarily the critical factor. Ring-porous red oaks have much larger xylem vessels than do the diffuse-porous red maples. Red oak must add new vessels each year to maintain evapotranspiration flow to the leaves because large vessels more often freeze, embolize, and hence become functionless (Zimmermann and Brown, 1971). Diffuse porous maples with smaller vessels can utilize older ones for more years and hence do not require as much additional xylem annually. Red maples were observed living in the understory with annual radial xylem increments of less than 0.0016 inches (0.04 millimeters) and in some years the xylem may not have been produced at all in the lower parts of the stem (Appendix 4). Even in a dying red oak the smallest annual xylem radial increment was 0.0083 inches (0.21 millimeters). A larger requirement of dry matter for annual xylem formation by the red oaks may exclude them from living in the lower strata even though red oaks leaves may be no more efficient than red maples in net photosynthesis at low light intensities.

The large xylem vessels of red oaks may not allow them to survive under as low photosynthate assimilation rates as the birches and maples. The oak vessels, however, may be instrumental in their more efficient height growth. The larger red oak vessels allow transport in the xylem to occur at a more efficient rate (Zimmermann and Brown, 1971). Red oaks would be able to maintain high growth rates longer than their small-vesselled associates at times when the rates of movement of water and nutrients to the apical meristems may be the factor limiting growth.

Root Systems of Associated Species

The generally deep root systems of red oak seedlings compared to red maples and black birches may account for their slow initial growth and sustained later growth. From data of Stout (1956) it can be inferred that the average depth of woody lateral roots growing in a deciduous forest follows a pattern of stratification by species, with oaks in the deepest strata. Red oak lateral roots average 12 inches beneath the surface in deep soils. In shallower soils the pattern of stratification did not seem to change, but the relative depths of the different species decreased. In deep soils Lyford (1974) has found that red oak lateral roots generally grow at an angle downward to about 12 to 16 inches (30 to 40 centimeters) before levelling off. These laterals then send up feeder roots into the A-horizon. Red oak growth may be directed at the development of a deep root system during its early stages rather than at fast shoot growth. Later, the well-developed root system may allow oak to maintain steady height growth longer than its more superficially rooted competitors.

Terminal Growth Forms and Terminal Breakages

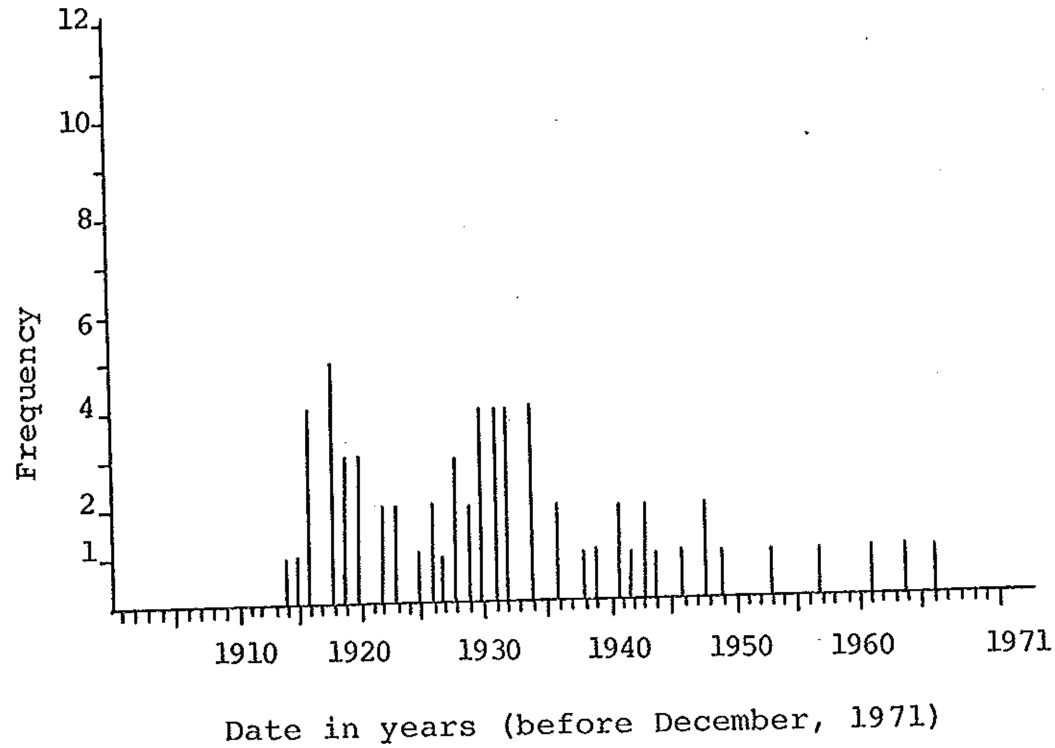
A third factor possibly contributing to the ascendance and maintenance of red oaks in the upper canopy positions may be their terminal growth forms and their abrasion-resistant branches. Many red maples and black birches contained injuries in their stems where the terminals had been broken and a lateral branch assumed apical control. Height-age curves (Appendix 5) indicated a decline or temporary hiatus of height growth at about the time of the injury. It became evident from studies of the extent of xylem rot at the point of terminal injury that the breaks occurred when the red maple and black birch twigs were generally less than 1.5 inches (3.75 centimeters) in diameter. Breaks were extremely common; but it was not clear whether they were the result of sporadic episodes of acute damage (such as severe wind or glaze storms or insect outbreaks) or if they were a quite regular, chronic phenomenon. For this reason it was desirable to determine if many breaks had occurred simultaneously.

It is estimated from height-age curves that the times of breakage could be dated to within approximately three years. It could be assumed that a single, unusual circumstance caused the phenomenon if all injuries appeared to occur within a very few years of each other. The approximate date of each injury to each red maple and black birch sectioned for height in the 60- and 74-year-old stands (Stands I, II, III, and IV; Chapters 2 and 3) are shown in Figure 23. The frequency of injuries by years showed the injuries to have occurred on a quite regular basis. Even years of severe windstorms — 1938, 1950, and 1954 — showed no apparent rise in number of breakages.

Incidence of breakage was chronic rather than being limited to a few specific years, but was greatest in the early life of the stands. Part of the chronic breakage may be caused by a combination of wind action and the frequent, minor glaze storms of the region. Red oaks, even with their stronger limbs, may suffer from this injury; however, another bud would more readily assume the terminal growth position than in the cases of maples and birches because the oak terminals assert less apical control than do the others (see Kozlowski, 1971; Zimmermann and Brown, 1971).

The relatively thin branches of birches and maples were observed to batter against the stout lateral branches of oaks when blown about during windstorms and during ordinary glaze storms accompanied by winds. Such batterings probably contribute to the injuries to the stems observed in this study. The relatively week apical control of red oaks allow them to develop large, strong lateral branches which might act to inhibit the height growth of competing vegetation while protecting the terminal buds of the oaks from similar such injury. In this way the lack of apical control may be very important in the ascendance to and maintenance of

Figure 23: Frequency of black birch and red maple stem injuries for each year in trees sectioned in Plots I-1, I-2, II-1, II-2, III-1, III-2, and III-3.


12
10
8
6
4
2
1
Frequency
1910
1920
1930
1940
1950
1960
1971
Date in years (before December, 1971)

northern red oak in the B-stratum.

Stratification of Other Species

There also seemed to be a distinct pattern in the temporal and spatial stratification of other species within the stands studied. Height-age curves were developed only for red maples and black birches, in their relation to red oaks; however, observations of other species suggest certain patterns which are described as follows:

Aspens

Quaking aspens (*Populus tremuloides* Michx.) and bigtooth aspens (*Populus grandidentata* Michx.) have been found to hybridize in central New England (Remington, 1974). A single aspen in the 33-year-old stand was larger in diameter (9.2 inches; 23.4 centimeters) than any associates and existed in the A-stratum above the continuous crown canopy. Only fallen aspens (not pushed over by the 1938 hurricane) were found in the 60-year-old stands; this species makes rapid early height and diameter growth but does not live long.

Paper-Gray Birch Complex

Paper birch (*Betula papyrifera* Marsh.) and gray birch (*Betula populifolia* Marsh.) can form a sterile hybrid (Remington, 1973, 1974). One form appearing to be of this genetic complex maintained height and diameter growth characteristics similar to red oak for a longer period than did red maple and black birch. The same relationship was observed by McKinnon *et al* (1935). This birch appeared to lose its place in the B-stratum about 65 years after stand initiation where the red oak and this birch were relatively widely spaced.

Hickories

Hickories (the genus *Carya*) do not appear very prominent in these forests, possibly because they begin to assert dominance even later than red oaks. Hickory stems observed in all stands seemed to have started with the other stems at the time of stand initiation. It was only in the 107-year-old stand that hickories were observed to be emerging into the B-stratum, there competing with red oaks. The physical toughness of the hickory limbs seemed able to break the relatively brittle oak twigs, thus creating room for the hickories to emerge.

Eastern Hemlock

Although the one eastern hemlock [*Tsuga canadensis* (L.) Carr.] studied had existed as a seven-feet tall (2.1 meter) advanced-growth sapling in the previous old field white pines of Stand I, it was soon relegated to a substratum position by younger and faster growing oaks, maples, and birches originating from less than one foot high. Even in the lower canopy strata the hemlock was larger in diameter than some of its taller associates. It generally responded to disturbances in the overstory by temporarily increasing its diameter growth rate, as was found by analysis of the ring patterns in the present study and by Marshall (1927) and Lutz (1928).

Sugar Maple

Sugar maples (*Acer saccharum* Marsh.) behaved very similarly to red maples often accompanying them or even replacing them on the moister sites. More than any other species, sugar maples seemed able to germinate and survive at much later times during the life of the stand than other species. These younger saplings grew extremely slowly if not released.

Conclusions

A minimum of effort can be expended in trying to manipulate upland central New England forest stands by recognizing that they develop after clearcutting into even-aged, stratified, mixed-species, oak-dominated forests according to the pattern shown in Figures 12, 13, and 14. It is necessary to ensure that only a small portion of the advanced regeneration is red oak at the time of harvest to obtain what becomes after several decades an oak-dominated stand. Alternatively, if one desires another species as the dominant, it is necessary to get rid of all red oaks even if the oaks seem to be small, permanent laggards during the first few decades.

The number of dominant oaks stems desirable per acre (or hectare) will, of course, depend on the landowner's objectives. Figure 21 shows an estimate of volume variation with stocking for red oaks at 60 years old. It is possible that on longer rotations, even fewer trees per acre are needed to yield the greatest volume. In any event, the desired number of upper-canopy oaks per acre is remarkably small.

Oaks respond to thinning of competing, upper canopy trees over a wide range of ages and diameters. The 1938 hurricane's thinning of the upper canopy of the studied stands provided a fortuitous opportunity to observe the response of the remaining red oaks to release. Studies of this thinning revealed oaks accelerated diameter growth after release between the ages of 20 and 71 years and between the diameters of two inches (5.1 centimeters) and 13.5 inches (34.3 centimeters). This evidence indicates that both precommercial and commercial crown thinnings within this age range will result in accelerating the growth of the oaks. Also, responses of red and sugar maples, hemlocks, and black birches at a variety of ages indicate that some of these species could be encouraged to develop as a second crop upon removal of the oaks.

Red oaks, red maples, black birches, and other species initiated growth from seedlings, sprouts, and seeds. Red maples, black birches, and similar species appear to dominate the stand for the first 25 years. These species are more numerous and often taller in height and larger in diameter than the red oaks. After all species are about 25 years old and 30 to 40 feet (9.2 to 12.2 meters) tall, red oaks maintain a steady height and diameter growth relative to the declining growth rates of their associates. By 60 years red oaks form a continuous canopy above the other species. The forest then appears as a stratified mixture — stratified by crown strata and species. Because of its broad variation in diameters by this time, such forests have often been mistaken as being all-aged.

Results of this investigation demonstrate that the presence of a species in the lower strata of a mixed stand does not necessarily mean that this species is younger than those of the upper strata or that it is foreordained to dominate in some later stage of succession. In this case, red maples and black birches lapse into the lower strata after a period of initial dominance. They did not all succumb as is commonly the case with true pioneer tree species which, in this instance, would have been such species as gray birch, aspen or pin cherry (*Prunus pennsylvanica* L.). Many of them instead persisted in the lower strata. It is not clear whether red maples or black birches in the lower strata might survive long enough and retain enough capacity for response to release to regain dominance when the red oak stratum began to die.

Red oak is normally a very long lived species and the oldest stand examined (107 years) was not so old that oaks had begun to dwindle.

SUMMARY

Much of the upland forest of central New England consists of red oaks (*Quercus rubra* L.), red maples (*Acer rubrum* L.), black birches (*Betula lenta* L.), and other species. Such stand develop a definite stratification, with a few red oaks ultimately occupying much of the upper continuous canopy and the more numerous maples, birches, and other species generally occupying the lower crown positions.

The stands are commonly even-aged in spite of the broad range of diameters and crown classes after about 40 years, which gives these forests an all-aged appearance. Initiating from a severe disturbance of the previous forest — such as a clearcutting or a hurricane blowdown — the stands grow from understory seedlings, sprouts, and seeds. They first appear to be dominated by red maples, black birches, and other species. It is only later that the few red oaks, although present all along, begin to dominate.

For best diameter growth on individual red oak trees, it may be desirable to have only 45 well placed red oak seedlings (or seedling sprouts) per acre (111 per hectare) in the reproduction, relying on the more numerous red maples, black birches, and other species to keep the red oaks pruned. The resulting wide spacing of the oaks in the ultimate main canopy produces the same rapid diameter growth that could be secured by only frequent and intensive thinning if the stands were of pure oaks and started with hundreds or thousands of seedlings per acre.

APPENDICES

APPENDIX 1

Location of stands on the Yale and Harvard Forests

Six of the seven studied stands were in the Yale Forest near Union, Connecticut. The compartment(s) according to the map in "The Yale Forest in Tolland and Windham Counties, Connecticut" (Meyer and Plusnin, 1945) containing each of these stands is listed below. The seventh stand, also listed below, was in the Harvard Forest in Petersham, Massachusetts.

Stand Number	Compartment Number	Location
I	31	Yale Forest
II	145	" "
III	96 & 97	" "
IV	7 & 8	" "
V	28	" "
VI	98	" "
VII	Tom Swamp I	Harvard Forest

APPENDIX 2

Analysis of Species Stratification in Extensive Areas of Mixed Forests

Appendix 2A

To analyze the vertical, spatial stratification of tree crowns in an extensive forested area, it was necessary to devise a sampling system which was quick, objective, quantitative, and informative from a silvicultural framework. The method employed for this purpose was not the same as that used for reconstructing stand histories.

A modification of the point-sampling (prism) inventory method was developed. The plots were located on an essentially random basis and the sample trees were those tress which would ordinarily be included in a point-sampling inventory. Each sample was described by species, diameter, and crown class. Four crown strata were recognized, similar to those recognized by Richards (1957): Emergent (A-stratum), B-, C-, and D-strata. The following method of distinguishing between crown strata was developed to be as informative and objective as possible:

> A tree was assigned to the emergent (or A-) stratum if over one half of its live crown vertical length was above the height of the upper continuous crown canopy of the forest. Such outstanding trees, where present, were widely spaced and did not form a continuous canopy. They were not close enough to form contact between lateral branches of other emergent trees. Because of its aloof nature, a tree thus defined as being in the outstanding crown class was not used in further descriptions of the interactions with other trees.

The relations and methods of determining crown positions of trees in the other three classes are described as follows:

> A tree was defined as *interacting* with the sample tree if the sample *subordinated* it, *overtopped* it, was *subordinated by* it, or was *overtopped by* it. These four methods of interaction are defined below and shown representatively in Figure 2.1:
>
> > A sample tree *overtopped* another tree if a horizontal projection of the crown of the other tree was entirely beneath the horizontal projection of the crown of the sample tree.
> >
> > A sample tree *subordinated* another tree if the sample tree did not *overtop* the other tree yet more than one half of the horizontal distance between the center and edge of the crown of the other tree along any radius was covered by a horizontal projection of the crown of the sample tree.
> >
> > A sample tree was *overtopped by* another tree if the other tree *overtopped* the sample tree. Hence, the sample tree was *overtopped by* the other if a horizontal projection of the crown of the sample tree was entirely within the horizontal projection of the crown of the other tree.
> >
> > A sample tree was *subordinated by* another tree if the other tree *subordinated* but did not *overtop* the sample tree. Hence, the sample tree was *subordinated by* the other if not *overtopped by* it and if more than one half of the horizontal distance between the center and edge of the crown of the sample tree along any radius was covered by a horizontal projection of the crown of the other tree.

Table 2.1 shows a representative record sheet from a single plot of an inventory (based on the schematic forest of Figure 2.1). All sample trees and the trees interacting with them are shown.

To get a more complete picture of the forest of an area, all trees listed on the record sheet (Table 2.1) — whether in the sample or interacting with the sample — were defined herein as being *associated*

Figure 2.1: A schematic sample area. All trees here are assumed to be on a single plane; hence, all measurements are assumed on a line between the bases of the trees. Trees within the sample are designated by a triangle at the base. Table 2.1 shows a record sheet of this schematic sample. Examples of the various crown positions are as follows:

White Pine #1 is *outstanding* since the portion of its crown (XY) above the dominant canopy (plane Y) is greater than half of the total length of the crown (YZ).

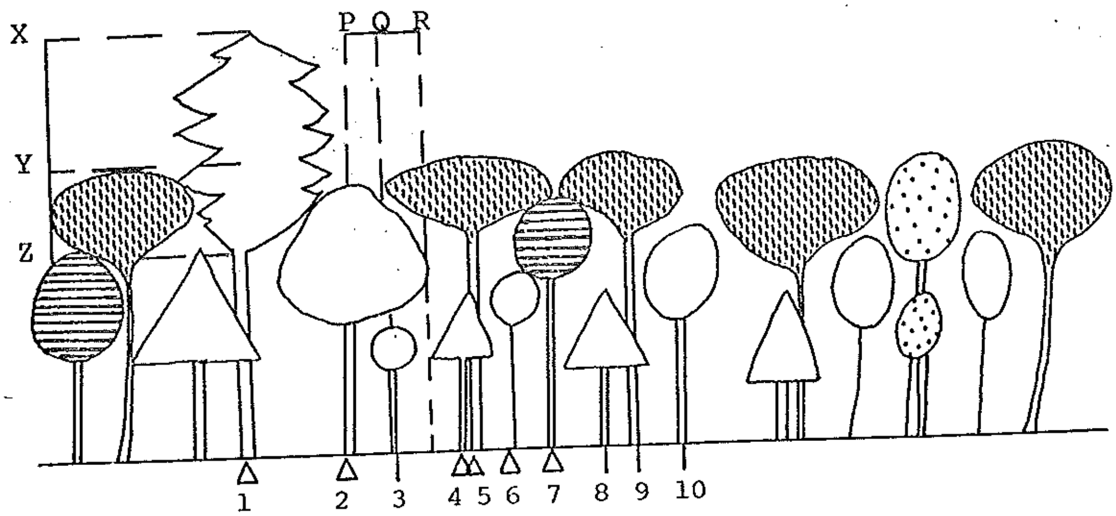
Red Maple #2 is *subordinated by* Red Oak #5, since the overshadowed distance of the crown of Red Maple #2 (QR) is greater than one half of the distance from the center to the edge of the crown of Red Maple #2 (PR).

Red Maple #2 *overtops* Red Maple #3 since the entire two dimensional surface area of the horizontal projection of the crown of Red Maple #3 is within a similar projection of the crown of Red Maple #2.

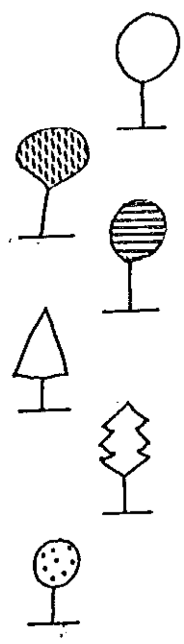
Red Maple #3 is similarly *overtopped by* Red Maple #2 and *subordinated by* Red Oak #5.

Red Oak #5 *subordinates* Red Maple #2, Red Maple #3, and Black Birch #7; but *overtops* Hemlock #4 and Red Maple #6.

Trees #1, 2, 3, 4, 5, 6, 7, 8, and 9 are all defined as *associated* with each other since they are either sample trees or are *interacting* with (*subordinating, overtopping, subordianted by,* or *overtopped by*) with sample trees.



Legend:



RM Red maple

RO Red oak

BB Black birch

Hem Hemlock

WP White pine

OS Other species

PLOT # sample DATE: ________ SAMPLED BY: ________

Does plot meet criteria to be considered within a population to be studied? yes

Sample Tree #	Species	DBH	Is it an "emergent" tree?	Overtops	Subordinated	Overtopped by	subordinated by
1	WP	13.0	yes	X	X	X	X
2	RM	5.6	no	RM 2.5"(#3)	-	-	NRO #5
4	Hem	6.0	no	-	-	NRO #5	-
5	NRO	11.0	no	Hem #4 RM #6	RM #2 BB #7	-	-
6	RM	2.5	no	-	-	NRO #5	BB #7
7	BB	6.0	no	-	RM #6 Hem 12"(#8)	-	N RO #5 N RO 10"(#9)

Table 2.1: Example of record sheet taken from schematic forest of Figure 1.1.

with each other. Two trees hence did not have to be interacting with each other to be associated with each other.

For a given inventory the structure of the average forest can be obtained by separating all sample trees into four relative strata. These strata are similar to those described by Richards (1957) and are lettered sequentially beginning with "A" as the uppermost stratum:

A stratum (Emergent crown class): those trees with one half of their live crown length above the height of the upper continuous crown canopy (B stratum). They do not form a continuous crown canopy and they are not close enough to have contact between lateral branches of other "outstanding" trees.

B stratum: those trees which are neither overtopped by nor subordinated by any tree except emergents. (The "overtopped by" and "subordinated by" columns of Table 2.1 are blank.)

C stratum: those trees which are subordinated by at least one other tree, but are not overtopped by any. (The "subordinated by" column of Table 2.1 contains at least one tree, but the "overtopped by" column is blank.)

D stratum (Overtopped crown class): those trees which are overtopped by at least one other tree. (The "overtopped by" column of Table 2.1 contains at least one tree.)

By using normal point-sampling methods (Kulow, 1965), each sample tree in each class is described by basal area per acre (using appropriate conversion factors), species, diameter class and number per acre (using appropriate conversion factors). The forest can thus be depicted both graphically and tabularly by vertical crown class, species, diameter at breast height, number of stems per acre and basal area per acre as is shown in Figure 2.2 and 2.3 and Tables 2.2 and 2.3.

To deterimine if there were a specific pattern of interaction between two species, all sampled trees of both species were examined. Where the sampled trees of one of the studied species was found interacting with a tree of the other species, it was noted which tree occupied the higher (subordinating or overtopping) position with respect to the other. If a sample tree interacted with more than one individual of the other species, only one interaction was recorded — the interaction with the individual of the highest crown class. Hence, in the sample tally sheet (Table 2.1), althoug Red Oak #5 interacts with two red maples, it would be considered as being only one interaction. Where two sample trees interact, each tree is regarded as a separate sample; therefore, the actual interaction would be recorded twice — once under the consideration of each sample tree. For this reason, the consideration of Red Oak #5 and Red Maple #2 would be recorded as two interactions of red oak subordinating red maple.

If there were only a random pattern to the interaction of the two species, each species should assume the more subordinating position 50 percent of the time. Deviations from this indicate, by the laws of probability, a more patterned interaction between the species.

Appendix 2B. Application of method to Yale Forest in Union, Connecticut

Using the above method, 35 permanent sample plots located at random on a systematic grid at the 7,800 acre Yale Forest near Union, Conneticut, were inspected. The study was intended to determine the possibility of a pattern other than chance to the vertical stratification of the forests on upland sites having originated after a heavy cutting (or similar disturbance where root systems of advanced reproduction and seeds in the forest floor would not be destroyed). Therefore, plots or quadrants of plots were rejected if they had been cut or silviculturally manipulated within the past 33 years, if the uppermost canopy had initiated from old field succession, or if the plots were within swamps of standing water (in June). Twenty-five of the 35 plots were accepted as within the population of forest conditions to be studied.

A description of the 25 selected upland sample plots revealed red oak to be an associated species (as defined above) in 22 of the plots (Table 1.4). Red maple was associated with red oak in 21 of the 25 plots; black birch was associated with red oak in 13 of the plots; and all three species were in association in 12 of the 25 plots. The inventory revealed the distribution of species by crown class and diameter at 4.5 feet (1.4 meters) in the sampled forest to be as shown in Figures 2.2, 2.3 and Tables 2.2 and 2.3. As can be seen, red oak comprised less than eight percent of all stems, but accounted for over 40 percent of those in the B-stratum. Red maple and black birch, on the other hand, were found primarily in the lower two strata of the forest. Where red oaks were found in the lower two canopies, they were subordinated by or overtopped by other red oak trees (and not by other species) 75 percent of the time (Table 2.4).

