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RED PINE CROWN DEVELOPMENT IN RELATION TO SPACING

By

W. M. Stiell

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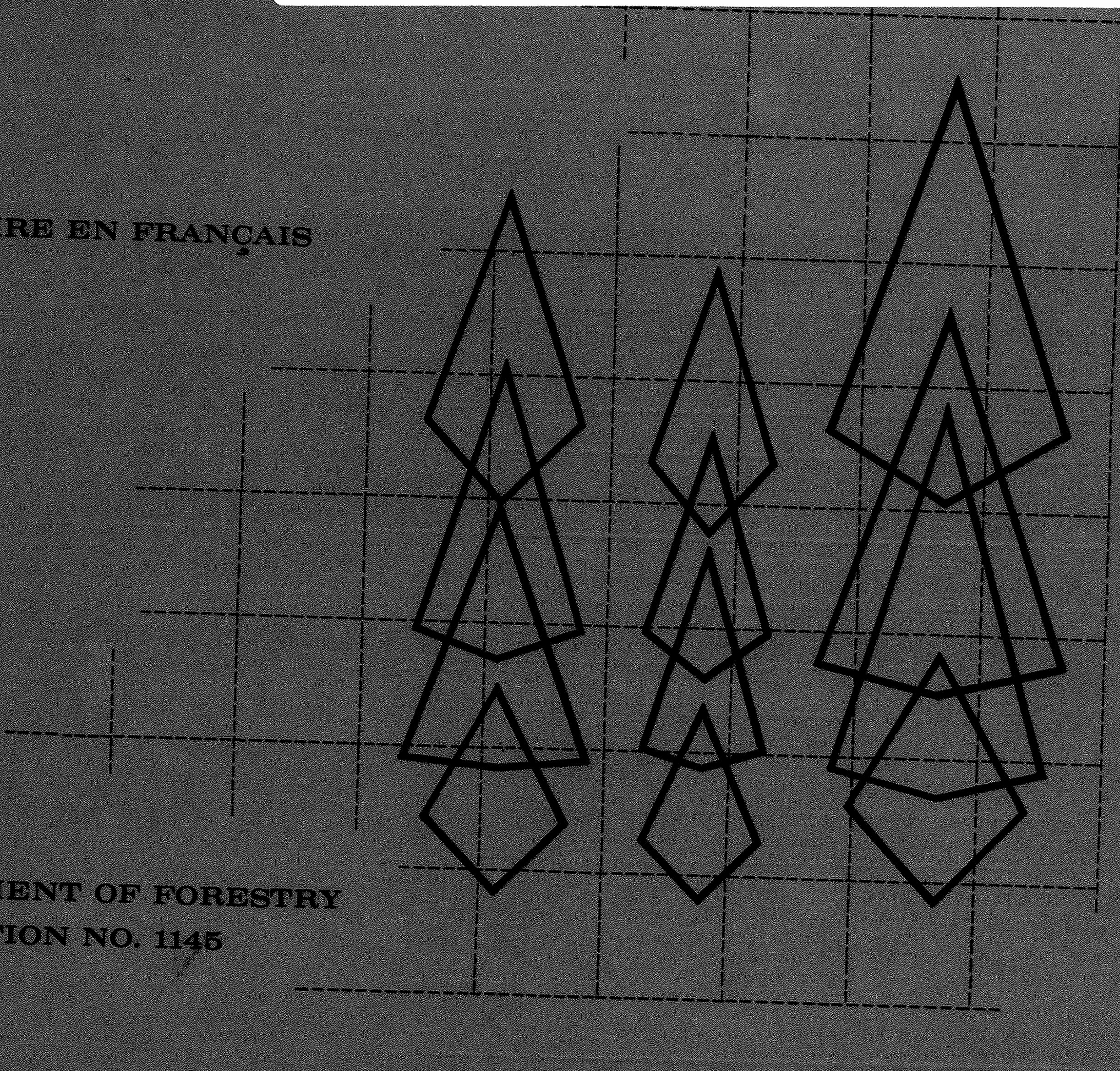

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ABSTRACT

Crown and stem measurements were taken periodically on selected trees in plantations of red pine (*Pinus resinosa* Ait.) over the period 17 to 37 years from seed. Spacings were 5 x 5, 7 x 7, 10 x 10, and 14 x 14 feet; some of these represented the original planting interval and others had been achieved by mechanical thinning at the start of the experiment. Little mortality occurred during the 20 years, and individual crown size tended to stabilize, with smaller crowns occurring with closer spacings. Periodic volume growth per acre was strongly correlated with average foliage weight for the period. Thinning was followed by an immediate but temporary increase in foliage efficiency, and wood production per kilo oven dry foliage ranged from 0.023 to 0.038 cubic feet. Crown length, width, and weight, once stabilized, did not show good correlation with parameters of individual stem growth which are cumulative. Height to crown continued to increase and was strongly correlated with total volume per acre and with the ratio average height/ $\sqrt[3]{\text{average spacing}}$. Breast-height growth of sample trees appeared to be a function of height to crown and foliage weight.

CONTENTS

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INTRODUCTION

Spacing can be controlled at planting and later by thinning, and the resulting growing space directly influences the crown -- the larger the space available to the individual tree (up to the point where it is fully open grown), the larger the crown. The mode of crown development is reflected in stem volume, with greater wood increment accompanying larger crowns; in stem form, where width of the annual ring at a given point on the bole varies in relation to crown position; in technical wood properties, where wood laid down within the crown tends to have a high proportion of thin-walled "earlywood" cells; and in lumber quality, where the presence and size of knots depend on natural pruning rates and branch diameter. Growth of the stem is thus controlled directly by the crown, and therefore indirectly by spacing. Hence a knowledge of crown-spacing relationships is important for conscious regulation of the amount and type of wood grown.

This study, carried out at the Petawawa Forest Experiment Station, near Pembroke, Ontario, deals with the crown development of plantation red pine (*Pinus resinosa* Ait.) growing at several spacings, and covers the period 17 to 37 years from seed. Four successive measurements of the same

[1] Research Officer, Dept. of Forestry of Canada, Petawawa Forest Experiment Station, Chalk River, Ont.

trees make it possible to trace the change in crown dimensions and height of the base of the crown above ground almost from the beginning of inter-tree competition well into the phase when mortality due to suppression has begun.

REVIEW OF LITERATURE

CROWN GROWTH

Red pine needles begin to develop in the spring and complete their growth by late summer; no further growth is made in subsequent years. Notwithstanding Sargent (1922), Harlow and Harrar (1941), and Horton and Bedell (1960), who give a maximum age of 5 growing seasons, red pine needles at Petawawa have been observed to persist for 6 full seasons, and this is taken to be their longest potential life span. Few needles in fact reach this age, the majority probably surviving only 3 growing seasons (Stiell 1962). Mortality usually occurs in early fall when the older needles turn brown and drop within a few weeks. Death of all needles on a branch results in death of the branch itself. Open-grown trees retain all their branches, the lowest and oldest continuing to elongate and bearing needles on the last 3 to 6 internodes of their main axis and on lower-order branches. Trees growing in a stand do not retain the full crown, and branches begin to die progressively up the stem from the base shortly before or after crown closure.

The onset of mortality seems to begin when the terminal shoots fail to produce buds, or only form buds that will not open (Stiell 1962). Hence no new foliage is formed, the existing needles live out their life span (5 more growing seasons at most), and the branch dies. Buds are not set if the branch terminal is injured by whipping, or is browsed, but the main cause is probably a physiological one due to changing environment. Toumey and Korstian (1937) stated that dying of lower limbs has usually been considered a result of low light intensity in the lower part of the crown, and cited Stålfelt (1931) on the apparent correlation between available light and failure of spruce buds to open, but contended that shading had not been definitely demonstrated to cause branch mortality. Mayer-Wegelin (1936) considered that lower, shaded branches are limited to the products of assimilation of their own foliage, and ultimately die as a result of the low rate of production occurring at such reduced levels of light. Kramer and Kozlowski (1960) felt that water deficit is involved also, decreased photosynthesis resulting in low concentrations of solutes and low osmotic forces, and hence reduced ability to compete for water with branches having higher photosynthetic rates. Shade, therefore, is apparently primarily responsible, weakening the branch until it is no longer capable of forming viable buds.

Since the lowest branches of open-grown trees persist, at least their terminals receive adequate light, and it is the mutual shading by competitors that causes branch mortality in a forest stand. Young trees do not cast sufficient shade to interfere with each other's growth, but the taller they become the broader and longer their shadows, and eventually the lower branches become too shaded to survive. It is obvious that the degree of shade between adjacent trees is a function both of their height and the distance between them, and spacing trials with red pine invariably show longer crowns at wider spacings for a given height (Stevenson and Bartoo 1939; Hawley and Lutz 1943; Bramble *et al.* 1949; Lemmien 1950; Stiell 1964). Thus spacing effects on crown development must be considered in relation to tree height, and have no meaning otherwise.

The pattern of branch mortality may be affected by site. As noted above, moisture deficiency is thought to be contributory, and on dry sites death of the lower branches may occur sooner under the same degree of shade than where moisture is not limiting. At Petawawa the lower whorls of red pine 30 feet tall, spaced at 12 x 12 feet and growing on gravelly soil, were dead although the crowns of adjacent trees had not closed (Stiell 1964); on the other hand, no branches had died in a plantation 16 feet tall, spaced at 4 x 4 feet and growing on fine sand much better supplied with moisture, 3 years after closure had occurred and the lower branches had overlapped by 2 feet (Berry 1965).

Crowns become longer through height growth of the tree. Height appears little affected by spacing, although reduced growth of red pine has been found at high densities on dry sites (Anon. 1954) and where the spacing was exceptionally close, i.e. 2 x 2 feet (Burns and Irwin 1942). However in most studies with red pine no particular association was found between stocking and height growth (Lemmien 1950; Engle and Smith 1951; Smithers 1954; Byrnes and Bramble 1955; Schantz-Hansen 1956; Lemmien and Rudolph 1959; Buckman 1962; Day and Rudolph 1962; Richards *et al.* 1962; Stiell 1964). Lengthening of the crown from above, then, usually proceeds independently of spacing.

Crown width increases through extension of the branches, and Richards *et al.* (1962) found that the rate of branch length growth was highly correlated with the concurrent rate of height growth. On trees growing at wide rather than close spacings the lower branches live longer, and grow longer and thicker before the stand closes. Since closure occurs later with widely-spaced trees, they enter this phase with longer crowns (because they are older and taller) and with wider crowns also. Hence they individually contain a greater weight of foliage than closely-spaced trees. With the onset of branch mortality the first limitations are imposed on crown expansion; longitudinal extension is to some extent offset by recession at the base, and the plane of greatest width begins to move upwards. Abrasion from whipping by adjacent trees in dense stands of red pine has been reported to limit crown spread (Richards *et al.* 1962).

Decker (1962) assumed that a crown would stop enlarging after it became completely surrounded by crown canopy, its photosynthetic capacity remaining essentially constant while the tree grew taller and larger, and from a study of red pine up to 35 years old and 60 feet tall Stiell (1962) thought it likely that crown size might become constant provided the stocking remained unaltered. As height growth slows with age, rate of crown elongation must diminish, and Bennett (1960), discussing slash pine (*Pinus elliottii* var. *elliottii*), considered that crown length could not be appreciably increased through additional height increment after the period of fast height growth. Branch extension also appears to slow down with age, and Smithers (1954) found that in relatively open grown red pine branch growth decreased as the age of trees increased, with the effect becoming marked at 45 years and up. Changes in stocking brought about by natural mortality or thinning will tend to maintain or increase total crown size by permitting further branch extension and retarding branch mortality at the base, but as noted will not increase crown length by faster height growth.

