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LIGHTNING DAMAGE TO DOUGLAS-FIR TREES IN SOUTHWESTERN MONTANA

by

ALAN RAY TAYLOR

B.S. Montana State University, 1960

Presented in partial fulfillment of the requirements for the degree of

Master of Science in Forestry

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1962

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Chairman, Board of Examiners

Dean, Graduate School

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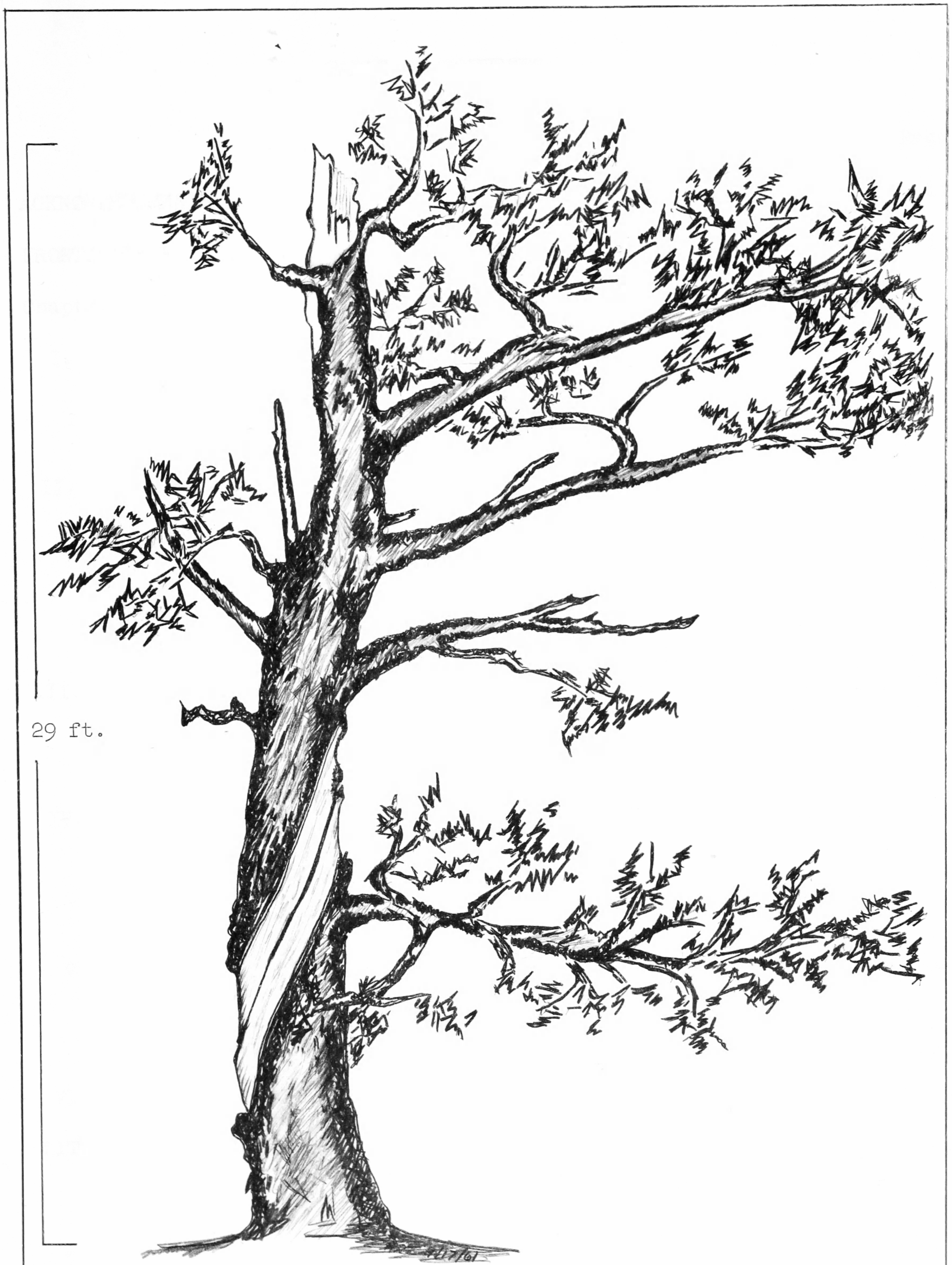

"Lightning is not averse to striking more than once in the same spot
--but frequently once is sufficient."
--McEachron

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CHAPTER I

THE PROBLEM AND ITS SIGNIFICANCE

I. INTRODUCTION

Lightning causes about 10,000 forest fires annually in the United States. During the summer of 1961, more than 2,000 lightning-caused fires occurred in Region 1 of the U. S. Forest Service.

Cloud-to-ground lightning flashes ignite snags, downed-logs, grass, duff, and live trees. Little is known about the complex relations between a lightning discharge, fuel, and meteorological conditions that result in ignition. One thing is certain--lightning causes great damage to forest stands by starting fires and inflicting severe physical damage to standing trees.

The following statements may be generalized from field observations:

1. Trees struck by lightning usually suffer structural damage.
2. Most trees damaged by lightning do not catch fire.

Structural damage is common both to trees that are ignited and to those that do not catch fire. Knowledge of the features common to both fire and non-fire situations could lead to an explanation of why some fuels are ignited while others only receive various degrees of damage. Structural damage--and the way it varies in extent from tree-to tree--is the subject of this paper.

The extent of lightning damage varies widely. Visible damage to a standing tree may vary from a superficial scar to nearly complete destruction of the tree. The reason for this wide variation in damage is not known. The variance may arise from the following considerations:

1. Variance in the character of the lightning discharge.
2. Variance in the physical and environmental characteristics of the tree.

The study was limited to an investigation of (2), the physical and environmental conditions of lightning-damaged trees.

II. OBJECTIVES

Objectives of the study were twofold. The first was to test this hypothesis: The extent of lightning-caused structural damage exhibited by live Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco *glauca*) is a linear function of tree-to-tree differences in the following parameters:

1. Diameter of tree at breast height.
2. Girard form class.
3. Live crown ratio.
4. Age of tree.
5. Shape of top.
6. Crown class.
7. Elevation above Mean Sea Level.

The second objective was to gather descriptive data from lightning-damaged trees to learn more about the nature of the damage. For a complete list of the damage attributes observed, see Table II, Appendix D., page 83. The most noteworthy of these are treated in Chapter IV.

CHAPTER II

REVIEW OF LITERATURE

I. INCIDENCE OF LIGHTNING DAMAGE TO TREES

Lightning Frequency

About 1,800 thunderstorms are in progress throughout the world at any one moment (Schonland, 1950).

McCann (1942) estimated that these storms send fifty lightning discharges to earth per second, or 2 billion per year. These discharges, if equally distributed, would strike each square mile of the earth's surface eight times.

Near Philipsburg, Montana, Fuquay and Baughman recorded 1,336 cloud-to-ground flashes during twenty-one storm days in 1961. All these flashes occurred within an area of about 20 by 20 miles square.[1]

Lightning and Trees

Viemeister (1961) estimated that lightning strikes thousands of trees daily around the world. Mortality studies in the United States tend to confirm this. Reynolds (1940), Wadsworth (1943), and Lindh (1949) declared lightning one of the greatest causes of mortality and volume loss in certain forest stands.

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[1]Fuquay, D. M. and R. G. Baughman. Project Skyfire lightning research, annual report to National Science Foundation, for the period November 15, 1960, to November 15, 1961. 18 pp. Illus. 1962. (Intermountain Forest and Range Expt. Sta., U. S. Forest Service.)

Nelson's study (1958) of mortality on 1,300 acres of mature eastern hemlock (Tsuga canadensis, Carr.) in Pennsylvania included 1,314 dead trees. Lightning, the greatest known single cause, killed more than 25 per cent of them.

Damage Surveys

Spaulding (1912) estimated that in 1911 lightning damaged three or four chestnut (Castanea) trees per square mile in Maryland.

Greater damage concentrations have been reported. Bliss (1928) counted 42 scarred trees on one acre in Colorado. Lightning had struck some of them four times. Belt found 33 damaged Douglas-fir trees on a 74-acre plot in southwestern Montana in 1960.[2]

Forest workers often see lightning damage on trees near telephone lines. Gisborne and Apgar counted 21 newly damaged trees along 2,900 feet of telephone line in northern Idaho. Apparently, one powerful flash traveled along the line, jumped to the nearby trees, and damaged them.[3]

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[2]Belt, G. H. Lightning damage survey. 1961. U. S. Weather Bureau, Dept. of Commerce. (Unpub. manuscript, 10 pp. typed. Illus. On file at Northern Forest Fire Laboratory, Missoula, Mont.)

[3]Gisborne, H. T. Memorandum to files, Subject: RF-NRM, PREVENTION, Lightning, Damage. 1949. Northern Rocky Mountain Forest and Range Expt. Sta. (On file at Northern Forest Fire Laboratory, Missoula, Mont.)

Group Damage

Lightning kills or injures groups of trees as well as individual trees. External damage is usually visible on one or two trees in the group (LaRue, 1922; Murray, 1958). Other trees near the damaged stems eventually die, often in a circular pattern (Hauberg, 1960).

Group damage has been observed in such widely separated places as Sumatra, Honduras, England, Germany, New Zealand, Scotland, and the United States (LaRue, 1922; Reinking, 1938; Peace, 1940; Shipley, 1946; New Zealand Forest Service, 1954; Murray, 1958; Stevens, H. E., 1918).

Murray (1958) described the killing of one hundred 45-year-old Japanese larch (*Larix leptolepis*, Sieb.) on three-quarters of an acre in Scotland. Peace (1940) reported the group-killing of six 60-year-old Douglas-fir trees in England. These examples approximate the range of reported group deaths.

II. NATURE AND EXTENT OF DAMAGE

Range of Damage

Frequently the discharge rips out a narrow strip of bark along the bole, leaving a furrow. This is the most common damage characteristic (Moorhouse, 1939; Murray, 1958).

Many trees are struck, yet show no sign of external damage (Stone, 1914; Stevens, N. E., 1916; Hawley, 1937). On other trees lightning removes only the outer bark flakes in its path along the bole (Dodge, 1936).

On the other hand, lightning destroys some trees. Stevens, A. F. (1921:241) gave this account of severe damage to a live post oak (Quercus stellata, Wangehn.):

> The entire body of the tree was riven into pieces and none of it left near the place where it had been standing. About 18 feet of the top with many branches intact lay immediately over the place where the tree stood. What remained in the ground was torn off at the surface of the ground, but was riven and shivered into slivers.

Similar destruction has been reported by West (1903), Norbury (1927), McEachron (1940), and Viemeister (1961). Typically, the evidence suggested a violent explosion in the middle or lower reaches of the bole. The upper portion of each tree fell intact to the ground.

Thompson's observations (1946:198) on 352 damaged shade trees in the United States showed that damage ranged from a " . . . slight tearing of a single strip of bark to complete demolition of the struck tree."

The tree bole suffers most; but roots (Dorsey, 1925) and branches (Dodge, 1936; Plummer, 1912) are also damaged by lightning.

The Furrow

According to Shipley (1946) and Murray (1958), the furrow may be straight but is usually spiral. What is the explanation of spirality in lightning scars? The remarks of the Russian worker, Gribanov (1955:431) are typical: "The direction and steepness of [the] spiral [furrow] correspond almost exactly to the twisting of the tree fibers in . . . spiral-grained trees." Most writers agree that lightning damage follows the tree fibers, whether straight or spiral.

Lightning usually makes a single furrow on the tree, but Plummer (1912) reported double scars. Sporn and Lloyd (1930) described a tree having four parallel scars--all caused by the same lightning flash.

Shipley (1946) observed that the furrow usually extended from the uppermost branch to the base of the tree; but Fisher (1907) and McAdie (1929) placed the upper scar limit several feet below the tree tip. From observations on 1,351 damaged trees in Belgium, Vanderlinden (1907) concluded that the upper scar limit most frequently coincided with the base of the crown. He also noted that the scar often did not reach ground level. Thompson (1936), Dodge (1936), and Murray (1958) reported that furrows were either continuous or discontinuous.

III. ASSOCIATION OF TREE CHARACTERISTICS AND EXTENT OF DAMAGE

This study deals with attributes that may govern the extent of damage--not those that may determine which tree is struck. All references to the probability of a tree being struck have been omitted here.[4]

Electrical Resistivity

Dead wood is usually a poor conductor of electricity. Its insulation properties have long been utilized in power transmission systems (Peek, 1929; Melvin, 1930 and 1933; Sporn and Lusignan, 1938). But live wood cannot be considered a good insulator. A live tree is a much better conductor than air (Defandorf, 1955). Thus, a tree is often the earth

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[4]For a recent review of this subject see Viemeister, P. E. The Lightning Book. Doubleday and Company, New York. pp. 181-184. 1961.

terminus of the lightning discharge.

One measure of a tree's ability to conduct electricity is its direct-current resistance. Defandorf (1955) showed that the ohmic resistance to ground of a live tuliptree (Liriodendron tulipifera, L.) increased markedly from ground level to leaf tips. Also, longitudinal resistance of the branches varied inversely with temperature.

This last point led Defandorf (1956) to state that a " . . . sudden application of high voltage between ends of a green specimen, because of its large negative temperature coefficient of resistance, would lead to a filamentary concentration of the conduction current." He indicated that this could explain the furrow configuration on damaged trees.

Szpor's (1945) resistance measurements on 384 trees in Switzerland showed: (1) wide variations between species, and (2) an inverse relation between daily air temperature change and bole (and branch) resistance.

Other factors that influence direct-current resistivity of wood are moisture content (Earle, 1938; Szpor, 1945; Defandorf, 1956), alignment of the fibers, and kind of wood (Brown, Panshin, and Forsaith, 1952).