Figure 2.2: Distribution of all trees of upland forests of the Yale Forest in northern Connecticut based on point sampling of 25 plots.

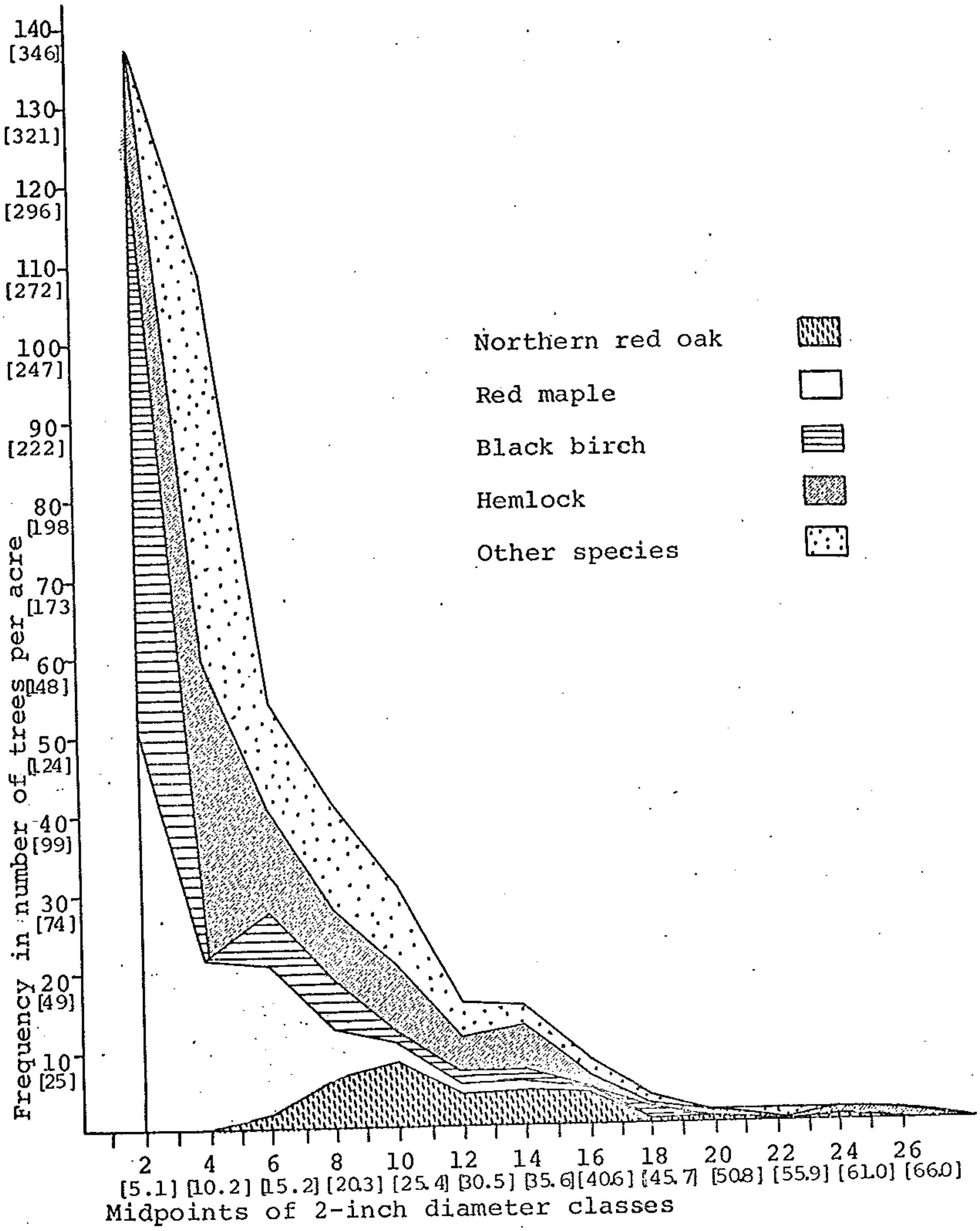
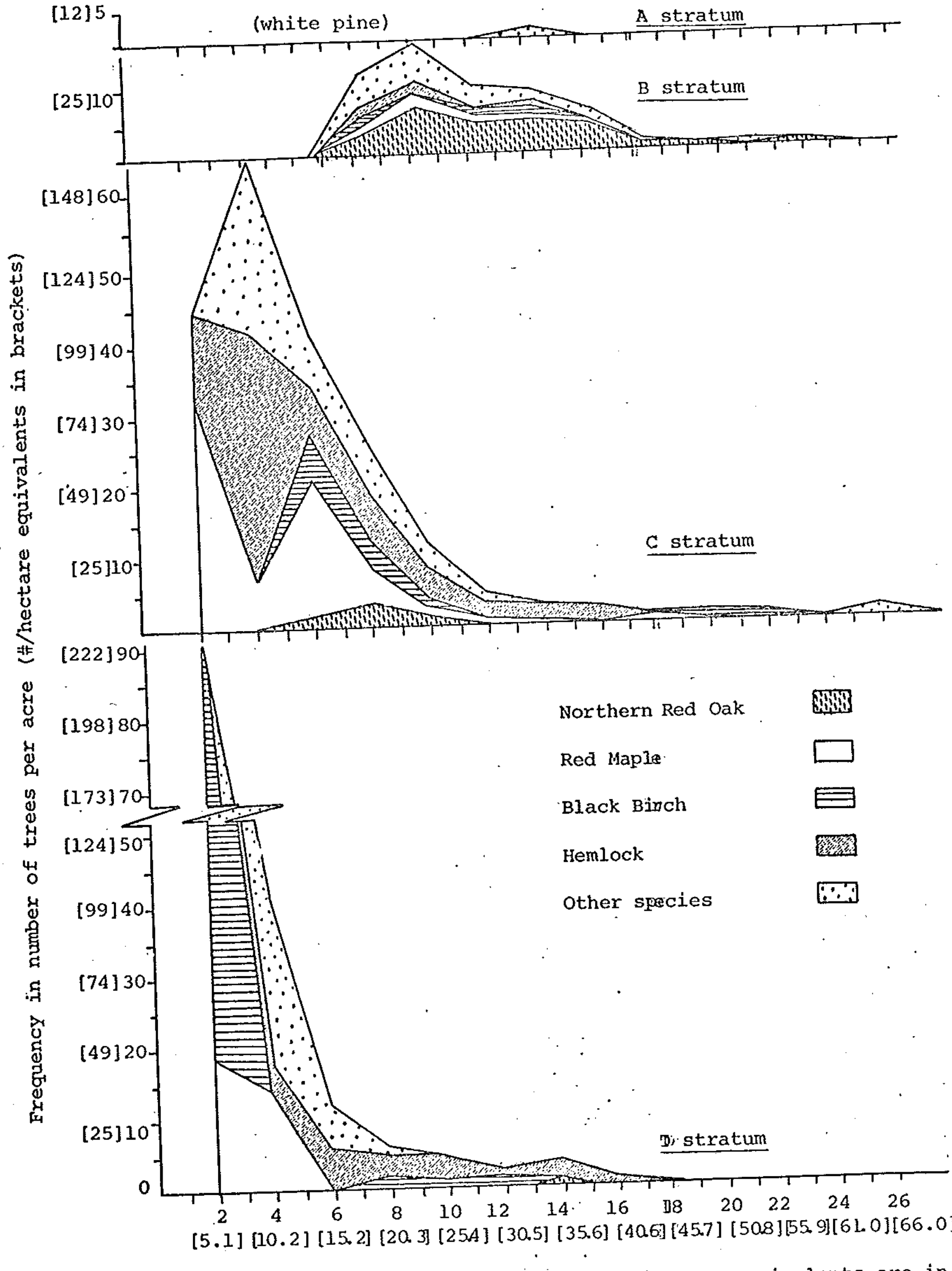

Northern red oak
Red maple
Black birch
Hemlock
Other species
Frequency in number of trees per acre
140 [346]
130 [321]
120 [296]
110 [272]
100 [247]
90 [222]
80 [198]
70 [173]
60 [148]
50 [124]
40 [99]
30 [74]
20 [49]
10 [25]
2 [5.1]
4 [10.2]
6 [15.2]
8 [20.3]
10 [25.4]
12 [30.5]
14 [35.6]
16 [40.6]
18 [45.7]
20 [50.8]
22 [55.9]
24 [61.0]
26 [66.0]
Midpoints of 2-inch diameter classes

Figure 2.3: Stratification of the forest of Figure 2.2 by crown strata.



Midpoints of 2-inch diameter classes (diameter equivalents are in brackets)

Table 2.2: Average number of trees per acre of uplands (based on a cruise of 25 plots).

	All crown classes		A-stratum		B-stratum		C-stratum		D-stratum	
	#	%	#	%	#	%	#	%	#	%
All species	382.4	100	0.4	100	54.5	100	166.2	100	161.4	100
% of all trees	100		0.01		14.2		43.5		42.2	
Red Oak	29.7	7.8	0	0	22.5	41.4	6.8	4.1	0.4	.2
% of all trees	7.8		0		5.9		1.8		0.1	
% of red oak	100		0		75.8		22.9		1.3	
Red Maple	68.6	17.9	0	0	3.5	6.5	32.4	19.4	32.7	20.3
% of all trees	17.9		0		0.9		8.5		8.5	
% of red maple	100		0		5.1		47.2		47.7	
Black Birch	89.9	23.5	0	0	2.6	4.8	11.5	6.9	75.8	47.0
% of all trees	23.5		0		0.7		3.0		19.8	
% of black birch	100		0		2.9		12.8		84.3	
Hemlock	98.3	25.7	0	0	4.9	9.0	73.1	43.8	20.3	12.6
% of all trees	25.7		0		1.3		19.1		5.3	
% of hemlock	100		0		5.0		74.4		20.6	
Black Oak	7.7	2.0	0	0	2.0	3.7	5.7	3.4	0	0
% of all trees	2.0		0		0.5		1.5		0	
% of black oak	100		0		26.0		74.0		0	
White Oak	11.1	2.9	0	0	4.4	8.1	3.1	1.8	3.6	2.2
% of all trees	2.9		0		1.1		0.8		0.9	
% of white oak	100		0		39.6		27.9		32.4	

Table 2.2 continued:

Table 2.2 continued: Average number of trees per acre of uplands (based on a cruise of 25 plots).

	All crown classes #	All crown classes %	A-stratum #	A-stratum %	B-stratum #	B-stratum %	C-stratum #	C-stratum %	D-stratum #	D-stratum %
White Pine	18.8	4.9	0.4	100	2.8	5.1	7.0	3.0	8.6	5.3
% of all trees	4.9		0.1		0.7		1.8		2.2	
% of white pine	100		2.1		14.7		37.2		45.7	
Yellow Birch	9.9	2.6	0	0	5.0	9.2	0	0	4.9	3.0
% of all trees	2.6		0		1.3		0		1.3	
% of yellow birch	100		0		50.5		0		49.5	
White Ash	4.3	1.1	0	0	1.4	2.6	2.9	1.7	0	0
% of all trees	1.1		0		0.4		0.8		0	
% of white ash	100		0		32.6		67.4		0	
Hickory	21.2	5.5	0	0	2.4	4.4	10.9	6.5	7.9	4.9
% of all trees	5.5		0		0.6		2.8		2.1	
% of hickory	100		0		11.3		51.4		37.3	
White-Gray Birch	2.6	0.7	0	0	0	0	2.6	1.6	0	0
% of all trees	0.7		0		0		0.7		0	
% of white-gray birch	100		0		0		100		0	
Sugar Maple	11.7	3.0	0	0	1.5	2.8	10.2	6.1	0	0
% of all trees	3.0		0		0.4		2.7		0	
% of sugar maple	100		0		12.8		87.2		0	
Black Cherry	8.6	2.2	0	0	1.4	2.6	0	0	7.2	4.5
% of all trees	2.2		0		0.4		0		1.9	
% of black cherry	100		0		16.3		0		83.7	

Table 2.2 continued: Average number of trees per acre of uplands (based on a cruise of 25 plots).

	All crown classes #	All crown classes %	A-stratum #	A-stratum %	B-stratum #	B-stratum %	C-stratum #	C-stratum %	D-stratum #	D-stratum %
White Pine	18.8	4.9	0.4	100	2.8	5.1	7.0	3.0	8.6	5.3
% of all trees	4.9		0.1		0.7		1.8		2.2	
% of white pine	100		2.1		14.7		37.2		45.7	
Yellow Birch	9.9	2.6	0	0	5.0	9.2	0	0	4.9	3.0
% of all trees	2.6		0		1.3		0		1.3	
% of yellow birch	100		0		50.5		0		49.5	
White Ash	4.3	1.1	0	0	1.4	2.6	2.9	1.7	0	0
% of all trees	1.1		0		0.4		0.8		0	
% of white ash	100		0		32.6		67.4		0	
Hickory	21.2	5.5	0	0	2.4	4.4	10.9	6.5	7.9	4.9
% of all trees	5.5		0		0.6		2.8		2.1	
% of hickory	100		0		11.3		51.4		37.3	
White-Gray Birch	2.6	0.7	0	0	0	0	2.6	1.6	0	0
% of all trees	0.7		0		0		0.7		0	
% of white-gray birch	100		0		0		100		0	
Sugar Maple	11.7	3.0	0	0	1.5	2.8	10.2	6.1	0	0
% of all trees	3.0		0		0.4		2.7		0	
% of sugar maple	100		0		12.8		87.2		0	
Black Cherry	8.6	2.2	0	0	1.4	2.6	0	0	7.2	4.5
% of all trees	2.2		0		0.4		0		1.9	
% of black cherry	100		0		16.3		0		83.7	

Table 2.3: Average basal area (in square feet) of species per acre of uplands (based on a cruise of 25 plots).

	All crown classes		A-stratum		B-stratum		C-stratum		D-stratum	
	B.A.	%	B.A.	%	B.A.	%	B.A.	%	B.A.	%
All species	95.3	100	0.4	100	40.2	100	38.1	100	16.6	100
% of all trees	100		0.4		42.6		40.0		17.4	
Red Oak	21.7	22.8	0	0	19.3	48.0	2.0	5.2	0.4	2.4
% of all trees	22.8		0		20.2		2.1		0.4	
% of red oak	100		0		88.9		9.2		1.8	
Red Maple	10.8	11.3	0	0	2.4	6.0	6.8	17.7	1.6	9.6
% of all trees	11.3		0		2.5		7.1		1.7	
% of red maple	100		0		22.2		63.0		14.8	
Black Birch	6.5	6.8	0	0	1.6	4.0	3.2	8.3	1.7	10.2
% of all trees	6.8		0		1.7		3.4		1.8	
% of black birch	100		0		24.6		49.2		26.2	
Hemlock	29.4	30.8	0	0	2.8	7.0	17.7	46.0	8.9	53.6
% of all trees	30.8		0		2.9		18.6		9.3	
% of hemlock	100		0		9.5		60.2		30.3	
Black Oak	2.8	2.9	0	0	1.6	4.0	1.2	3.1	0	0
% of all trees	2.9		0		1.7		1.2		0	
% of black oak	100		0		57.1		42.9		0	
White Oak	5.7	6.0	0	0	3.3	8.2	1.6	4.2	0.8	4.8
% of all trees	6.0		0		3.5		1.7		0.8	
% of white oak	100		0		17.5		28.1		14.0	

Table 2.3 continued:

Table 2.3 continued: Average basal area (in square feet) of species per acre of uplands (based on a cruise of 25 plots).

	All crown classes		A-stratum		B-stratum		C-stratum		D-stratum	
	B.A.	%	B.A.	%	B.A.	%	B.A.	%	B.A.	%
White Pine	4.4	4.6	0.4	100	1.2	3.0	1.6	4.2	1.2	7.2
% of all trees	4.6		0.4		1.2		1.7		1.2	
% of white pine	100		9.1		27.3		36.4		27.3	
Yellow Birch	4.4	4.6	0	0	3.6	9.0	0	0	0.8	4.8
% of all trees	4.6		0		3.8		0		0.8	
% of yellow birch	100		0		81.8		0		18.2	
White Ash	1.6	1.7	0	0	1.2	3.0	0.4	1.0	0	0
% of all trees	1.7		0		1.2		0.4		0	
% of white ash	100		0		75.0		25.0		0	
Hickory	3.6	3.8	0	0	1.2	3.0	1.6	4.2	0.8	4.8
% of all trees	3.8		0		1.2		1.7		0.8	
% of hickory	100		0		33.3		44.4		22.2	
White-Gray Birch	1.2	1.2	0	0	0	0	1.2	3.1	0	0
% of all trees	1.2		0		0		1.2		0	
% of white-gray birch	100		0		0		100		0	
Sugar Maple	2.0	2.1	0	0	1.2	3.0	0.8	2.1	0	0
% of all trees	2.1		0		1.2		0.8		0	
% of sugar maple	100		0		60.0		40.0		0	
Black Cherry	1.2	1.2	0	0	0.8	2.0	0	0	0.4	2.4
% of all trees	1.2		0		0.8		0		0.4	
% of black cherry	100		0		66.7		0		33.3	

Table 2.4: Comparisons of interactions observed in upland forest inventory.

Total number of sample plots in Yale Forest	35
Number of plots accepted as within the population of older, undisturbed forest on upland sites:	25
Number of accepted plots with red oak in the *association* (defined in text):	22
Number of accepted plots with red oak and red maple *in association*:	21
Number of accepted plots with red oak and black birch *in association*:	13
Number of accepted plots with red oak, red maple, and black birch *in association*:	12
Total number of *interactions* (defined in text) between red oak and red maple:	50
Number of times red oak *subordinated* or *overtopped* (defined in text) red maple in these interactions:	50
Number of times red maple *subordinated* or *overtopped* red oak in these interactions:	0
Probability that this pattern of stratification is a random phenomenon is negligible.	
Total number of *interactions* between red oak and black birch:	31
Number of times red oak *subordinated* or *overtopped* black birch in these interactions:	30
Number of times black birch *subordinated* or *overtopped* red oak in these interactions:	1
Probability that this pattern of stratification is a random phenomenon is negligible.	
Total number of sample red oaks found in C- or D-strata	7
Number of times red oak in the intermediate or overtopped class was not *subordinated* by or *overtopped* by another red oak:	6
Number of times red oak was *subordinated* by or *overtopped* by another species:	1

The red oak and red maple interacted on 16 plots with a total of 50 interactions (Table 2.4). Red oak subordinated or overtopped the red maple in all 50 interactions. The probability that the red oak might be above the red maple in all 50 instances as a matter of chance is infinitesimally small. Hence, there is reason to believe there is a pattern to the interaction of these two species in such stands. Similarly there is reason to believe there is a pattern to the interaction between red oak and black birch (Table 2.4) since red oak was above black birch in 30 of 31 interactions.

APPENDIX 3

B-stratum Red Oak Ages and Growth

Appendix 3A. B-stratum red oaks sampled from Stands I, II, and III

The red oak trees measured from Stands I, II, and III were chosen by the author walking through the stands and selecting trees from the upper continuous canopy. No other pattern was intended in the selection of these individuals except that the author was aware of attempting to maintain a distribution of trees throughout the stand with a broad distribution of diameters. The parameters of each stand which are estimated from the sample are age and diameter growth pattern. Since a well distributed range of diameters was selected from throughout the stands and there is no relation between diameter and age within these samples (Table 3.1), there is no reason to believe the sample was biased for the purposes of the present study — the investigation of growth rate and age distribution of dominant red oaks. Figure 3.1 shows that for each of the three stands, an approach to a normal distribution of diameters was achieved in the sample.

A total of 63 red oak trees were cored at 4.5 feet (1.4 meters) with an increment borer to determine diameter growth and age patterns (Table 3.1). The most intensive sample was taken of Stand I. As the age and diamter growth patterns became apparent, progressively less intensive samples were taken of Stands II and III.

Because of its eccentric growth pattern (Sorenson and Wilson, 1964), the piths were not reached on 28 of the trees even after repeated corings

(Table 3.1). The trees which were cored to the pith were aged at 4.5 feet (1.4 meters) by counting the annual xylem rings. For those trees which were cored to the center, a regression analysis of diameter to age (at 4.5 feet; 1.4 meters) showed there is no meaningful relation between these ages and diameters ($r^2 = 0.008$).

Table 3.1

Stand #	Total # trees samples	# trees where pith was reached	# trees where pith was not reached
I	34	16	18
II	18	13	5
III	11	6	5
Total	63	35	28

An estimate of the sample size for each stand can be made as follows: The area studied of each of the three stands was found using the Yale Forest map (Meyer and Plusnin, 1945). Knowing the diameter of each tree, the portion of an acre of a dominant tree of this size occupied was obtained from Chapter 7. The sum of the portions of an acre occupied for each tree of a stand divided by the number of acres in each stand gave the following sampling percentages for the three stands (Table 3.2).

Table 3.2

Stand #	Total # acres/stand	Sample where pith was reached		All trees sampled	
		#acres	%sample	#acres	%sample
I	6.8	0.18	2.7	0.39	5.7
II	11.4	0.16	1.4	0.22	1.9
III	10.0	0.07	0.7	0.09	0.9

Analysis of variance showed that, based on the samples taken, Stands I, II, and III contained dominant red oaks which have diameters and ages whose means are not significantly different (5 percent level of significance). This proved true for the diameters of all trees measured and for the subsample of those where the pith was reached. For studying diameter growth and age measures, therefore, all three stands are considered to be in the same population.

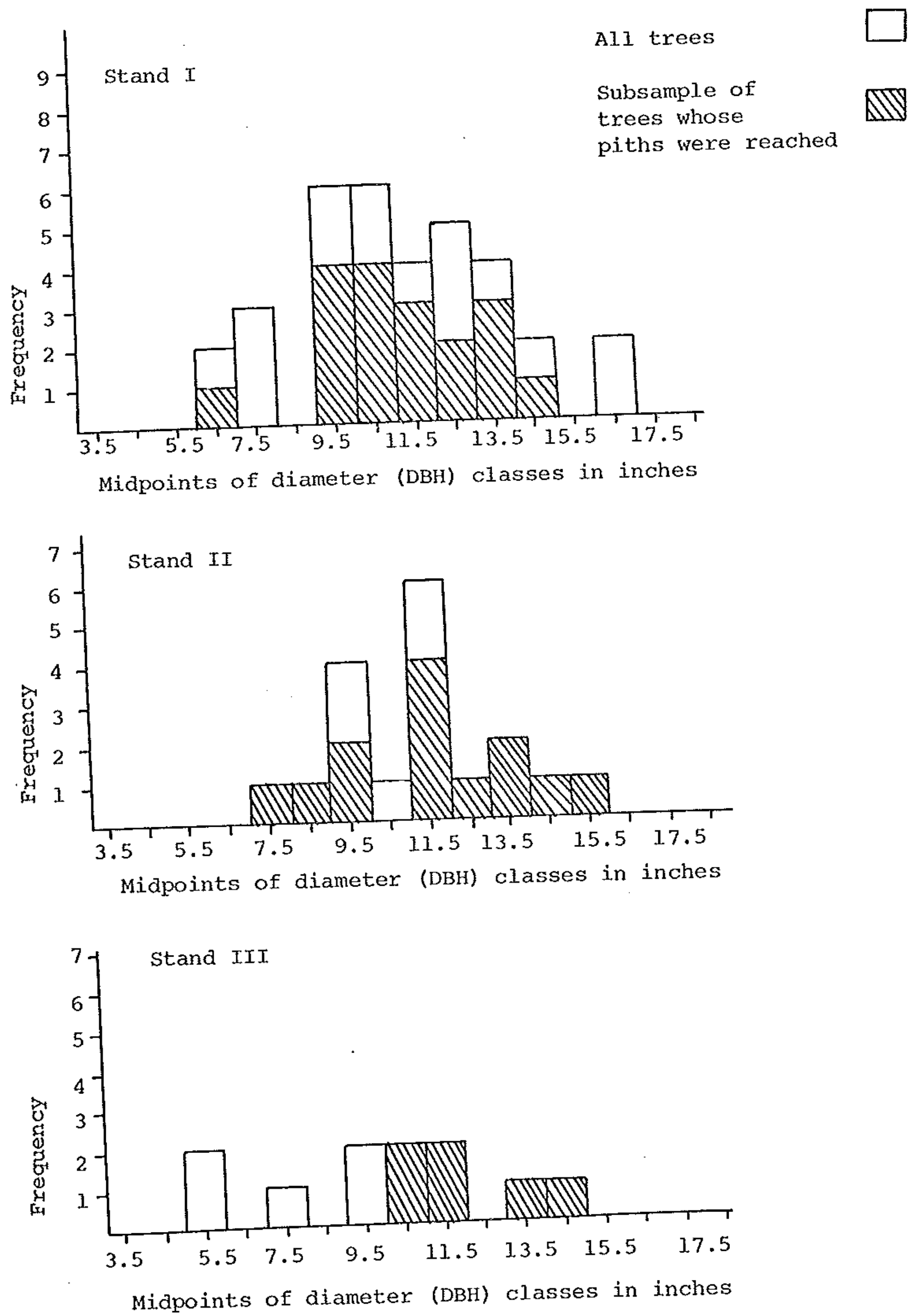


Figure 3.1: Histograms of diameter distributions of sampled B-stratum northern red oaks.