CROWN MEASUREMENT

Crown measurements are of two general types:

(a) Those aimed at defining crown size as a means of estimating photosynthetic capacity and hence total wood production. Length is the crown dimension that has been most commonly measured, and when expressed as a percentage of tree height (the live crown ratio) is widely regarded as an index of tree vigour and intensity of stocking. However it is not a quantitative expression of the amount of foliage, which requires one or more measurements of crown width as well. Smithers (1954) measured branch length of red pine at different levels in the tree as a basis for estimating crown surface area which gave good correlations with current diameter growth. It is doubtful if effective surface area of the crown can be accurately defined or measured, or that it is necessarily a good measure of photosynthetic capacity. Total weight of foliage is probably a better one (Holsoe 1948) and can be calculated for red pine by an equation using the length and maximum width of the crown (Stiell 1962).

(b) Those measurements which indicate the position of the crown with respect to the stem, and the thickness of branches, and can be related to wood quality. Height to the crown is the complement of crown length and is indicative of pruning rates and distribution of mature wood. Branch diameter governs knot size.

EXPERIMENTAL MATERIAL AND METHODS

THE PLANTATIONS

These studies were established by Bickerstaff[2] in 1940 in four plantations (A,B,C and D) which were 17 years old from seed at the end of the 1939 growing season. Plantations A and B were planted in May, 1926 at spacings of 5 x 5 feet with 3-0 red pine believed to be of local origin. Plantations C & D were planted the following May at 7 x 7 feet with 2-2 transplants from the same seed lot used the previous year. Planting was carried out by spade in ploughed furrows, and considerable care was taken to ensure consistent spacings.

Planting sites were old fields, on terrain varying from almost level to steeply sloping. The soils were dry or incipient podsols developed on medium to fine sand of windblown or lake-laid origin. The profiles showed plough layers except where wind had eroded or buried the top soil. The parent

[2] Bickerstaff, A. 1941. Crown development in red pine plantations. Canada Dept. Mines & Resources, Mines, Forests & Scientific Services Branch, Dom. For. Service, P.F.E.S. Binder No. 126. Unpub. MS.

material was mainly siliceous, with some concentration of feldspar and mica in unstratified windblown layers, and of siliceous material in lake-laid stratified layers.

The soils generally permitted very extensive root development. The feeding roots were concentrated in the finer strata, with sinkers extending downwards and branching out in the finer layers. The concentration of roots in the upper layers was less than in natural stands, possibly a result of low nutrient and moisture supply in the top soil following farming and wind erosion. From these and older plantations growing on similar soils it appears that growth is maintained at a surprisingly good rate on such windblown and lake-laid materials. Differences in site quality did occur between plantations, however; plantations A and C apparently were growing under more favourable moisture conditions (Table 1).

All planting sites supported a continuous cover of grass sod, but by 1939 crown closure had shaded out much of the vegetation. Typically the forest floor was then covered with dry needle litter to a depth of half an inch, beneath which was a partially decomposed layer about a quarter inch thick. The humus layer on top of the mineral soil was less than an eighth inch in depth.

Survival in 1939 varied from 87 to 98 per cent for the four plantations. The stands were healthy and had suffered no significant damage.

TREATMENT AND METHODS

Each plantation was divided into two parts, one of which was left at the original spacing of 5 or 7 feet and the other thinned systematically in a geometric spacing to 7, 10, or 14 feet. Two permanent sample plots were established in each plantation, one in the original and one in the new spacing condition. The distribution of plots by treatment and spacing is shown in Table 2.

All plots were permanently established and thinned

TABLE 1. SOIL AND SITE CONDITIONS

Plot	Slope	Moisture Regime	Parent Material
		Block A	
A-5 A-5/7	Gentle roll.	Somewhat dry to fresh	Aeolian fine sand over lake-laid fine and very fine sand interbanded.
		Block B	
B-5	Gentle roll.	Dry.	Aeolian medium sand with pockets of fresh, finer sand.
B-5/10	Gentle roll.	Dry.	Aeolian medium sand with bedrock near surface on north, east, and south boundaries.
		Block C	
C-7	Almost level.	Fresh	Lake-laid medium sand with silt and clay bands below the weathered profile.
C-7/10	Almost level.	Fresh	Lake-laid medium sand, with dry medium sand without bands in southeast portion.
		Block D	
D-7	Steep grade on lee of dune.	Somewhat dry.	Aeolian medium and fine sand over lake-laid bands of very fine sand.
D-7/14	Gently rolling.	Somewhat dry.	Aeolian medium and fine sand but shallow over bedrock on western portion, and bisected by erosion channel from west to east.

TABLE 2. PLOT DISTRIBUTION

Approximate Spacing	Number of Plots	Plot Designation	Treatment
5 feet	2	A-5 B-5	Original planted spacing " " "
7 feet	3	A-5/7 C-7 D-7	Thinned from 5 x 5 feet Original planted spacing " " "
10 feet	2	B-5/10 C-7/10	Thinned from 5 x 5 feet " " 7 x 7 feet
14 feet	1	D-7/14	Thinned from 7 x 7 feet

in June, 1940. The individual trees were numbered, tagged and mapped. Height and diameter measurements were made then and at the end of the 1945, 1950 and 1959 growing seasons. Crown measurements, with which this paper is chiefly concerned, were made at the same dates on at least 25 trees in each plot. These trees were undamaged and not situated next to gaps, but otherwise were selected at random throughout the plots. The following observations were made on each sample tree:

(1) Total height of tree.

(2) Height to the base of the crown (first fully live whorl).

(3) Maximum width of the crown at right angles to the row.

(4) Height to plane of maximum crown width.

Early measurements were made with a graduated pole, but later an Abney level or Haga altimeter was used for total height. In 1959 crown width was measured with a special instrument of the type described by Turnock and Ives (1957).

In 1959 the basal diameters of dead branches, at heights corresponding to the base of the live crown at the various measurement dates, were taken with a diameter tape on two trees of approximately mean plot d.b.h. in each spacing.

The various crown dimensions of sample trees surviving in 1959 were compiled by plots, and by 1939 one-inch d.b.h. classes within plots, for successive measurements. The dry weight of foliage was estimated from the equation derived by Stiell (1962): weight in grams = (10.62)(cubic foot volume of the crown considered as a paraboloid)+1403.5. Per acre foliage values were determined by plotting weight over d.b.h. and summing the diameter class values for each plot.

DESIGN AND ANALYSIS

Four plots in this experiment remained at their original planted spacings of 5 or 7 feet. One plot was thinned to 7 feet, two to 10 feet, and one to 14 feet. The design is, therefore, not orthogonal with respect to treatment or final spacing. Two types of crown development have taken place, that influenced only by initial spacing and increasing tree height, and that occurring in response to the sudden increase in growing space occasioned by the thinning. Comparisons were, therefore, made between treatments (i.e. each thinned plot and its control), and between groups making up the final spacings.

This experiment is complicated by site differences between plantations (Tables 1 & 3), but this difficulty is partly allowed for by the grouping of plots into their final spacings (Table 4). Moreover, the slope of the straight-line regression of dominant[3] height in 1939 on numbers of trees per acre is not significant, and it is assumed that despite individual plot difference there is no important interaction between spacing and site <u>for the relationship as a whole</u>.

Finally it should be noted that even by 1939 some

[3] Here expressed as the average height of the tallest 10 per cent of the stand.

TABLE 3. STAND DATA 1939, BEFORE TREATMENT

Plot	No. Trees per Acre	Av.Dom. Ht.(ft.)	Av. D.B.H. (ins)	Basal Area (Sq.ft. /ac.)	Total Vol. (cu.ft. /ac.)	Plot Area (ac.)
A-5	1461	25.0	3.7	108	1108	0.23
A-5/7	1541	23.7	3.8	120	1239	0.22
B-5	1529	21.4	3.4	94	765	0.24
B-5/10	1425	19.0	3.1	75	624	0.28
C-7	850	23.0	4.3	85	854	0.12
C-7/10	750	21.8	4.3	76	638	0.20
D-7	812	21.2	3.8	66	552	0.40
D-7/14	833	20.1	3.8	66	514	0.52

effects of spacing were already evident in that crowns of trees planted at 7 x 7 feet were slightly longer and wider, and had a greater weight of foliage, greater height to crown and crown length/height ratio, and thicker branches than did crowns of trees at the initial 5 x 5 foot spacing.

Only sufficient stem growth data are presented to allow consideration of crown-stem relationships. Two types of association have been investigated:

(1) Concurrent crown and stem measures
  (a) sample tree crown dimensions vs. d.b.h.
  (b) average plot crown dimensions vs. plot volume
(2) Periodic stem or plot growth and average crown measures for the period
  (a) sample tree crown dimensions vs. tree basal area increment
  (b) average plot crown dimensions vs. plot net volume increment per acre.

RESULTS

STEM GROWTH

Height

Heights of sample trees are shown in Table 4. The range in average plot heights was 5.9 feet in 1939, 9.7 feet in 1959, and extremes of height growth for the period differed between plots by 9.1 feet. Since site differences exist, uniform height growth would not be expected, and whether or not it has been affected by spacing is best determined from behaviour of the individual plot pairs. Considered in this way, 20-year growth differed by less than 1.5 feet between pair members, except for plots A-5 and A-5/7 where the latter grew 3.2 feet more. While height growth was significantly less on A-5, there was no indication that a change in spacing was elsewhere accompanied by a change in height growth of practical

TABLE 4. AVERAGE HEIGHT OF SAMPLE TREES IN FEET

Spacing Group	Plot	1939	Annual Growth 1939-45	1945	Annual Growth 1945-50	1950	Annual Growth 1950-59	1959
5	A-5	22.5	1.65	32.4	1.42	39.5	1.22	50.5
	B-5	19.2	1.75	29.7	1.32	36.3	1.48	49.6
	Av.	20.8	1.70	31.0	1.37	37.9	1.35	50.0
7	A-5/7	22.1	1.95	33.8	1.50	41.3	1.33	53.3
	C-7	21.4	2.07	33.8	1.66	42.1	1.72	57.6
	D-7	19.3	2.10	31.9	1.78	40.8	1.31	52.6
	Av.	20.9	2.04	33.2	1.65	41.4	1.46	54.5
10	B-5/10	16.6	1.57	26.0	1.64	34.2	1.58	48.4
	C-7/10	21.0	2.12	33.7	1.84	42.9	1.69	58.1
	Av.	18.8	1.84	29.8	1.74	38.6	1.63	53.2
14	D-7/14	18.0	2.08	30.5	1.72	39.1	1.48	52.4

importance. All plots showed a reduced rate of growth after 1945, except plot B-5/10 which maintained a fairly constant rate for the 20 years.

Diameter

The usual relationship of larger d.b.h. at wider spacings was established early in the experiment and maintained thereafter. The rate of basal area growth of sample trees, although consistently higher at wider spacings, declined on all plots after 1945 (Table 5).

Volume

All thinned plots made less volume growth per acre 1939-45 than the untreated plots, but increased their rate (except for B-5/10 and D-7/14) to equal or surpass growth on their respective controls by 1950-59 (Table 6).

BRANCHES

The number of branches per whorl at the base of the crown seemed to be independent of spacing, height above ground, or date (Table 7). Branch diameters were progressively greater with wider spacing for a given height, with much the largest sizes developing at 14 x 14 feet. At spacings of 5 x 5 and 7 x 7 feet, branch diameter appeared to reach a maximum within 20 feet from the ground, but at the wider spacings was still increasing at that height.