Three writers concluded that a continuous film of rainwater on the tree bole became electrolytic and provided a low-resistance path to ground without damage to the tree (U. S. Bureau of Standards, 1929; Dodge, 1936; Botley, 1951). Other workers discredited this view (Szpor, 1945; Shipley, 1946; Defandorf, 1955).

The literature revealed no factual comparison of resistance values between lightly and severely damaged trees; but Fisher (1907), Covert

(1924), and Thompson (1936) associated severe damage with high resistance, and superficial damage with low resistance.

Bark and Wood

European workers observed that smooth-bark trees showed less severe damage than rough-bark trees (Vanderlinden, 1907; Szpor, 1945). They reasoned that thick, irregular bark impeded movement of the current along the bole, resulting in serious damage. Vanderlinden further noted that lightning removed rough bark in uniform strips, but removed smooth bark in slabs of uneven dimensions.

The brittle giant sequoia (*Sequoia gigantea*, L.) is nearly always shattered when struck by lightning (Viemeister, 1961). Vanderlinden (1907) reported that individual softwood trees sustained more breakage than hardwoods. Fisher (1907), Covert (1924), and Thompson (1936) claimed that unsound wood had high electrical resistance and was therefore liable to severe damage. On the other hand, Defandorf (1956) reported low resistance values for unsound wood and stated that it would be difficult to predict the effect of lightning on unsound trees.

IV. FACTORS IN THE PRODUCTION OF DAMAGE

What actually takes place within the tree when lightning strikes? Humphreys (1929) aptly stated:

> Many of the effects of lightning appear at first difficult to explain, but, except for the physiological, which, indeed, are but little understood, and probably some of the chemical, nearly all depend upon the sudden and intense heating along its path.

Several authors have offered explanations for the mechanical and thermal effects observed.

Vaporization of Moisture

The view most often expressed is this: Intense heat liberated by the discharge converts moisture to steam, and the resulting expansion ruptures the bole (Fisher, 1907; Creighton, 1922; Norbury, 1927; U. S. Bureau of Standards, 1929; Dodge, 1936).

Current-Flow Pressure

McEachron (1940) conceded that vaporization of moisture within the tree contributed to the damage but said the main damage factor was pressure--created by the discharge. The passage of a lightning stroke " . . . causes a pressure to be developed which is dependent upon the amount of current in the discharge." He said the current generates heat, which causes the pressure. "The greater the current flow," he concluded, "The greater the heat effect and the more violent the disruption of the wood. The violence itself is some measure of the rate of current rise."

Other workers have found evidence of this pressure, both in laboratory and field (Bellaschi, 1935; McEachron and Hagenguth, 1942; Woodhead, 1951; Ashmore, 1951).

Dissociation and Distillation

According to Orr (1959) the stroke may break down water molecules in the tree, forming free hydrogen and oxygen. The U. S. Bureau of Standards (1929) estimated that this change of state in hydrogen would produce pressures much greater than 1300 atmospheres within the wood.

The Bureau noted the possibility that free hydrogen, oxygen, and hydrocarbons may be distilled from the woody material of the tree by lightning.

Repulsion of Electrons

Dorsey (1927) suggested that the mutual electrostatic repulsion between electrons caused damage to trees. He pictured a fast-moving "dart" of electrons striking the tree's midsection, spreading damage up and down the bole.

V. SUMMARY

The literature reveals that:

1. Lightning frequently damages trees in nearly all parts of the world.
2. The range of structural damage varies from superficial tearing of bark to destruction of the tree.
3. Little is known of possible associations of tree characteristics and extent of damage.
4. The sudden and intense heating along the discharge path probably accounts for most observed effects; beyond this generalization there is little agreement upon what takes place within the struck tree.

Most inferences about the effects of lightning on trees have been based upon observed damage. The extent of damage seldom has been measured. More often, workers have created word pictures to describe the damage. The present study has arisen from the inadequacies of word pictures. Inferences made here are based on actual measurements of tree damage.

CHAPTER III

PLAN OF INVESTIGATION

The purpose of this chapter is to acquaint the reader with the study area, and the techniques employed to meet the study objectives.

The investigation was made under cooperative agreement with the Northern Forest Fire Laboratory and the School of Forestry at Montana State University.[5] One of the Fire Laboratory's current studies, Project Skyfire, conducts research on electrical characteristics of fire-setting lightning storms. The study at hand was designed in part, to supplement the larger project with information about the effects of lightning on forest trees in the project area.

Since June, 1959, the field site for Skyfire research has been a 380 square-mile area about 50 miles west of the Continental Divide in southwestern Montana. The lightning damage study area covers about one-tenth (38 square miles) of the Project Skyfire field site.

I. STUDY AREA

Location

Situated in the center of the Skyfire site, the area lies 45 airline miles south-southeast of Missoula, Montana (see Figure 1). Specifically, the study area includes portions of townships 7 and 8

[5]The Northern Forest Fire Laboratory at Missoula, Montana is a unit of the Intermountain Forest and Range Experiment Station, U. S. Forest Service, Ogden, Utah.

Figure 1. Key map. West half of Montana and the study area.
Scale: 1 inch = approximately 60 miles.

north, range 14 west on the Philipsburg Ranger District, Deerlodge National Forest (see Figure 2).[6]

Description

The area lies in the John Long Mountains at elevations ranging from 5,200 to 7,000 feet MSL. Open, uneven-aged stands of Douglas-fir predominate the lower ridgetops and south and east slopes. Lodgepole pine (*Pinus contorta*, Dougl.) is the predominant species on higher ridges and on north and west slopes. Some ponderosa pine are present on the drier southwest slopes, and some Engelmann spruce (*Picea engelmanni*, Parry ex Engelm.) are found in moist creek bottoms.

The forest soils are grey-wooded. The predominant soils on the grassy slopes bordering the Philipsburg valley are chernozem with traces of podzolic soils. This indicates that present grasslands were once forested. The parent material in the area is predominantly quartzite, with some argylite in evidence.[7]

II. METHODS

After a preliminary survey of the area during the summers of 1959 and 1960, it was decided that a sample size of 50 trees would be commensurate with the time and funds available.

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[6]The map reproduced in Figure 2 is subdivided by the 10,000 Meter Universal Transverse Mercator Grid System. The study area is in zone 12, bounded by coordinates UG1:5, UG3:5, UG3:3, and UG1:3.

[7]Source of soils information: Personal interview with R. Dunmire Soil Conservation Service, Missoula, Montana.

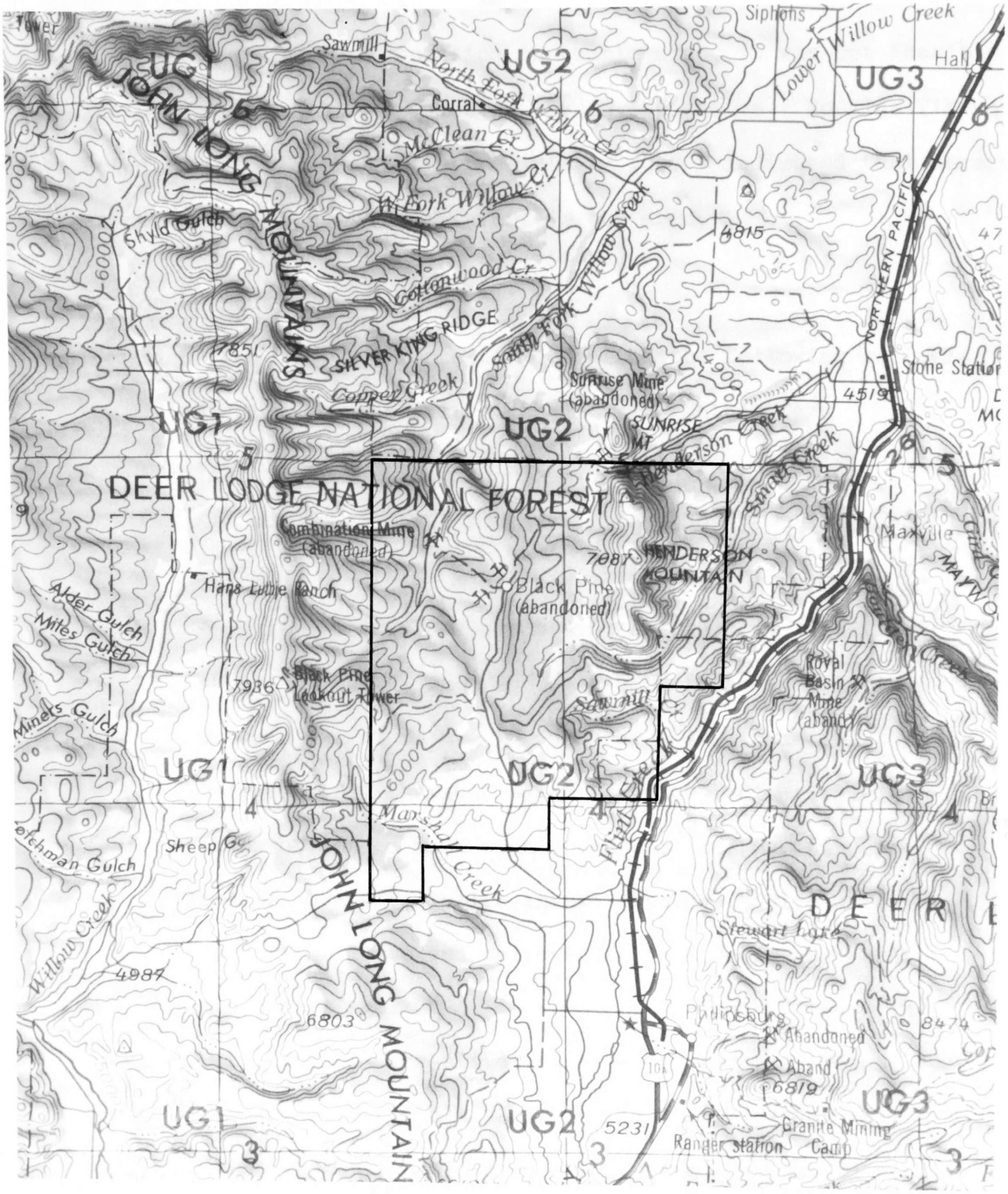

Figure 2. Relief map of study area (inked outline) and surrounding terrain. Scale: 1 inch = 2.9 miles.

Because of this restriction on sample size, it was not feasible to include more than one species in the investigation. Douglas-fir was selected for study because the preliminary survey indicated that damaged trees of this species were prevalent in the area.

Selection of Study Trees

Each tree selected for study satisfied the following criteria:

1. Species--Douglas-fir of the Rocky Mountain form (*Pseudotsuga menziesii* Mirb. Franco *glauca*).
2. Age of Damage--tree must not have added the sixth latewood growth ring since damage occurred.
   Here is the reason for the above criterion: The first study objective (page 2) dealt with possible relations between extent of damage and tree characteristics. This required that estimates of height, diameter, and shape of top be made soon after the tree was struck, because these variables change with age. Five to six years time lapse was believed to be a reasonable maximum damage age.
3. Condition of Tree-alive; must exhibit green needles.
4. Damage--recognizable as lightning damage beyond reasonable doubt; must show loss of bark or bark and wood.

The study trees were not selected at random. Preliminary surveys by the author and by Belt[8] indicated that only a few trees on any sec-

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[8]Belt, *loc. cit.*

tion (1 square mile) would meet the damage age criterion. The time required to obtain a sample of 50 trees in this area by randomization techniques was prohibitive.

In lieu of random sampling, a plan of "purposive selection" was adopted. This plan called for 100 per cent sampling of as much of the area as time and funds permitted. Cochran (1953) described the purposive selection technique as one in which the sample is restricted to units believed to be typical of the population or convenient for sampling. The Douglas-fir units examined were believed typical of those throughout the 38 square mile study area.

The following point is noteworthy: The statistician consulted on sampling techniques for this study observed that it is possible that natural forces have randomly selected the trees that are damaged.[9] If so, this could lend an element of random selection to the technique adopted.

An aerial photo mosaic showed that Douglas-fir stands covered about 16,000 of the 24,000 acres of land in the 38 square mile area. The natural stand boundaries were outlined in red on the photo mosaic, and each stand was called a search unit. The units ranged from 20 to 200 acres in size.

Five Project Skyfire field assistants, and one U. S. Weather Bureau field assistant helped search the units for damaged trees as time permitted. Progress of the search was plotted on the photo mosaic. The search party carried aerial photos into the field to insure correct

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[9]This opinion expressed by Dr. H. E. Reinhardt in April, 1961, then Assistant Professor of Mathematics, Montana State University.

orientation and complete coverage of each unit. Prospective study trees were located on these photos for subsequent inspection.

The investigator checked all prospective study trees for compliance with the four selection criteria. If a tree met the criteria, it was tagged and measured immediately in accordance with the procedure described on page 24.

Two versatile trail scooters logged a total of 150 miles in the tree measuring phase of the study. They permitted rapid spot checking of completed search units; and were an excellent mode of cross-country travel between study trees.

Determination of Damage Age

Damage age was determined by slashing diagonally with an axe into the bark and wood adjoining the scar. The growth rings added after the tree was struck were counted on the exposed diagonal surface. The method is illustrated in Figure 3. In old-growth trees, black ink and a hand lens were used to differentiate earlywood and latewood rings.

Classification of Damage

Lightning causes both structural and physiological damage to trees. This study dealt with structural damage that resulted in the removal of bark and wood from standing trees.