Appendix 3B. B-stratum red oaks studied

On Table 3.3 are listed the B-stratum red oaks aged by coring to their centers at 4.5 feet (1.4 meters) throughout the course of this study. Also listed are their diameters and heights at 50 years (where obtained); the casue of origin of the present stands; and, where documented by natural history evidence, the time of origin of each stand. The trees of stands I, II, and III were a sample (Appendix 3A) to determine the pattern of red oak growth. The trees of Stands IV and VII were selected as having growth characteristics and associated species similar to those of Stands I, II, and III (Appendix 3C); hence, these trees were assumed to represent trees at a later stage of a similar line of development as the trees of Stands I, II, and III. Plots in Stands V and VI were selected as random one-fiftieth acre plots within younger stands which appeared to represent younger stages of stands developing similar to the previously mentioned, older stands. The dominant red oaks of these younger stands also showed growth patterns similar to those of the older stands (Appendix 3C).

Table 3.3: Ages and diameters at 4.5 feet (1.4 meters) of B-stratum red oaks of stands studied

Stand #	Origin of Present Stand	Documented Age (Yr.)	Ht. of Selected Individuals at 50 yr.	Tree #	Years of Age at 4.5 ft. [1.4 m]	DBH	Plot # where Intensively Studied
I	regeneration after stand of old field white pine was clearcut	60 - 65		1	52	12.3	
				3	58	13.2	
			59	5	58	11.3	I-1
				7	62	11.5	
				9	51	10.5	
				11	61	9.7	
				15	60	13.2	
				21	61	11.5	
			59	22	59	10.6	I-2
				23	61	14.6	
				25	61	13.7	
				28	60	12.6	
				51	62	6.9	
				54	60	9.1	
				55	62	10.2	
				58	61	9.7	
	Mean				59.3	11.3	
	Best est. of std. dev. of pop.				3.41	1.97	
II	regeneration after stand of old field white pine was clearcut	undocumented		1	59	11.9	
				2	58	14.3	
			66	4	60	13.9	II-1
				5	58	11.4	
				7	58	8.8	
			63	8	57	12.7	II-2
				10	57	14.9	
				11	58	11.2	
				12	56	9.7	
				13	59	11.1	
				14	61	9.5	
				18	58	13.6	
				19	59	7.8	
	Mean				58.3	11.6	
	Best est. of std. dev. of pop.				1.32	2.23	

Table 3.3 continued.

Table 3.3 continued:

Stand #	Origin of Present Stand	Documented Age (Yr.)	Ht. of Selected Individuals at 50 yr.	Tree #	Years of Age at 4.5 ft. [1.4 m]	DBH	Plot # where Intensively Studied
III	regeneration after stand of old field white pine was clearcut	57 - 62	63	1	59	14.0	III-1
			65	11	57	10.4	III-2
			64	21	58	11.8	III-3
				31	59	13.3	
				3	56	10.2	
				6	57	11.7	
	Mean				57.7	11.9	
	Best est. of std. dev. of pop.				1.21	1.5205	
IV	regeneration after stand of old field white pine was clearcut	74 - 78	66	1	69	14.3	IV-1
			64	2	68	14.5	IV-2
			56	3	71	13.0	IV-3
	Mean				69.3	13.9	
	Best est. of std. dev. of pop.				1.53	.81	
V	regeneration after stand of old field white pine was clearcut	undocumented		51	38	4.7	V-1
				81	41	7.3	V-1
				151	42	7.9	V-1
				82	43	7.2	V-2
				102	44	7.6	V-2
				152	39	6.9	V-2
	Mean				41.2	6.93	
	Best est. of std. dev. of pop.				2.31	1.13	
VI	regeneration after stand of old field white pine was blown down in 1938 hurricane	33		1	29	6.2	VI-1
				23	23	4.0	VI-1
				25	28	5.5	VI-1
				28	29	4.9	VI-1
	Mean				27.25	5.15	
	Best est. of std. dev. of pop.				2.86	.92	

Table 3.3 continued.

Table 3.3 continued:

Stand #	Origin of Present Stand	Documented Age (Yr.)	Ht. of Selected Individuals at 50 yr.	Tree #	Years of Age at 4.5 ft. [1.4 m]	DBH	Plot # where Intensively Studied
VI	regeneration after patch clearcuttings for fuelwood	undocumented		15	104	19.2	VII-1
				1'	106	16.8 *	
				2'	106	20.3 *	
				4'	101	16.5 *	
				6'	116	18.7 *	
	Mean				106.6	18.3	
	Best. est. of std. dev. of pop.				5.59	1.60	

*Data taken from Harvard Forest Records (TSI Tract, Harvard Forest, Petersham, MA). Diameters are as of January 1973.

Appendix 3C. Growth patterns of B-stratum red oaks

Samples of the B-stratum northern red oaks from Stands I, II, and III were cored at 4.5 feet (1.4 meters) with an increment borer to determine their growth patterns (Appendix 3A). Annual diameter growth of each tree cored was approximated by measuring the width of each growth ring. At first, each tree was cored at 4.5 feet (1.4 meters) 180 degrees apart. Since there seemed to be little difference in the growth patterns as shown by the two cores from the same tree, later only one core was taken from each tree. The side cored was selected as not being beneath one large lower branch and not on either the upper or lower face of a sweep in the bole.

Where the core did not pierce the center of the tree, ring width was measured along the xylem ray. The distance which the center was missed was estimated by subtracting the sum of the ring widths found in this way from the length of the increment from the cambium to the point where the xylem rays are perpendicular to the long axis of the increment core — where the axis is tangential to the growth rings. For each of two diameter growth patterns observed (as discussed later) there was no significant difference (5 percent level of significance) in the means of the growth rates before 1938 of trees which were cored to the center and trees which the increment borer did not pierce the pith and whose growth was estimated from the rings measured.

Diameter outside of the bark for northern red oak was obtained from diameter inside the bark by the empirical formula (calculated in millimeters):

$$DOB = 1.282\ (DIB)^{.968}$$

$(r^2 = 0.999$; see Appendix 7)

Two distinct growth patterns were observed from graphs of the annual diameter growth rates of 63 dominant red oaks cored in Stands I, II, and III (mean age 58.7).

1. An abrupt increase in diameter growth beginning in or shortly after 1939.

2. No abrupt increase in diameter growth in or shortly after 1939.

Examples of the annual diameter and basal area growth patterns for the two groups are shown in Figure 3.2.

Of the 15 trees which showed an abrupt increase in growth after 1938, remnants of a tree blown down in the hurricane of September 21, 1938 (Appendix 2) were found very close to 14 of them. This indicates that the hurricane probably caused a release of the trees from nearby competitors, creating the upsurge in diameter growth. It is possible that the fifteenth tree was released by a competing tree's being blown down, and this blowdown was not detected; or it is possible that the hurricane damaged the adjacent trees but did not actually blow the trees over.

Immediately after the 1938 hurricane, a period of one to several years was observed (Table 3.4B) during which the annual diameter growth of the released trees was less than the mean growth of the tree from 1943 to 1971. This was probably caused by the tree's becoming adjusted to its less competitive condition, and possibly by its recovering from damage done to its crown by the hurricane. The average duration of this growth lag was 1.3 years.

Trees not showing a sudden increase in growth after 1939 were grouped together. This group included trees with a variety of diameter growth patterns from gradually accelerating to gradually decelerating, as can be seen in Table 3.4A.

Several diameter growth parameters (as defined below) were calculated for both the released and unreleased B-stratum red oaks. Average annual diameter outside bark growth rates, referred to hereafter as "mean total growth", were obtained for each red oak cored. The diameter growth for each tree was also divided into two periods of growth: the period before 1939, a time of 26 years for the trees of mean age of Stands I, II, and III; and the period from 1943 through 1971, a time of 29 years. The average annual diameter (outside bark) increment for each period will be referred to henceforward as "early growth" and "late growth", respectively. The ratio of late growth to early growth was found and is referred to as the "late:early ratio".

The purpose of dividing the diameter growth into the two periods was twofold. It allowed the comparison of diameter growth rates of trees released and not released by the 1938 hurricane by dividing the periods to coincide with pre- and post-hurricane growth. It also allowed the comparison of growth of unreleased trees during their first 25 to 30 years with the growth during the next approximately equal time period.

There was, as expected, a highly significant difference in the means of the late/early growth ratios between the released and not released trees.

Seven red oaks from the sample of dominant red oaks of Stands I, II, and III were selected for more intensive study on the basis of the composition of the associated understory. The selected red oaks were:

Stand	Tree	Plot
I	5	I-1
I	22	I-2
II	4	II-1
II	8	II-2
III	1	III-1
III	2	III-2
III	3	III-3

The trees selected all proved to have growth values near the center of the distribution of values of the various diameter growth characteristics. Figure 3.3 shows the distribution of ages and diameters of the dominant red oaks cored to the center in Stands I, II, and III. If the population from which these values are a sample approaches a normal distribution in age and diameter (and Figures 3.6A and 3.6B suggest they do), both the ages and diameters of the seven selected trees were within a central area containing 80 percent ($z = 1.28$) of the values of the population. Similarly, these oak trees had values of early growth, late growth, mean total growth, and late:early ratio also within a value of 1.28 standard deviations of the mean of all unreleased dominant red oaks sampled from the three stands. Figures 3.6C through 3.6F show histograms of the growth characteristics, and Figures 3.3, 3.4, and 3.5 show the relative distributions of the seven selected oaks.

As the study was extended to younger and older stands with similar canopy arrangements, origin, and species associations, the growth rates of some of the B-stratum red oaks from these stands were measured. With one exception — the center red oak of Plot IV-3 — the trees selected for more intensive study showed no release by the 1938 hurricane. As an added test to see if these older and younger stands acutally were similar in development to Stands I, II, and III, the diameter growth patterns of the dominant red oaks studied were adjusted to represent similar developmental periods as those of the red oaks of the three 60-year-old stands. Thus mean annual diameter (outside bark) growth of a selected tree for its first 26 years was considered "early growth"; growth between the ages of 30 and 59 [mean age at 4.5 feet (1.4 meters) of red oaks sampled of Stands I, II, and III] was considered "late growth". Mean annual growth and the late:early growth ratio were calculated similarly. Where a tree was less than 59 years old the growth measurement was obtained from that part of the period contained within the tree. These growth characteristics are listed in Table 3.4C and plotted on Figures 3.3 through 3.5.

As can be seen from Table 3.4 and Figures 3.3 through 3.5, the growth characteristics were very similar to those of the trees of Stands I, II, and III. All derived diameters at adjusted ages, early growth rates, late growth rates, mean annual growth rates, and late: early ratios were within 1.96 standard deviations (the 5 percent confidence interval) of the same values of the trees of the original three stands; and, with two exceptions, all were within the 20 percent confidence interval (1.28 standard deviations). This gives further justification to the assumption that these older and younger stands represent later and earlier stages of the same pattern of succession.

Table 3.4A: Growth rates of B-stratum red oaks in 60-year-old stands not released in 1938.

Stand #	Tree #	DBH	Dist. Missed (in.)	# Rings Cored	Av. DOB Gro./Yr. annually	Av. DOB Gro./Yr. before 1939	Av. DOB Gro./Yr. 1943-71	Growth after / before	Trees in More Intense Plots
I	1	12.3	0	52	.24	.27	.21	.78	
	5	11.3	0	58	.20	.22	.16	.73	I-1
	15	13.2	0	60	.22	.24	.19	.79	
	21	11.5	0	61	.19	.21	.16	.76	I-2
	22	10.6	0	59	.18	.22	.14	.64	
	23	14.6	0	61	.24	.25	.23	.92	
	25	13.7	0	61	.23	.22	.22	1.00	
	28	12.6	0	60	.21	.24	.17	.71	
	54	9.1	0	60	.15	.10	.20	2.00	
	55	10.2	0	62	.16	.21	.11	.52	
	58	9.7	0	61	.16	.18	.13	.72	
	902	12.8	.69	56	.20	.19	.20	1.04	
	904	11.9	.33	59	.19	.18	.19	1.04	
	913	14.3	.14	57	.24	.30	.19	.64	
	914	13.4	.16	60	.22	.25	.17	.68	
	919	10.9	.59	55	.17	.23	.13	.56	
	920	16.4	.47	57	.27	.31	.23	.74	
	924	10.8	.68	59	.16	.20	.12	.59	
	926	9.7	.15	60	.16	.19	.12	.61	
	927	12.6	.35	58	.20	.23	.18	.77	
	956	6.2	.39	56	.09	.13	.07	.51	
	957	9.0	.76	55	.13	.16	.10	.66	
	960	7.7	.18	59	.12	.16	.08	.50	
II	2	14.4	0	58	.25	.27	.22	.81	
	5	11.4	0	58	.20	.21	.16	.76	
	7	8.8	0	58	.15	.17	.12	.71	
	10	15.0	0	57	.26	.32	.20	.62	
	12	9.7	0	56	.17	.27	.10	.37	
	13	11.1	0	59	.19	.22	.14	.64	
	18	13.6	0	58	.23	.29	.17	.59	
	4	13.9	0	60	.23	.26	.20	.77	II-1
	8	12.7	0	57	.22	.26	.19	.73	II-2
	17	11.2	0	58	.19	.21	.18	.86	
	14	9.5	0	61	.16	.16	.14	.88	
	19	7.8	0	59	.13	.16	.11	.69	
	903	10.9	.27	53	.19	.21	.17	.81	
	909	11.2	.57	52	.19	.26	.14	.54	
	916	9.4	.16	58	.16	.18	.13	.72	
	917	9.9	.08	57	.17	.20	.14	.70	
	920	11.4	.57	53	.19	.25	.16	.64	

Table 3.4A continued.

Table 3.4A continued:

Stand #	Tree #	DBH	Dist. Missed (in.)	# Rings Cored	Av. DOB Gro./Yr. annually	before 1939	1943-71	Growth after / before	Trees in More Intense Plots
III	1	14.0	0	59	.24	.24	.23	.96	
	11	10.4	0	57	.18	.20	.16	.80	III-1
	21	11.8	0	58	.20	.23	.18	.78	III-2
	31	13.3	0	59	.23	.27	.18	.67	III-3
	3	10.2	0	56	.18	.19	.17	.89	
	6	11.7	0	57	.21	.18	.21	1.17	
	902	5.1	.20	51	.09	.12	.07	.59	
	907	9.4	.61	55	.15	.20	.09	.46	
Mean		11.30			.1894	.2171	.1596	.7514	

Table 3.4B: Growth rates of B-stratum red oaks in 60-year-old stands released in 1938.

Stand #	Tree #	DBH	Dist. Missed (in.)	# Rings Cored	Av. DOB Gro./Yr. annually	before 1939	1943-71	Growth after / before	# Yr. After 1938 Gro. Below Av. 1943-71
I	3	13.2	0	58	.23	.20	.24	1.20	1
	7	11.5	0	62	.19	.17	.17	1.00	0
	9	10.5	0	51	.21	.18	.21	1.17	1
	11	9.7	0	61	.16	.12	.18	1.50	1
	51	6.9	0	62	.11	.07	.137	1.96	2
	906	12.9	.51	55	.21	.20	.20	1.01	0
	908	9.7	.35	57	.16	.09	.19	2.11	1
	916	16.1	.77	56	.26	.26	.23	.87	1
	953	10.1	.26	59	.16	.07	.22	3.02	2
	959	7.0	.18	56	.12	.11	.11	1.03	0
	961	9.7	.60	46	.18	.07	.22	3.27	3
II	1	11.9	0	59	.20	.11	.28	2.55	1
III	904	5.8	.12	56	.10	.09	.09	.98	0
	908	9.6	.52	51	.16	.06	.20	3.13	0
	909	7.8	.15	50	.15	.05	.19	3.55	7
Mean		10.9			.173	.124	.191	1.267	1.33

Table 3.4C: Growth rates of B-stratum red oaks in stands older and younger than 60 years.

Stand #	Tree #	DBH*	Dist. Missed (in.)	Age at DBH	Av. DOB Gro./Yr. first 59 yr.*	Av. DOB Gro./Yr. first 26 yr.**	Av. DOB Gro./Yr. age 30*** to present	Growth Ratio late/early	Plot # where Intensively Studied
UNRELEASED TREES									
IV	1	12.78	0	59	.2166	.2044	.2200	1.0766	IV-1
	2	12.51	0	59	.2158	.2006	.2123	1.0587	IV-2
V	51	4.71	0	38	.1241	.1329	.0963	.7242	V-1
	81	7.31	0	41	.1782	.2022	.1340	.6630	V-1
	151	7.91	0	42	.1883	.2136	.1417	.6634	V-1
	82	7.25	0	43	.1685	.2090	.0991	.4740	V-2
	102	7.57	0	44	.1722	.2179	.1382	.6343	V-2
	142	6.88	0	39	.1764	.1881	.1379	.7335	V-2
VI	1	6.21	0	27	.2298	.2347			VI-1
	23	3.95	0	23	.1718	.1718			VI-1
	25	5.53	0	28	.1975	.1975			VI-1
	28	4.8593	0	29	.1676	.1676			VI-1
VII	1	11.90	0	59	.2017	.2587	.1391	.5376	VII-1

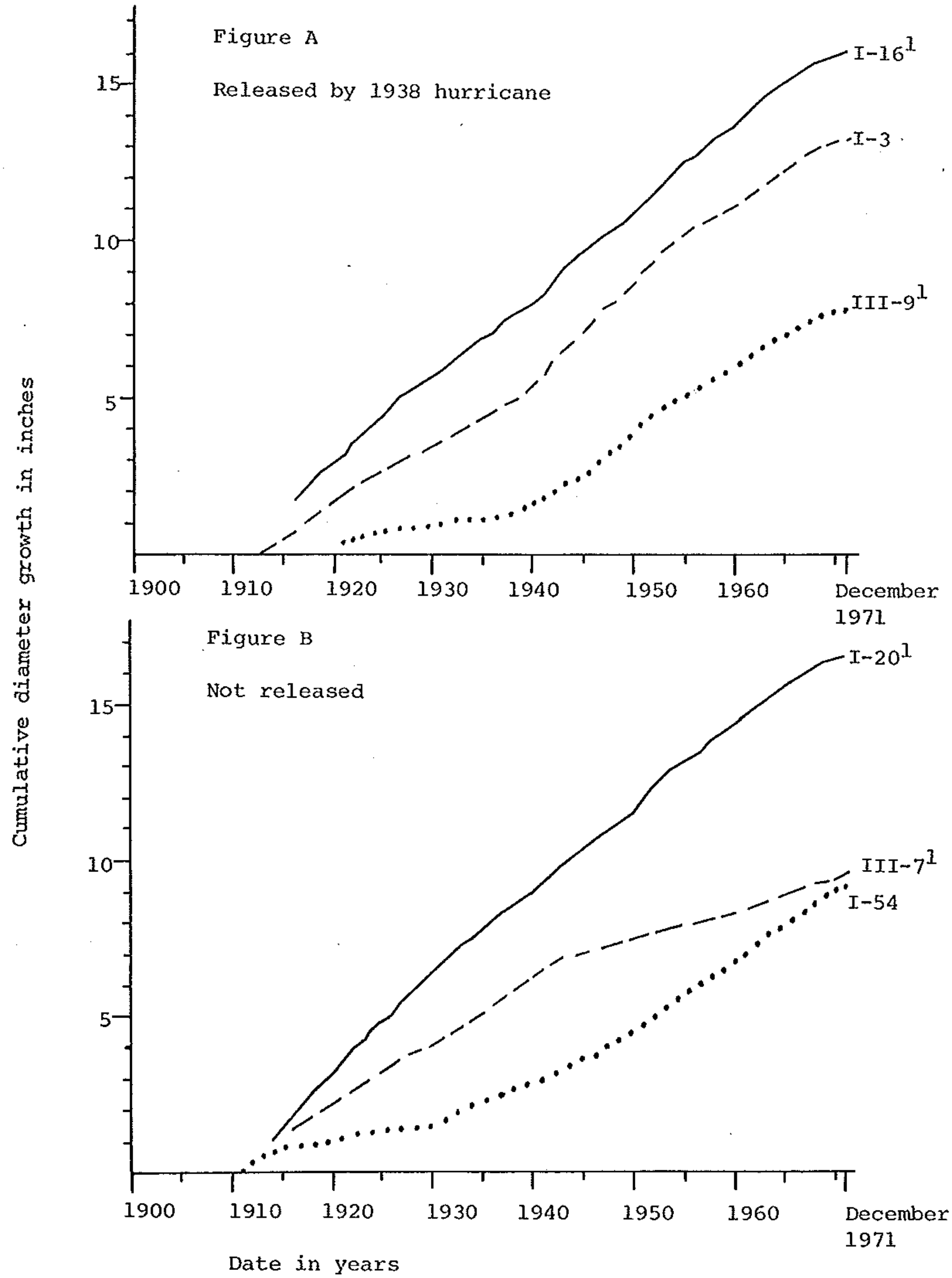
Stand #	Tree #	DBH*	Dist. Missed (in.)	Age at DBH	first 59 yr.*	first 26 yr.**	Average Growth Before Release	Average Growth After Release	Plot # where Intensively Studied
RELEASED TREE									
IV	3	10.60	0	59	.1797	.1220	.1234	.2625	IV-3

*For age or 59 years (whichever comes first).

** Equivalent of growth before 1939 for trees of original stand.

***Age 30 to present age or 59 years (equivalent of growth from 1943-71 for trees of original stand.

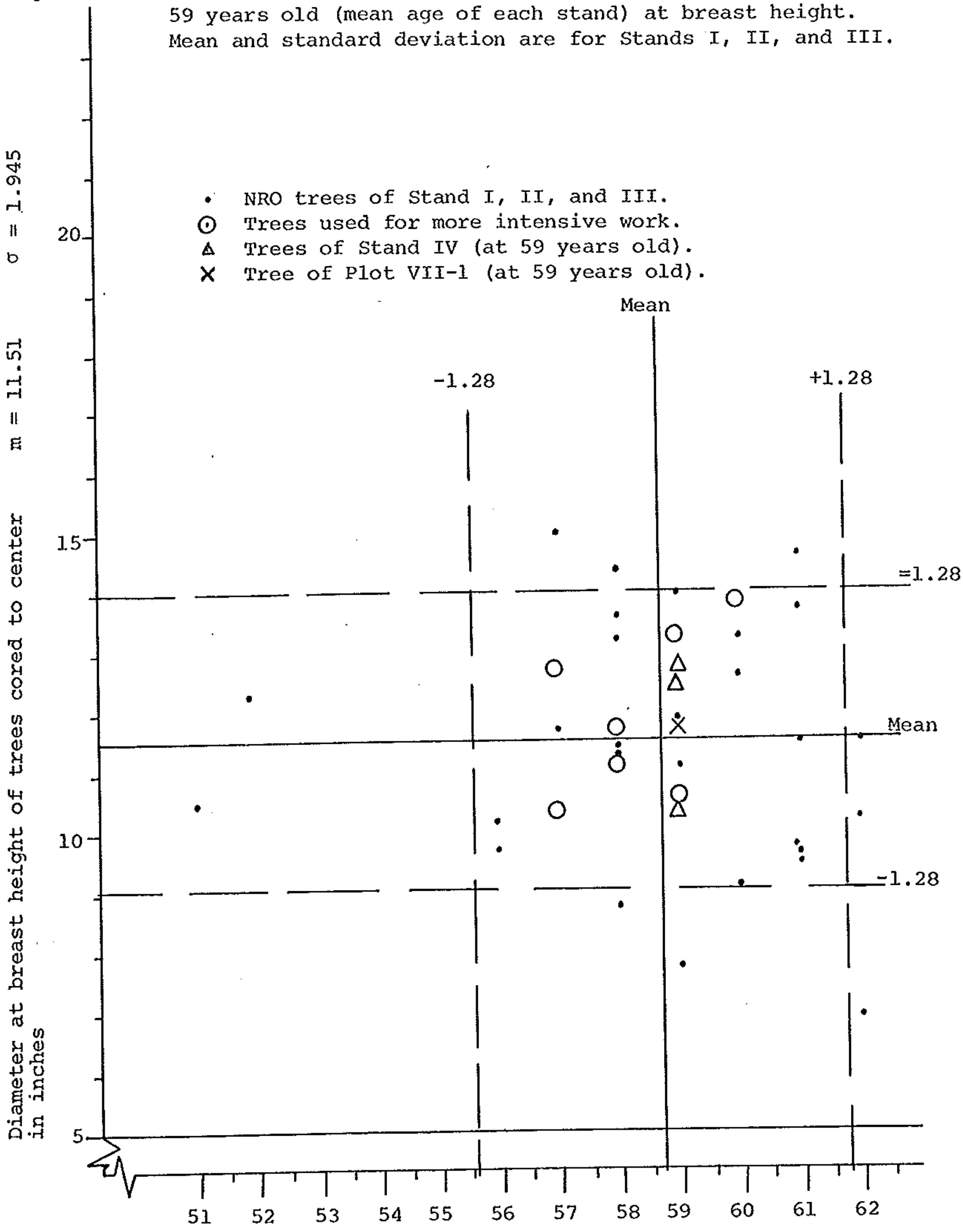
Figure 3.2: Cumulative diameter growth outside bark of representative released (A) and unreleased (B) trees.