HEIGHT TO CROWN

Relation to Spacing

Changes in height to the live crown were similar at spacings of 5 x 5 and 7 x 7 feet where the average dead-branched length of stem in 1959 was about 34 feet (Table 8). Rate of branch mortality was progressively slower with wider spacings, the base of the live crown occurring at 23 feet above ground

TABLE 5. SAMPLE TREE DIAMETER GROWTH

Spacing Group	Plot	Average d.b.h., inches 1939	1945	1950	1959
5	A-5	3.82	4.55	4.88	5.30
	B-5	3.39	4.45	4.93	5.59
	Av.	3.60	4.50	4.90	5.44
7	A-5/7	3.89	5.51	6.30	7.00
	C-7	4.62	6.21	6.89	7.57
	D-7	4.22	5.77	6.49	7.17
	Av.	4.24	5.83	6.56	7.25
10	B-5/10	2.92	5.51	6.91	8.50
	C-7/10	4.61	7.58	8.94	10.24
	Av.	3.76	6.54	7.92	9.37
14	D-7/14	3.99	7.61	9.57	11.86

Spacing Group	Plot	Basal area increment, square feet per year 1939-45	1945-50	1950-59
5	A-5	0.006	0.003	0.002
	B-5	0.007	0.005	0.004
	Av.	0.006	0.004	0.003
7	A-5/7	0.014	0.010	0.006
	C-7	0.016	0.010	0.006
	D-7	0.015	0.009	0.006
	Av.	0.015	0.010	0.006
10	B-5/10	0.020	0.019	0.015
	C-7/10	0.033	0.023	0.015
	Av.	0.026	0.021	0.015
14	D-7/14	0.038	0.037	0.030

TABLE 6. NET VOLUME GROWTH IN CUBIC FEET PER ACRE PER YEAR

Spacing Group	Plot	1939-45	1945-50	1950-59
5	A-5	196.2	212.8	205.4
	B-5	212.7	248.6	257.4
	Av.	204.4	230.7	231.4
7	A-5/7	188.2	238.4	215.6
	C-7	210.0	247.0	224.8
	D-7	223.0	190.0	192.9
	Av.	207.1	225.1	211.1
10	B-5/10	104.8	150.8	187.1
	C-7/10	179.3	225.4	237.3
	Av.	142.0	188.1	212.2
14	D-7/14	82.7	128.6	180.8

in 1959 for the 14 x 14 foot plot. Rate of change was most rapid during 1939-45 at 5 x 5 and 7 x 7 feet, but increased with time at the two wider spacings. Dead branches to a height of one log-length (17 feet) was reached by 1945 at 5 x 5 foot and 7 x 7 foot spacings, about 1952 at 10 x 10 feet, and about 1955 at 14 x 14 feet.

Within plots there was no great variation in height to crown; except for B-5 in 1939, the maximum difference between diameter classes was less than 3 feet at any date.

For plot pairs the thinned plot in all cases showed a slower rate of branch mortality and had the shortest dead length in 1959. Height to crown on plot A-5/7 was similar to that of the other 7 x 7 foot plots by 1945.

Relation to Stem Growth

For each spacing the plotted values of mean sample tree d.b.h. over mean height to crown yielded a smooth curve (Figure 1). Annual basal area growth and average height to

TABLE 7 BRANCH DEVELOPMENT AT BASE OF CROWN*

Plot	Date	Height to Crown, feet Plot Mean	Height to Crown, feet Sample Mean	No. Branches per Whorl	Mean Branch Diameter, in.	Maximum Aggregate** Diameter, in.
B-5	1939	4.8	5.2	6.5	0.65	4.20
	1945	16.4	16.2	6.5	0.61	4.16
	1950	21.4	20.6	4.0	0.88	4.74
	1959	32.2	31.2	2.0	0.71	2.56
C-7	1939	5.4	5.2	6.0	0.76	4.99
	1945	18.1	17.2	6.5	0.92	6.56
	1950	23.8	23.9	6.0	0.91	5.81
	1959	36.8	34.9	5.0	0.88	4.63
B-5/10	1939	4.2	3.7	4.0	0.68	3.60
	1945	6.8	7.1	4.5	0.71	4.04
	1950	12.0	13.2	6.0	0.95	5.92
	1959	24.0	24.8	5.0	1.13	6.07
D-7/14	1939	2.6	3.1	5.0	0.72	3.70
	1945	6.4	6.5	6.5	0.93	6.67
	1950	11.7	12.3	6.0	1.34	9.58
	1959	23.2	22.1	6.5	1.46	10.74

* Dwarf branches not included.

** Sum of branch diameters in 1' section.

crown were apparently inversely related (Figure 2). The relationship of height to crown with height and spacing is clearly brought out in Figure 3 where values for each plot and measurement date are presented.

Average height to crown for the plot and plot total volume per acre were also closely correlated, with no differentiation by spacings (Figure 4). Annual volume growth did not show a clear association with average height to crown for the period.

TABLE 8. AVERAGE HEIGHT TO CROWN IN FEET

Spacing Group	Plot	1939	Annual Change 1939-45	1945	Annual Change 1945-50	1950	Annual Change 1950-59	1959	Annual Change 1939-59
5	A-5	9.0	1.77	19.6	1.04	24.8	1.11	34.8	1.29
	B-5	4.8	1.93	16.4	1.00	21.4	1.20	32.2	1.37
	Av.	6.9	1.85	18.0	1.02	23.1	1.16	33.5	1.33
7	A-5/7	9.3	1.28	17.0	0.98	21.9	1.30	33.6	1.22
	C-7	5.4	2.12	18.1	1.14	23.8	1.44	36.8	1.57
	D-7	3.4	1.95	15.1	1.32	21.7	1.12	31.8	1.42
	Av.	6.0	1.78	16.7	1.15	22.5	1.29	34.1	1.40
10	B-5/10	4.2	0.43	6.8	1.04	12.0	1.33	24.0	0.99
	C-7/10	4.7	1.12	11.4	1.44	18.6	1.51	32.2	1.38
	Av.	4.4	0.78	9.1	1.24	15.3	1.42	28.1	1.18
14	D-7/14	2.6	0.63	6.4	1.06	11.7	1.28	23.2	1.03

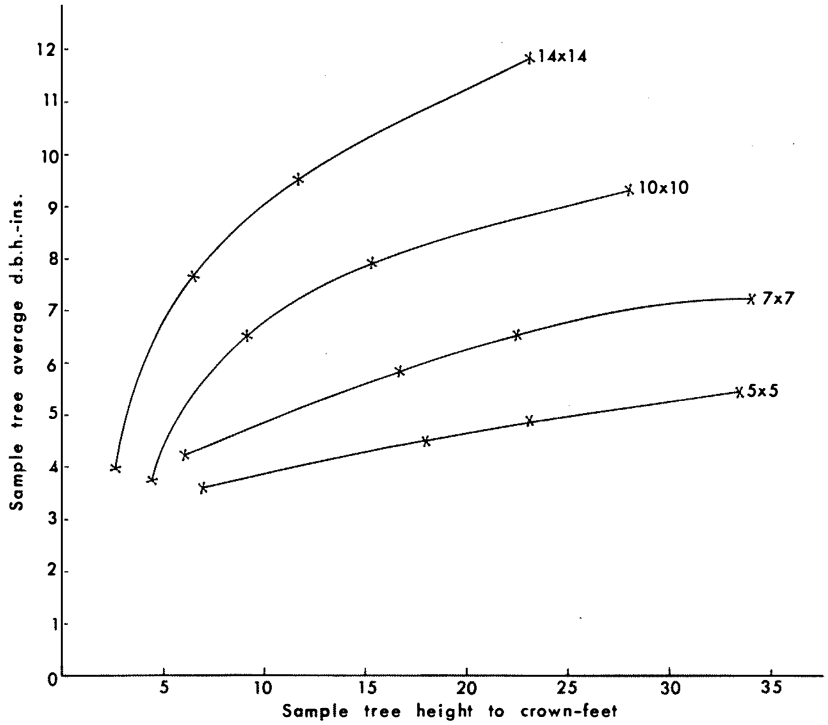

Figure 1. Relationship sample tree diameter at breast height to height to crown.

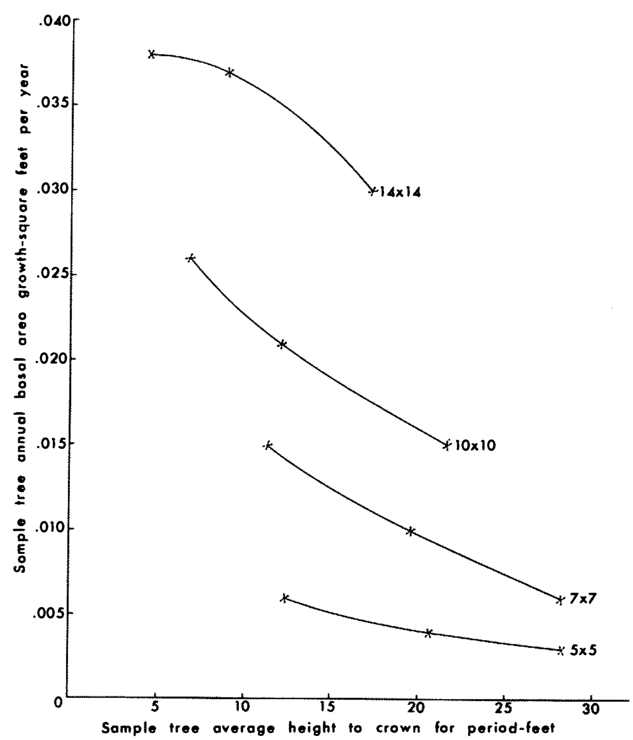

Figure 2. Relationship sample tree basal area growth to height to crown.

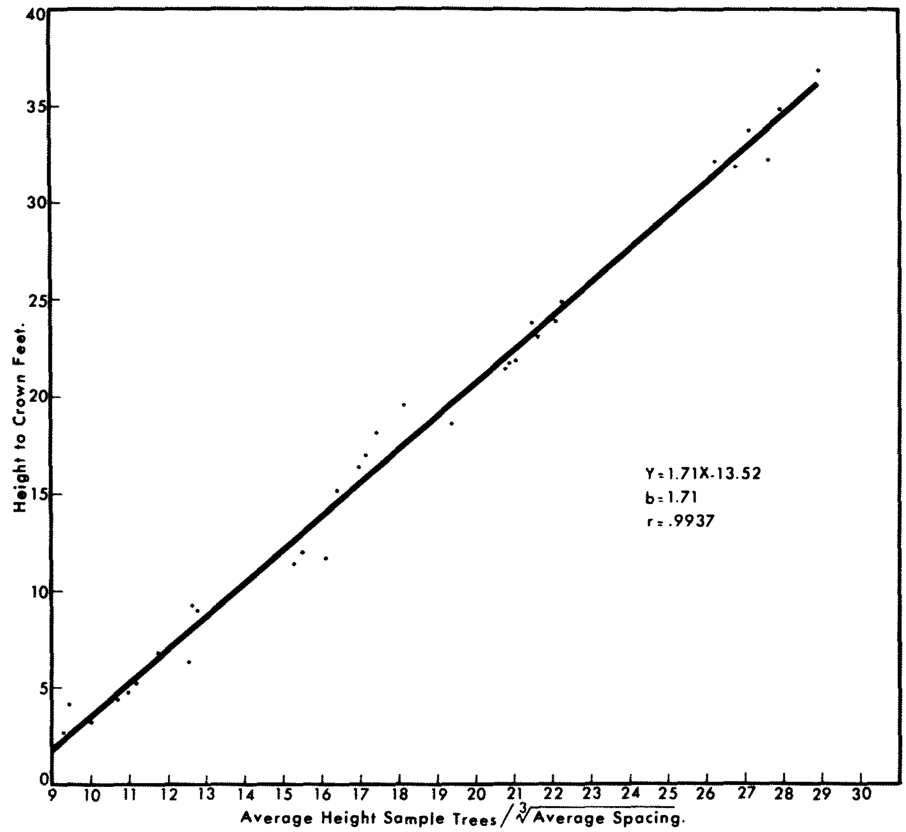

Figure 3. Relationship height to crown to tree height and spacing.