Structural damage was classed under two type headings for the purposes of this study:

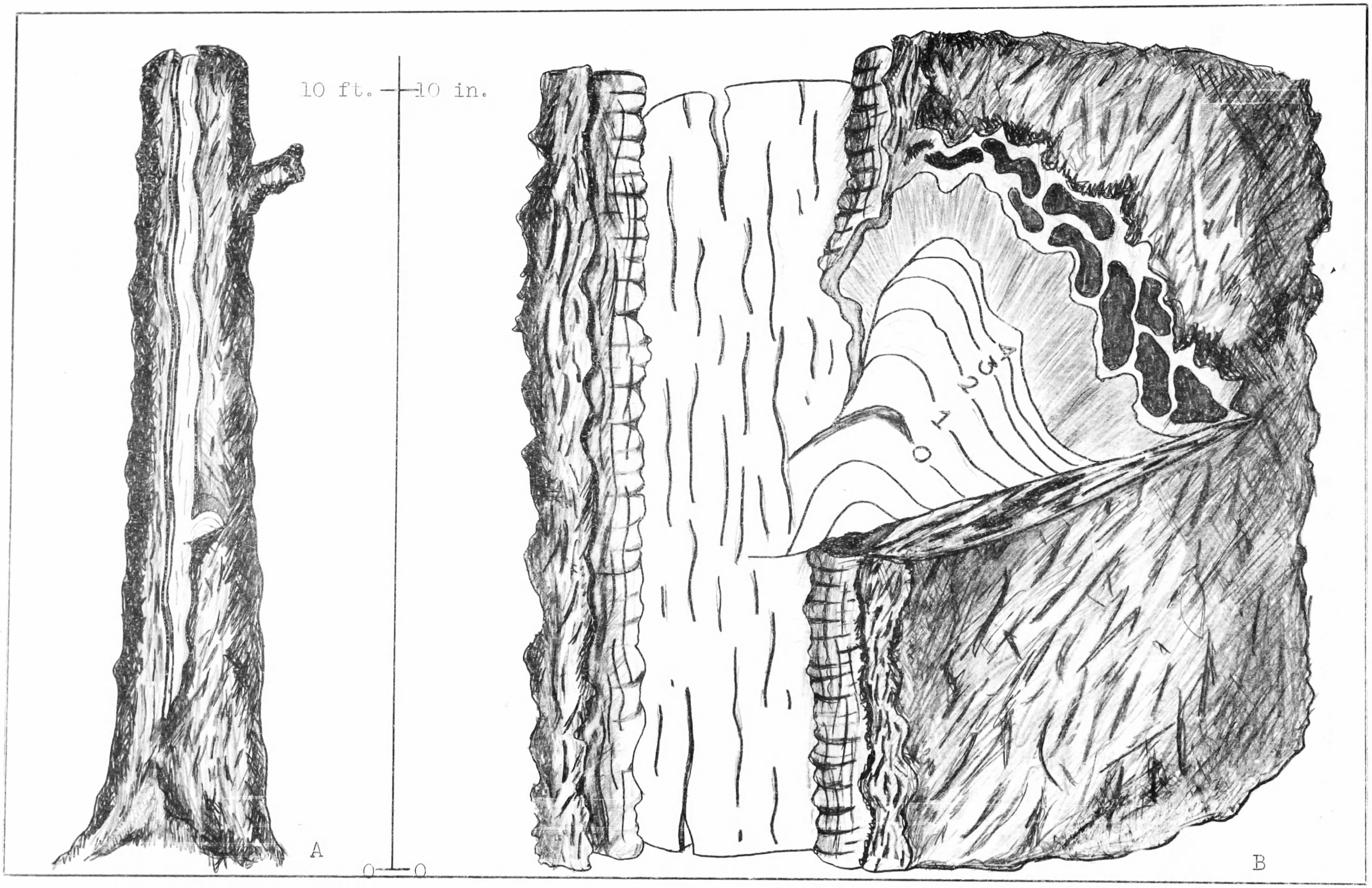


Figure 3. Damage age determination: A, wood adjoining the scar was slashed diagonally to permit counting of growth rings added after tree was struck; B, close-up view.

1. Loss of length of tree--a severed top or other length.

2. Loss of woody material lengthwise along the bole--a furrow.

Each tree was examined on the basis of these two classifications.

The objective of these classifications was to compare the total damage of one tree with the damage of another tree, and to provide a grouping by extent of damage. The relation between the amount of material removed by the flash and the estimated amount of material present before the damage occurred was selected as one measure of the damage.

The most accurate way to determine this relation requires that the tree be felled and treated with standard mensurational techniques. Those methods were not suited to this study.

Method for evaluating length-loss damage to the bole. The length-loss damage was evaluated in accordance with the following instructions:

1. Estimate the height of the standing portion of the tree in feet.
2. Estimate the severed length in feet.
3. Express the severed length as a per cent of the total length. This is the length-loss damage ratio (see Figure 4-A).

Method for evaluating furrow damage to the bole. This method is based on the assumption that the width and depth dimensions of a furrow are approximately uniform throughout the furrow's length. This is generally true from about 10 feet above the base of the tree to the furrow's upper extremity.

This method has three steps:

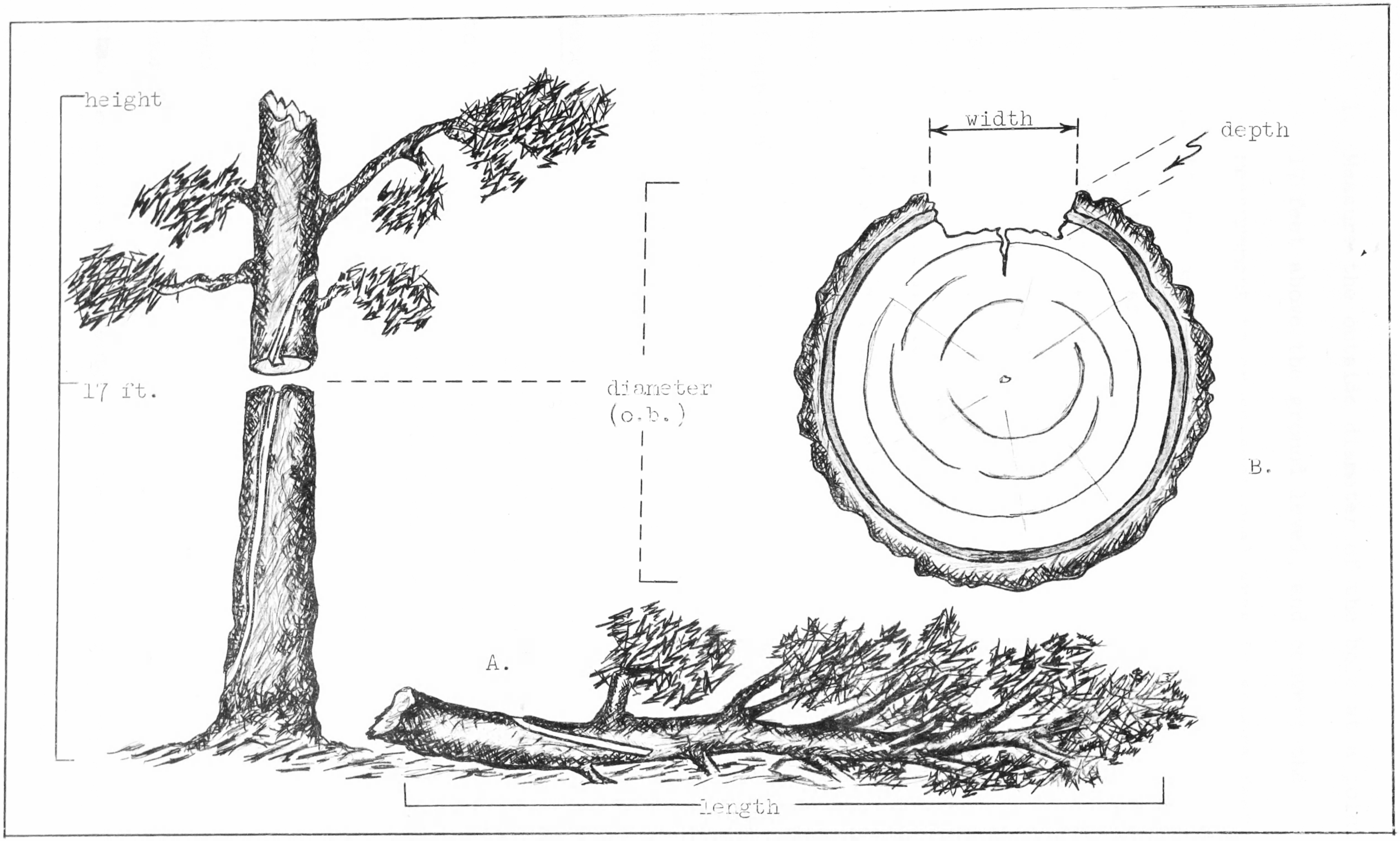


Figure 4. Lightning damage classification methods: A, length-loss damage ratio (severed length over total tree height); B, cross-sectional area damage ratio (area of scar over area of bole at 17 ft. height on the standing tree). Cross-sectional bole area value obtained from diameter measurement.

1. Measure the outside diameter of the bole at a point 17 feet above the ground level, and convert the measurement to cross-sectional area in square feet.
2. At the same height, measure the scar depth in inches and the scar width (bark edge to bark edge) in inches. Convert the product of the width and depth measurements to area in square feet.
3. Express the area removed as a per cent of the total area obtained in step 1. This is called the cross-sectional area damage ratio (see Figure 4-B).

Each study tree was assigned a cross-sectional area damage ratio, and if applicable, a length-loss ratio. All measurements were made on the standing tree. Figure 4 shows a hypothetical cross-section to illustrate the method.

Estimation of Tree Characteristics

All heights except the 17 foot height on the bole were measured to the nearest foot with the aid of a Spiegel-Relaskop. The 17 foot height was taped. Diameters (o.b.) were measured to the nearest .1 inch with a diameter tape. Furrow widths and depths were measured to the nearest .1 inch with an engineer's scale.

Tree age at damage time was estimated to the nearest 10 years by boring at the 1 foot height on the bole, adding 5 years to the actual ring count, and subtracting the damage age. For trees having radii greater than the 12 inch borer length at the 1 foot height, the core was taken at breast height, and 15 years were added to the ring count. Some tree radii exceeded borer length at breast height. On the basis of recently felled trees of the same size in the study area, these trees were classed as "age 300+".

Elevation of the tree above Mean Sea Level was measured to the nearest 100 feet with an altimeter held at the base of the tree. Crowns were classed as either dominant, codominant, intermediate or suppressed. Shapes of tops were classed as to whether the silhouette of the upper half of the crown approximated the shape of a triangle, a half-disc, or a rectangle (pointed, rounded, flat).

Forms and Records

The standard observations for each study tree were recorded on a specially prepared 5 x 8 inch hand-punch card (see Appendix D for sample punch card). Each tree received a numbered metal identification tag (attached to the bole with a soft aluminum nail). The identification number and all subsequent information for a given tree were recorded on the proper punch card.

In addition to the cards, a daily journal of field activities was maintained. Supplemental observations, questions, diagrams, and sketches made in the field were recorded in the journal.

Several trees of special interest were photographed with a 35 millimeter camera. It was believed, however, that field sketches were the best medium for recording both the usual and distinctive damage attributes; and 39 sketches and diagrams were made in the field. The illustrations in this paper were reproduced from the writer's field notes.

At the time of damage measurement, the geographical location of each study tree was permanently located on a 9 x 9 inch aerial photo (RF 1/20,000). The tree image was located with a pocket stereoscope, pen-pricked and identified by tree number on the back of one of the stereo pair. This provided a permanent record of the tree location.

Procedure

The following procedure was followed for each tree that met the selection criteria.

1. Attach numbered identification tag to tree.
2. Measure tree characteristics.
3. Measure damage variables and obtain damage ratios.
4. Observe and record damage characteristics.
5. Locate tree on aerial photo.
6. Make necessary notes, sketches, and photographs.

Analysis of Data

This section presents a brief discussion of the types of analyses performed, and a statement of caution concerning the statistics presented in the paper. Detailed statistical models may be found in Appendix C.

Multiple linear regression and correlation. To test the hypothesis proposed in the first study objective, that is, that damage is a function of certain tree characteristics, observations were made on damage and tree parameters. Measurements of the seven tree characteristics and the cross-sectional area damage ratios were then subjected to an IBM-7090 computer analysis. The job was handled by the Western Data Processing Center, Graduate School of Business Administration, University of California at Los Angeles. The Division of Biostatistics of the University of California at Los Angeles School of Medicine furnished the computer program. This program, the BIMD-06 Multiple Regression and Correlation Analysis No. 1, tested all possible combinations of the following variables for linear association:

Dependent variable	Independent variables
	X_1 : age of tree
	X_2 : diameter of b.h.
	X_3 : Girard form class
Y : cross-sectional area damage ratio	X_4 : shape of top
	X_5 : crown length-tree height ratio
	X_6 : crown class
	X_7 : tree elevation

The null hypothesis of a no linear association between Y and X_1 through X_7 was tested at the pre-designated .05 level of significance.

A similar analysis using length-loss as the dependent variable was prescribed in the work plan for this study, but the paucity of length-loss trees led to its cancellation.

Simple regression and correlation. According to Ostle (1954) the scatter diagram is an effective tool in a search for functional relations between variables. Eighteen of the 24 variables listed in Table II, Appendix D, were treated as measurement data. A total of 143 scattergrams were plotted in search of associations among these data. Those of interest are presented in Chapter V and Appendix A.

The measurement of association was accomplished in three steps:

1. Determination of the form of the association--the regression line.

2. Measurement of variation about the line of regression--the standard error of estimate.

3. Expression of the measurement of association on a relative basis--the correlation coefficient.

The methods used here are from Arkin and Colton (1956), and are presented in step fashion in Statistical Model 1, Appendix C. The correlation coefficients, r, and standard errors of estimates, Se, were adjusted by Arkin and Colton's corrections for small samples (see Statistical Model 2, Appendix C).

F tests for significance of linear regression. The method for analysis of variance for regression was taken from Freese (1956), and is shown in Statistical Model 3, Appendix C. Tests for significance of regression were specified at the .05 level, but the actual calculated F value is shown on each graph presented in Chapter V and Appendix A.