---

[1] Trees not cored to center.

Figure 3.3: Relation of diameter to age of B-stratum red oaks at 59 years old (mean age of each stand) at breast height. Mean and standard deviation are for Stands I, II, and III.



Age of trees cored to center [all older and younger trees (Stands IV and VII) were plotted at mean age of 59 years]
m = 58.66 σ = 2.425

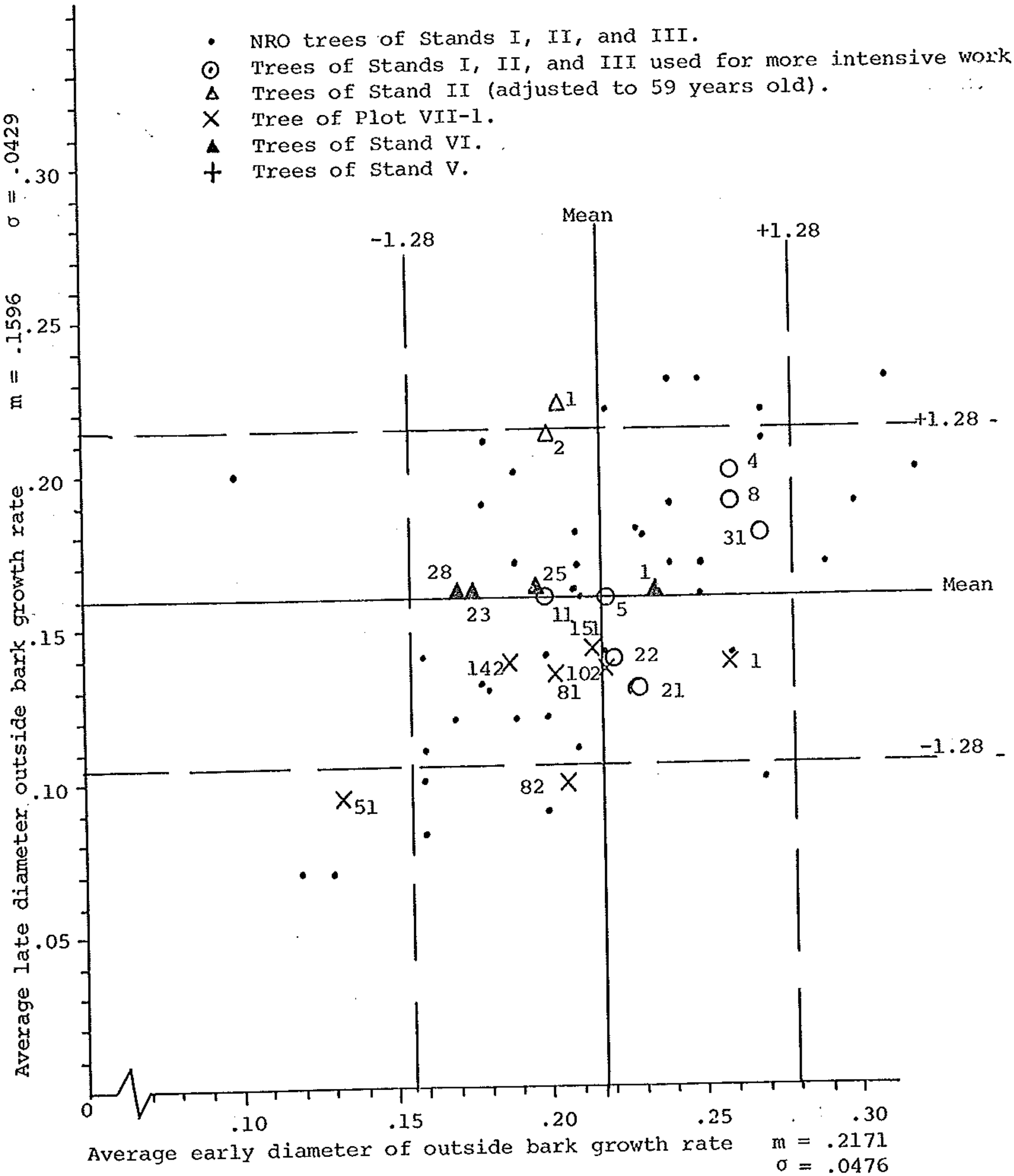
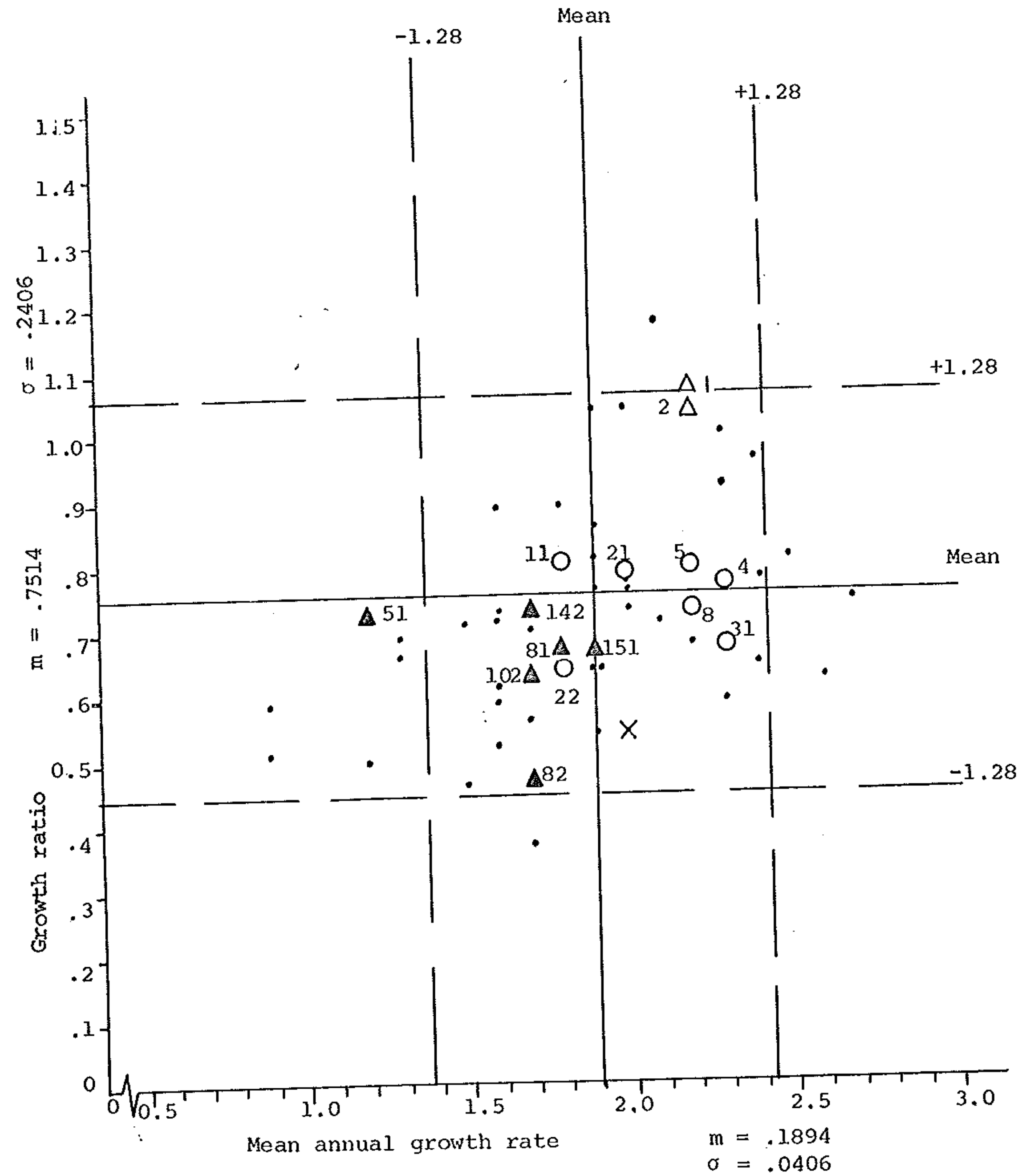


Figure 3.4: Relation of "early" growth to "late" growth of B-stratum red oaks at 59 years old (mean age of each stand at breast height. Mean and standard deviation are for Stand I, II, and III. Where "late" growth was not obtained (Stand VI) "mean total growth" was substituted.

Figure 3.5: Relation of mean annual growth to "late:early ratio" (see text) of B-stratum red oaks at 59 years old (mean age of each stand) at breast height. Mean and standard deviations are for Stands I, II, and III.



- • NRO trees of Stands I, II, and III.
- ⊙ Trees of Stand I, II, and III used for more intensive work.
- Δ Trees of Stand IV (adjusted to 59 years).
- X Tree of Plot VII-1.
- ▲ Trees of Stand V.

Figure 3.6 A: Histogram of distribution of ages of B-stratum northern red oaks cored to the center in Stands I, II, and III.

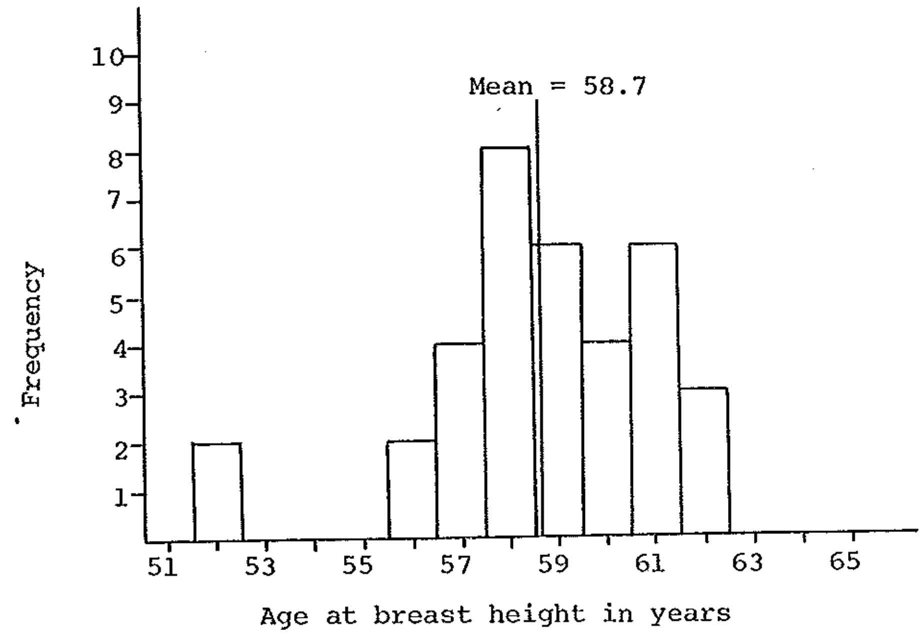


Figure 3.6 B: Histogram of distribution of diameters by classes of B-stratum northern red oaks cored to the center in Stands I, II, and III.

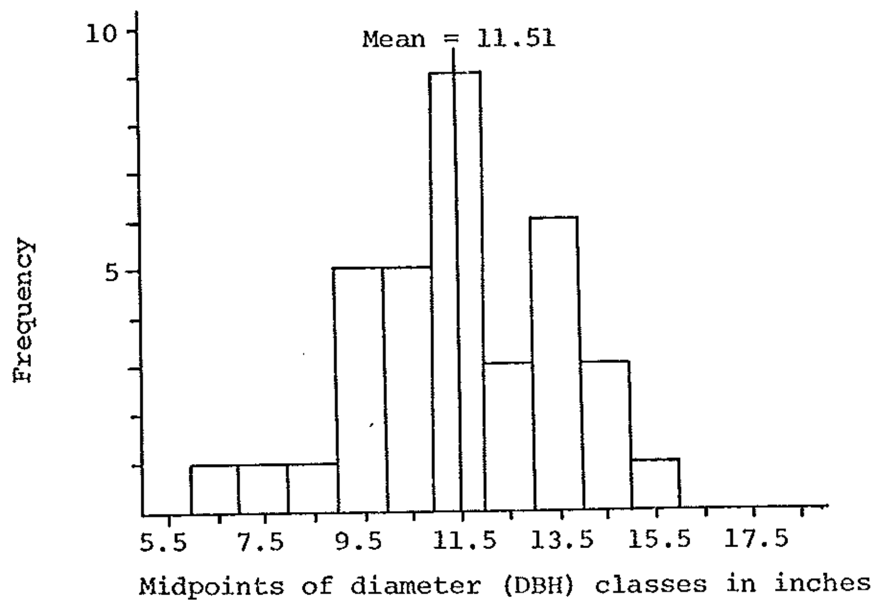


Figure 3.6 C: Histogram of "early" diameter growth rates (outside bark) of B-stratum northern red oaks of Stands I, II, and III.

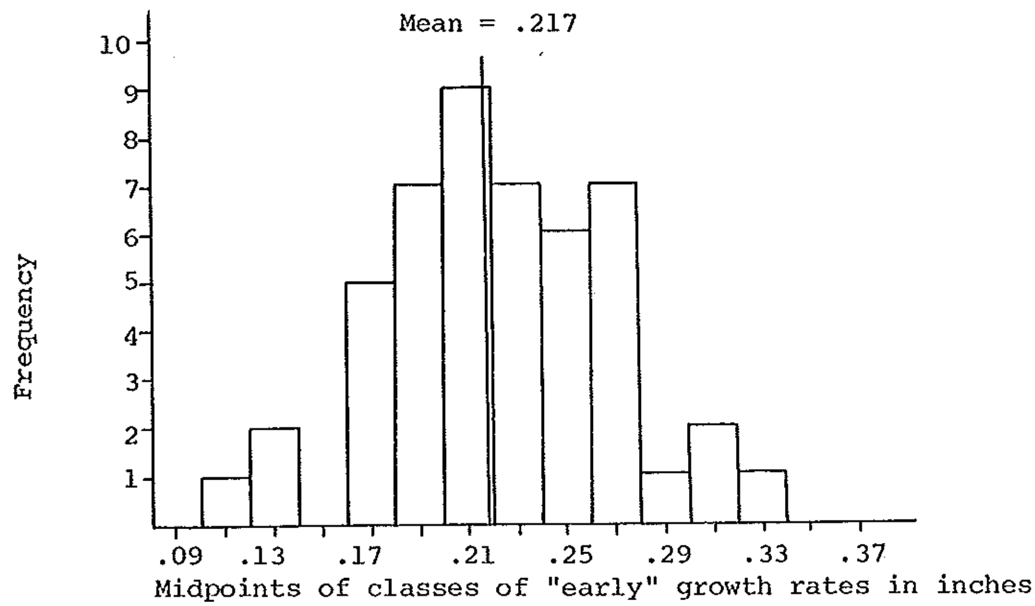
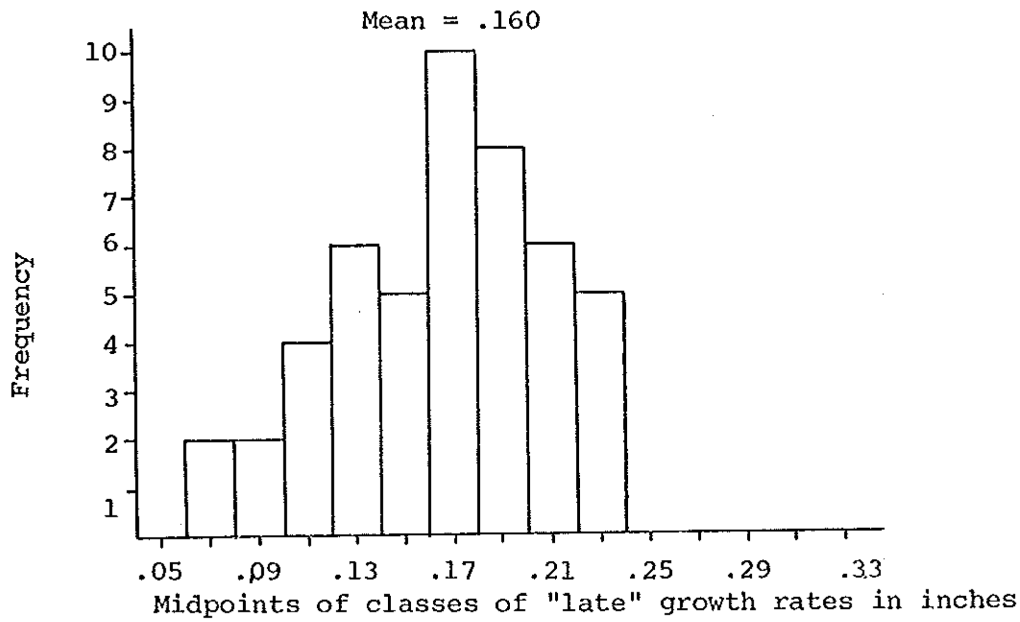


Figure 3.6 D: Histogram of "late" diameter growth rates (outside bark) of B-stratum northern red oaks of Stands I, II, and III.



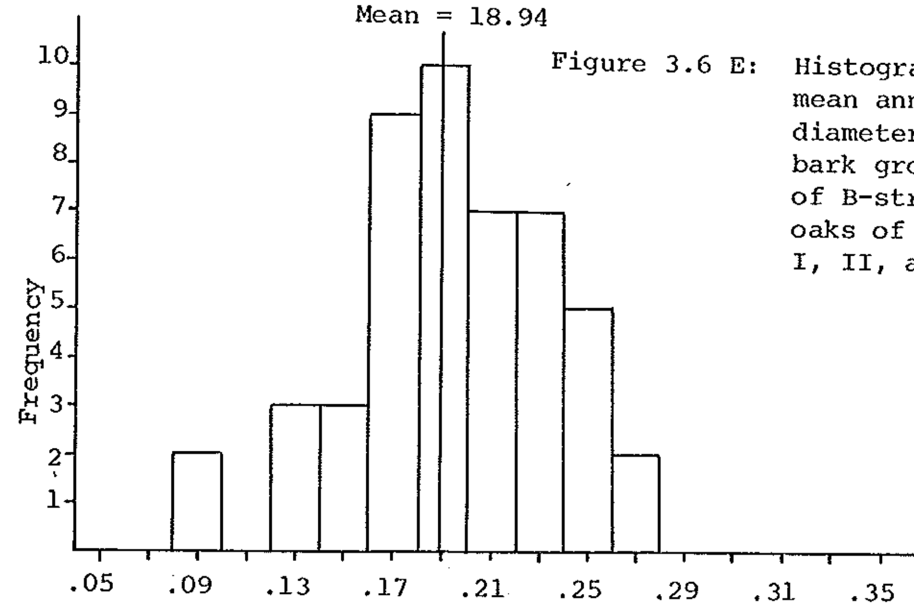


Figure 3.6 E: Histogram of mean annual diameter outside bark growth rates of B-stratum red oaks of Stands I, II, and III.

Midpoints of mean annual diameter growth (outside of bark) classes of B-stratum northern red oaks cored in Stands I, II, and III.

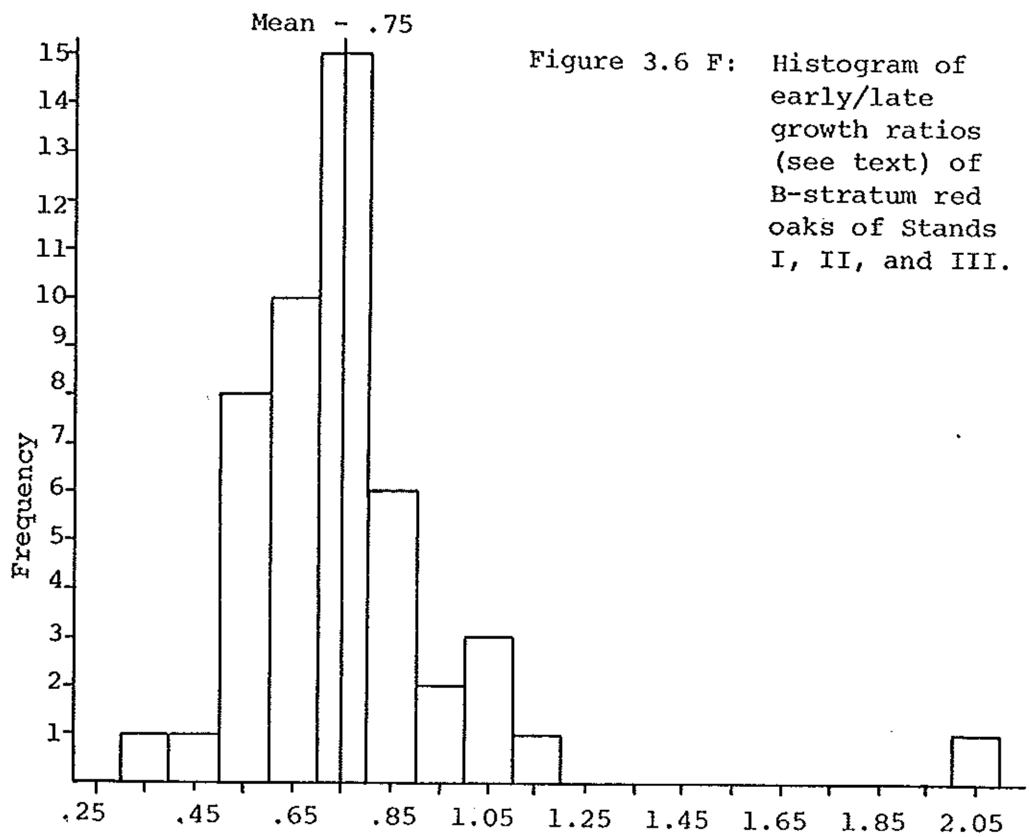


Figure 3.6 F: Histogram of early/late growth ratios (see text) of B-stratum red oaks of Stands I, II, and III.

Midpoints of late/early growth ratio classes (see text for details)

APPENDIX 4

Ages of Trees Studied in the 14 Plots

Appendix 4A: Obtaining sections for aging.

In the intensive study of B-stratum red oaks and their associated species on the 14 plots of this study, the relative location, diameter growth pattern at 4.5 feet (1.4 meters), and age at one foot was investigated for all trees within each sample plot. The position of the base of each tree was located on a horizontal plane with a compass and tape measure or with a surveyor's transit and steel tape, depending on the degree of accuracy desired. Each tree was marked (on the east side) with tacks and tags at one foot and 4.5 feet. Sections perpendicular to the long axis of the stem at each marked section were cut and collected. After preparation, the age and radial growth rate was determined for each section (as described more fully in Appendix 4B).

For selected individuals, knowledge of the vertical relationships of the trees through time was desired as well. Before falling, the vertical position of significant branches and forks of these trees were found with an altimeter or with a surveyor's transit. After it had been felled, the stems and noted branches and forks were marked every four feet (beginning at eight feet) up the stem in addition to the marks at one foot and 4.5 feet. Here, too, sections perpendicular to the long axis at these points were cut, prepared, and measured for age and diameter growth rate. A height-age curve was reconstructed for each tree by plotting the height of the section studied on the vertical axis and its age on the horizontal axis. These height-age curves may be seen in Appendix 5.

Also from these measures, relative growth through time could be reconstructed, as shown in Chapter 2. For reconstruction of the crown development of the B-stratum red oak of Plot I-2c, each branch and fork was mapped by triangulation with a transit. After the tree was felled, these branches and forks and supplementary positions at known distances between the points noted before felling were tagged. All sections were cut and aged at all marked positions. By reconstructing the tree in both horizontal and vertical two-dimensional maps from these points and putting ages at the known points, the growth patterns of the presently living branches were reconstructed.

Appendix 4B: Determining tree ages

Age was determined, with adjustments as described below, by counting the number of annual rings in each disk. For ring porous hardwoods the rings were most easily counted by using a dissecting scope. Except for occasional razor cuttings, no refinishing of the section surfaces was required after their initial cut with a chain saw. Conifer and diffuse porous hardwood sections were prepared by sanding with progressively finer sandpaper (and steel wool where necessary). A dissecting scope was used to locate and mark annual rings for later measurement. Where necessary, petroleum jelly was used to make the rings more visible. Safranin or fast green did not readily prove helpful in making the rings more visible. The width of each annual ring was then recorded by measuring each ring along an average radius using an Addo-X tree ring counter. Cumulative diameter growth of selected trees are plotted in Appendix 5.