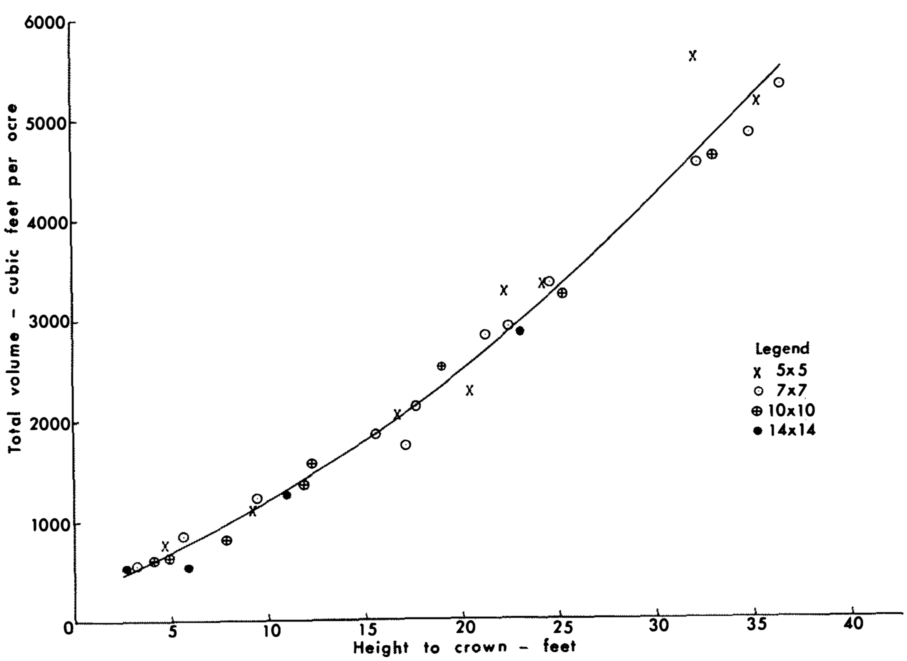

Figure 4. Relationship volume per acre to average height to crown.

TABLE 9. AVERAGE CROWN LENGTH IN FEET

Spacing Group	Plot	1939	Annual Growth 1939-45	1945	Annual Growth 1945-50	1950	Annual Growth 1950-59	1959	Annual Growth 1939-59
5	A-5	13.5	-0.12	12.8	+0.38	14.7	+0.11	15.7	+0.11
	B-5	14.4	-0.18	13.3	+0.32	14.9	+0.28	17.4	+0.15
	Av.	14.0	-0.15	13.0	+0.35	14.8	+0.19	16.6	+0.13
7	A-5/7	12.8	+0.67	16.8	+0.52	19.4	+0.03	19.7	+0.34
	C-7	16.0	-0.05	15.7	+0.52	18.3	+0.28	20.8	+0.24
	D-7	15.9	+0.15	16.8	+0.46	19.1	+0.19	20.8	+0.24
	Av.	14.9	+0.25	16.4	+0.50	18.9	+0.17	20.4	+0.28
10	B-5/10	12.4	+1.13	19.2	+0.60	22.2	+0.24	24.4	+0.60
	C-7/10	16.3	+1.00	22.3	+0.40	24.3	+0.18	25.9	+0.48
	Av.	14.3	+1.06	20.8	+0.50	23.2	+0.21	25.2	+0.54
14	D-7/14	15.4	+1.45	24.1	+0.66	27.4	+0.20	29.2	+0.69

CROWN LENGTH

Crown length increased on all plots over the 20-year period, and even by 1945 was progressively greater at wider spacings (Table 9). The increase in length 1939-59 averaged only 2.5 feet at 5 x 5 feet, but was nearly 14 feet at 14 x 14 foot spacing.

The principal gain by thinned over unthinned plots and by wider over closer spacings was made in 1939-45. Increase was very slight on all plots after 1950.

Within plots, longer crowns generally accompanied larger stem diameters. In several instances crowns in 1945 or 1950 were actually shorter than in 1939.

Relation to Stem Growth

Mean crown length did not show a good association with mean d.b.h. except at 14 x 14 foot spacing. Basal area growth of sample trees seemed to be inversely related to average crown length for the period, with curves for the spacings well separated (Figure 5).

Volume per acre and plot crown length were not clearly associated, nor were volume growth and crown length for the period except at 14 x 14 feet.

LIVE CROWN RATIO

Plots were aligned with lower ratios at closer spacings by 1945, and this relationship was maintained (Table 10). By 1959 all ratios were greatly reduced -- to 31 per cent on plot A-5 (the lowest) and 56 per cent on plot D-7/14 (the highest). Reductions were more rapid during 1939-45 at 5 x 5 and 7 x 7 feet, but during 1945-50 at wider spacings.

In 1959 ratios within plots showed a tendency to be higher for larger diameter classes.

Relation to Stem Growth

The mean d.b.h. of sample trees is inversely related

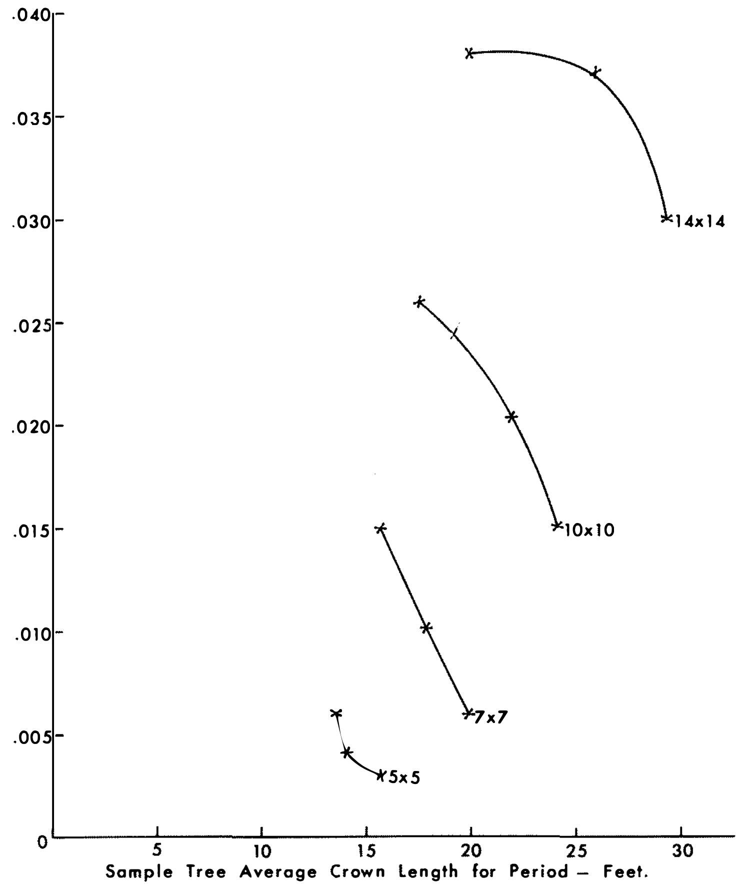

Figure 5. Relationship sample tree basal area growth to crown length.

to mean live crown ratio (Figure 6). Basal area growth shows a positive correlation with average ratio for the period (Figure 7). In both cases the curves separate by spacing.

Plot volume is inversely related to crown ratio, by spacing, but volume growth does not show a clear association with average live crown ratio.

CROWN WIDTH

Relation to Spacing

Even by 1945 greater crown width was consistently associated with wider spacing. Crown width fluctuated at the 5 x 5 foot spacing, resulting in a slight decrease by 1959 (Table 11). Little net change occurred at 7 x 7 feet after 1945. Width was still increasing by 1959 at 10 x 10 feet, and

TABLE 10. AVERAGE PER CENT LIVE CROWN RATIO

Spacing Group	Plot	1939	Annual Change 1939-45	1945	Annual Change 1945-50	1950	Annual Change 1950-59	1959	Annual Change 1939-59
5	A-5	60.0	-3.41	39.5	-0.46	37.2	-0.68	31.1	-1.44
	B-5	75.0	-5.03	44.8	-0.76	41.0	-0.66	35.1	-2.00
	Av. *	66.9	-4.13	42.1	-0.62	39.0	-0.66	33.1	-1.69
7	A-5/7	57.9	-1.37	49.7	-0.54	47.0	-1.11	37.0	-1.04
	C-7	74.8	-4.73	46.4	-0.58	43.5	-0.82	36.1	-1.94
	D-7	82.4	-4.95	52.7	-1.18	46.8	-0.81	39.5	-2.14
	Av.	71.1	-3.58	49.6	-0.78	45.7	-0.91	37.5	-1.68
10	B-5/10	74.7	-0.15	73.8	-1.78	64.9	-1.61	50.4	-1.22
	C-7/10	77.6	-1.90	66.2	-1.92	56.6	-1.33	44.6	-1.65
	Av.	76.3	-1.13	69.5	-1.82	60.4	-1.46	47.3	-1.43
14	D-7/14	85.6	-1.10	79.0	-1.73	70.1	-1.60	55.7	-1.50

* Spacing group averages are based directly on height and crown length data and are not means of the respective plot ratios.

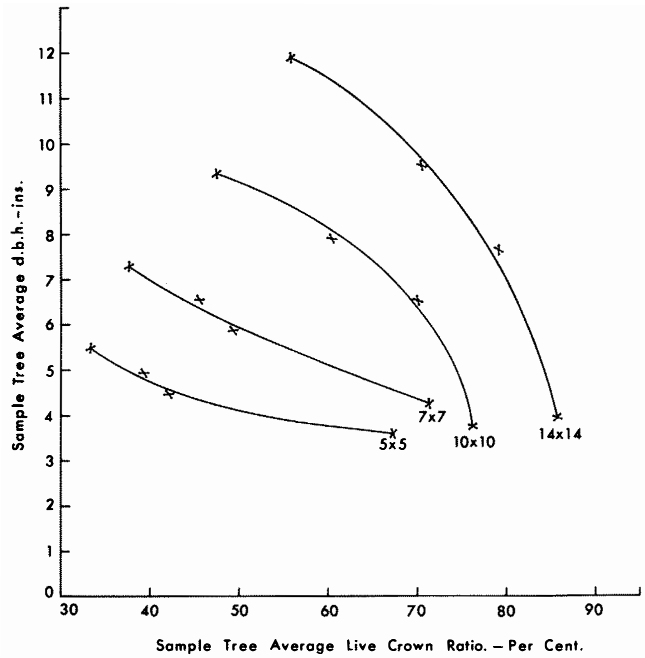

Figure 6. Relationship sample tree diameter to live crown ratio.