Chi square tests for independence. Ten of the 24 variables listed in Table II, Appendix D, were treated as enumeration data. Some of them were also treated as measurement data in the search for associations described in the preceding discussion. Here the numbers of trees falling into each of two categories were compared to determine whether the categories were independent. Forty-three such tests were made on the 10 enumeration characteristics observed. The method used is from Dixon and Massey (1957), and is illustrated by Statistical Model 4, Appendix C. The null hypothesis of no dependence was tested at the .05 level of significance for each of the 43 tests. Results of these tests are discussed in Chapter V.

t-tests for differences between sample means. Chapters IV and V discuss two types of furrow damage. These types, called "bark-loss" and "wood-loss" damage, were examined with respect to their arithmetic means for several parameters common to both of them. The method is from Arkin and Colton (1956), and is outlined in Statistical Model 5, Appendix C. In each instance the null hypothesis of no significant difference between means was tested at the .05 level of significance.

Statement of caution. The reader is cautioned against taking at face value any of the significance test results presented in this paper. The reasons for this are twofold:

1. The statistics and the tests based upon them tend to lose some of their meaning when the sample is not completely randomized.
2. Only the IBM-7090 computer analysis was prescribed in the work plan for this study. All of the other tests were selected after the field data were collected.

The test results may, in fact, be correct, but one cannot be *certain* that they are correct because of the reasons shown above. The results are presented to point out worthwhile "working hypotheses" for future work in this field.

CHAPTER IV

PRESENTATION OF DATA

Results of the field work are presented here. Field sketches, histograms, and informal tables were employed to reduce lengthy descriptions to a minimum. Appendix A contains supplemental histograms. The original field observations are reproduced in Appendix D.

Fifty-three study trees were located and measured during the summer of 1961. Of the 16,000 acres in Douglas-fir timber type, 10,700 acres were searched under the 100 per cent sampling scheme. About 1,000 damaged trees were observed; and some 250 of these exhibited two or more scars of different ages.

I. DAMAGE RATIOS

The damage ratios are "first approximations" of the extent of damage on individual trees. They permit comparisons of one tree to another with respect to the relative extent of damage on each tree.

Length-loss Ratios

Only 7 of the 53 study trees showed loss of bole length. Because of this small number, the ratios themselves are of little interest. Suffice to say that the mean length loss was 28 per cent of total tree height with standard deviation $\pm$ 11 per cent.

Cross-sectional Area Damage Ratios

These ratios express the percentage of cross-sectional bole area (including bark) removed by lightning at the 17 foot height on the tree. The frequency distribution of these ratios is shown in Figure 5. The mean bole-area loss was 3 per cent of total cross-sectional bole area, with standard deviation ± 3 per cent. The most severely damaged study tree is pictured in the frontispiece. Its area damage ratio was 16 per cent.

II. TREE CHARACTERISTICS

The ratios presented above give a measure of the damage. The first study objective (page 2) was to see if the extent of damage is a linear function of differences in seven tree characteristics. Table I describes five of them, listing measures of central tendency and dispersion. Frequency histograms for these variables are presented in Figures 21-25, Appendix A.

TABLE I

CENTRAL TENDENCY AND DISPERSION OF FIVE TREE CHARACTERISTICS

Variable	Unit	Arithmetic mean	Standard deviation	Range
Diameter, b. h.	inches	24	7.9	12-43
Form class	per cent	76	5.8	67-89
Crown length-tree height ratio	per cent	81	8.2	59-95
Elevation	feet, MSL	6300	400	5400-7000
Age	years	180	80	50-300+*

*12 trees were classed as "300+", inducing an error in the mean and standard deviation. A more realistic mean is 200 years, with standard deviation about 90 years.

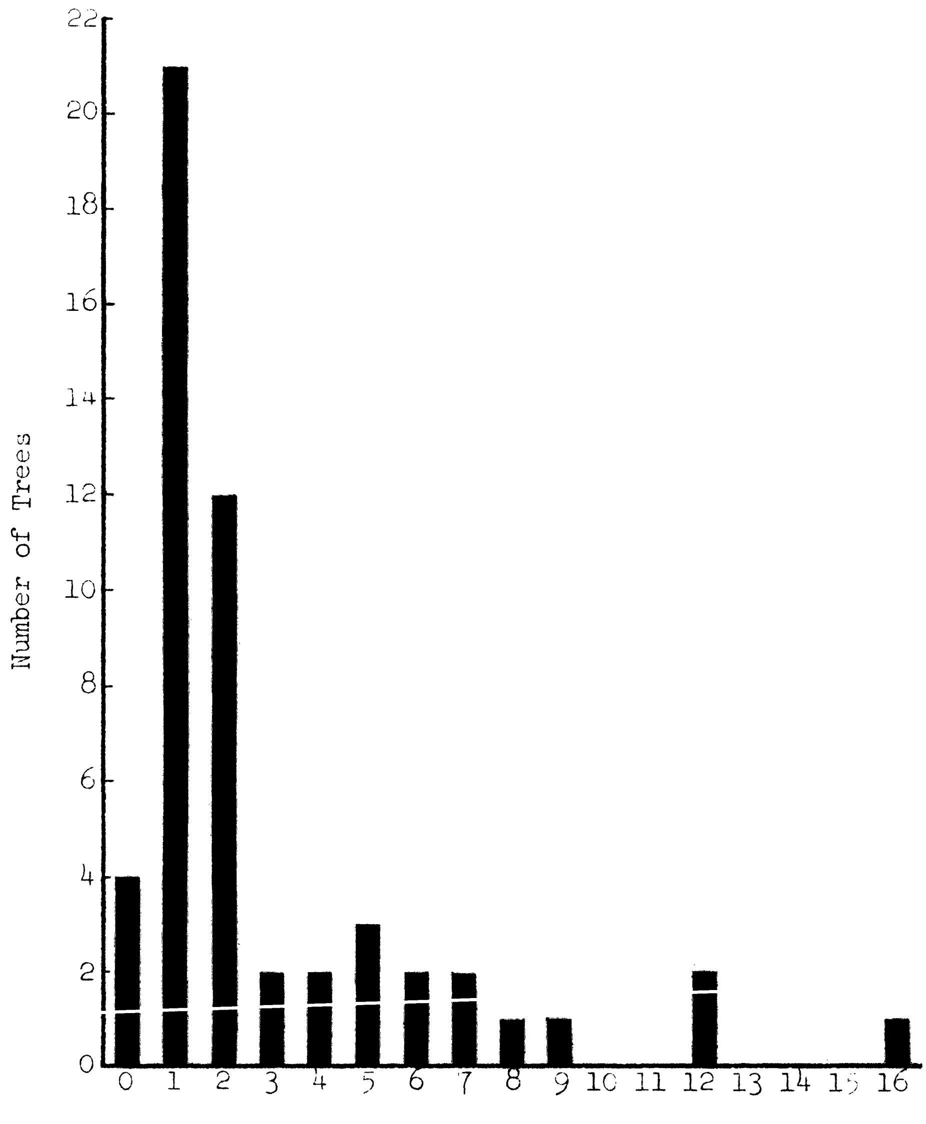


Figure 5. Distribution of damage ratios among 53 trees.

The other two characteristics listed under the first objective were: (1) crown class, (2) shape of top. The 53 trees were about evenly divided between dominant and codominant crown classes, as shown here:

Dominant	Codominant	Intermediate	Suppressed	Total
28	23	2	0	53

The estimates for shape of top were as follows:

Pointed top	Rounded top	Flat top	Total
26	26	1	53

III. DAMAGE CHARACTERISTICS

These data were taken in order to satisfy the second study objective (page 2). The most noteworthy are presented here.

Bark-loss and Wood-loss Damage

Lightning removed only a strip of the live cambium and dead outer bark on most of the trees, but it gouged out deeper furrows on others, causing loss of wood. The two types of damage are illustrated in Figure 6. The bark-loss trees outnumbered the wood-loss trees as shown here:

Bark-loss only	Wood-loss	Total
38	15	53

In all wood-loss trees the wood was removed in two parallel strips of nearly equal dimensions (see Figure 6-B). For example, one tree's wood loss was a pair of slabs, each 8 inches wide, 3 inches deep, and 44 feet long.

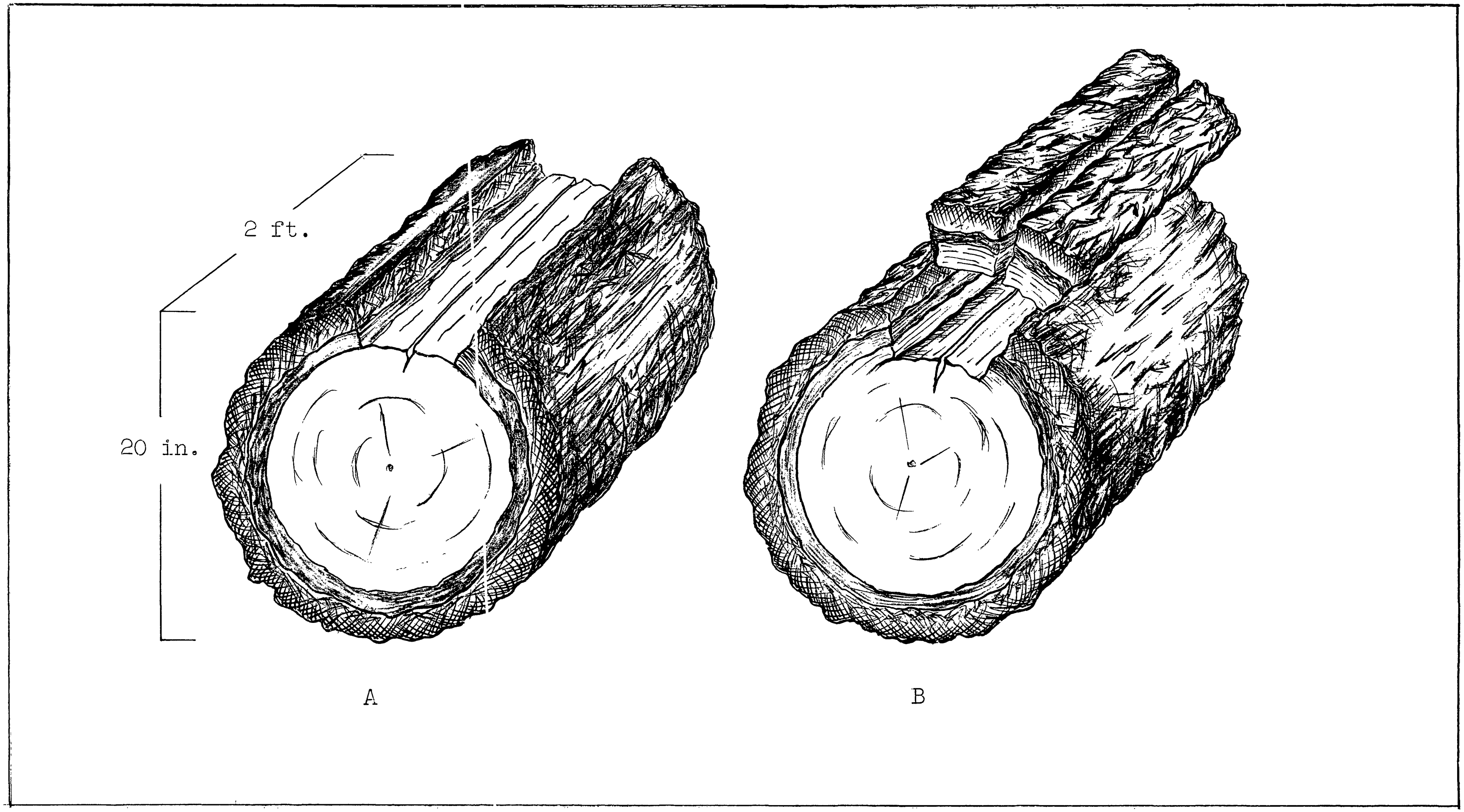


Figure 6. A, typical bark-loss furrow; B, wood-loss furrow, showing wood removed in two slabs of nearly equal dimensions. Ncte that each bole has a crack along the furrow axis.

Scar Configuration

Lightning scars tend to follow several configuration patterns. In this study all scars were classified as to their alignment with the vertical axis of the tree bole. Three broad alignment classes were recognized: (1) straight, (2) oblique, (3) spiral (Figure 7-A, B, C). In order to be classed as spiral, the furrow must have made at least one complete revolution of the bole. Oblique scars tended toward spirality, but did not make a complete revolution. The number of trees in each alignment class were:

Straight	Oblique	Spiral	Total
7	24	22	53

Ten of the spiral scars were right-hand spirals; that is, ascending to the right as in Figure 7-C; and 12 were left-hand spirals.

The scars illustrated in Figure 7-D, F, and G are deviations from the more common single-channel, continuous scars of A, B, and C. They are shown as straight scars here for simplicity, but several fell into the oblique and spiral classes. Dual-aspect scars (Figure 7-E) were noted on two trees. On both trees the charge apparently ripped the cambium along one face of the bole for some 20 feet; and then in a vertical distance of 2 to 4 feet it traveled 180° around the bole, removing only the outer bark flakes in its path. The charge then continued along that face of the bole in the usual manner, tearing the cambium.