Larson (1956) and Bormann (1965) have found that rings or parts of rings may disappear upon approaching the basipetal portion of the trunk of suppressed trees. Evidence of the rings or portions of them being very small or disappearing was found in the suppressed diffuse porous trees of the present study. The rings were found to be larger if formed when that portion of the stem was within or close to the living crown. Outer rings, therefore, became wider, more distinct, and more varied in width as they approached the top of the tree.

To determine more accurately the age near the base of the suppressed trees which were sectioned every four feet for their entire height, the following method was developed:

1. For each section measured, the radial width of each annual ring was plotted on the vertical axis; and the number of rings (roughly the age) away from the present cambium was plotted on the horizontal axis (Figure 4.1).

2. Graphs of consecutive sections were placed above the next lower one on parallel horizontal axes, and with the zeroes (cambial ring) of the horizontal axes in a vertical line, as can be seen in Figure 4.1.

3. Beginning with the uppermost section, patterns of large and small annual radial growths were observed. These patterns were traced to the next lower section, where the outer portions were less distinct. Patterns from inside rings not even present in the higher sections were found and traced to the lower sections as the outer patterns became oblivious. The number of years lost in counting because of small or disappeared rings could be traced from the top (where the outer rings were present) through progressively inward patterns. An example of four sections from a tree thus traced is shown in Figure 4.1.

For those stems sectioned only at one foot and 4.5 feet, the ring patterns were compared between the two sections. The ages of these samples were probably slightly less accurately determined, although great care was taken in counting all rings.

Portion of Red Maple #6A, Plot III-2

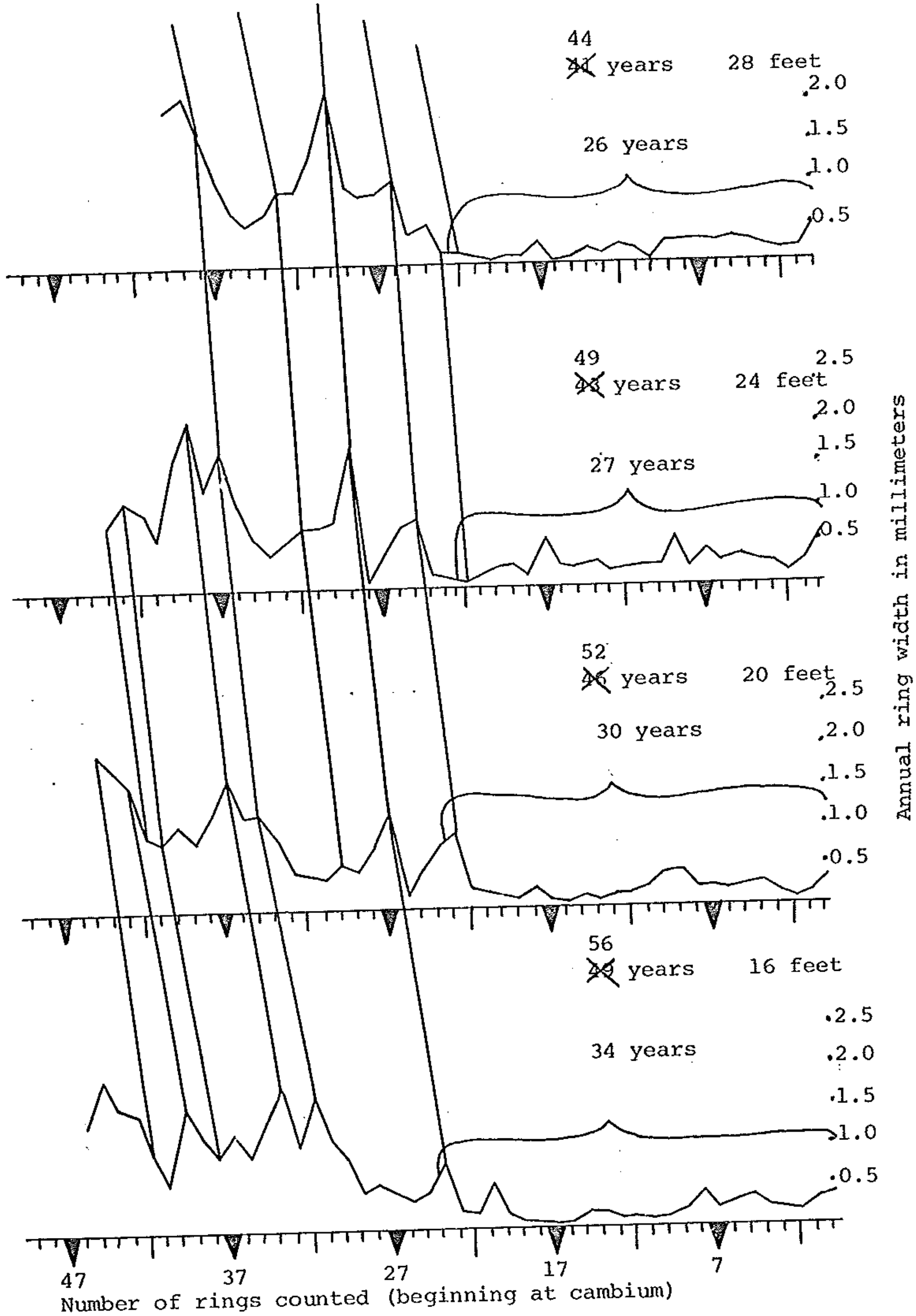


Figure 4.1: Example of method of determining age from sequential sections of a tree stem where lower outer rings may have disappeared or been miscounted because of their small size.

Appendix 4C: Species, diameters, and ages of trees in 14 studied plots

On the following pages are listed all the living trees studied in the original 14 plots (Chapter 2). The plots are listed by stand from youngest to oldest. Each living tree is listed by species, age at one foot and 4.5 feet, diameter at 4.5 feet, and (where obtained) total height.

The trees in extended plots I-1 and I-2 (Chapter 2) are listed in Appendix 6.

Table 4.1: Ages, diameters, species, and heigts (where obtained) of trees studied intensively in 14 plots of seven stands.

Stand #	Plot #	Area (in acres)	Tree #	Species	Age at 4.5 ft.	Age at 1 ft.	DBH	Total Height as of December 1972
I	I-1a	.012	1	NRO	58	64	11.3	65.0
			2	NRO	56	59	6.5	54.0
			11	RMA	59	63	5.0	50.5
			9	RMA	59	61	3.4	42.0
			10	RMA	49	52	3.2	32.8
			4	RMA	39	40	1.7	22.5
			5	RMA	61	64	4.9	48.0
			6	RMA	59	69(70)	5.0	47.0
			8	RMA	56	59	3.5	28.2
			3	BBI	58	60	8.0	45.0
			7	SMA	30	31	1.4	21.5
I	I-2a	.010	7	NRO	59	65	10.6	61.0
			5	RMA	59	59	5.4	47.2
			6	RMA	61	62	3.6	39.0
II	II-1	.019	1	NRO	61	62	13.9	76.2
			6	RMA	57	60	4.2	42.7
			13	RMA	56	59	5.5	52.5
			21	RMA	61	62	6.5	59.0
			22	RMA	11	16	0.5	
			23	RMA	63	63	4.8	
			24	RMA	59	63	5.0	
II	II-2	.011	1	NRO	57	60	12.7	70.0
			10	BOA	55	58	9.5	
			2	RMA	42	46	1.6	21.8
			3	RMA	59	64	4.3	39.0
			9	RMA	57	58	2.5	
			4A	RMA	46	49	1.9	
			5A	RMA	59	64	3.0	
			7	BBI	58	61	6.7	53.0
			6A	BBI	60	62	4.4	38.0
			6B	BBI	57	59	3.6	39.0
III	III-1	.008	1	NRO	57	59	10.4	68.7
			10	RMA	56	58	3.2	
			2	RMA	58	60	3.3	41.7
			3	RMA	57	57	2.8	39.0
			5	RMA	30	33	1.3	
			7	RMA	49	53	1.3	
			9	WGB	57	58	6.8	

Table 4.1 continued.

Table 4.1 continued:

Stand #	Plot #	Area (in acres)	Tree #	Species	Age at 4.5 ft.	Age at 1 ft.	DBH	Total Height as of December 1972
III	III-2	.009	1	NRO	58	59	11.8	73.8
			3A	NRO	58	58	5.7	
			50	BOA	58	59	5.9	
			2	RMA	54	56	2.9	41.0
			7	RMA	57	59	3.0	
			5A	RMA	40	42	1.4	
			6A	RMA	57	58	3.5	45.2
			6B	RMA	42	44	2.5	
			6C	RMA	37	38	2.2	
			6D	RMA	52	53	3.7	
			8A	RMA	50	51	2.3	
III	III-3	.014	1	NRO	59	60	13.3	73.0
			2	BBI	54	57	6.8	53.0
			5	BBI	57	61	6.2	58.0
IV	IV-1		1	NRO	69	72(76)	14.3	78.8
			5	RMA	71	74	6.8	54.0
			2	RMA	60	67	3.0	27.5
			6	BBI	70	73	6.0	52.8
			4	SMA	71	72	3.7	
IV	IV-2		1	NRO	68	71	14.5	76.2
			2	RMA	66	72	6.0	60.1
			3	RMA	48	54	1.6	
			4	RMA	67	71	7.5	51.9
			8	RMA	67	71	4.7	49.5
			12	RMA	73	74	9.4	
			14	RMA	68	74	4.4	50.0
			7	BBI	66	71	9.4	69.7
			11	BBI	69	74	6.2	54.8
			9	SMA	71	76	4.6	
			10	SMA	42	46	0.7	
			12	SMA	24	30	0.6	
			13	SMA	22	22	0.5	
			15	SMA	56	57	1.8	
			5A	SMA	29	50	2.7	
IV	IV-3		1	NRO	71	74	13.0	73.0
			6	RMA	69	77	5.3	59.8
			9A	RMA	76	77(92)	10.3	72.8
			2	RMA	64	68	3.6	
			7	SMA	65	69(73)	5.4	
			8	YBI	64	69	3.3	

Table 4.1 continued.

Table 4.1 continued:

Stand #	Plot #	Area (in acres)	Tree #	Species	Age at 4.5 ft.	Age at 1 ft.	DBH	Total Height as of December 1972
V	V-1		5	NRO	38	42	4.7	44.2
			8	NRO	41	45	7.3	52.5
			15	NRO	42	46	7.9	46.6
			31	RMA	28	42	2.8	38.8
			3	RMA	35	35	2.0	19.8
			4	RMA	28	39	2.5	29.1
			6	RMA	34	42	1.6	16.3
			13	RMA	43	44	3.9	39.7
			14	RMA	41	44	2.7	35.0
			17	RMA	43	43	3.0	31.5
			18	RMA	26	26	1.4	19.9
			21	RMA	41	44	3.3	39.7
			24	RMA	41	42	2.9	43.5
			16	RMA	43	45	2.1	26.8
			33	BBI	33	35	1.3	15.4
			2	BBI	41	44	2.8	34.2
			7	BBI	36	41	1.1	20.5
			10	BBI	36	42	1.5	20.0
			11	BBI	35	42	3.9	15.5
			12	BBI	38	43	3.4	35.0
			20	BBI	32	35	1.5	23.3
			22	BBI	38	40	1.4	19.5
			25	BBI	31	35	1.0	13.1
			1	BBI	42	45	3.6	37.8
			9	WGB	39	43	5.0	49.8
			19	WPI	36	39	2.6	12.2
			27	WOA	25	32	1.8	13.8
			23	WOA	33	39	2.2	22.4
V	V-2		8	NRO	43	46	7.2	58.6
			10	NRO	44	46	7.6	53.8
			14	NRO	39	44	6.9	47.7
			16	NRO	38	40	2.3	21.9
			4	RMA	41	44	3.8	37.6
			6	RMA	41	44	2.0	27.0
			11	RMA	40	44	2.8	36.9
			13	RMA	38	40	2.9	32.0
			1	BBI	34	45	5.0	39.7
			2	BBI	40	40	3.6	45.5
			3	BBI	43	43	5.6	52.5
			5	BBI	41	46	5.1	47.0
			7	BBI	40	46	4.1	38.7
			9	BBI	34	36	0.9	11.4
			12	BBI	29	34	1.5	15.6

Table 4.1 continued.

Table 4.1 continued:

Stand #	Plot #	Area (in acres)	Tree #	Species	Age at 4.5 ft.	Age at 1 ft.	DBH	Total Height as of December 1972
VI	VI-1		1	NRO	27	27	6.2	45.1
			7	NRO	23	26	1.6	19.4
			8	NRO	21	25	3.2	33.5
			23	NRO	23	26	4.0	41.7
			25	NRO	28	29	5.5	46.5
			28	NRO	29	30	4.9	45.6
			13	RMA	32	32	4.6	44.2
			14	RMA	31	33	2.7	25.9
			19	RMA	28	30	1.6	16.0
			20	RMA	31	31	4.6	38.5
			21	RMA	28	31	2.4	37.2
			27	RMA	30	32	3.7	37.7
			30	RMA	31	32	3.2	40.4
			26	Asp	29	29	9.2	55.0
			2	Bch	31	32	2.2	26.9
			3	Bch	30	32	1.6	16.5
			9	Hic	22	24	1.4	16.7
			10	Hic	17	21	0.7	10.8
			24	Hic	23	24	1.1	17.1
			29	Hic	27	24	1.0	13.0
			4	WAS	28	30	1.5	22.9
			22	WAS	28	29	1.9	23.9
			11	WGB	22	22	1.0	16.8
			17	WGB	29	30	4.0	38.5
			18	WGB	·28	23	3.5	38.5
			15	WPI	14	19	1.3	12.9
			33	WPI	33(42)	33(43)	8.8	31.0
			16	WPI	13	17	0.9	9.1
VII	VII-1		1	NRO	104	106	19.2	87.5
			2	BBI	100	106	8.6	59.5
			3	SMA	104	106	6.4	58.5

APPENDIX 5

Example of Plot Maps and Height and Diameter Growth Curves

Plot maps, each delineated by a vertical projection of the crown of the B-stratum red oak (Plots VII-1, V-1, V-2, and VI-1 excluded) were made to show the relative position of each living stem as of December, 1971.

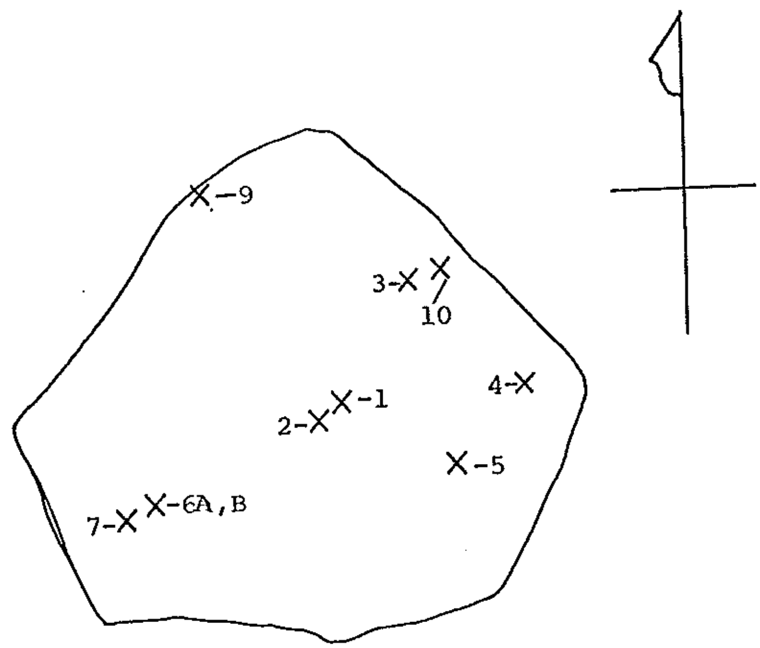
Annual diameter growth of each stem within the 14 plots was obtained by measuring the width of each growth ring along an average radius of the tree section taken from 4.5 feet (1.4 meters). The cumulative diameters obtained from these measurements were converted to diameter-outside-bark by empirical formulas for each species (Appendix 7). From these cumulative diameter-age curves were constructed.

Cumulative height-age curves of selected trees in the 14 plots were constructed by aging tree sections from one foot, 4.5 feet, eight feet, and every four feet thereafter up the stem.

Pictures to accompany the cumulative height curves were reconstructed from photographs and from measures of points of stem breaks, heights of red oak limbs on the trunks, and widths of the red oak crowns.

These plot maps and cumulative height and diameter growth curves were used in the present study to analyze the growth relations of the species studied. These plot maps and height and diameter curves from Plot II-2 are shown in this appendix as an example of this data.

Figure 5.0: Map of Plot II-2. Area of plot delineated by horizontal projection of canopy of center dominant Red Oak #1. Numbers refer to locations of living trees measured and aged within plot.



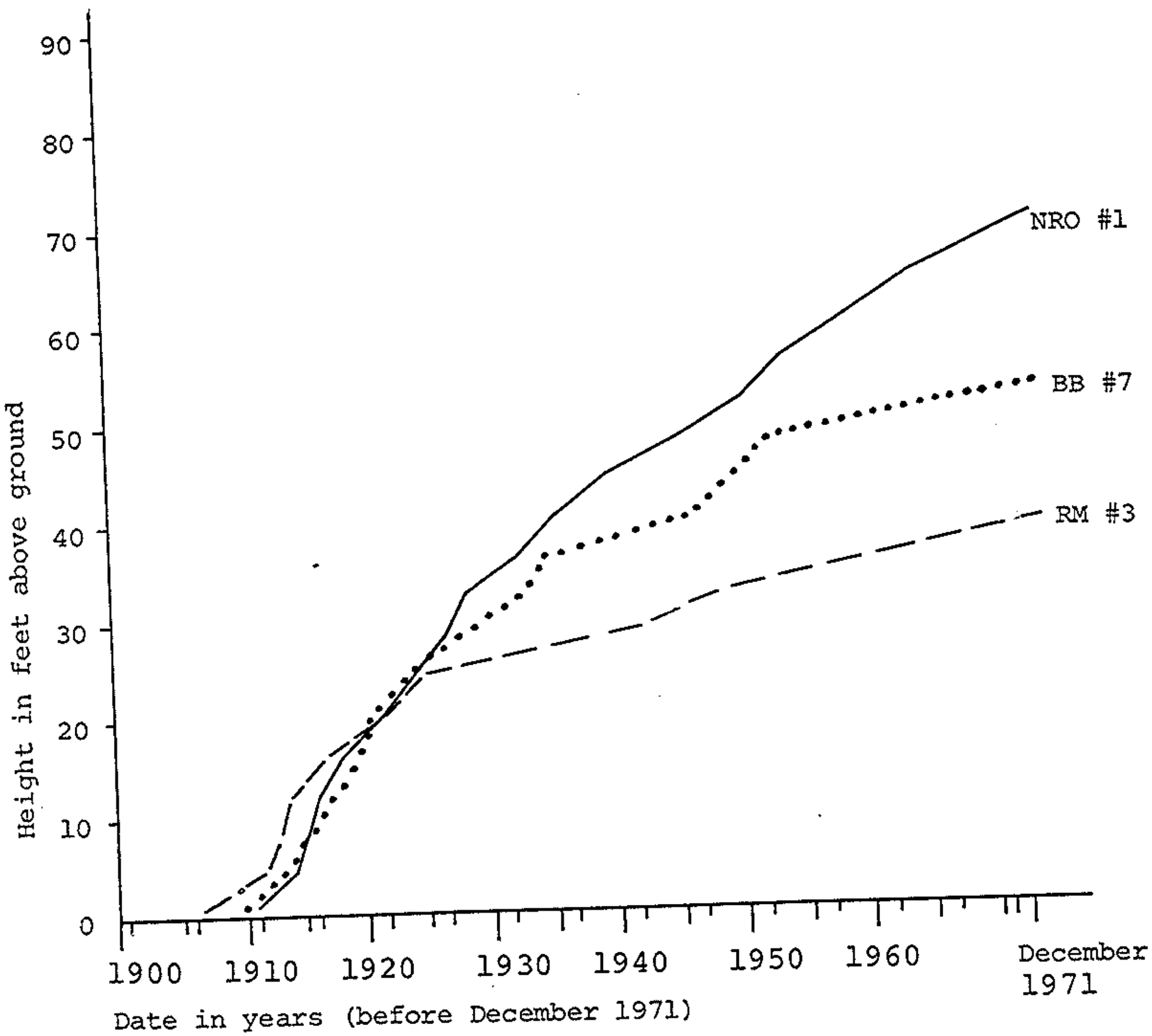
Scale: 1 inch = 10 feet

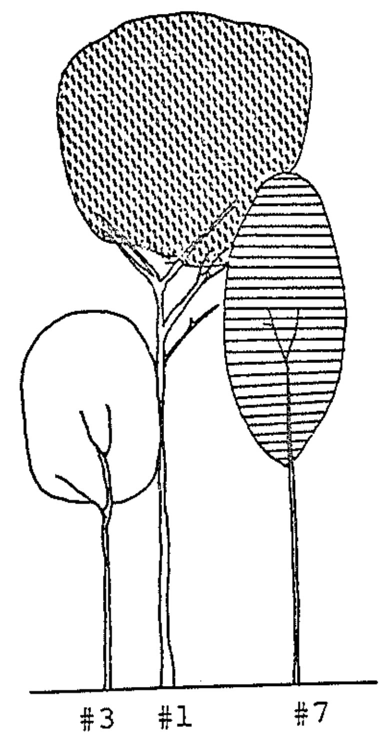
Legend: Area = 0.011 acre

Tree Number	Species
1	Red Oak
2	Red Maple
3	Red Maple
4	Red Maple
5	Red Maple
6A	Black Birch
6B	Black Birch
7	Black Birch
9	Red Maple
10	Black Oak

Limits of horizontal projection of B-stratum red oak crown

X - 6 Location and number of trees.





Schematic picture of relative heights of trees and distances from B-stratum red oak (Scale: 1 in. = 20 ft.)

Figure 5.1: Height-age curves of tallest red maple, black brich, and B-stratum red oak of Plot II-2.