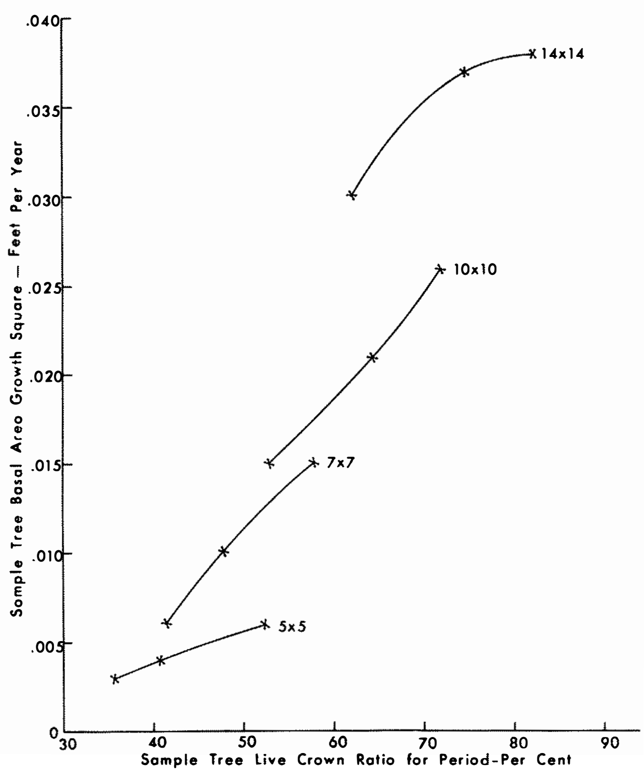

Figure 7. Relationship sample tree basal area growth to live crown ratio.

TABLE 11. AVERAGE CROWN WIDTH IN FEET

Spacing Group	Plot	1939	Annual Growth 1939-45	1945	Annual Growth 1945-50	1950	Annual Growth 1950-59	1959	Annual Growth 1939-59
5	A-5	8.0	+0.08	8.5	-0.20	7.5	-0.02	7.3	-0.04
	B-5	9.2	-0.05	8.9	-0.18	8.0	+0.01	8.1	-0.06
	Av.	8.6	+0.02	8.7	-0.19	7.8	-0.01	7.7	-0.05
7	A-5/7	8.3	+0.52	11.4	-0.12	10.8	-0.05	10.3	+0.10
	C-7	10.7	+0.02	10.8	-0.12	10.2	-0.01	10.1	-0.03
	D-7	9.3	+0.23	10.7	-0.06	10.4	-0.09	9.6	+0.02
	Av.	9.4	+0.26	11.0	-0.10	10.5	-0.05	10.0	+0.03
10	B-5/10	8.2	+0.57	11.6	+0.28	13.0	+0.02	13.2	+0.25
	C-7/10	10.5	+0.60	14.1	+0.20	15.1	+0.13	16.3	+0.29
	Av.	9.4	+0.58	12.8	+0.24	14.0	+0.08	14.8	+0.27
14	D-7/14	9.2	+0.80	14.0	+0.48	16.4	+0.16	17.8	+0.43

at 14 x 14 feet where the crowns were more than twice the diameter of those on the 5 x 5 foot plots.

Crown width on thinned plots showed its greatest rate of increase during 1939-45. Within plots, wider crowns uniformly occurred on trees with larger diameters. There was a tendency, particularly in unthinned plots, for crown width of a given d.b.h. class to decrease with time, e.g. for 6-inch trees in 1945 to have wider crowns than 6-inch trees in 1950.

Relation to Growth

The only variable showing good correlation with mean crown width was mean sample tree d.b.h., and then only for the 10 x 10 and 14 x 14 foot spacings.

FOLIAGE WEIGHT

Relation to Spacing

Average foliage weight of the crown at 5 x 5 foot spacing fluctuated somewhat between 1939 and 1959, but there was no consistent trend. At 7 x 7 feet there was little change after 1945. At wider spacings crowns were still increasing in weight by 1959, although at diminished rates. Plots that had been thinned showed immediate response in 1939-45 (Table 12). On the individual plots heavier crowns were almost invariably associated with trees of larger d.b.h. Crown weight of a given d.b.h. class also tended to decrease with time.

The 5 x 5 foot plots carried the greater weight of foliage per acre in 1939 before thinning (Table 13). Thereafter the 5 x 5 foot plots generally showed the greatest rate of increase 1939-45, and for the two wider spacings were still gaining by 1959. The 14 x 14 foot plot had the lowest weight of foliage per acre until 1950.

Relation to Growth

Mean crown foliage weight showed some correlation with mean sample tree d.b.h. at the 10 x 10 and 14 x 14 foot

TABLE 12. OVEN-DRY FOLIAGE WEIGHT OF AVERAGE CROWN IN KILOS

Spacing Group	Plot	1939	Annual Change 1939-45	1945	Annual Change 1945-50	1950	Annual Change 1950-59	1959	Annual Change 1939-59
5	A-5	5.01	+0.04	5.26	-0.08	4.85	-	4.89	-0.01
	B-5	6.49	-0.12	5.80	-0.08	5.38	+0.09	6.16	-0.02
	Av.	5.75	-0.04	5.53	-0.08	5.12	+0.04	5.52	-0.01
7	A-5/7	5.08	+0.91	10.51	+0.06	10.80	-0.08	10.12	+0.25
	C-7	9.04	-	9.04	+0.06	9.34	+0.10	10.25	+0.06
	D-7	7.14	+0.38	9.42	+0.12	10.02	-0.07	9.40	+0.11
	Av.	7.09	+0.43	9.66	+0.08	10.05	-0.02	9.92	+0.14
10	B-5/10	4.88	+1.48	13.78	+0.65	17.05	+0.23	19.13	+0.71
	C-7/10	8.90	+1.83	19.90	+0.92	24.51	+0.62	30.10	+1.06
	Av.	6.89	+1.66	16.84	+0.79	20.78	+0.43	24.62	+0.89
14	D-7/14	6.84	+2.38	21.10	+2.21	32.14	+0.87	39.99	+1.46

TABLE 13. OVEN-DRY FOLIAGE WEIGHT PER ACRE IN KILOS

Spacing Group	Plot	1939	Annual Change 1939-45	1945	Annual Change 1945-50	1950	Annual Change 1950-59	1959	Annual Change 1939-59
5	A-5	6775	+ 94.2	7340	-159.0	6545	+21.7	6740	- 1.8
	B-5	9910	-202.5	8695	- 81.0	8290	+69.5	8915	-49.8
	Av.	8342	- 54.2	8018	-120.0	7418	+45.6	7828	-25.7
7	A-5/7	3655	+668.3	7665	+127.0	8300	-65.6	7710	+202.8
	C-7	6780	+ 76.7	7240	- 56.0	6960	+52.8	7435	+ 32.8
	D-7	5200	+315.0	7090	+ 47.0	7325	-39.4	6970	+ 88.5
	Av.	5212	+353.3	7332	+ 39.2	7528	-17.3	7372	+108.0
10	B-5/10	2080	+545.0	5350	+465.0	7675	+ 25.0	7900	+291.0
	C-7/10	3023	+558.2	6372	+316.9	7956	+225.9	9989	+348.3
	Av.	2552	+551.5	5861	+391.0	7816	+125.3	8944	+319.6
14	D-7/14	1320	+390.0	3660	+394.0	5630	+221.7	7625	+315.2

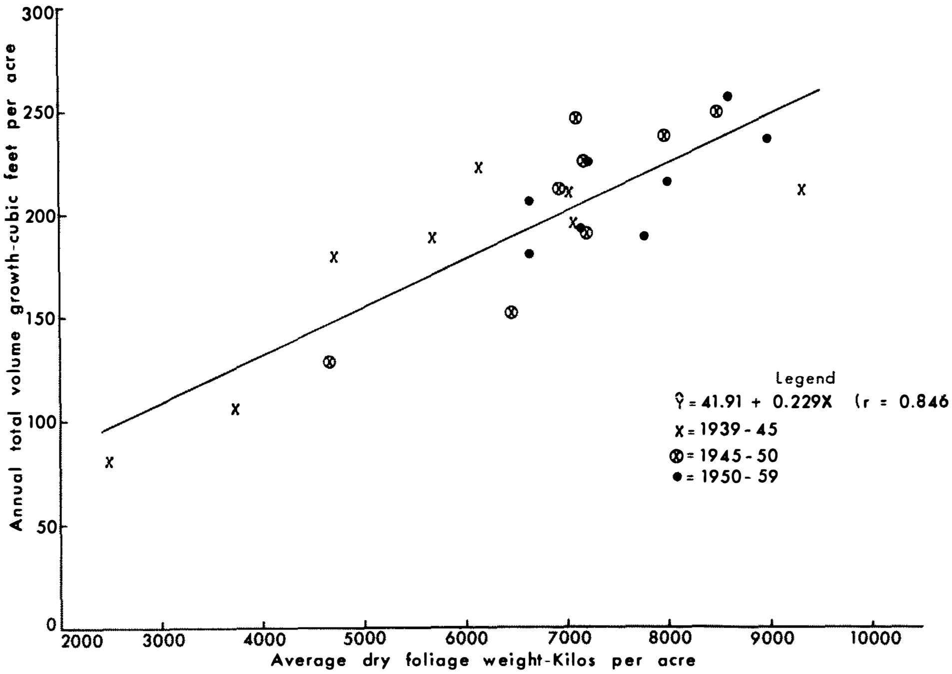

Figure 8. Regression volume growth per acre on foliage weight.

spacings, but did not show a good association with basal area growth.

Periodic volume growth per acre was strongly correlated (r=0.846) with average foliage weight for the period (Figure 8). Wood production per kilo of foliage ranged from 0.023 to 0.038 cubic feet (Table 14). In this respect thinned plots showed the greater efficiency 1939-45 (except at 14 x 14 feet), but in later periods were less productive than corresponding untreated plots.

DISCUSSION AND CONCLUSIONS

Where spacing is virtually unaltered, average crown size eventually appears to become more or less constant. The closer the spacing, the earlier this occurs and the smaller the size attained. While becoming approximately fixed in size, the crown continues of course in a state of self-renewal, regularly adding whorls at the top and dying, more erratically, at the base. By contrast, stem growth is cumulative and stem

TABLE 14. TOTAL WOOD VOLUME PRODUCTION IN CUBIC FEET PER KILO DRY FOLIAGE

Spacing Group	Plot	1939-45	1945-50	1950-59
5	A-5	0.028	0.031	0.031
	B-5	0.023	0.029	0.030
	Av.	0.026	0.030	0.030
7	A-5/7	0.033	0.030	0.027
	C-7	0.030	0.035	0.031
	D-7	0.036	0.026	0.027
	Av.	0.033	0.030	0.028
10	B-5/10	0.028	0.023	0.024
	C-7/10	0.038	0.032	0.026
	Av.	0.033	0.028	0.025
14	D-7/14	0.033	0.028	0.027
	Mean	0.031	0.029	0.028

dimensions continue to increase, and thus could not be expected to show correlation with individual crown parameters once the latter have stabilized. This explains why there was some correlation between d.b.h. and crown parameter at the 10 x 10 and 14 x 14 foot spacings where crown size was still increasing, but none at 5 x 5 and 7 x 7 feet where the crowns had stabilized early in the experiment or even before it had begun.

D.b.h. and crown size may be correlated within a stand at one age, or rather height; but since a given d.b.h. class near the top of the diameter distribution at an early age necessarily occupies a lower position in the distribution at later dates, no over-all association is possible where crown sizes are stable.