Upper Scar-reach Deficit

None of the furrows reached to the tips of the trees. The distance

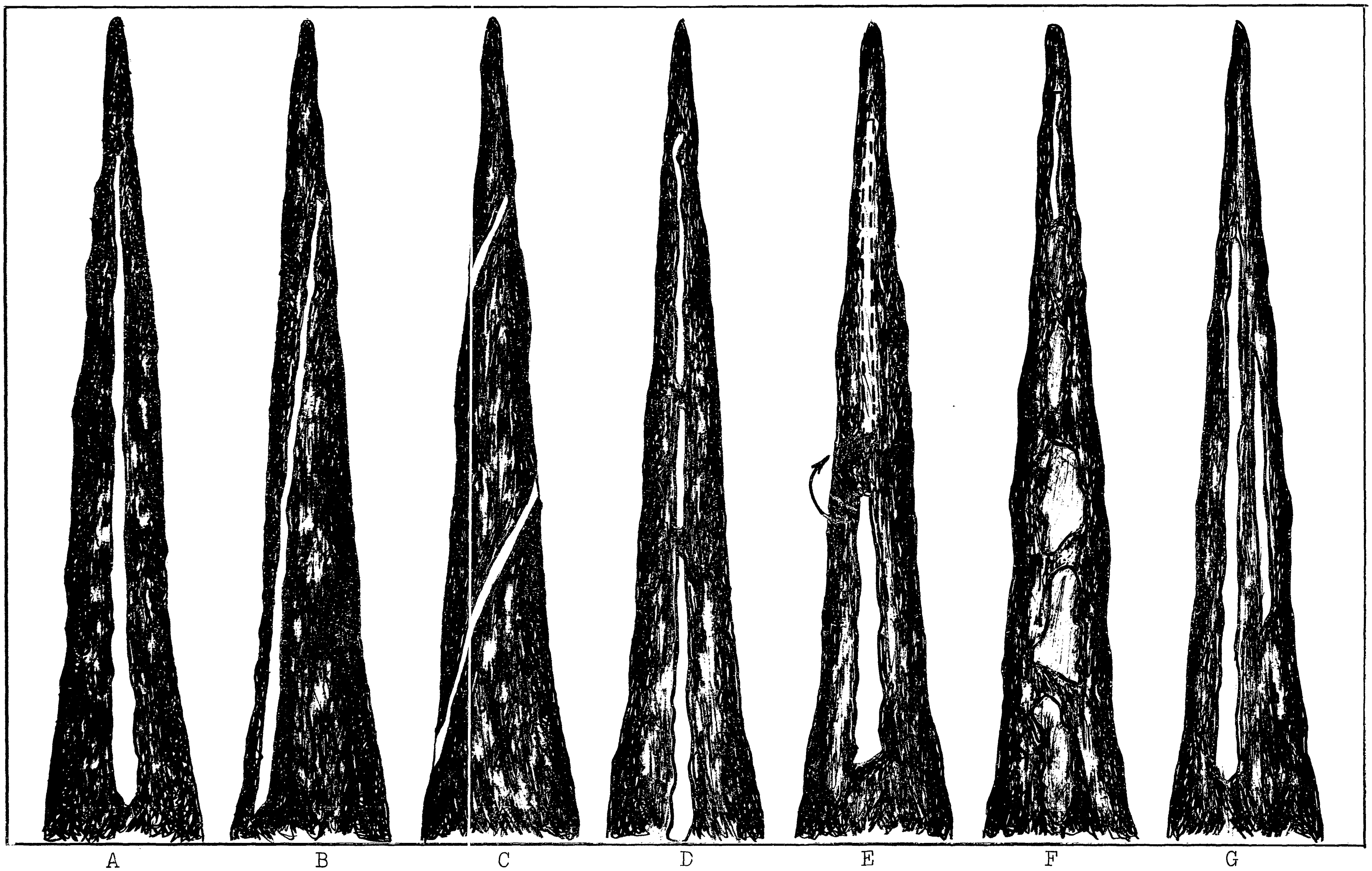


Figure 7. Scar configuration types observed in the study area: A, straight, B, oblique, C, spiral, D, discontinuous, E, dual aspect, F, superficial, G, dual channel.

in feet from the upper end of the scar to the tip of the tree is called the upper scar-reach deficit. This deficit ranged from 3 to 22 feet, with a mean of 10, and standard deviation $\pm$ 5.2. The distribution of upper deficits for bark-loss and wood-loss trees is shown in Figure 8. The two categories are similarly distributed.

One might expect the upper scar end to be tapered to a point. Actually the furrow terminates squarely, as Figure 7, page 34, indicates.

Lower Scar-reach Deficit

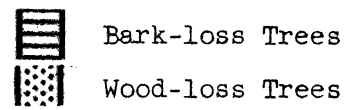
About one-half of the scars reached ground level. The others showed deficits in this respect. Figure 9 shows the distribution of these deficits. Here also the bark and wood-loss categories are similar. A deficit of zero means that the furrow reached ground level. The maximum observed deficit was 6 feet. Figure 3-A, page 19 shows a lower deficit of about 14 inches.

Bole Crack

Most of the study trees exhibited a crack along the bole. It usually ran the full length of the scar, and almost always occupied the center of the scar's width, as illustrated in Figure 10.

The crack was present on most of the bark-loss and wood-loss trees alike:

Bole crack present	Bole crack absent	Total
40	13	53



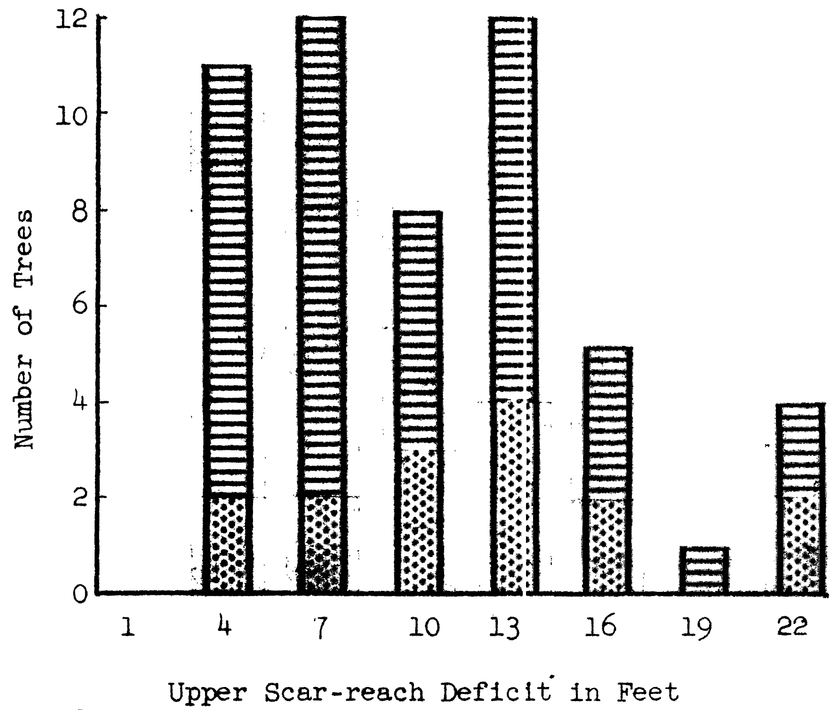


Figure 8. Distribution of upper scar-reach deficits among 15 wood-loss trees and 33 bark-loss trees.

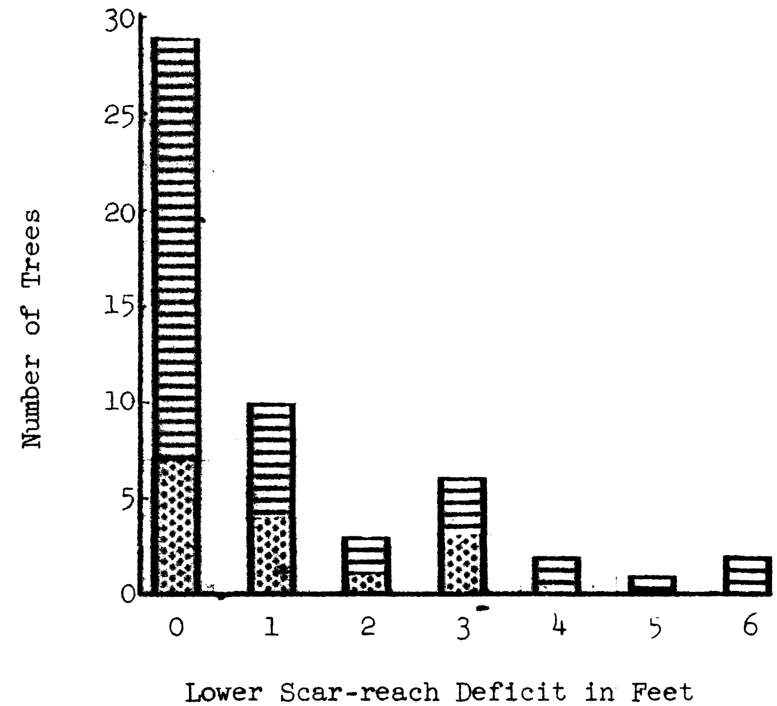


Figure 9. Distribution of Lower scar-reach deficits among 15 wood-loss trees and 38 bark-loss trees.

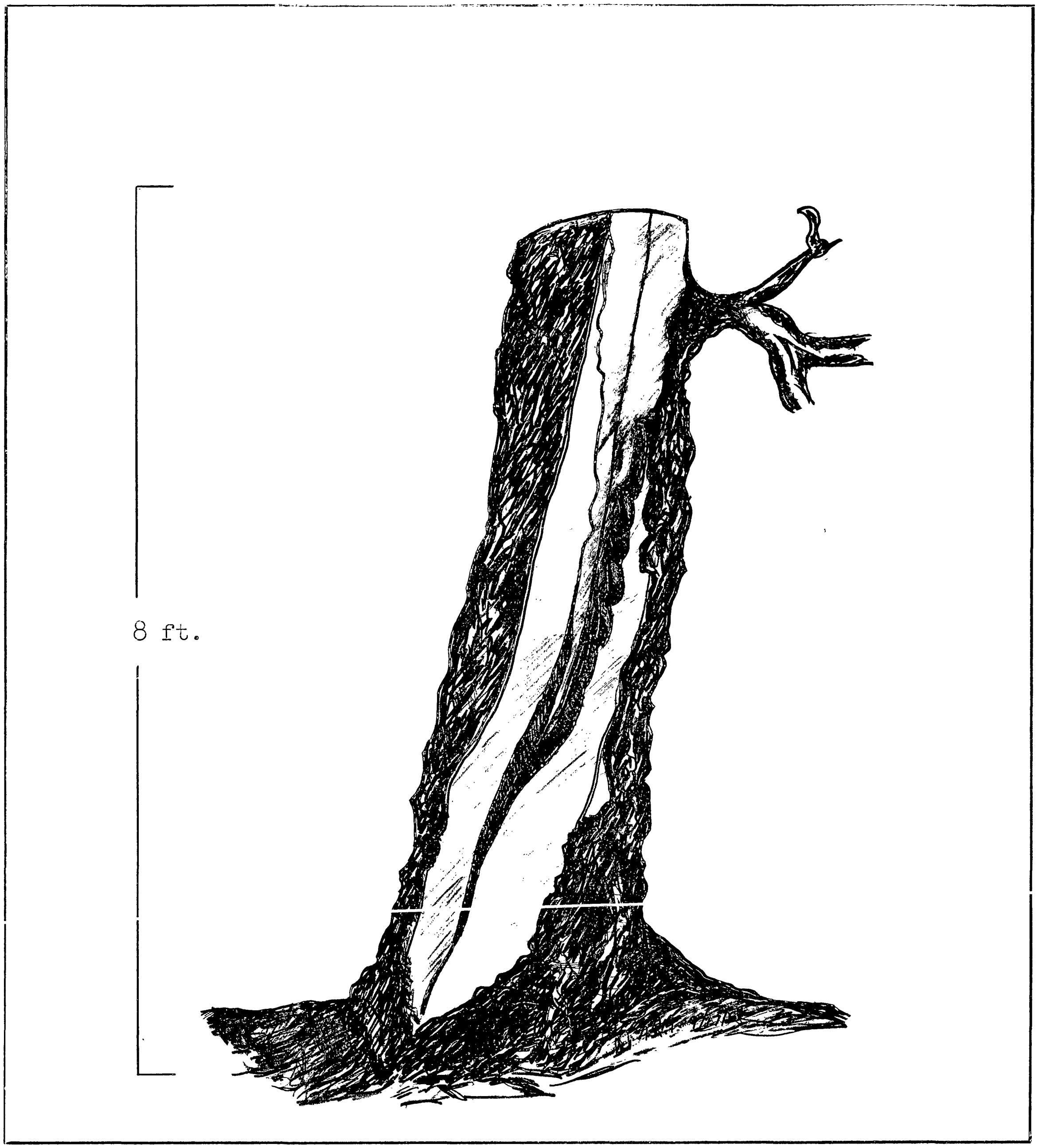


Figure 10. Lower portion of a severely damaged tree, showing bole crack along furrow axis. Note that the crack is visible in both the outer and inner layers of exposed wood. In some trees the crack penetrates to the center of the bole.

All wood removed from wood-loss trees was separated into two parallel slabs along this bole crack. In some trees the crack apparently penetrated to the center of the bole, as shown by boring cores taken at right angles to the scar.

Crack in bole center	No crack in bole center	Unable to reach center	Total
15	15	10	40

Cambium Strip

Lightning sometimes leaves a narrow strip of cambium fibers along the axis of the furrow on bark-loss trees. This strip, illustrated in Figure 11, occupies the same position on the bole that the bole creck does. Figure 11 is reproduced from a field sketch made a few days after this tree was struck. When the fibers were scraped away, a smooth shallow groove on the bole was revealed, as in Figure 11-B. One tree, examined two hours after it had been struck, exhibited the cambium strip on its lower reaches and the bole crack on its upper half.

The cambium strip was first observed midway through the field season. Twenty-one of the study trees were inspected for it, and it was present on 12 of them.