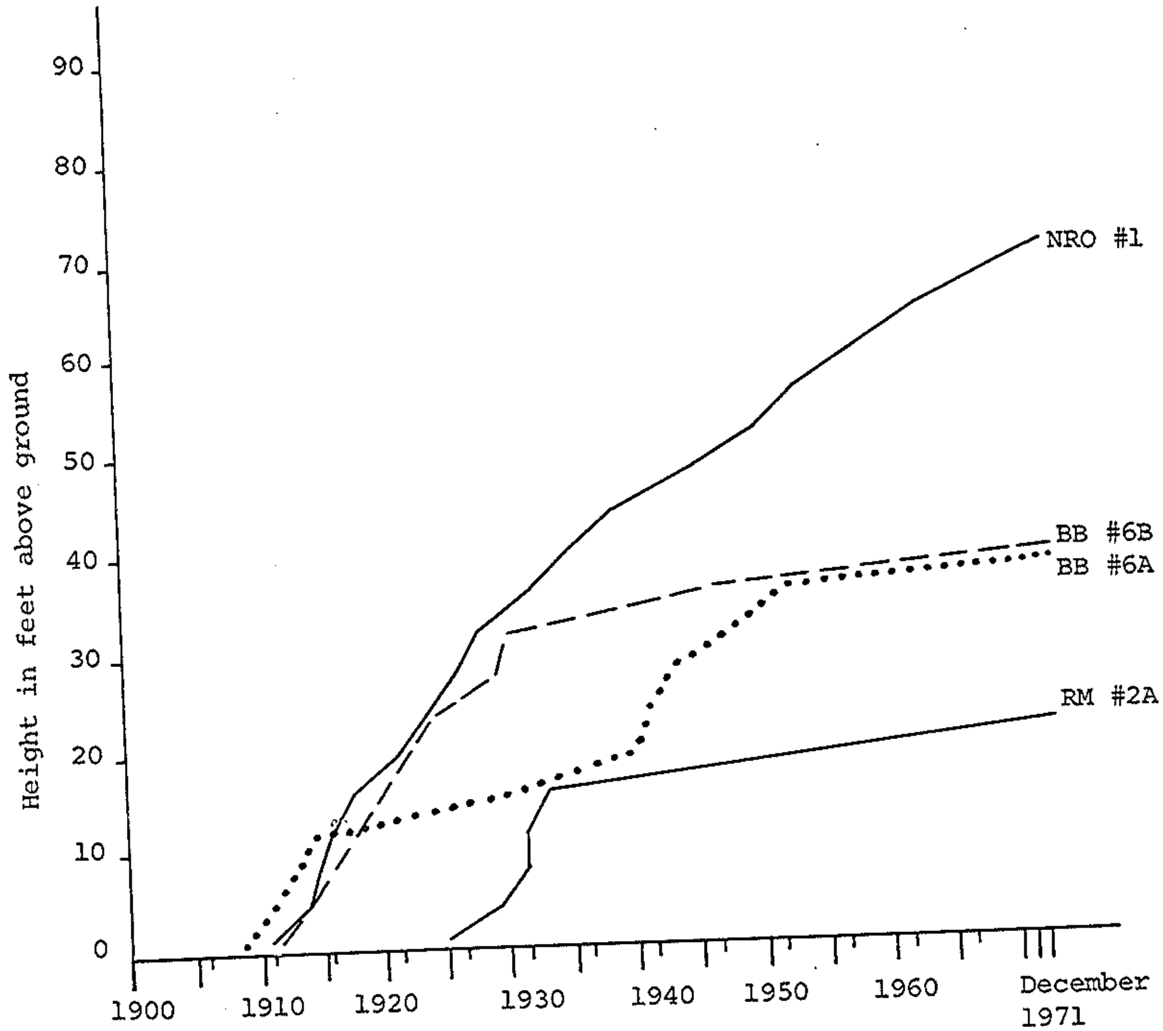
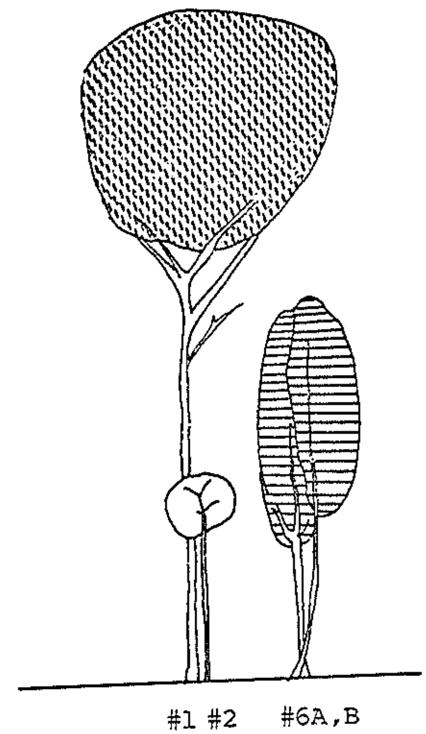
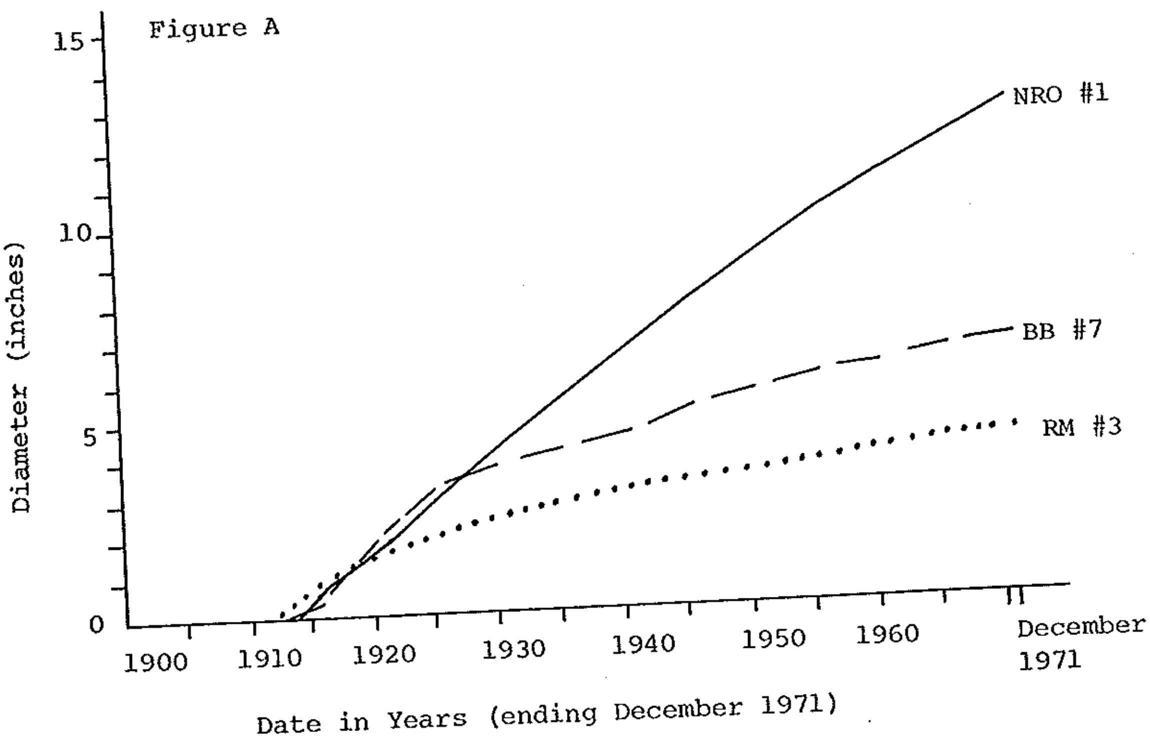


Figure 5.2: Height-age curves of other studied trees of Plot II-2.



Schematic picture of relative heights of trees and distance from B-stratum red oak (Scale: 1 in. = 20 ft.)

Figure 5.3: : Cumulative diameter growth outside bark at 4.5 feet of B-stratum red oaks and largest diameter red maple and black birch (Figure A) and other trees (Figure B through D) growing in Plot II-2.



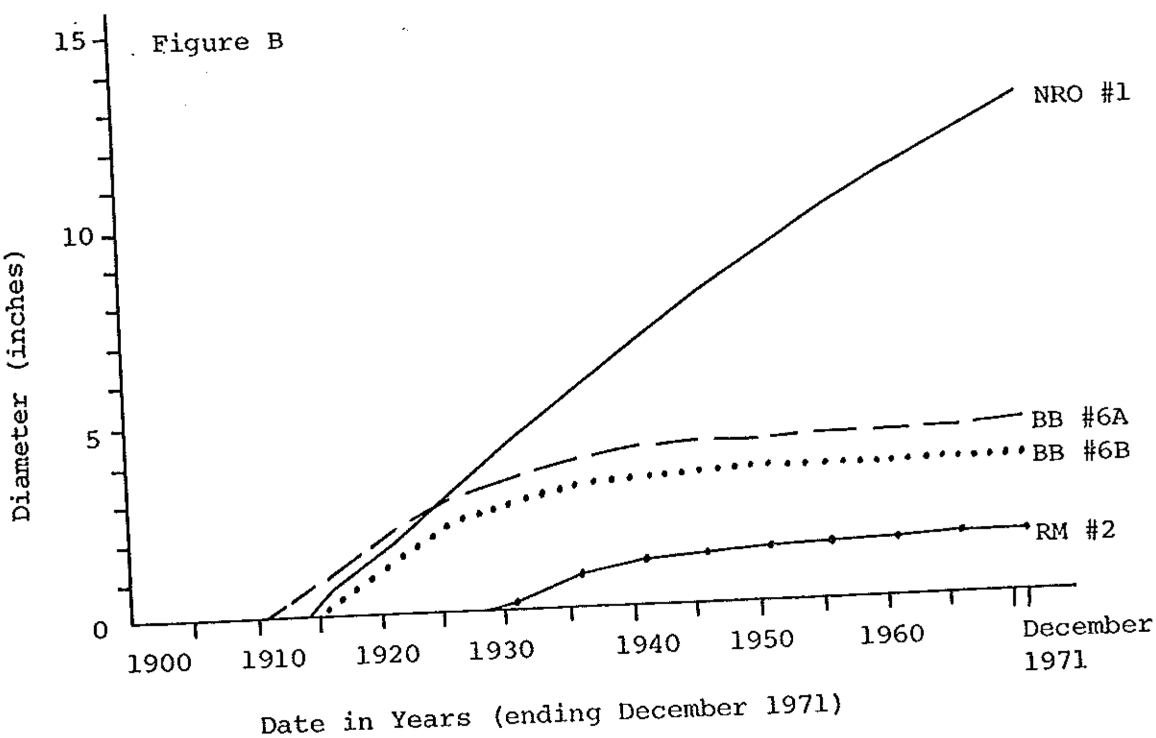
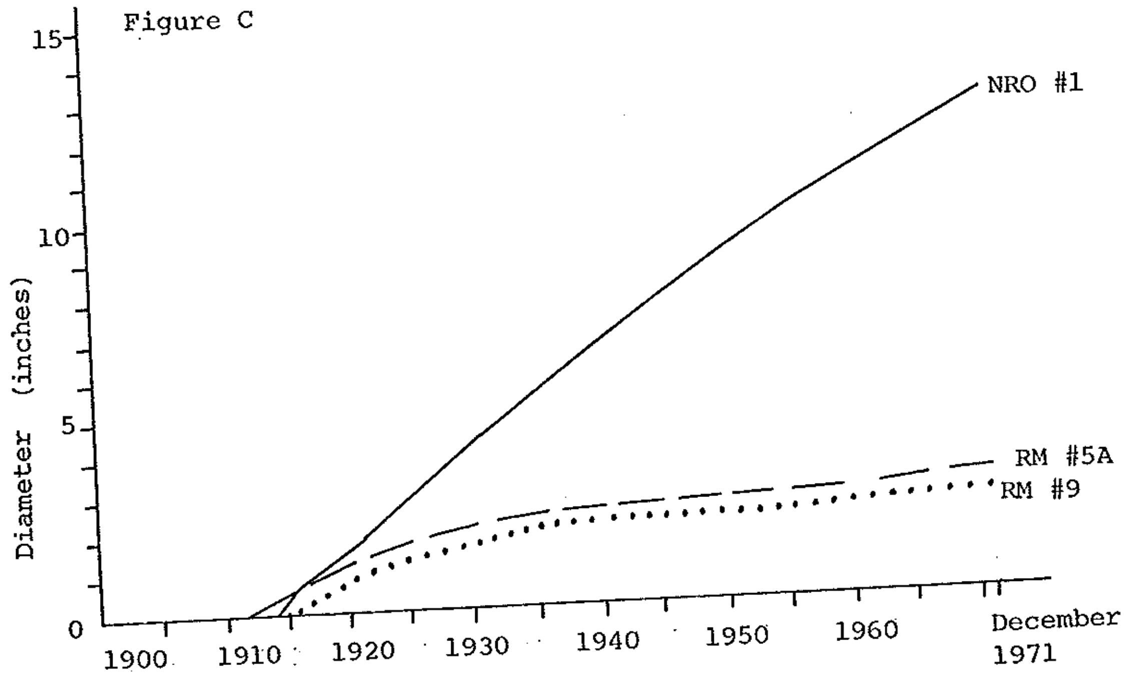
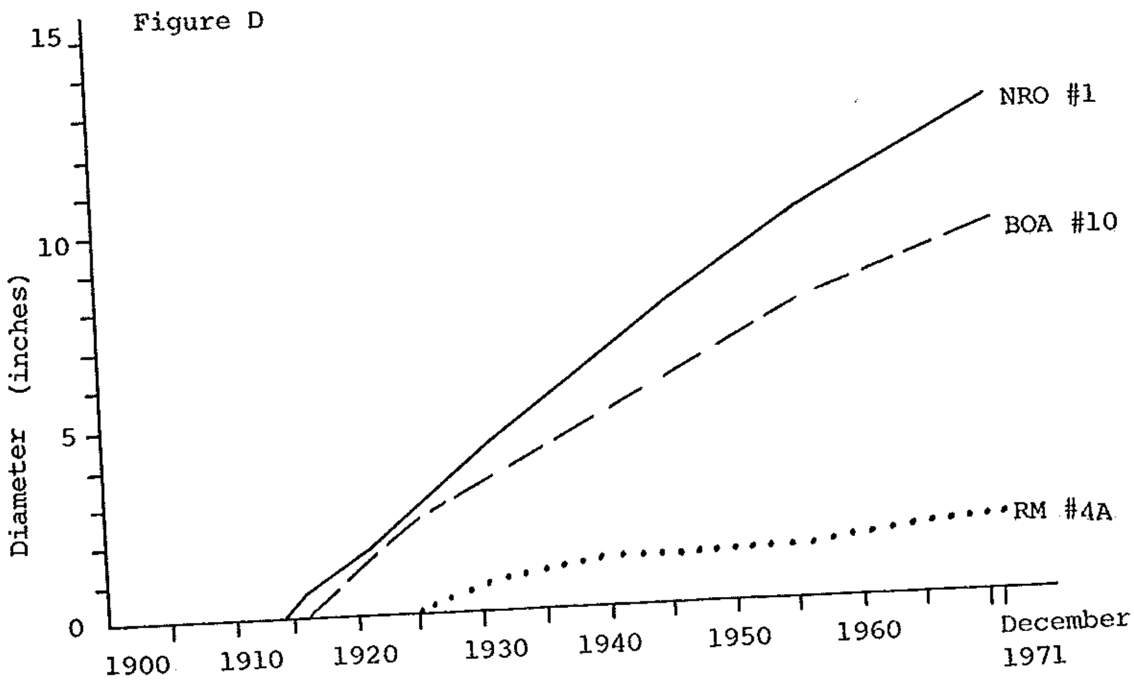


Figure 5.3 continued.

Figure 5.3: Cumulative diameter growth outside bark at 4.5 feet of B-stratum red oaks and largest diameter red maple and black birch (Figure A) and other trees (Figure B through D) growing in Plot II-2. (continued)



Date in Years (ending December 1971)



Date in Years (ending December 1971)

APPENDIX 6

Intensive Study of Selected Areas

Appendix 6A: Extended Plots I-1 and I-2

Three plot boundaries were assigned to each of two plots in the 60-year-old stands (Plots I-1 and I-2) for use in three intensities of sampling. One size (Plots I-1a and I-2a) was initially used to compare growth of B-stratum oaks with that of trees beneath its canopy. Plots I-1b and I-2b were used to compare the ages, diameters, and height relations of trees outside the vertical projection of the B-stratum red oak trees to those within it (Chapter 2). The third plot sizes (Plots I-1c and I-2c) were used to determine estimates from an unbiased sample of the number of stems per acre of each species, age, and diameter.

Figures 6.1 and 6.4 show maps of the crown projections of the B-stratum red oaks of Plots I-1 and I-2 (these lines bounded Plots I-1a and I-2a) as well as the vertical projections of the crowns of the surrounding B-stratum trees (in these cases all were red oaks). These lines are represented as # 1 in the legend.

By drawing a line midway between the canopy projections of the B-stratum red oaks, the entire area was divided into unequal sized areas, with each part assigned to a B-stratum tree. This division marked the perimeter of Plots I-1c and I-2c. It is represented for the central red oak of Figures 6.1 and 6.4 by the line # 4 of the legend.

The entire area within which all trees were mapped and sectioned for age, height, and diameter analyses (Appendix 4) was considered within Plots I-1b and I-2b. This area is also represented in Figure 6.1 for

Plot I-1 and Figure 6.4 for Plot I-2 and is bounded by line # 5 of the legend.

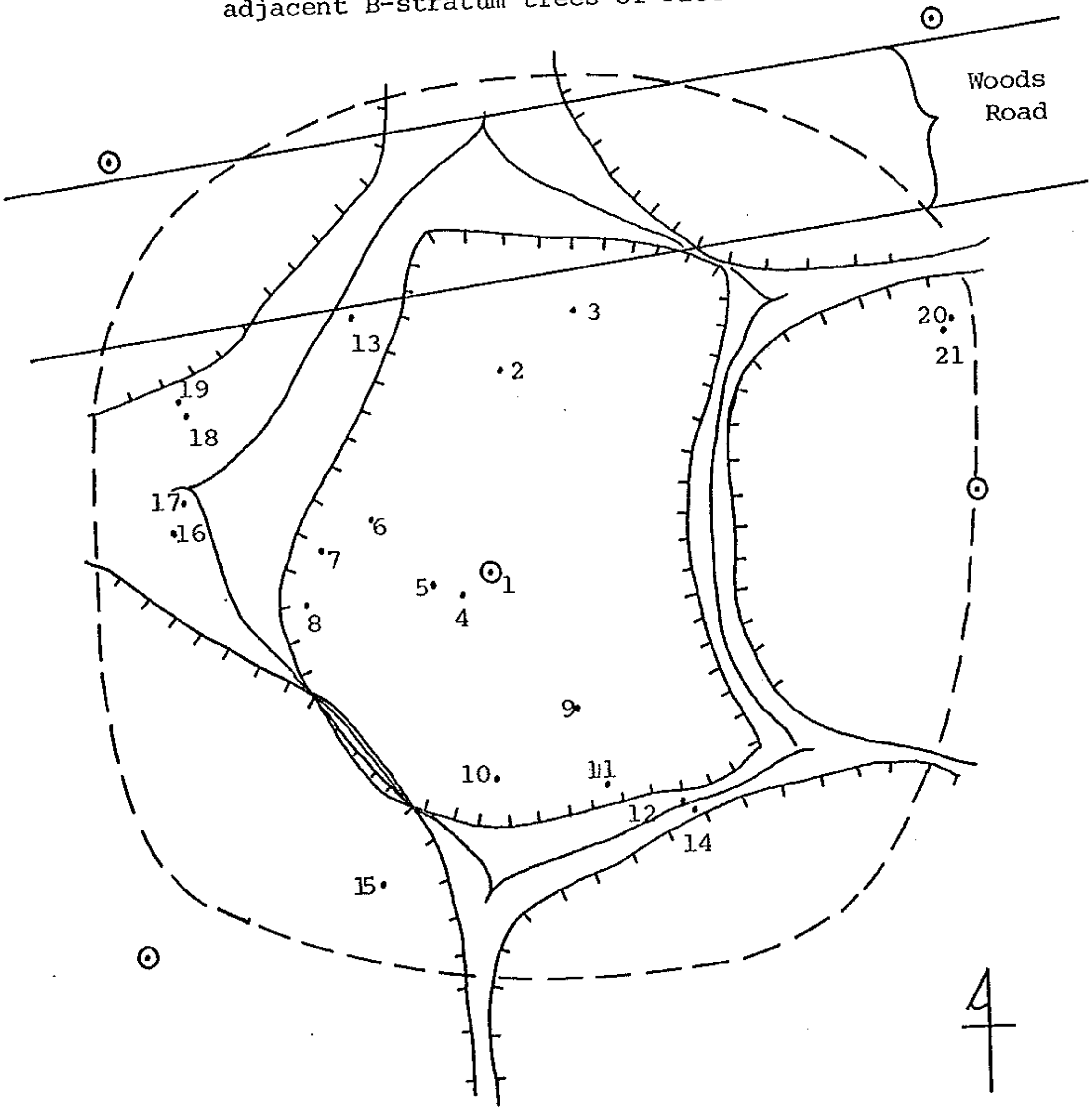
Figure 6.1 and Table 6.1 maps and describes all living trees found within Plots I-1a, b, and c; and Figure 6.4 and Table 6.4 maps and describes all living trees found within Plots I-2a, b, and c.

To obtain an accurate estimate of the number of stems per acre which had initiated and died since the clearcutting of the old field white pine, Plots I-1c and I-2c were used. The L and F horizons were carefully removed and any traces of stumps, stump holes, or standing or fallen stems was identified by species and mapped. The positions of these dead stumps is shown in Figure 6.2 and described in Table 6.2 for Plots I-1a, b, and c; and in Figure 6.5 and Table 6.5 for Plots I-2a, b, and c. Since the severe logging had probably damaged any stems standing beneath the original white pine overstory, it is probably that the stems shown in Figures 6.2 and 6.5 had all initiated shortly after the clearcut.

The white pine stumps from the clearcut initiating the present stand were found and mapped when removing the L and F horizons. These stumps, as well as a single red cedar probably arising with the white pines in the abandoned field are shown in Figures 6.3 and 6.6 and described in Tables 6.3 and 6.6.

Line AB (# 6 of the legend) of Figures 6.4, 6.5, and 6.6 is the line representing the plane along which the stand growth (Chapter 3) was reconstructed. For reconstructing the crown development of the B-stratum red oak of Plot I-2b, each branch and fork was mapped by triangulation with a transit. After the tree was felled, these branches and forks and supplementary positions at known distances between the points noted before felling were tagged. All sections were cut and aged at all marked positions. By reconstructing the tree in both horizontal and vertical two-dimensional maps from these points and putting ages at the known points, the growth patterns of the presently living branches were reconstructed.

Figure 6.1: Map of stems living in December 1971 as vertical crown projection of crowns of central B-stratum red oak and adjacent B-stratum trees of Plot I-1.



Scale 1 inch = 10 feet

LEGEND:

1. Vertical projection of canopies of B-stratum trees (all are red oaks). Central tree's canopy border bounds Plot I-1a.
2. Positions of stems of B-stratum trees.
3. Positions and identification number of other living trees. •15
4. Border of Plot I-1c, occupied by Red Oak #1 when stand area is partitioned among B-stratum trees.
5. Limit of Plot I-2b, largest area studied intensively.

Table 6.1: Species, age (as of December 1971) at one foot height, diameter at 4.5 feet, and total of living trees of Plot I-1 as numbered in Figure 6.1). (Height-age curves, cumulative diameter curves, and basal area by species can be seen in Appendix 5.)

A: Trees within Plot I-la (within Red Oak # 1).

Tree #	Species	Age	DBH (in.)	Total Height (ft.)
1	Red Oak	64	11.3	63.0
2	Red Oak	59	6.5	53.0
3	Black Birch	60	8.0	22.5
4	Red Maple	40	1.7	48.0
5	Red Maple	64	4.9	47.0
6	Red Maple	61(68)	5.0	21.5
7	Sugar Maple	31	1.4	28.1
8	Red Maple	59	3.5	42.0
9	Red Maple	61	3.4	32.9
10	Red Maple	52	3.2	50.5
11	Red Maple	63	5.0	

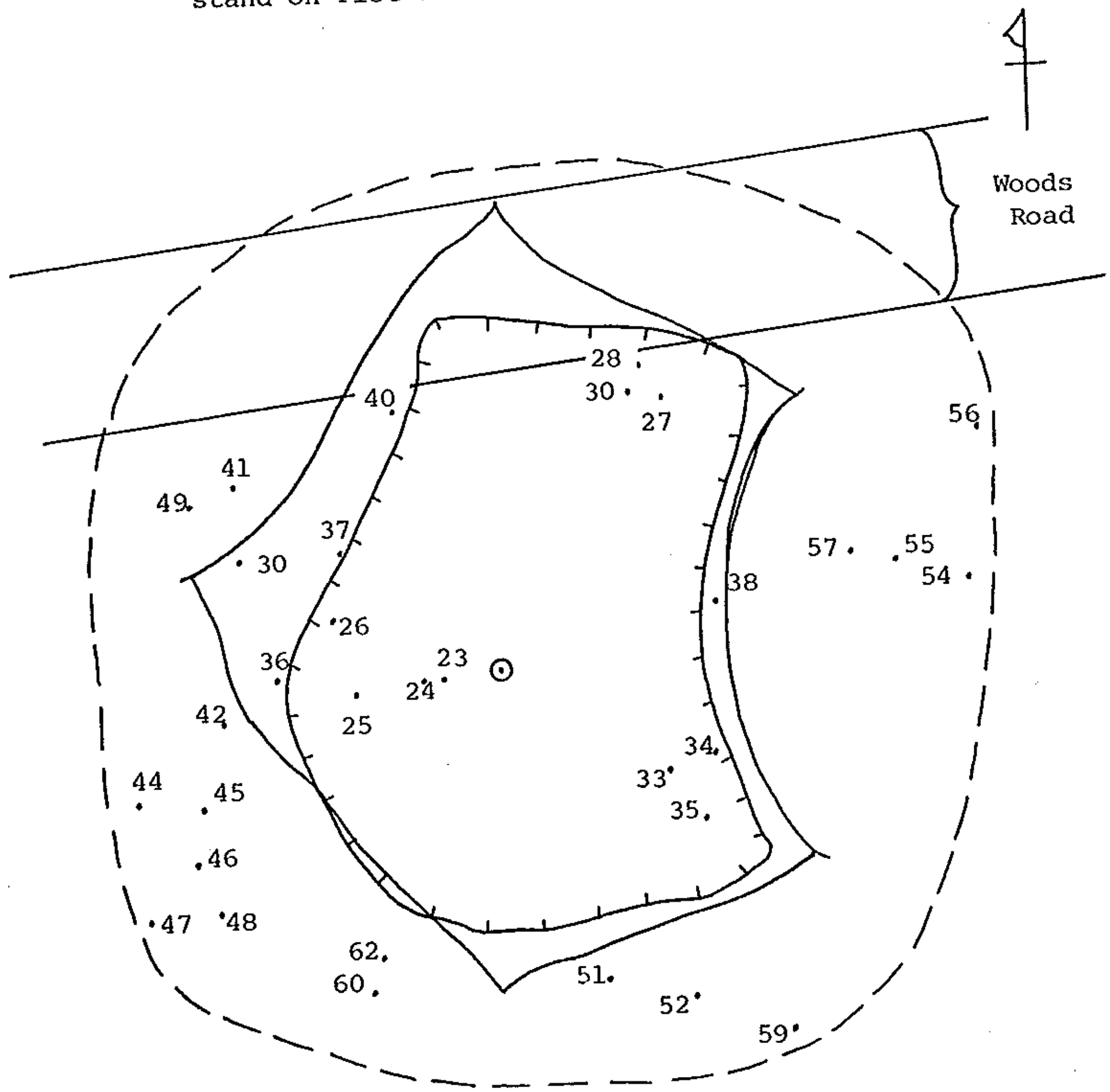
B: Trees within Plot I-lc, but not within Plot I-la [not within vertical projection of crown of Red Oak # 1 (trees not in Table 6.1A) but within area relegated to Red Oak # 1 when stand area is partitioned among dominant trees.]