Foliage weight per acre also seems to reach a constant value, with earlier stabilization taking place at closer spacings. By providing more growing space, thinning allows individual crowns to resume enlarging, perhaps until the same amount of foliage per acre has been reached again. Such behaviour is exemplified by plot A-5/7 where previously stabilized crowns enlarged following thinning, achieving a new maximum weight per tree, but much the same foliage weight per acre, within about 6 years. In at least two other investigations it was concluded that foliage weight per unit area did not increase beyond a certain level. Mar: Möller (1947) in studies of beech (*Fagus* sp.) leaf fall found the dry weight of foliage per hectare reaching a maximum soon after "full growth" was attained, but only making a slight increase between ages 20 and 120 years. In an age series of Scots pine (*Pinus sylvestris* L.) plantations 3 to 55 years old, Ovington (1957) concluded that foliage weight per tree increased up to the thicket stage, became more or less constant, and then increased again with the advent of thinning; foliage per hectare reached a maximum constant weight at about 20 years, although apparently fluctuating following thinning.

In this experiment foliage weight on the heavily thinned plots had not clearly reached a maximum 20 years after treatment, and the data do not fully support the supposition that an approximately uniform weight of foliage per acre would be reached at all spacings. Evident inconsistencies (plot C-7/10) may arise from site differences or imperfect field technique. The amount of foliage that a closed red pine stand will carry cannot therefore be stated, but the data suggest that it is a fluctuating one, probably varying between 7,500 and 10,000 Kg. per acre, values that are similar to those obtained for Scots pine by Ovington (1957).

Thinning seems to be followed by an immediate increase in stem wood production per unit of foliage. This may be a result of accelerated photosynthesis under the higher average light intensities. An increased moisture supply via grafts with root systems of the thinned trees may also be a factor.

This effect does not seem to last for more than a few years, and not necessarily until crowns have closed again, and foliage efficiency is not clearly related to spacing itself.

Full occupancy of the site might be taken as occurring when individual crowns have just stabilized. Later, crowns are the same size but stems are larger and thus there is less foliage per unit of bole. With constant crown size, constant wood production might be inferred, but if so, the layer of wood laid down over the increasingly larger stem must get thinner every year. Hence basal area growth declined on all plots in this study, although crown size did not; even where crowns were still enlarging, basal area increment was not maintained. It follows that growth at breast-height will be a function of quantity of foliage and the length of stem over which wood increment must be applied. This can be expressed as the ratio of crown weight to height to crown, which shows a good correlation with basal area growth (Figure 9). As opposed to actual crown dimensions that tend to stabilize, the derivative measures of height to crown and live crown ratio continue to change and to show some association with concomitant stem measurements. Height to the crown seems to be the more useful indicator both of tree basal area growth, as just discussed, and of volume per acre, with neither relationship varying with spacing. A very consistent relationship between height to crown and the ratio average height $/\sqrt[3]{\text{average spacing}}$ also exists (Figure 3). Live crown ratio by itself is not particularly meaningful.

Wood quality is affected in several ways by relative branchiness or crown position. Clear lumber could not be obtained with any of these spacings without resort to pruning, but the much larger branch diameters within the first 17-foot length at 10 x 10 and 14 x 14 foot spacing suggest a progressively more difficult pruning job as spacing increases. Poles are important products of red pine plantations, but specifications forbid knot diameters in any one-foot section to aggregrate

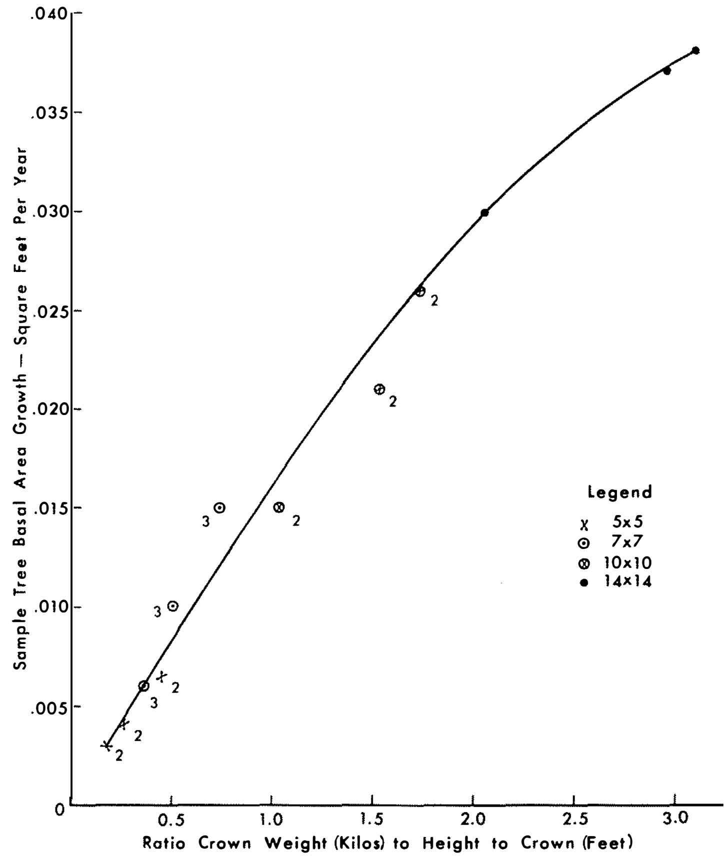

Figure 9. Relationship sample tree basal area growth to ratio crown weight/ height to crown.

more than 8 inches (Anon. 1960). In this respect stock from the 14 x 14 foot spacing would be unacceptable as poles. Crown position affects stem form, and a separate study of selected trees on plots C-7 and D-7/14 indicated a much lower form class associated with the longer crowns at 14 x 14 feet spacing (Berry 1964).

SUMMARY

1. Crown studies were carried out over a 20-year period in red pine plantations growing at spacings of 5 x 5, 7 x 7, 10 x 10 and 14 x 14 feet. These spacings were attained by keeping parts of plantations at their original spacings of 5 x 5 or 7 x 7 feet and by mechanically thinning parts of them

to the wider spacings when the stands were 17 years old from seed. Measurements of crown width and length were taken on selected trees immediately after the thinning, and periodically until the plantations were 37 years old. Concurrent stem measurements were made as well. Crown weights were calculated by formula, and foliage weights per acre estimated by relating crown weight to d.b.h. and summing the diameter classes.

2. Prior to thinning, trees on the 7 x 7 foot plots had somewhat longer and wider crowns than those spaced at 5 x 5 feet.

3. Thinned plots showed immediate response, enlarging their crowns much more rapidly than their untreated controls.

4. Over the next 20 years a clear association of larger crowns with wider spacings was established.

5. Without further increase in spacing, individual crown size tended to stabilize. The closer the spacing the earlier this occurred and the smaller the size attained.

6. Foliage weight per acre also seemed to reach a maximum, and eventually may be the same for all spacings, probably fluctuating between 7,500 and 10,000 Kg, oven-dry weight.

7. Periodic volume growth per acre was strongly correlated with average foliage weight for the period (r=0.846).

8. Wood production per kilo of oven dry foliage ranged from 0.023 to 0.038 cubic feet. Thinning was followed by an immediate but temporary increase in foliage efficiency.

9. Crown length and width and weight, once stabilized, did not show good correlations with parameters of individual stem growth which are cumulative.

10. Height to crown continued to increase, and was strongly correlated with total volume per acre, and with the ratio average height $/\sqrt[3]{\text{average spacing}}$.

11. Breast-height growth of sample trees declined at all spacings, and appeared to be a function of crown weight and height to crown.

12. Branch diameters were progressively greater with

wider spacing for a given height, and at 10 x 10 and 14 x 14 foot spacings were still increasing at a height of 20 feet above the ground.

13. Trees at 14 x 14 foot spacings would not be acceptable for pole stock owing to excessively thick branches.

SOMMAIRE

1. On a observé pendant vingt ans, du point de vue de la croissance de leur cime, des pins rouges plantés à espacement de 5 pi. sur 5, 7 pi. sur 7, 10 pi. sur 10 et 14 pi. sur 14. Pour obtenir ces espacements, on a conservé à certains secteurs de la plantation leur espacement initial de 5 pi. sur 5 ou de 7 pi. sur 7, mais on a pratiqué des coupes d'éclaircie à la machine dans certains autres secteurs, 17 ans après l'ensemencement des sujets, pour en arriver aux plus grands espacements précités. La largeur et la longueur des cimes des sujets choisis ont été mesurées immédiatement après la coupe d'éclaircie, et ensuite périodiquement jusqu'à ce que les sujets eurent atteint 37 ans. On prenait en même temps des mesures de la tige des sujets. On a calculé le poids des cimes en se servant d'une formule, et on a estimé le poids du feuillage à l'acre en établissant le rapport entre le poids de la cime et le diamètre à hauteur de poitrine, puis en totalisant les diverses classes de diamètre.

2. Avant les coupes d'éclaircie, les cimes des sujets des secteurs à espacement de 7 pi. sur 7 étaient quelque peu plus longues et plus larges que celles des sujets des secteurs à espacement de 5 pi. sur 5.

3. Les sujets des secteurs éclaircis ont immédiatement réagi au traitement, leurs cimes s'élargissant beaucoup plus rapidement que celles des sujets des secteurs témoins laissés intacts.

4. Au cours des vingt années qui ont suivi, le rapport entre les cimes les plus larges et les espacements les plus

grands s'établissait nettement.

5. Sans autre accroissement des espacements, les dimensions de chaque cime avaient tendance à se stabiliser. Plus l'espacement entre les sujets était faible, plus vite cette tendance se manifestait et plus les dimensions atteintes diminuaient.

6. En outre, le poids du feuillage à l'acre a semblé atteindre un maximum, et ce poids pourrait bien, en fin de compte, être le même pour tous les espacements, avec des variations probables qui s'établiraient entre 7,500 et 10,000 kilos (poids anhydre).