Length of Scar

The distribution of scar lengths for wood-loss and bark-loss trees is shown in Figure 12. Note that 26 (68%) of the bark-loss trees had scars less than 50 feet long; and that 10 (67%) of the wood-loss trees had scar lengths in excess of 50 feet. The means and standard deviations

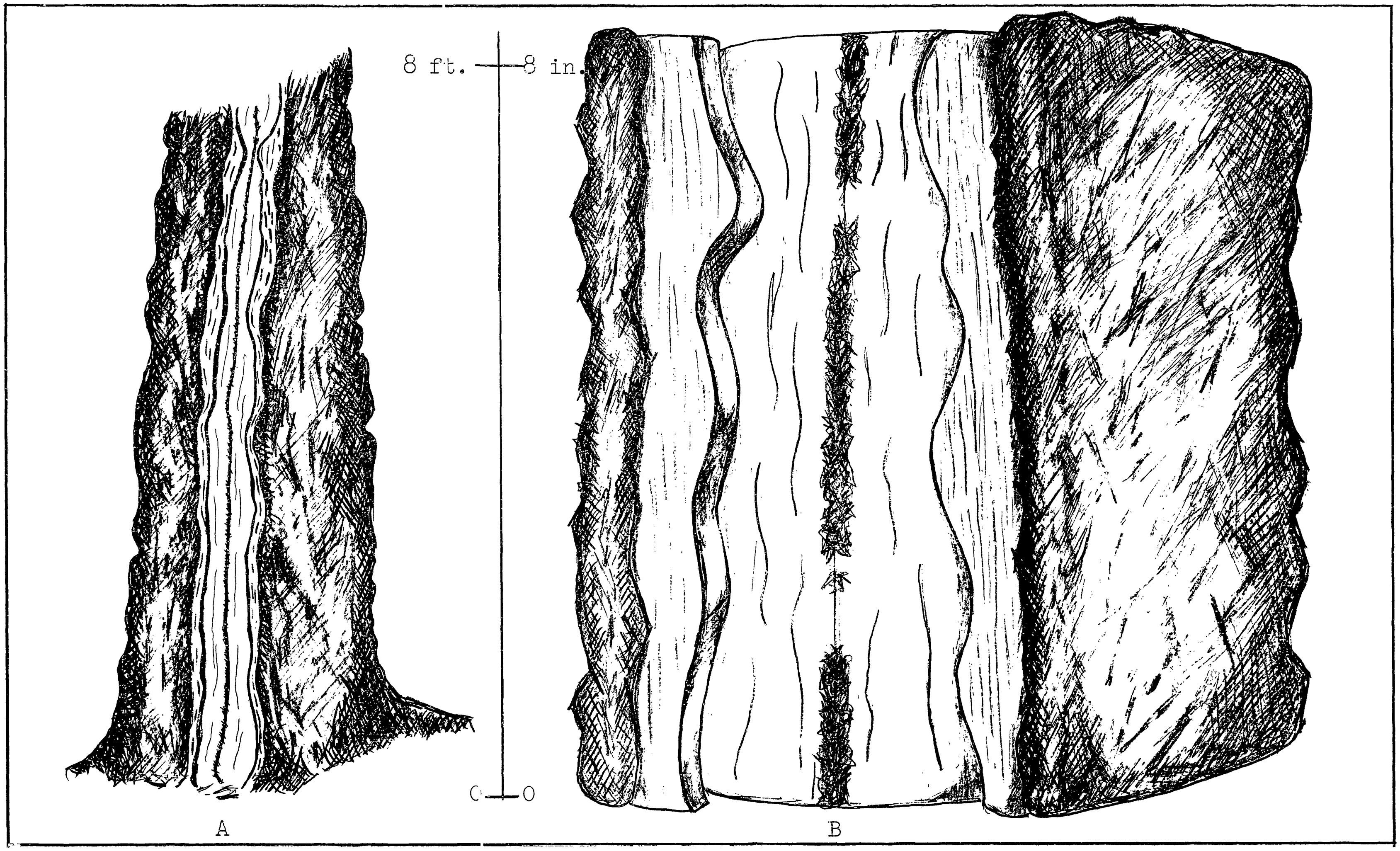
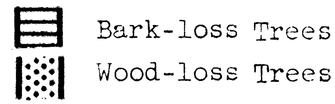


Figure 11. Lightning sometimes leaves a narrow strip of shredded cambial fibers along the axis of the furrow on bark-loss trees: _A_, distant view, _B_, close-up view. When strip is removed, a smooth, shallow groove on the bole is revealed.



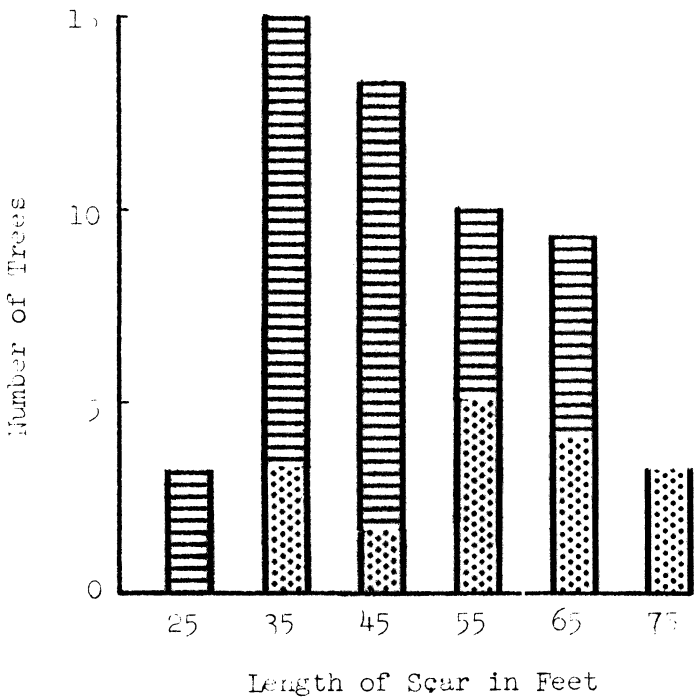


Figure 12. Distribution of scar lengths among 15 wood-loss trees and 38 bark-loss trees.

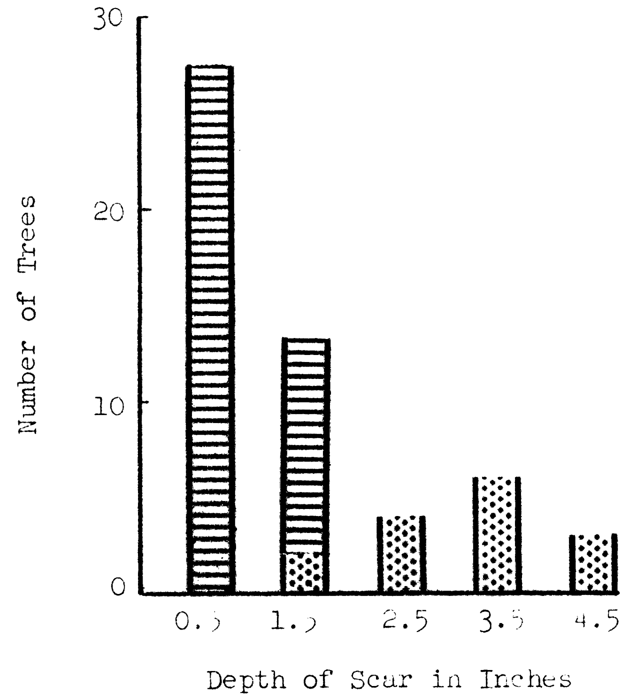


Figure 13. Distribution of scar depths among 15 wood-loss trees and 38 bark-loss trees.

for these damage types are:

	$\bar{X}$	S_x
wood-loss	54 ft.	$\pm$ 12.6
bark-loss	46 ft.	$\pm$ 12.3

Depth of Scar

From the descriptions of wood-loss and bark-loss damage (page 31) one would expect scar depths to be greater on wood-loss trees. This is borne out by the histogram in Figure 13. Here are the statistics:

	$\bar{X}$	S_x
wood-loss	3.4 in.	$\pm$ 0.7
bark-loss	0.8 in.	$\pm$ 0.3

Width of Scar

The distribution of scar widths, shown in Figure 14, is of considerable interest. Wood-loss scars were generally wider than bark-loss scars. Thirty-three (87%) of the bark-loss furrows were less than 6 inches wide; but 13 (87%) of the wood-loss furrows were wider than 6 inches. These statistics describe the differences in the two classes:

	$\bar{X}$	S_x
wood-loss	11.3 in.	$\pm$ 4.3
bark-loss	3.8 in.	$\pm$ 2.5

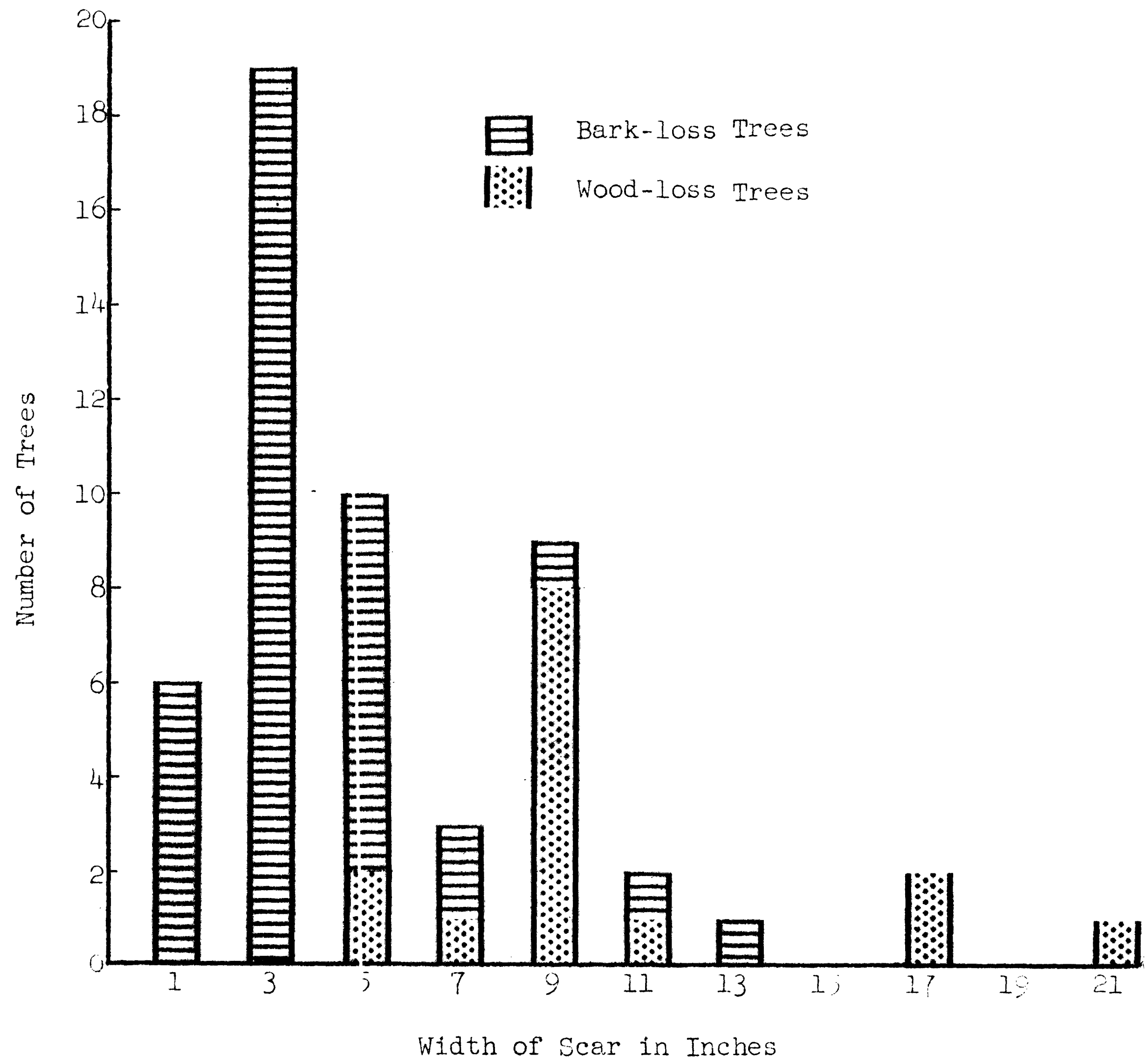


Figure 14. Distribution of scar widths among 15 wood-loss trees and 38 bark-loss trees.

Summary

Here are the salient points of this brief data presentation:

1. The damage ratios devised for this study afford rough approximations of the extent of structural damage on individual trees.
2. The percentage of cross-sectional bole area removed (at the 17 foot height) by lightning is usually small.
3. The damaged trees showed wide ranges of values for the seven tree characteristics observed. (Diameter at breast height, ranging from 12 - 43 inches, is perhaps most notable.)
4. Bole scars show two distinct types of damage-- wood-loss and bark-loss.
5. Lightning scars tend to follow several broad configuration patterns. Forty-six of the sample scars were either spiral or inclined toward spirality.
6. None of the scars extended upwards to the bole tips; but half of them reached ground level on the bole.
7. Lightning apparently cracked most of the boles along the furrow, and sometimes left thin "cambium strips" along bark-loss scars.
8. The frequency histograms for scar length, depth and width differ markedly between bark and wood-loss damage types.

CHAPTER V

DISCUSSION OF RESULTS

This chapter presents the results of several data analyses, points out apparent relations between variables, and discusses possible explanations of observed phenomena.

I. ASSOCIATION OF TREE CHARACTERISTICS AND EXTENT OF DAMAGE

Damage Ratios and Seven Tree Variables

The IBM computer analysis showed that the null hypothesis of no linear association between cross-sectional area ratios and seven tree characteristics was accepted. This means that the extent of damage, as reflected by the ratios, was not a linear function of tree-to-tree differences in:

X_1 : age of tree

X_2 : diameter at b.h.

X_3 : Girard form class

X_4 : shape of top

X_5 : crown length-tree height ratio

X_6 : crown class

X_7 : tree elevation

The statistics are presented in Appendix B.