Tree #	Species	Age	DBH (in.)	Total Height (ft.)
12	Red Maple	59	3.0	33.5
13	Black Birch	64	7.3	38.7

C: Trees within Plot I-lb, but not Plots I-la and c (not in Tables 6.1A and 6.1B but within area studied intensively).

Tree #	Species	Age	DBH (in.)	Total Height (ft.)
14	Red Maple	53	3.4	38.7
15	Black Birch	62	6.6	
16	Red Maple	54	2.6	31.0
17	Red Maple	61(72)	5.0	51.0
18	Red Maple	53	2.7	40.0
19	Red Maple	26	1.1	20.0
20	Red Maple	31	1.5	28.0
21	Red Maple	30	1.3	22.3

Figure 6.2: Map of stumps of dead stems and remnants of stems originating after clearcutting of old field white pine stand on Plot I-1.



Scale: 1 inch = 10 feet

Legend:

1. Border of Plot I-1a vertical projection of canopy of B-stratum Red Oak # 1.
2. Position of stem of B-stratum Red Oak # 1.
3. Positions of identification numbers of dead stumps of post-clearcut trees. (•49)
4. Border of Plot I-1c, occupied by Red Oak # 1 when stand area is partitioned among B-stratum trees.
5. Limit of Plot I-1b, largest area studied intensively.

Zai, Luther E. 1957. Report on fieldwork and preliminary office computations of Keen and Union Forest Inventory. [Unpublished report.] Yale University School of Forestry and Environmental Studies, New Haven, Connecticut. 19 pp.

Zimmermann, Martin H., and Claud L. Brown. 1971. *Trees: structure and function*. Springer-Verlag, New York. 336 pp.

Table 6.2: Species of dead stems and remnants of stems originating after clearcutting of old field white pine stand on Plot I-1.

A: Dead stems within Plot I-1a.

Tree #	Species
23	Red Maple
24	Red Maple
25	Red Oak
26	Red Maple
27	Black Birch
28	Black Birch
30	Black Birch
33	White Pine
34	White-Grey Birch
35	Black Birch
36	Black Birch

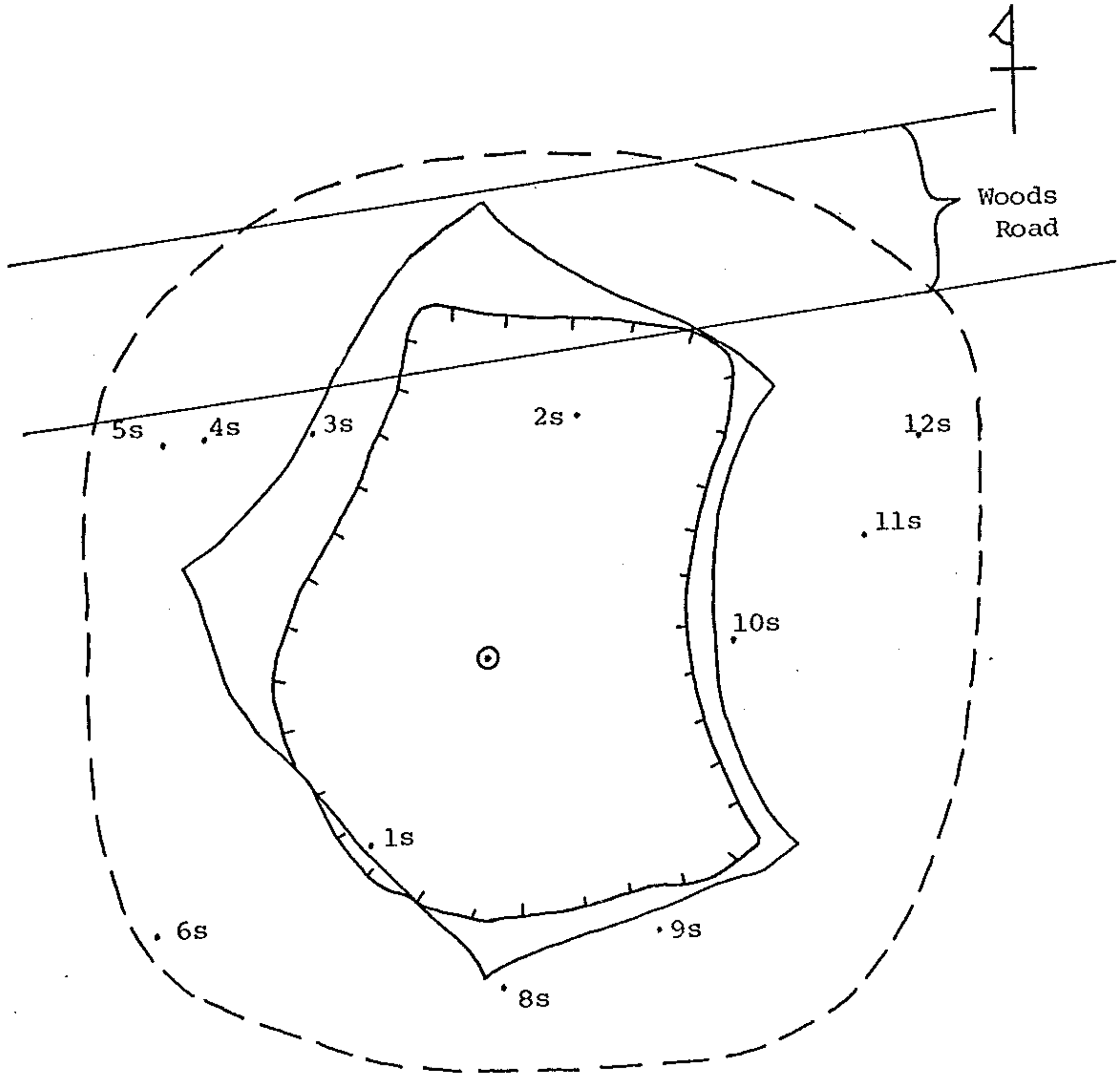
B: Dead stems not within Plot I-1a, but within Plot I-1c.

Tree #	Species
37	unidentified
38	Black Birch
39	Red Maple
40	Black Birch

C: Dead stems not within Plots I-1a and c, but within Plot I-1b.

Tree #	Species
41	Big Leaf Maple
42	unidentified
44	Red Maple
45	Laurel
46	Red Maple
47	Aspen
48	Black Birch
51	unidentified
52	Oak
54	Black Birch
55	White-Grey Birch
56	Red Maple
57	White Pine
58	White Pine
59	Red Maple
60	Black Birch
61	Red Maple
62	Black Birch

Figure 6.3: Map of white pine stumps remaining after clearcutting of old field white pine stand (circa 1910).



Scale: 1 inch = 10 feet

<u>Legend</u>:

1. Border of Plot I-1a. Vertical projection of B-stratum Red Oak # 1.

2. Positions of stems of B-stratum Red Oak # 1.

3. 4s — Positions and identification number of stumps of white pines clearcut before initiation of present stand (circa 1910).

4. Border of Plot I-1c, occupied by Red Oak # 1 when stand area is partitioned among B-stratum trees.

5. Limit of Plot I-1b, largest area studied intensively.

Table 6.3: Diameters of stumps of clearcut white pines which grew after abandonment of field (clearcut approximately 1910).

A: White pine stumps within Plot I-1a.

Tree #	Species	Diameter of Stump
1s	White Pine	13.2
2s	" "	18.0

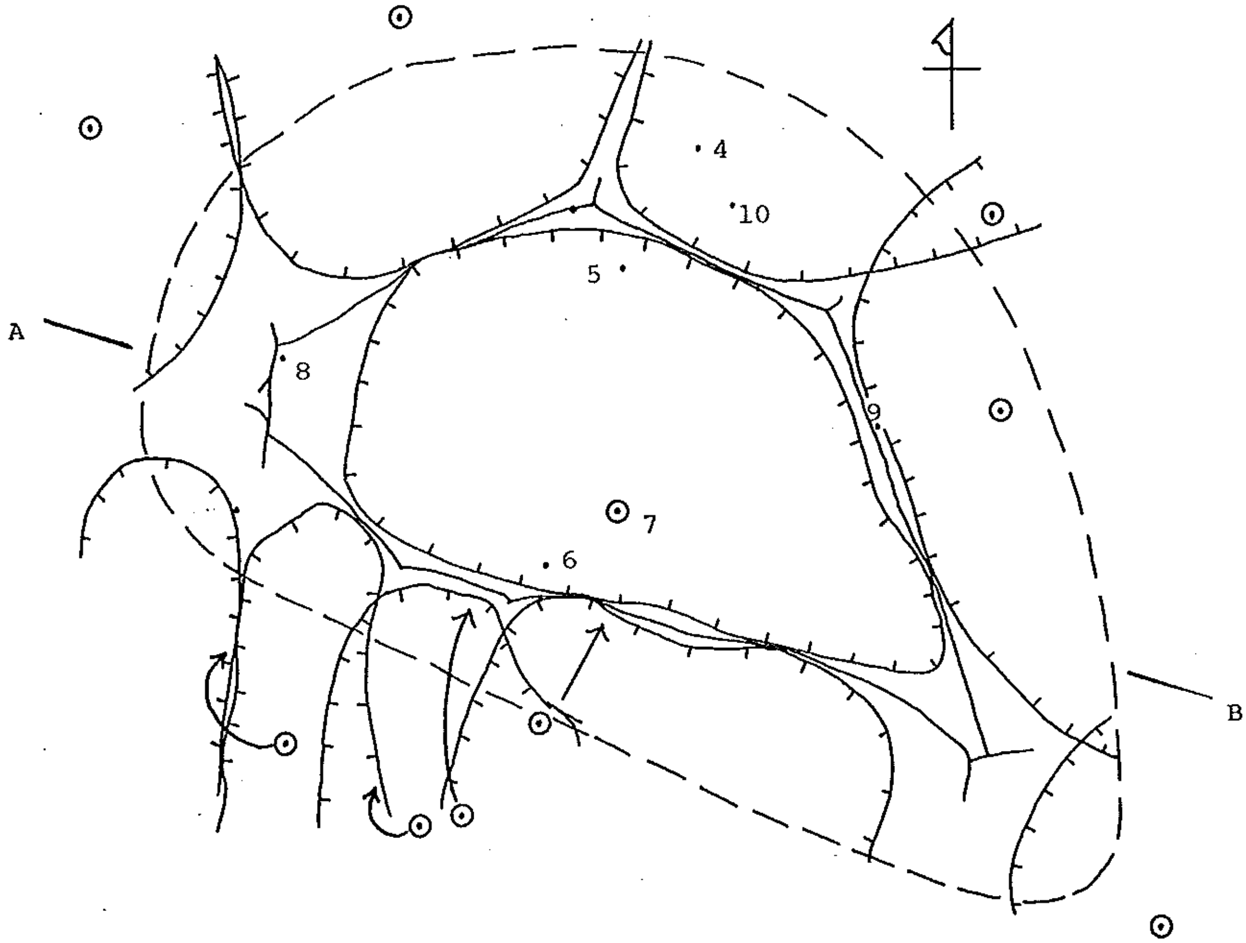
B: White pine stumps not within Plot I-1a, but within Plot I-1c.

Tree #	Species	Diameter of Stump
3s	White Pine	3.1

C: White pine stumps not within Plots I-1a and c, but within Plot I-1b.

Tree #	Species	Diameter of Stump
4s	White Pine	17.6
5s	" "	10.2
6s	" "	16.4
8s	" "	18.0
10s	" "	19.3
11s	" "	17.6
12s	" "	18.0
13s	Red Cedar	7.0

Figure 6.4: Map of stems living as of December 1971 and vertical projection of crowns of central B-stratum oak and adjacent B-stratum trees of Plot I-2.



Scale: 1 inch = 10 feet

Legend:

1. Vertical projection of canopies of B-stratum trees (all were red oaks). Central tree's canopy border bounds Plot I-2a.

2. Positions of stems of B-stratum trees.

.5 3. Positions and identification numbers of other living trees.

4. Border of Plot I-2c, occupied by Red Oak #7 when stand area is partitioned among B-stratum trees.

5. Limit of Plot I-2b, largest area studied intensively.

A B 6. Plane along which Figure 13 (Chapter 3) is viewed.

Table 6.4: Species, age (as of December 1971) at one foot height, diameter at 4.5 feet, and total living trees of Plot I-2 as numbered in Figure 6.4. (Height-age curves and some cumulative diameter curves by species can be seen in Appendix 5.)

A: Trees within Plot I-2a (within vertical projection of crown of B-stratum Red Oak #7).

Tree #	Species	Age	DBH(in.)	Total Height(ft.)
5	Red Maple	59	5.4	47.0
6	Red Maple	62	3.6	39.0
7	Red Oak	65	10.6	

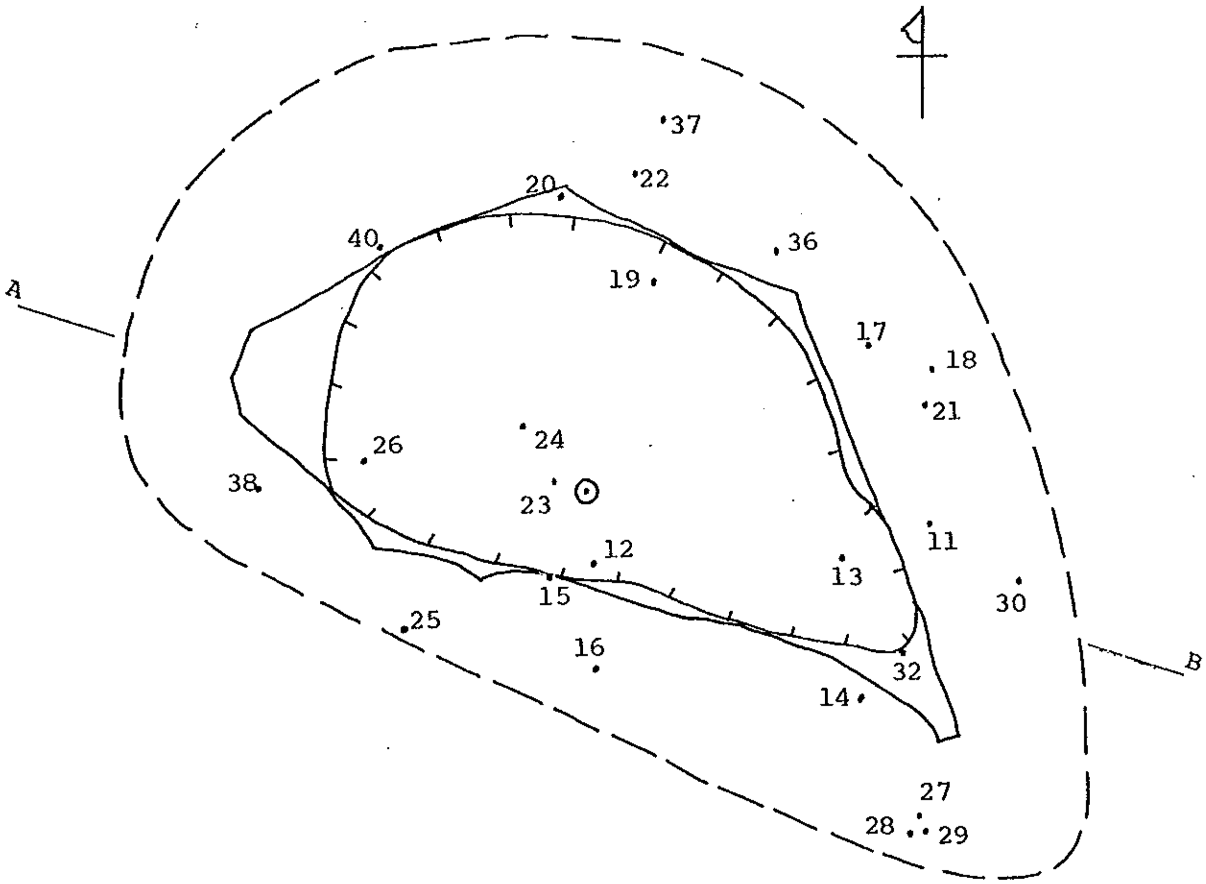
B: Trees not within Plot I-2a, but within Plot I-2c [not within vertical projection of crown of Red Oak #7 (trees not included within Table 6.4A) but within area relegated to Red Oak #7 when stand area is partitioned among B-stratum trees].

Tree #	Species	Age	DBH(in.)	Total Height(ft.)
2	Red Maple	58	5.1	52.5
8	Hemlock	61(78)	12.8	35.5

C: Trees within Plot I-2b, but not within Plots I-2a and c (not included in Tables 6.4A and 6.4B, but within area studied intensively).

Tree #	Species	Age	DBH(in.)	Total Height(ft.)
1	Red Maple	64	8.3	55.5
4	Red Maple	61	5.3	45.5
9	White Pine	56	3.2	20.0
10	Black Birch	58	3.1	28.0

Figure 6.5: Map of stumps of dead stems and remnants of stems originating after clearcutting of old field white pine stand on Plot I-2.



Scale: 1 inch = 10 feet

<u>Legend</u>:

1. Border of Plot 1-2a. Vertical projection of canopy of B-stratum Red Oak #7.
2. Position of stem of B-stratum Red Oak #7.
3. •15 Positions of identification numbers of dead stumps of post-clearcut trees.
4. Border of Plot I-2c, occupied by Red Oak #7 when stand area is partitioned among B-stratum trees.
5. Limit of Plot I-2b, largest area studied intensively.
6. A—B Plane along which Figure 13 (Chapter 3) is viewed.

Table 6.5: Species of dead stems and remnants of stems originating after clearcutting of old field white pine stand on Plot I-2.

A: Dead stems within Plot I-2a.

Tree #	Species
12	White-Grey Birch
13	unidentifiable
19	Red Maple
23	Red Maple
24	Red Maple
26	Red Maple

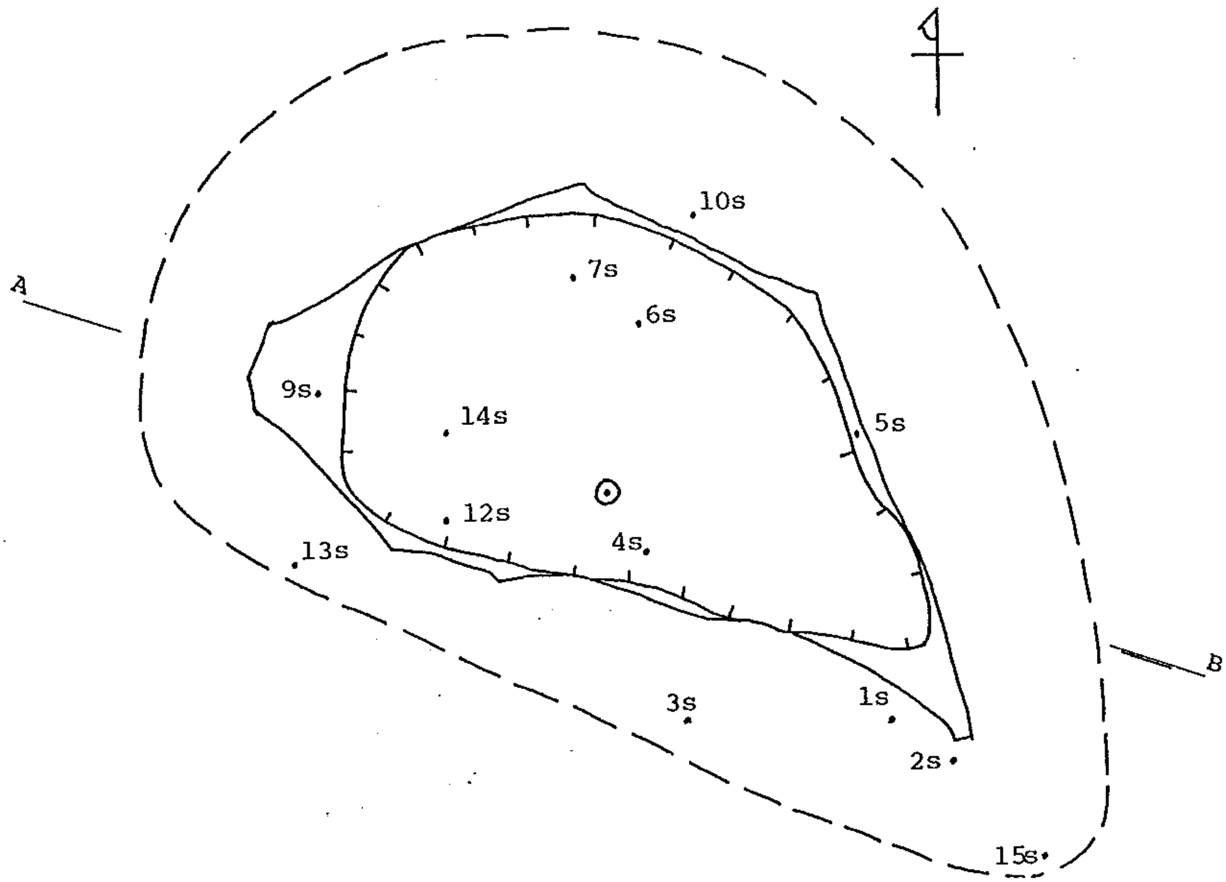
B: Dead stems not within Plot I-2a, but within Plot I-2c.

Tree #	Species
20	Red Maple
32	Black Birch

C: Dead stems not within Plots I-2a and c, but within Plot I-2b.

Tree #	Species
11	White-Grey Birch
14	unidentifiable
15	Red Maple
16	Red Maple
17	Red Maple
18	Black Birch
21	Red Maple
22	Red Maple
25	Red Oak
27	Black Birch
28	Black Birch
29	Black Birch
30	White-Grey Birch
36	Red Oak
37	Red Maple
38	Red Oak
40	Hemlock

Figure 6.6: Map of white pine stumps remaining after clearcutting of old field white pine Stand I-2 (circa 1910).



Scale: 1 inch = 10 feet

Legend:

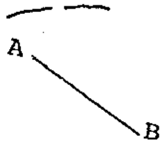
 1. Border of Plot I-2a. Vertical projection of canopy of B-stratum Red Oak # 7.

 2. Positions of stems of B-stratum Red Oak # 7.

4s . 3. Positions and identification numbers of stumps of white pines clearcut before initiation of present stand (circa 1905).

 4. Border of Plot L-2c, occupied by Red Oak # 7 when stand area is partitioned among B-stratum trees.

 5. Limit of Plot I-2b, largest area studied intensively.



6. Plane along which Figure 13 (Chapter 3) is viewed.

Table 6.6: Diameters of stumps of clearcut white pines which grew after abandonment of field (clearcut approximately 1910).

A: White pine stumps within Plot I-2a.

Tree #	Species	Diameter of Stump (in.)
4s	White Pine	13.4
6s	" "	11.8
7s	" "	17.3
12s	" "	20.2
14s	" "	10.8

B: White pine stumps not within Plot I-2a, but within Plot I-2c.

5s	White Pine	12.8
9s	" "	11.7

C: White pine stumps not within Plots I-2a and c, but within Plot I-2b.

1s	White Pine	13.6
2s	" "	11.3
3s	" "	18.6
10s	" "	20.2
13s	" "	9.8
15s	" "	12.2

Appendix 6B: Regeneration by species after a disturbance initiating a stand

It was desirable to determine the total number of stems initiating on a plot since the time of the previous overstory removal. Since almost all of the stems initiated soon after the disturbance (Chapter 2), it was believed that an estimate of the total number of living and dead stems and stump remnants of stems found in the stand would be a conservative estimate of the total number of stems living soon after stand initiation. Because of the severity of the disturbance, it was believed that any stump standing would have had to be from trees living after the overstory removal.

Sample plots were studied for total stem number in a 60-year-old stand, the 45-year-old stand, and the 33-year-old stand.