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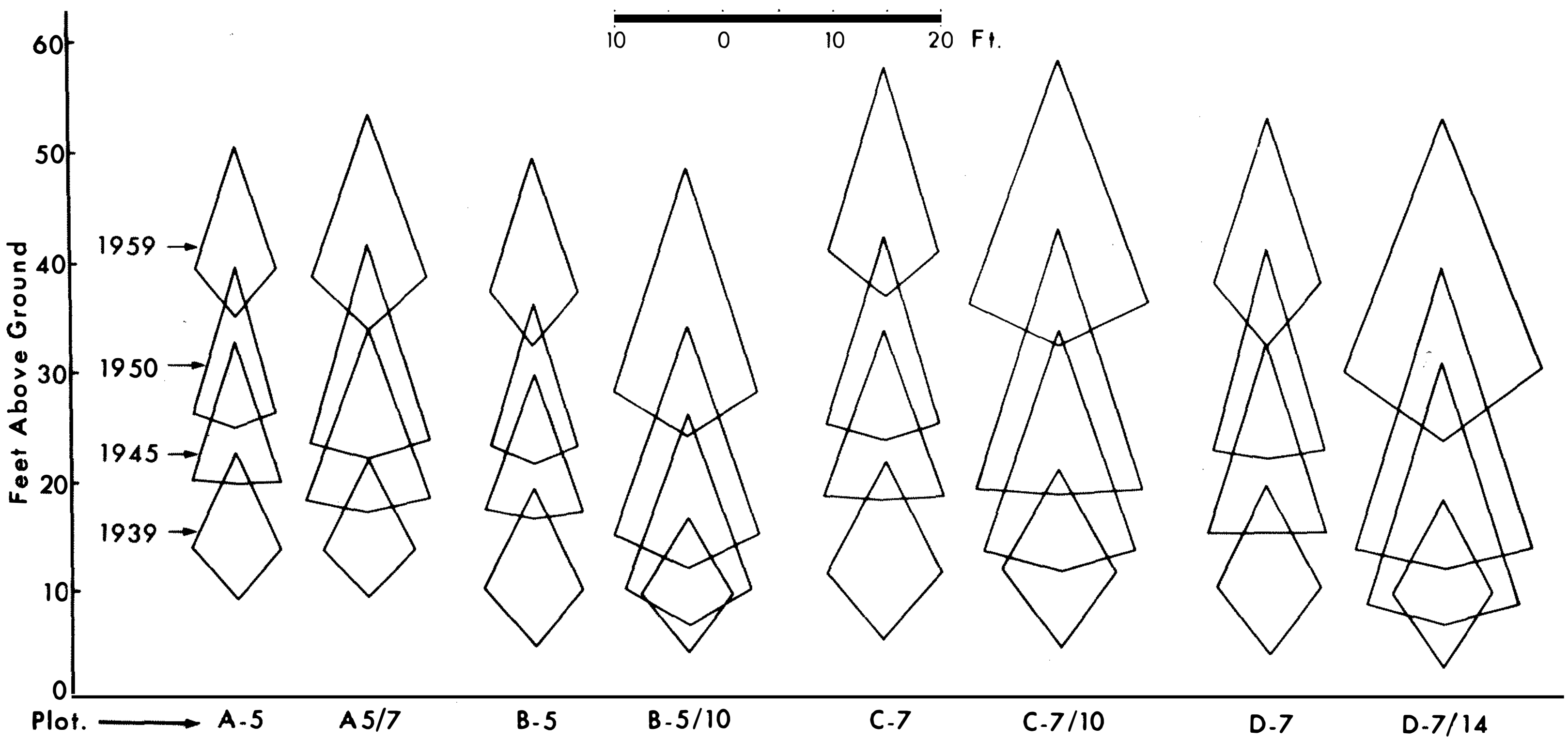
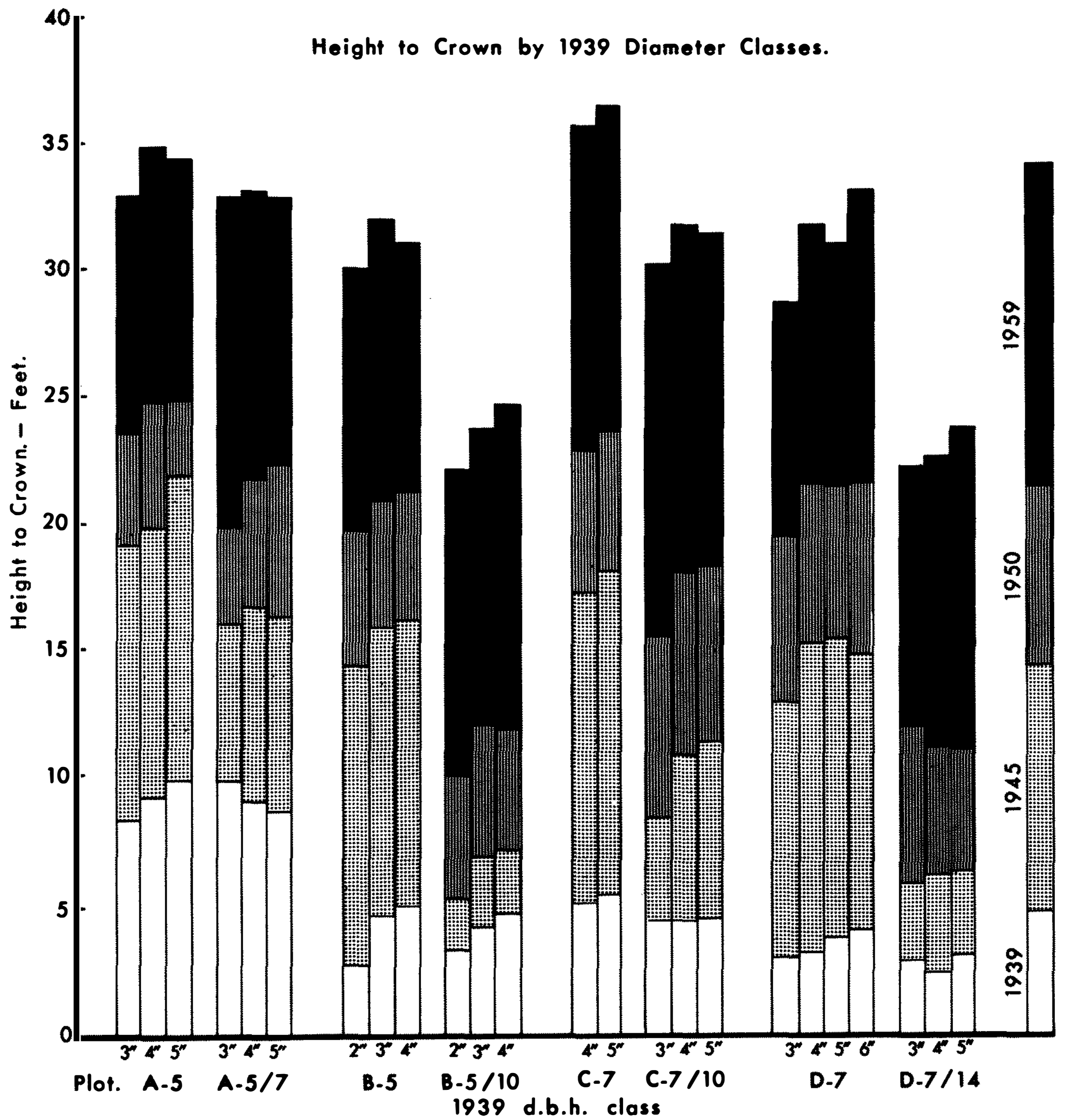
APPENDIX 1

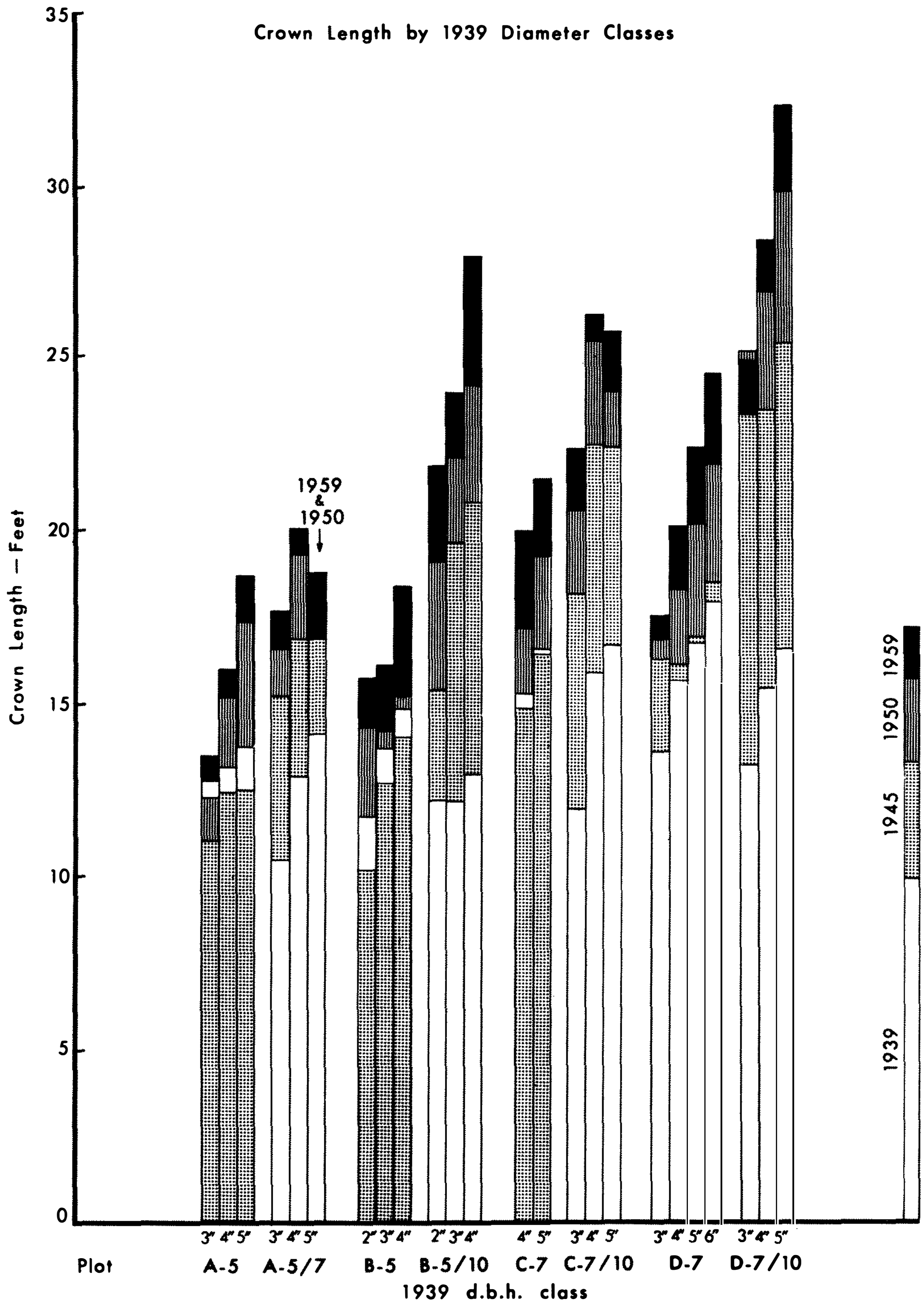
SCHEMATIC CROWN PROFILES OF SAMPLE TREES