With the description of damage characteristics (Chapter IV), and the evaluation of the computer analysis (above), the objectives of this study (see page 2) were fulfilled. But at this point the data were almost "untouched," and a search for meaningful patterns seemed warranted.

Thorough sifting of the field data brought to light several apparent associations between variables. In general, the relations described in this chapter are not well understood. Most require further study. The purpose here is to point them out and to offer explanations where possible.

Extent of Damage and Tree Size

Consider the following statement: The amount of material removed from the bole of a tree by lightning varies with tree size. The statement oversimplifies the facts, but its validity and limitations will become apparent in the paragraphs that follow.

Cross-sectional area of the scar and bole--12 wood-loss trees.[10] Figures 15 and 16 show that large wood-loss trees lost more bole material than small trees, but that the per cent of the bole removed was greater on small trees. The cross-sectional area damage ratios in Figure 15 decreased logarithmically with increasing bole area; but Figure 16 shows

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[10]Fifteen trees were originally classed as wood-loss trees, but when plotted on scattergrams, 3 of them grouped sufficiently far removed from the other 12 to be considered belonging to a different population. These trees (I.D. numbers 244, 949, 969 in Table II, Appendix D) had actual wood-loss scar depths (excluding bark) of less than 1.0 inch. For this reason they are not represented in Figures 15, 16, 19, 28, and 29.

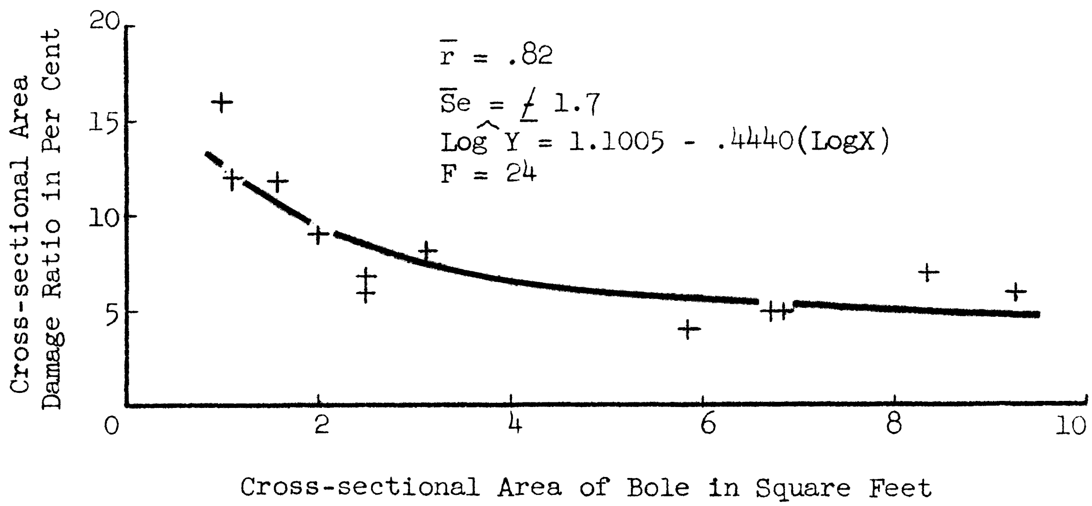

Figure 15. Damage ratio over cross-sectional area of bole at 17 ft. height, for 12 wood-loss trees.

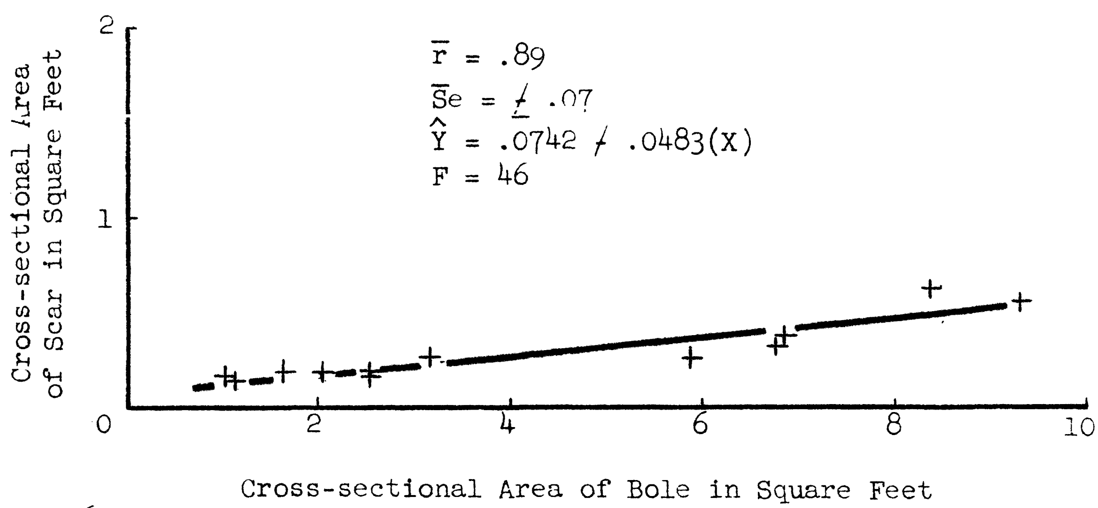

Figure 16. Area of scar over cross-sectional area of bole at 17 ft. height, for 12 wood-loss trees.

that the actual scar area increased with increasing bole area. An example may be helpful here. Tree A has cross-sectional bole area of 1 square foot (diameter 14 inches, o.b. at 17 ft. height). Tree B has bole area of 9 square feet (diameter 41 inches). The two are compared below:

	Per cent of bole area removed (damage ratio)	Actual amount of bole area removed, sq. ft.
(A) 14 inch dia.	13	0.1
(B) 41 inch dia.	5	0.5

The smaller tree lost only 14 square inches of bole area, but that amounted to 13 per cent of its total bole area. The larger tree lost 72 square inches, or 5 per cent of its bole area.

The correlation coefficients and the regressions in Figures 15 and 16 are significant at the prescribed .05 level, and also at the .01 level. For 1 and n-2 degrees of freedom, Snedecor's (1946) Table of F gives $F_{.05} = 4.96$, and $F_{.01} = 10.04$. The calculated F values in Figures 15 and 16 exceed these values. They are 24 and 46, respectively. This means that less than one time in a hundred would we expect the associations in Figures 15 and 16 to occur due to chance, assuming the 100 samples of 12 trees each were randomly selected from a normally distributed population. This explanation should serve as a guide to interpreting the remainder of the curves in the paper.

Cross-sectional area of the scar and bole--38 bark-loss trees. The picture is somewhat different with the bark-loss trees. Figure 17 indicates no association between damage ratios and size of bole. The

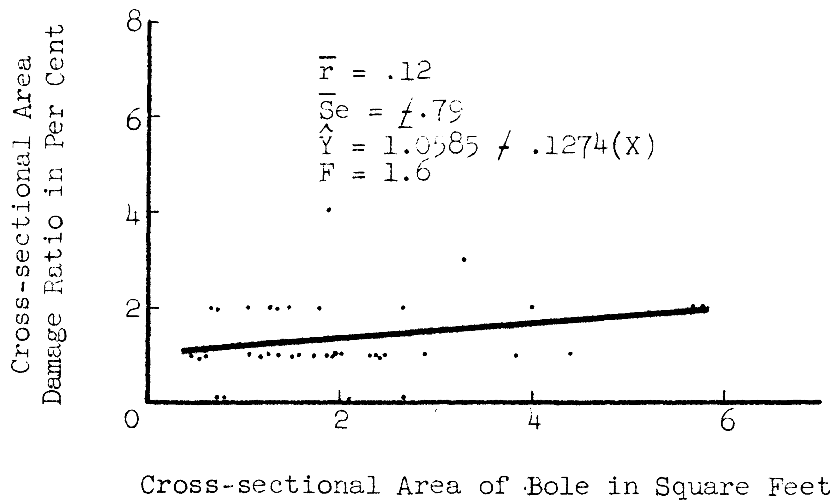

Figure 17. Damage ratio over cross-sectional area of bole at 17 ft. height, for 38 bark-loss trees.

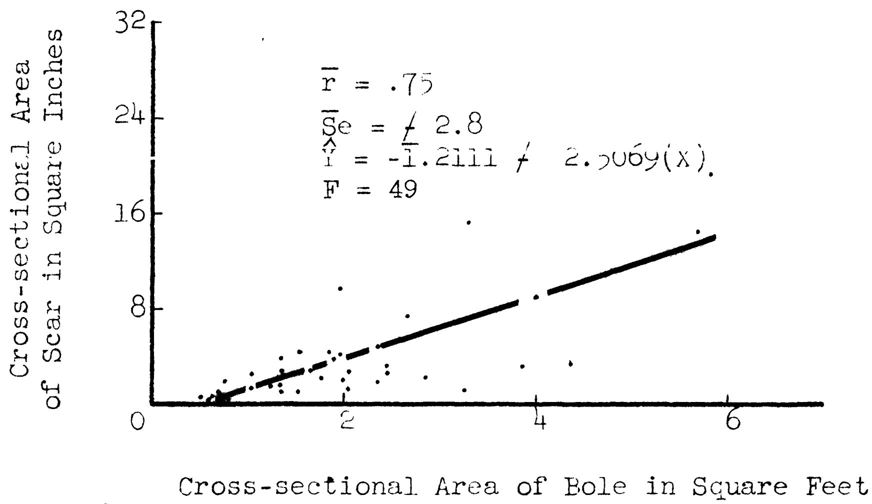

Figure 18. Area of scar over cross-sectional area of bole at 17 ft. height, for 38 bark-loss trees.

damage ratios varied from about 1 to 3 per cent whether the tree had 1 or 6 square feet of cross-sectional area at the 17 foot height. The regression and correlation are not significant. Figure 18 shows that the actual amount of bark and cambium removed varied with size of the bole. Considering Figures 17 and 18 together, one may conclude that the bark loss increased with bole size, but that per cent of the bole removed remained nearly constant. The increase in bark loss is partly explained by the fact that bark depth increases with tree size. The regression of bark loss on bole area is significant.

If one dared to predict from this sample, he might conclude that Figures 15, 16, 17, and 18 show that any size bole having less than 6 square feet area can become either a bark-loss or wood-loss tree; but if it is a bark-loss tree, the damage will probably amount to only about 1 to 3 per cent of the bole area. If the tree suffers wood-loss, the per cent of damage will probably decrease logarithmically as size of bole increases. Similar relations were noted when damage ratios were plotted over tree height and tree diameter, b.h.; that is, the logarithmic decay curve for wood-loss trees, and the no-association curve for bark-loss trees showed up in both scattergrams. Because the bark-loss damage varies over a very narrow range, the bark-loss damage ratios calculated here may not be sensitive enough to show association with tree variables.

Volume of scar and bole. The preceding section described the tree and lightning damage in two dimensions. This section introduces a third dimension, length, and compares scar volume to bole volume.

Estimates of scar volume were obtained by multiplying the cross-sectional area by length of scar. Length of scar was calculated by summing the estimates of lower and upper scar-reach deficits, and subtracting that value from total tree height. The method assumes uniformity of scar width and depth throughout scar length. Estimates of cubic-foot volume were obtained from Kemp's (1957) formula:

$$V = bx$$

where V = cubic-foot volume inside bark from a 1-foot stump to a 4.0 inch top d.i.b.

b = Kemp's regression coefficient based on diameter b.h. (o.b.) and tree age

$$x = \frac{(\text{DBH in inches})^2\ (\text{total height in feet})}{100}$$

The scar volume estimates include bark, but the bole volume estimates do not. Some error is induced by this anomaly, but it is believed to be small. Figures 19 and 20 show the regressions of scar volume on bole volume. Both are significant, and indicate that scar volume is associated with tree volume.

No "volume damage ratios" were computed, but an inspection of Figure 19 reveals that the per cent of volume removed is about 20 per cent for 20-cubic-foot trees, 16 per cent for 40-cubic-foot trees, and 13 per cent for 280-cubic-foot trees. Figure 20 shows that about 4 per cent of the volume of bark-loss trees is removed, whether a tree has 40 cubic feet or 160 cubic feet of volume. The relations here are similar to those in Figures 15 to 18.

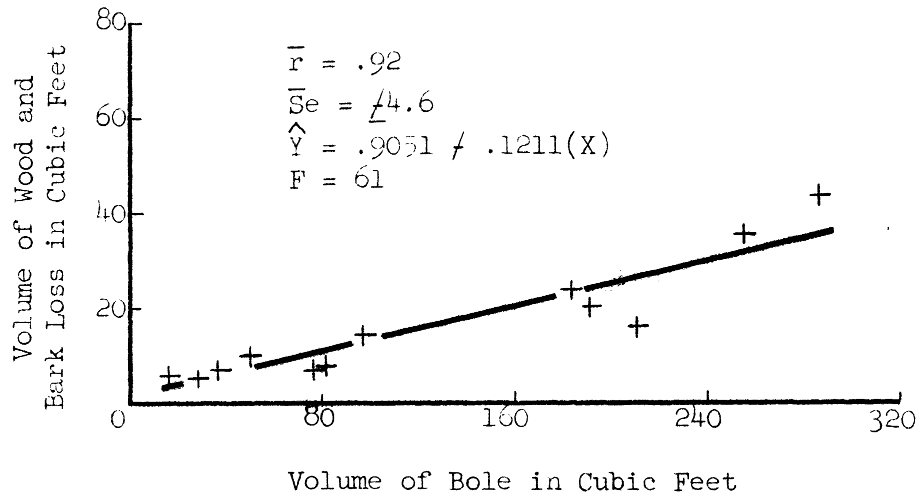

Figure 19. Estimated cubic volume of wood and bark removed by lightning over volume of bole, for 12 wood-loss trees.