In the 60-year-old stand, two plots (Plots I-1c and I-2c) selected to be representative of portions of an acre were studied. Detailed maps of these two regeneration plots are shown in Appendix 6A. From these two plots, estimates of the stem number per acre by species presently living and total number of stems per acre by species in the original regeneration were made, as shown in Table 6.7.

In the 45-year-old stand, two circular one-fifth-acre plots concentric to the one-twentieth-acre plots (Plots V-1 and V-2) described in Chapter 1 were studied. Here the litter was not removed, but all stems and stump holes were recorded by species and whether living or dead. These estimates of living stems per acre and total stems in the initial stand are also shown in Table 6.7.

A single one-tenth-acre plot concentric to the one-twentieth-acre plot (described in Chapter 2) was studied in the stand resulting from the blowdown of the old field white pine stand (Stand VI). As in the 45-year-old stand, the number of living and dead stems per acre was estimated as is shown in Table 6.7.

Table 6.7: Estimates of living trees per acre and total initial stems by species based on stump identification from three stands.

Species	60-year-old stands 2 plots* (total 0.031 acres)	47-year-old stands 2 plots (total 0.40 acres)	33-year-old stands 1 plot (total 0.10 acres)
Red oak			
total	129	152	150
living [dead]	98 [32]	134 [18]	130 [20]
Red Maple			
total	645	565	390
living [dead]	355 [290]	377 [188]	360 [30]
Black Birch			
total	323	578	150
living [dead]	65 [258]	270 [308]	40 [110]
Other			
total	226	336	1170
living [dead]	64 [162]	258 [78]	790 [380]
Included in Other			
Sugar Maple			
total	*65*	*22*	*10*
living	*32*	*20*	*10*
Paper x Grey Birch			
total	*97*	*168*	*80*
living	*0*	*120*	*70*
Hemlock			
total	*32*	*0*	*0*
living	*32*	*0*	*0*
White Pine			
total	*32*	*85*	*180*
living	*0*	*82*	*160*
Hickory			
total		*15*	*50*
living		*15*	*50*
White Oak			
total		*42*	*40*
living		*17*	*20*
Chectnut			
total		*2*	*0*
living		*2*	*0*

Table 6.7 continued:

Table 6.7: continued

Species	60-year-old stands 2 plots* (total 0.31 acres)	47-year-old stands 2 plots (total 0.40 acres)	33-year-old stand 1 plot (total 0.10 acres)
Black Oak			
total		*2*	*10*
living		*2*	*10*
White Ash			
total			*280*
living			*170*
Quaking Aspen			
total			*30*
living			*30*
Black Cherry			
total			*450*
living			*250*
Dogwood			
total			*40*
living			*20*
TOTAL—All Species	1323	1631	1860
living	581	1039	1340
dead	742	592	540

*Plots I-1c and I-2c.

APPENDIX 7

Relation of diameter inside bark to diameter outside bark for each species studied

It was desired to estimate the diameters outside bark from measures of diameter inside bark of the various species studied within the diameter ranges studied. For each species, trees were sectioned and measures of the diameter inside and outside of the bark were taken. Regression analyses of the natural log of the outside bark diameter (y) versus the natural log of the inside bark diameter (x) were performed to generate the following equations to be calculated in millimeter units. (In alphabetical order of common name.)

Ash, white (*Fraxinus americana* L.)

$y = 1.2049\ x^{0.9846}$

Number in Sample = 138

r^2 = .988

Range of DIB = 6.4 - 94.0 mm

Standard Error of the Residual is 0.6 % of the mean.

Aspen, big tooth (*Populus grandidentata* Michx.)

$y = 1.6119\ x^{0.9203}$

Number in Sample = 52

r^2= .997

Range of DIB = 10.7 - 230.1 mm

Standard Error of Residual is 0.9 % of mean.

Birch, black (*Betula lenta* L)

$y = 1.2050\ x^{0.9781}$

Number in Sample: 159

$r^2 = .999$

Range of DIB = 14.2 - 254.1 mm

Standard error of residual is 0.5 % of mean.

Birch, grey & paper (*Betula populifolia* Marsh. and *B. papyrifera* Marsh.)

$y = 1.2381\ x^{0.9689}$

Number in Sample: 99

$r^2 = .999$

Range of DIB = 4.3 - 164.5 mm

Standard error of residual is 0.6 % of mean.

Birch, yellow (*Betula alleghaniansis* Britton)

$y = 1.2762\ x^{0.9601}$

Number in Sample: 99

$r^2 = .999$

Range of DIB = 7.3 - 164.0 mm

Standard error of residual is 0.4 % of mean.

Cherry, black (*Prunus serotina* Ehrh.)

$y = 1.1822\ x^{0.9803}$

Number in Sample: 116

$r^2 = .999$

Range of DIB = 6.8 - 113.8 mm

Standard error of residual is 0.6 % of mean.

Hemlock, eastern [*Tsuga canadensis* (L.) Carr.]

$y = 1.2594\ x^{0.9692}$

Number in Sample: 69

$r^2 = .998$

Range of DIB = 8.1 - 347.2 mm

Standard error of residual is 0.5 % of mean.

Hickory (*Carya* spp.)

$y = 1.2167\ x^{0.9833}$

Number in Sample: 148

$r^2 = .996$

Range of DIB = 17.9 - 80.2 mm

Standard error of residual is 0.7 % of mean.

Maple, red (*Acer rubrum* L.)

$y = 1.1896\ x^{0.9748}$

Number in Sample: 354

$r^2 = .999$

Range of DIB = 5.6 - 286.0 mm

Standard error of residual is 0.4 % of mean.

Maple, sugar (*Acer saccharum* Marsh.)

$y = 1.1418\ x^{0.9887}$

Number in Sample: 112

$r^2 = .998$

Range of DIB = 8.0 - 277.5 mm

Standard error of residual is 0.9 % of mean.

Oak, black (*Quercus velutina* Lam.)

$y = 1.3609\ x^{0.9596}$

Number in Sample: 91

$r^2 = .999$

Range of DIB = 7.8 - 340.0 mm

Standard error of residual is 0.5 % of mean.

Oak, northern red (*Quercus rubra* L.)

$y = 1.2821\ x^{0.9676}$

Number in Sample: 263

$r^2 = .999$

Range of DIB = 7.5 - 463.8 mm

Standard error of residual is 0.6 % of mean.

Oak, white (*Quercus alba* L.)

$y = 1.5348\ x^{0.9279}$

Number in Sample: 65

$r^2 = .997$

Range of DIB - 28.6 -218.0 mm

Standard error of residual is 0.7 % of mean.

Pine, eastern white (*Pinus strobus* L.)

$y = 1.404\ x^{0.9458}$

Number in Sample: 86

$r^2 = .995$

Range of DIB = 7.1 - 154.7 mm

Standard error of residual is 1.3 % of the mean.

BIBLIOGRAPHY

Arend, John L., and Harold F. Scholz. 1969. Oak forests in the Lake States and their management. United States Forest Service Research Paper NC-31. 36 pp.

Assmann, Ernst. 1961. *Waldertragskunde*. (Original not seen; cited from translation by Sabine H. Gardiner. 1961. *The principles of forest yield study*. Pergamon Press, New York. 506 pp.)

Baird, Charles O. 1967. [Data studied in Forest Mensuration class by Chadwick Dearing Oliver and collected under Professor Baird's supervision] Department of Forestry, University of the South, Sewonee, Tennessee.

Beck, D. D. 1970. Effects of competition on survival and height growth of red oak seedlings. United States Forest Service Research Paper SE-56. 7 pp.

Berlyn, Graeme P. 1962. Some size and shape relationships between tree stems and crowns. *Iowa State Journal of Science* 37: 7-15.

Bormann, F. H., and M. F. Buell. 1964. Old-age stand of hemlock-northern hardwood forest in central Vermont. *Bulletin of the Torrey Botanical Club* 91: 451-465.

Bormann, F. H. 1965. Chanes in the growth pattern of white pine undergoing suppression. *Ecology* 46: 269-277.

Braun, E. Lucy. 1950. *Deciduous forests of eastern North America*. The Blakiston Company, Philadelphia. 596 pp.

Bromley, Stanley W. 1935. The original forest types of southern New England. *Ecological Monographs* 5: 61-89.

Buchanan, W. D., F. C. Liming, and W. Harrison. 1962. Diameter growth patterns of black oak trees. *Journal of Forestry* 60: 352-353.

Carvell, Kenneth L. 1971. Silvicultural aspects of intermediate cuttings. In *Oak Symposium Proceedings* (D. E. White and B. A. Roach, co-chairmen). United States Forest Service, Upper Darby, Pennsylvania. Pp. 60-64.

Clark, F. Bryan, and Richard F. Watt. 1971. Silvicultural methods for regenerating oaks. In *Oak Symposium Proceedings* (D. E. White and B. A. Roach, co-chairmen). United States Forest Service, Upper Darby, Pennsylvania. Pp. 37-43.

Clements, Frederic E. 1916. *Plant succession: and analysis of the development of vegetation.* The Carnegie Institution of Washington.

Core, Earl L. 1971. Silvical characteristics of the five upland oaks. In *Oak Symposium Proceedings* (D. E. White and B. A. Roach, co-chairmen). United States Forest Service, Upper Darby, Pennsylvania. Pp. 19-22.

Daubenmire, Rexford. 1968. *Plant communities: a textbook of plant synecology.* Harper and Row, New York. 300 pp.

Day, Gordon, M. 1953. The Indian as an ecological factor in the northeastern forest. *Ecology* 34: 329-346.

de Wit, C. T. 1961. Space relationships within populations of one or more species. In *Experimental symposium on competition of the British Society for Experimental Biology*: 315-329.

Dix, R. L., and J. M. A. Swan. 1971. The roles of disturbance and succession in upland forest at Candle Lake, Saskatchewan. *Canadian Journal of Botany* 49: 657-676.

Drury, William H., and Ian C. T. Nisbet. 1973. Succession. *Journal of the Arnold Arboretum* 54: 331-368.

Egler, Frank E. 1954. Vegetation science concepts I. Initial floristic composition. A factor in old-field vegetation development. *Vegetatio* 4: 412-417.

Eyre, F. H., and W. M. Zillgitt. 1953. Partial cuttings in northern hardwoods of the Lake States. United States Department of Agriculture Technical Bulletin Number 1076. 124 pp.

Forbes, Reginald D. 1955. *Forestry Handbook.* The Ronald Press Company, New York. 1143 pp.

Fowells, H. A. 1965. *Silvics of forest trees of the United States.* United States Department of Agriculture Handbook Number 271. 762 pp.

Frothingham, Earl H. 1912. Second-growth hardwoods in Connecticut. United States Forest Service Bulletin Number 96. 70 pp.

Gevorkiantz, S. R., and N. W. Hosley. 1929. Form and development of white pine stands in relation to growing space. *Harvard Forest Bulletin* Number 13. 83 pp.

Gibbs, Carter B. 1963. Tree diameter a poor indicator of age in West Virginia hardwoods. United States Forest Service Research Note. NE-11. 4 pp.

Gingrich, Samuel F. 1971. Management of upland hardwoods. United States Forest Service Research Paper N.E.-195. 26 pp.

Gingrich, Samuel F. 1971. Stocking, growth, and yield of oak stands. In *Oak Symposium Proceedings* (D. E. White and B. A. Roach, co-chairmen). United States Forest Service, Upper Darby, Pennsylvania. Pp. 65-73.

Goodlett, John C. 1954. Vegetation adjacent to the border of the Wisconsin drift in Potter County, Pennsylvania. *Harvard Forest Bulletin* Number 25. 93 pp.

Goodlett, John C., and Robert C. Zimmerman. 1973. Distribution of common oaks (*Quercus* spp.) and regional forest types in New England. Unpublished manuscript at the Harvard Forest, Petersham, Massachusetts.

Goodlett, John C. 1974. [Unpublished data on file.] Harvard Forest, Petersham, Massachusetts.

Harlow, William M., and Ellwood S. Harrar. 1958. *Textbook of dendrology*. McGraw-Hill Book Company, New York. 561 pp.

Harvard Forest Records. 1974. [Unpublished data on file.] Harvard Forest, Petersham, Massachusetts.

Henry, J. D., and J. M. A. Swan. 1974. Reconstructing forest history from live and dead plant material — an approach to the study of forest succession in southwest New Hampshire. *Ecology* 55: 772-783.

Hoisington, R. E., and J. A. Carr. 1949. [Site index chart for red oak compiled in an attempt to classify the Harvard Forest soils; unpublished student report.] File Number 1949-12. Harvard Forest, Petersham, Massachusetts.

Holsoe, Torkel. 1948. Crown development and basal area growth of red oak and white ash. *Harvard Forest Paper* Number 3. 6 pp.

Hough, A. F. 1932. Some diameter distributions in forest stands of northwestern Pennsylvania. *Journal of Forestry* 30: 933-943.

Hough, A. F., and R. D. Forbes. 1943. The ecology and silvics of forests in the high plateaus of Pennsylvania. *Ecological Monographs* 13: 299-320.

Ilgen, Lewis W., Allen W. Benton, Kenneth C. Stevens, Jr., Arthur E. Shearin, and David E. Hill. 1966. Soil survey of Tolland County Connecticut. United States Department of Agriculture Soil Conservation Service Series 1961, Number 35. 114 pp.

Janzen, Daniel H. 1969. Seed-eaters versus seed size, number, toxicity and dispersal. *Evolution* 23: 1-27.

Johnson, John W. 1972. Silvicultural considerations in clearcutting. In *A perspective on clearcutting in a changing world* (Ralph D. Nyland, editor). Proceedings of the winter meeting of the New York Section of the Society of American Foresters: February 23-25. Pp. 19-24.

Jones, E. W. 1945. The structure and reproduction of the virgin forest of the north temperate zone. *New Phytologist* 44: 130-148.

Karnig, J. J., and B. B. Stout. 1969. Diameter growth of northern red oak following understory control. *Black Rock Forest Paper* Number 30. 16 pp.

Kozlowski, T. T. 1971. *Growth and development of trees; Vol. I: seed germination, ontogeny, and shoot growth.* Academic Press, New York. 443 pp.

Kulow, D. L. 1965. Elementary point-sampling. West Virginia University Agricultural Experiment Station Circular 116. 23 pp.

Larson, Philip R. 1956. Discontinuous growth rings in suppressed slash pine. *Tropical Woods* 104: 80-99.

Loucks, Orie. 1970. Evolution of diversity, efficiency, and community stability. *American Zoologist* 10: 17-25.

Lutz, Harold J. 1928. Trends and silvicultural significance of upland forest successions in southern New England. *Yale University School of Foresty Bulletin* Number 22. 68 pp.

Lutz, Harold J. 1940. Disturbance of forest soil resulting from the uprooting of trees. *Yale University School of Forestry Bulletin* Number 45. 37 pp.

Lutz, Harold J. 1959. Aboriginal man and white man as historical causes of fires in the boreal forest with particular reference to Alaska. *Yale University School of Forestry Bulletin* Number 65. 49 pp.

Lutz, R. J., and A. C. Cline. 1947. Results of the first thirty years of experimentation in silviculture in the Harvard Forest, 1908-1938. *Harvard Forest Bulletin* Number 23. 182 pp.

Lyford, W. H., J. C. Goodlett, and W. H. Coates. 1963. Landforms, soils with frogipans, and forest on a slope in the Harvard Forest. *Harvard Forest Bulletin* Number 30. 68 pp.

Lyford, W. H., and D. W. MacLean. 1966. Mound and pit microrelief in relation to soil disturbance and tree distribution in New Brunswick, Canada. *Harvard Forest Paper* Number 15. 18 pp.

Lyford, W. H. 1974. Development of the root system of northern red oak (*Quercus rubra* L.) [Unpublished paper.] Harvard Forest, Petersham, Massachusetts.

Lyford, W. H. 1974. [Personal communications with Chadwick Dearing Oliver] May, 1974. Harvard Forest, Petersham, Massachusetts.

Marquis, David A. 1973. Factors affecting financial returns from hardwood tree improvement. *Journal of Forestry* 71: 79-83.

Marquis, David A. 1973. An appraisal of clearcutting on the Monongahela National Forest. United States Forest Service Northeastern Forest Experiment Station, Warren, Pennsylvania. 55 pp.

Marshall, Robert. 1927. The growth of hemlock before and after release from suppression. *Harvard Forest Bulletin* Number 11. 43 pp.

McGee, C. E. 1968. Northern red oak seedling growth varies by light intensity and seed source. United States Forest Service Research Note Number SE-90. 4 pp.

McKinnon, F. S., G. R. Hyde, and A. C. Cline. 1935. Cut-over old field white pine lands in central New England: a regional study of the composition and stocking of the ensuing volunteer stands. *Harvard Forest Bulletin* Number 18. 80 pp.

Meyer, H. Arthur, and D. D. Stevenson. 1943. The structure and growth of virgin beech-birch-maple-hemlock forests in northern Pennsylvania. *Journal of Agricultural Research* 67: 465-484.

Meyer, Walter A., and Basil A. Plusnin. 1945. The Yale Forest in Tolland and Windham Counties, Conneticut. *Yale University School of Forestry Bulletin* Number 55. 54 pp.

Minckler, Leon S. 1971. A Missouri forest of the past. *Transactions of the Missouri Academy of Science* 5: 48-56.

Minckler, Leon S. 1973. An appraisal of clearcutting on the Monongahela National Forest. *Congressional Record*, June 8, 1973: E3879-E3882.

Minckler, Leon S. 1974. Prescribing silvicultural systems. *Journal of Forestry* 72: 269-273.

Minuse, J. M. 1912. The silvics of red oak. [Unpublished student report on file. November 27, 1912.] Harvard Forest, Petersham, Massachusetts.

Morris, R. F. 1948. Age of balsam fir. Department of Agriculture of Canada Forest Insect Investigation bi-monthly progress report 4. (Original not seen; abstracted in *Forestry Abstracts* 10: 136-137.)

Olson, A. R. 1965. Natural changes in some Connecticut woodlands during thirty years. *Connecticut Agricultural Experiment Station Bulletin* Number 669. 52 pp.

Palmer, Ernest J. 1948. Hybrid oaks of North America. *Journal of the Arnold Arboretum* 24: 1-48.

Patton, Reuben T. 1922. Red oak and white ash: a study of growth and yield. *Harvard Forest Bulletin* Number 4. 38 pp.

Petrides, George A. 1972. *A field guide to trees and shrubs.* Houghton-Mifflin Company, Boston.

Phillips, Edwin Allen. 1959. *Methods of vegetation study.* Holt, Rinehart, and Winston, Inc., New York.

Plotkin, Henry S. 1973. Practical application in hardwood regeneration. Proceedings of the first annual hardwood symposium of the Hardwood Research Council.

Puissi, Pietro. 1966. Some characteristics of a second-growth northern hardwood stand. *Ecology* 47: 860-864.

Putnam, J. A., G. M. Furnival, and J. S. McKnight. 1960. Management and inventory of southern hardwoods. United States Department of Agriculture Handbook Number 181. 102 pp.

Raup, Hugh M. 1964. Some problems in ecological theory and their relation to conservation. *Journal of Ecology* 52 (Supplement, March 1964): 19-28.

Remington, Charles L. 1973. Suture-zones of hybrid interaction between recently jointed biotas. *Evolutionary Biology* 2: 321-428.

Remington, Charles L. 1974. [Personal discussion with Chadwick Dearing Oliver.] Department of Biology, Yale University, New Haven, Connecticut. May, 1974.

Richards, P. W. 1957. *The tropical rain forest: an ecological study.* University Press, Cambridge. 450 pp.

Roach, B. A. 1973. What is selection cutting and how do you make it work? What is group selection and why won't it work? [Unpublished paper.] United States Forest Service, Warren, Pennsylvania.

Roach, B. A. 1971. Research needed for improved management of upland oaks. United States Forest Service Research Paper NE- . 12 pp.

Russell, T. E. 1973. Survival and growth of bar-slit planted northern red oak studied in Tennessee. *Tree Planters' Notes* 24(3): 6-8.

Sander, Ivan L. 1971. Height growth of new oak sprouts depends on size of advance reproduction. *Journal of Forestry* 69: 809-811.

Sargent, Charles S. 1884. *Report on the forests of North America.* United States Department of the Interior: Census Office. 612 pp.

Scholz, Harold F. 1948. Diameter-growth studies of northern red oak and their possible silvicultural implications. *Iowa State College Journal of Science* 22: 421-429.

Scholz, Harold F. 1952. Age variability of northern red oak in the upper Mississippi woodlands. *Journal of Forestry* 50: 518-521.

Slaughter, C. W., Richard J. Barner, and G. M. Hansen. 1971. *Fire in the northern environment — a symposium.* United States Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Smith, David M. 1946. Storm damage in New England forests. Unpublished master's dissertation, Yale University Library. 173 pp.

Smith, David M. 1962a. *The practice of silviculture.* John Wiley and Sons, Inc., New York. 578 pp.

Smith, David M. 1962b. The forests of the United States. In *Regional silviculture of the United States* (J. W. Barrett, editor). Ronald Press Company, New York. Pp. 3-29.

Smith, Walton R. ca 1970. Research priorities for eastern hardwoods. Hardwood Research Council, Statesville, North Carolina.

Sorensen, Ronald W., and Brayton F. Wilson. 1964. The position of eccentric stem growth and tension wood in leaning red oak trees. *Harvard Forest Paper* Number 12. 10 pp.

Sprugel, Douglas G. 1974. Natural disturbance and ecosystem responses in wave-regenerated *Abies balsamea* forests. Unpublished doctoral dissertation, Yale University Library.

Spurr, Stephen H., and Burton V. Barnes. 1973. *Forest Ecology.* The Ronald Press Company, New York. 571 pp.

Stephens, Earl P. 1956. The historical-developmental method of determining forest trends. Unpublished doctoral dissertation, Harvard University Library. 228 pp.

Stephens, Earl P. 1956. The uprooting of trees: a forest process. *Soil Scinece Society of America Proceedings* 20: 113-116.

Stephens, George R., and Paul E. Waggoner. 1970. The forest anticipated from forty years of natural transitions in mixed hardwoods. *Connecticut Agricultural Experiment Station Bulletin* Number 707. 58 pp.

Stout, Benjamin B. 1952. Species distribution and soils in the Harvard Forest. *Harvard Forest Bulletin* Number 24. 29 pp.

Stout, Benjamin B. 1956. Studies of the root systems of deciduous trees. *Black Rock Forest Bulletin* Number 15. 45 pp.

Thompson, D. Q., and Ralph H. Smith. 1970. The forest primeval in the northeast — a great myth? *Proceedings of the Tall Timbers Fire Ecology Conference* Number 10: 255-265.

Trimble, George R., Jr., and George Hart. 1961. An appraisal of early reproduction after cutting in northern Appalachian hardwood stands. United States Forest Service Northeastern Forest Experiment Station Paper Number 162.

Trimble, George R., Jr., and E. H. Tryon. 1966. Crown encroachment in openings cut in Appalachian hardwood stands. *Journal of Forestry* 64: 104-108.

Trimble, George R., Jr. 1972. Reproduction seven years after seed tree harvest cutting in Appalachian hardwoods. United States Forest Service Research Paper NE-223.

Trimble, George R., Jr. 1973. The regeneration of central Appalachian hardwoods with emphasis on the effects of site quality and harvesting practice. United States Forest Service Research Paper NE-282.

Troedsson, T., and W. H. Lyford. 1973. Biological disturbance and small-scale spatial variations in a forested soil near Garpenberg, Sweden. *Studia Forestalia Svecica* 109.

Tryon, E. H., and K. L. Carvell. 1958. Regeneration under oak stands. *West Virginia University Agricultural Experiment Station Bulletin* 424T. 22 pp.

Ward, W. W. 1964. Live crown ratio and stand density in young, even aged, red oak stands. *Forest Science* 10: 56-65.

Weitzman, Sidney, and George R. Trimble, Jr. 1957. Some natural factors that govern the management of oaks. United States Forest Service Northeastern Forest Experiment Station Paper Number 88.

Westveld, Marinus. 1956. Natural forest vegetation zones of New England. *Journal of Forestry* 54: 332-338.

White, D. E., and B. A. Roach, co-chairmen. 1971. *Oak Symposium Proceedings*. United States Forest Service, Upper Darby, Pennsylvania. 161 pp.

Wilson, Brayton F. 1968. Red maple stump sprouts: development the first year. *Harvard Forest Paper* Number 18. 10 pp.

Wilson, Robert W., Jr. 1953. How second-growth northern hardwoods develop after thinning. United States Forest Service Northeastern Forest Experiment Station Paper Number 62. 12 pp.

Worley, David, and H. A. Meyer. 1951. The structure of an uneven-aged white pine-hemlock-hardwood forest in Luzerne County, Pennsylvania. *Pennsylvania State Forest School Research Paper* Number 15. 4 pp.

Yoder, R. A. 1941. Study of the growth and yield of an individual red oak. [Unpublished paper on file.] Harvard Forest, Petersham, Massachusetts.