APPENDIX 2

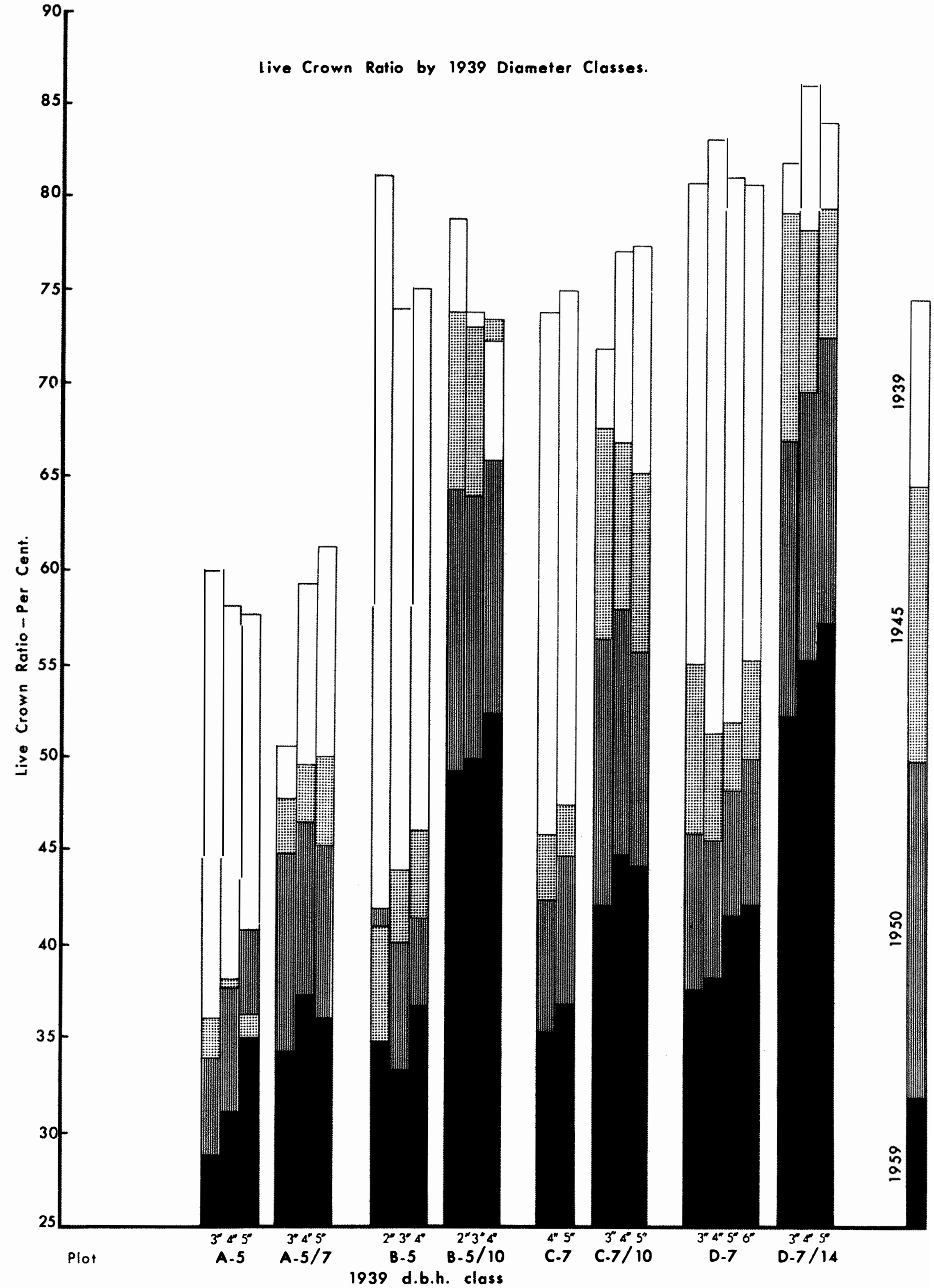

Height to Crown by 1939 Diameter Classes.
Height to Crown. – Feet.
40
35
30
25
20
15
10
5
0
1959
1950
1945
1939
3" 4" 5"
3" 4" 5"
2" 3" 4"
2" 3" 4"
4" 5"
3" 4" 5"
3" 4" 5" 6"
3" 4" 5"
Plot. A-5 A-5/7 B-5 B-5/10 C-7 C-7/10 D-7 D-7/14
1939 d.b.h. class

APPENDIX 3



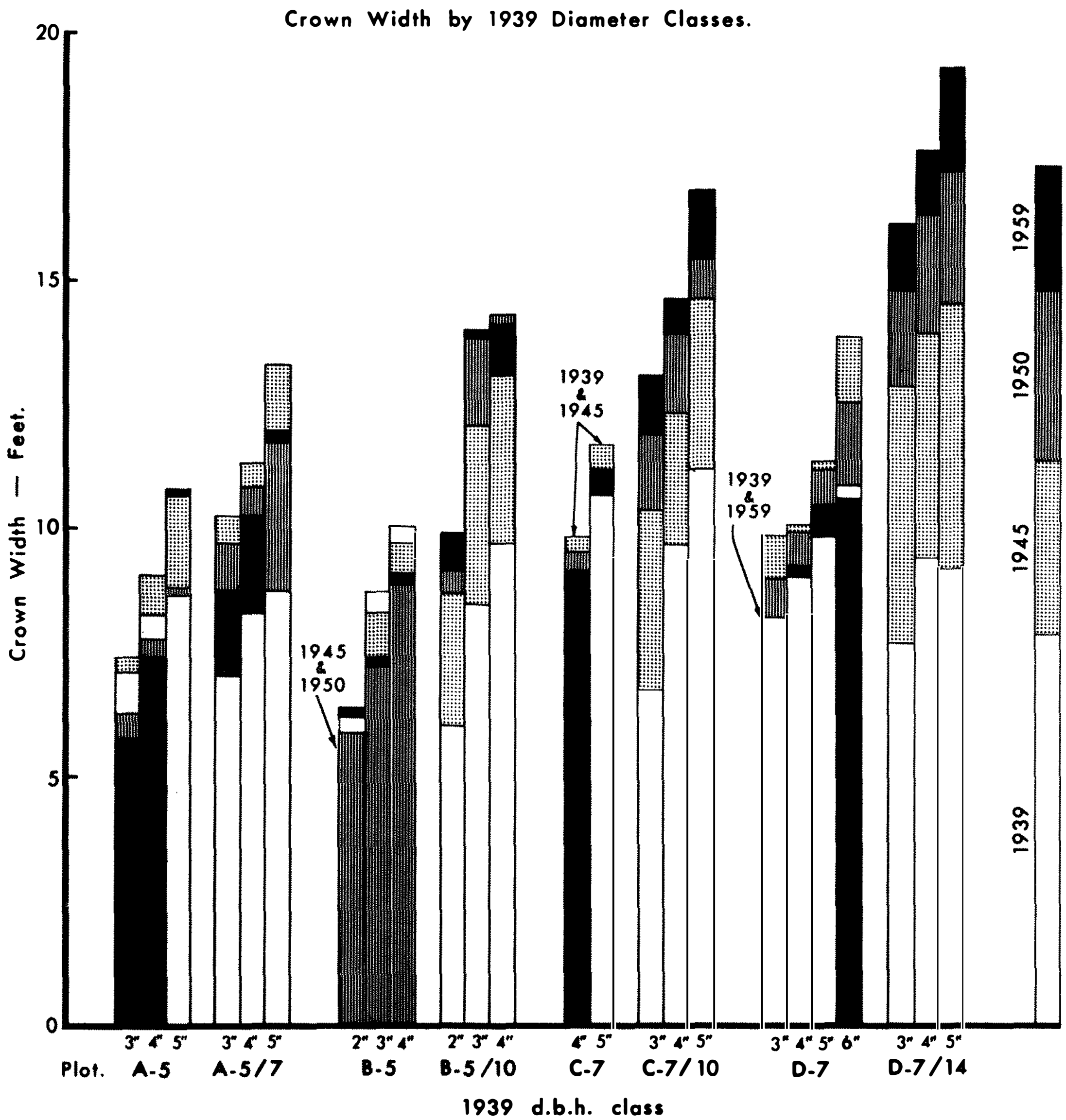
Crown Length by 1939 Diameter Classes
Crown Length — Feet
35
30
25
20
15
10
5
0
1959
&
1950
1959
1950
1945
1939
3" 4" 5" 3" 4" 5" 2" 3" 4" 2" 3" 4" 4" 5" 3" 4" 5" 3" 4" 5" 6" 3" 4" 5"
Plot A-5 A-5/7 B-5 B-5/10 C-7 C-7/10 D-7 D-7/10
1939 d.b.h. class

APPENDIX 4

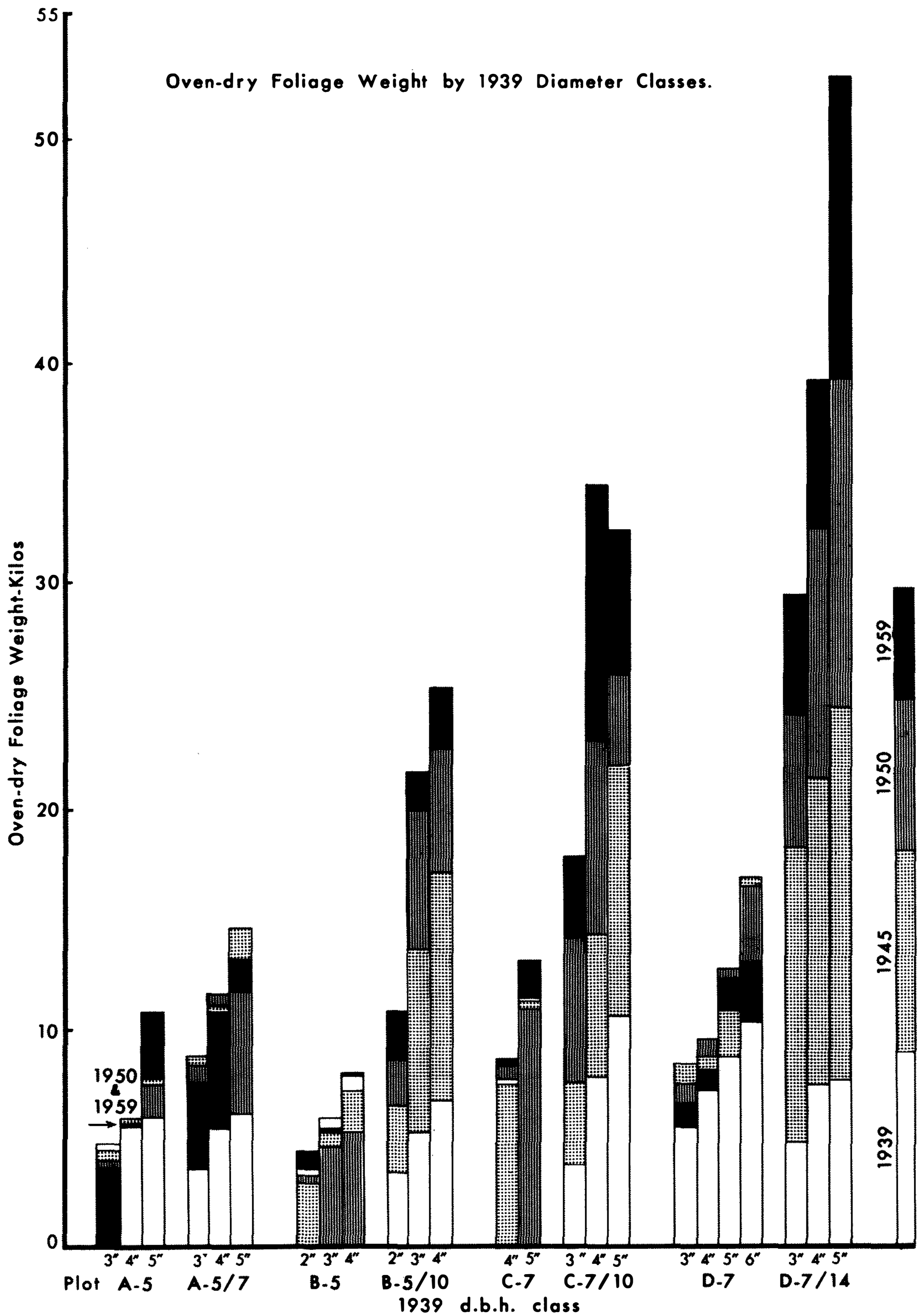


Live Crown Ratio by 1939 Diameter Classes.
Live Crown Ratio – Per Cent.
90
85
80
75
70
65
60
55
50
45
40
35
30
25
1939
1945
1950
1959
3" 4" 5"
3" 4" 5"
2" 3" 4"
2" 3" 4"
4" 5"
3" 4" 5"
3" 4" 5" 6"
3" 4" 5"
Plot
A-5
A-5/7
B-5
B-5/10
C-7
C-7/10
D-7
D-7/14
1939 d.b.h. class

APPENDIX 5


Crown Width by 1939 Diameter Classes.
Crown Width — Feet.
20
15
10
5
0
1945 & 1950
1939 & 1945
1939 & 1959
1959
1950
1945
1939
3" 4" 5"
3" 4" 5"
2" 3" 4"
2" 3" 4"
4" 5"
3" 4" 5"
3" 4" 5" 6"
3" 4" 5"
Plot. A-5 A-5/7 B-5 B-5/10 C-7 C-7/10 D-7 D-7/14
1939 d.b.h. class

APPENDIX 6



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