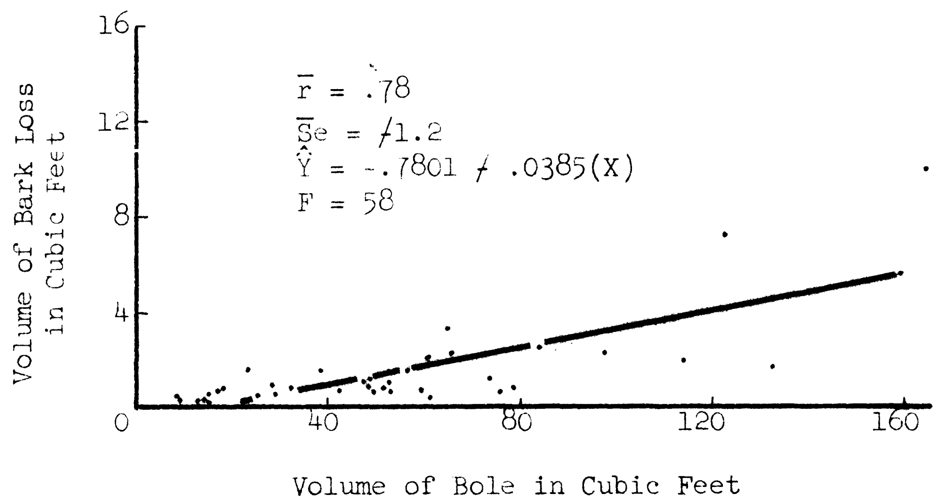

Figure 20. Estimated cubic volume of bark removed by lightning over volume of bole, for 38 bark-loss trees.

Four additional Figures are of interest (Figures 27 to 30, Appendix A). Figure 27 shows that scar length increased with tree height, at an increasing rate. For example, the lightning damaged 30 feet (75%) of 40-foot trees, and 66 feet (83%) of 80-foot trees. Figure 28 shows that width of scar increased with the square of bole diameter, but at a decreasing rate for both wood-loss and bark-loss trees. Figure 29 illustrates a similar linear relation between depth of scar and the square of bole diameter. Figure 30 indicates a linear association between width of scar and depth of scar.

Summary

Figures 16, 18, 19, 20, 27, 28, and 29 encompass nine linear associations of damage and tree measurements. All of them appear to be significant at the .01 level.[11] More important than the statistical significance are these points:

1. All of the curves indicate that the amount of wood and bark removed from the bole increased with increasing tree size height, diameter, and volume.
2. All curves except the one for length of scar show that the per cent of wood and bark removed from the bole remained nearly constant or decreased with increasing tree size.

[11] See statement of caution, page 27.

3. Except for length of scar, there appears to be a marked difference between associations involving wood-loss damage and bark-loss damage.

For example, Figures 19 and 20, page 51, show that a wood-loss tree of 80 cubic feet lost 10 cubic feet of material; but a bark-loss tree of 80 cubic feet lost 3 cubic feet of material from the bole.

Returning to the statement made at the beginning of this section: It is apparently true that the amount of material removed varies with tree size, but it is difficult to predict the damage, knowing tree size, because a tree picked at random may be either a wood-loss or bark-loss tree. Since one cannot at this point predict whether a tree will be a wood-loss or bark-loss victim, the applicability of the statement is severely limited.

There is little in the literature to confirm or refute the apparent associations reported here; however, McEachron (1940) stated that the amount of tree damage is a function of pressure, which is dependent upon the amount of current in the lightning discharge. The current varies from less than 1,000 to 200,000 amperes. The curves presented in this paper appear to be contrary to McEachron's findings. In the light of present-day knowledge, it seems reasonable that both the tree and the stroke play important roles in the complex relations between lightning and trees. Perhaps tree size or some related factor affects the "energy budget" of the stroke, causing more or less energy to be cast off or absorbed, as the situation demands.

II. DISCUSSION OF DAMAGE CHARACTERISTICS

Wood-loss and Bark-loss Damage

By now the reader is painfully aware of the importance placed upon the differences between these arbitrary classes of damage. Are the differences real? Is the importance justified? Figure 6, page 32, shows that they affect the bole at different depths. This is illustrated mathematically by the curves featuring both classes of damage.

Sample statistics for scar length, depth, and width were presented in Chapter IV. The means for each of these variables are different for wood-loss and bark-loss trees. The means were submitted to t-tests under null hypotheses of no significant difference at the .05 level. In each case the null hypothesis was rejected. The tests supported the observed differences, and indicated scar lengths, depths, and widths were, on the average, greater on wood-loss trees.

Do wood-loss trees themselves differ from bark-loss trees? Apparently they do, to some extent. Figure 26, Appendix A, shows the distribution of total tree heights for the two damage classes. The mean values of tree height, volume, and cross-sectional bole area (at 17 foot height) were tested for significant differences. The wood-loss trees were significantly greater in height, volume, and bole area at the .05 level.

One may now conclude with some assurance that wood-loss trees were, on the average, larger than bark-loss trees; and that the damage dimensions were greater on wood-loss trees.

What causes a tree to suffer loss of wood from lightning? Consider two possible explanations: (1) The discharge travels along the bole in the wood beneath the cambium--path of the current, (2) The discharge current is greater in wood-loss trees--amount of current.

In view of the tree size statistics just presented, (2) seems inappropriate. This explanation would lead one to conclude that high-current discharges usually seek out larger trees. Field observations and the literature indicate the charge may travel along the outer bark surface (Vanderlinden, 1907), within the cambium (Dodge, 1936), or within the wood of the bole (Viemeister, 1961). The first explanation seems the better of the two.

A third alternative should be considered: Some factor related to tree size may enhance the striking power of the discharge, causing wood loss. A discourse on the lightning stroke is beyond the scope of this paper; however, an oversimplified description is offered here and illustrated in Figure 31, Appendix A. The cloud initiates a downward stepped-leader, which lowers the negative cloud charge toward the earth. This produces a strong electric field between the leader and earth. When the leader approaches to within say, 30 to 100 feet of the earth, a positive streamer from the ground or a nearby tree makes a junction with the leader. This initiates the return stroke, which neutralizes the charges back toward the cloud along the path of the stepped-leader (Schonland, 1950; McEachron, 1940). Chalmers (1957) and Schonland (1950) have shown that trees accumulate positive charges (the familiar St. Elmo's fire is the visible and audible form) during thunderstorms. When a tree is struck, these charges become part of the damaging return stroke (McEachron, 1940). It is not known whether tree size is related to the accumulation of positive charges on the tree; or whether a large accumulation enhances the destructive power of the stroke, causing wood-loss damage.

Lower Scar-reach Deficit

Twenty-six of the furrows reached ground level on the bole, and 27 did not. Two-thirds of the scars reaching ground were on pointed-top trees, and two-thirds of the above-ground scars were on rounded-top trees. The trees in each category are shown here:

	Lower scar-reach		
	to ground	above ground	
Pointed top	18	9	27
Rounded top	8	18	26
	26	27	53

A Chi square test rejected the null hypothesis of independence at the .05 level of significance. This indicated some degree of dependence among the categories. Subsequent examination indicated that the probability of scars on pointed trees reaching the ground was $P > .50$, and the probability of scars on pointed trees not reaching the ground was $P < .49$. But this was true only at the .14 level of significance. This means that in 86 of 100 random samples of 27 pointed trees each, one could expect scars to reach the ground on more than half of the trees. A similar weak probability statement could be made concerning rounded-top trees having scars that did not reach the ground.

Recall from Chapter III, page 23, that the method employed to estimate shape of top was rather subjective. A more objective technique could verify or refute the shape of top--lower scar reach association suggested by the present data.

Forty-three Chi square tests of independence were conducted. Only the one mentioned above is noteworthy.

Upper Scar-reach Deficit

There appears to be no apparent association between this variable and any of the others presented here; but a possible explanation of the phenomenon is offered.

Defandorf (1955) made electrical resistance measurements on parts of a live tuliptree (Liriodendron tulipifera, L.). He showed that resistance to ground increased rapidly going up the bole and out to the tip end of a leaf on a twig. Resistance at the tip end of the twig was 400,000 ohms. At a point 10 feet down the 82 foot bole, the resistance was 80,000 ohms. It is interesting that this strong gradient takes place on the uppermost 10-foot length of the bole. This length corresponds to the mean value of 10 feet for the upper scar-reach deficit discussed in Chapter IV.

It would be hazardous to infer from this correspondence that the upper scar deficit owes its existence to a region of high electrical resistance near the tip of the bole; but the point seems worthy of further study.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

The conclusions presented here are believed applicable to Douglas-fir on the 38 square mile study area near Philipsburg, Montana.

1. The extent of structural lightning damage to boles of individual trees varies with tree size, as reflected by height, diameter and volume.
   a. The actual amount of wood and bark removed is a linear function of tree size, and increases with increasing tree size.
   b. The per cent of total wood and bark removed from wood-loss trees is a logarithmic function of tree size, and decreases with increasing tree size.
   c. The per cent of total bark removed from bark-loss trees remains nearly constant or decreases slightly with increasing tree size.
2. Structural damage to the bole may be classed as two types--wood-loss and bark-loss.
   a. Damage dimensions length, width, and depth of scar are greater on wood-loss trees than on bark-loss trees.
   b. Wood-loss trees are, on the average, greater in height, diameter, and volume.

II. RECOMMENDATIONS

This study has dealt only with one side of a complex cause and effect relation. Little is known about the cause--the lightning discharge--with respect to tree damage and ignition.

From laboratory measurements of artificial lightning, McEachron (1940) concluded that; (1) peak currents cause explosive damage to trees, (2) continuing, low currents cause ignition, (3) both continuing and peak currents may be present in a multiple discharge. Field corroboration of these views is still lacking.

It is recommended that an exploratory study be made to determine whether damage extent and probability of ignition vary with peak current. The inexpensive "magnetic link" device described by McEachron could be attached to many trees in a high lightning occurrence area. The link consists of strips of cobalt steel about two inches long, enclosed within a molded tubular container. The device is magnetized when the tree is struck by lightning, and indicates peak current in the discharge.

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APPENDIX A

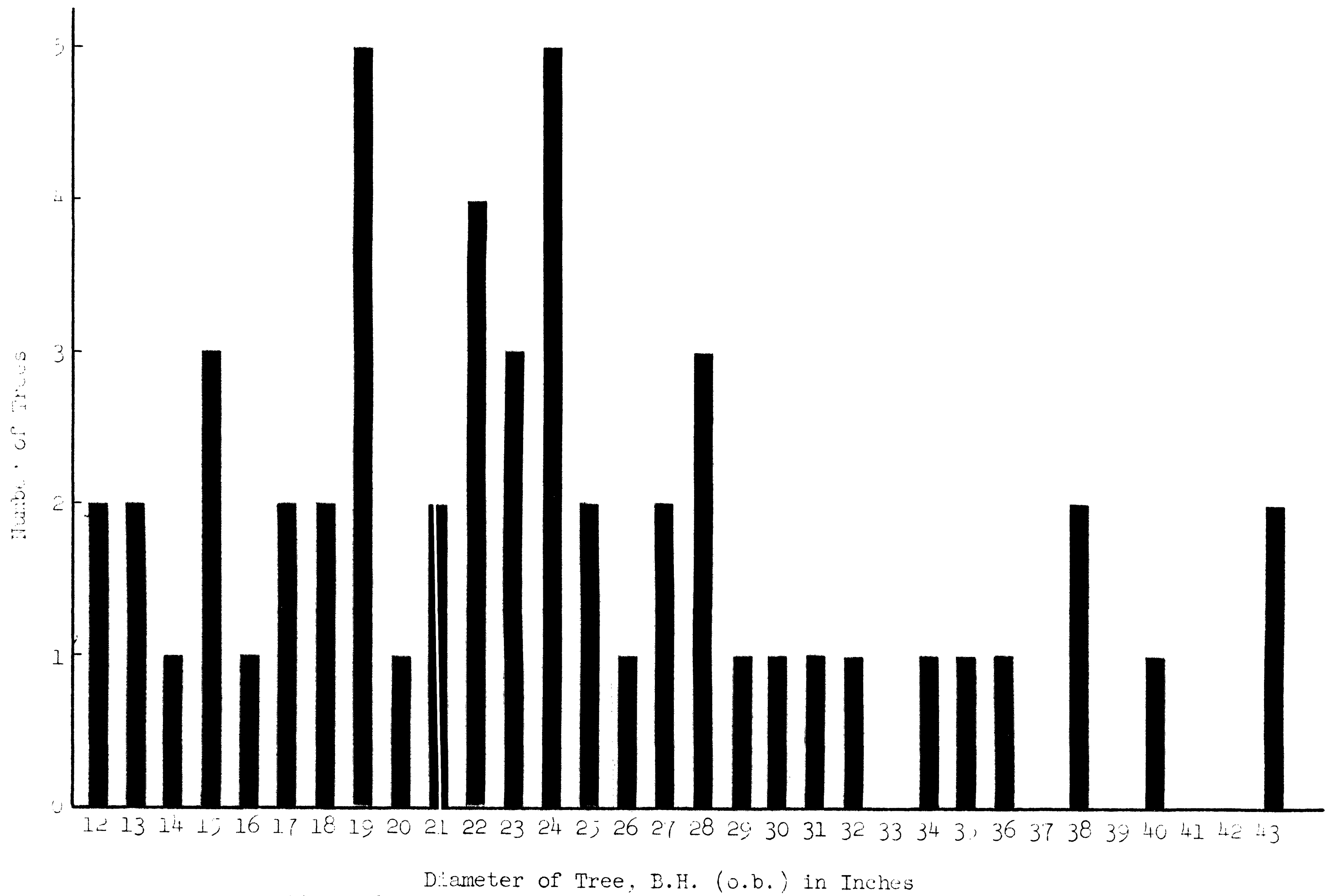

Figure 21. Distribution of breast high diameters among 53 trees.

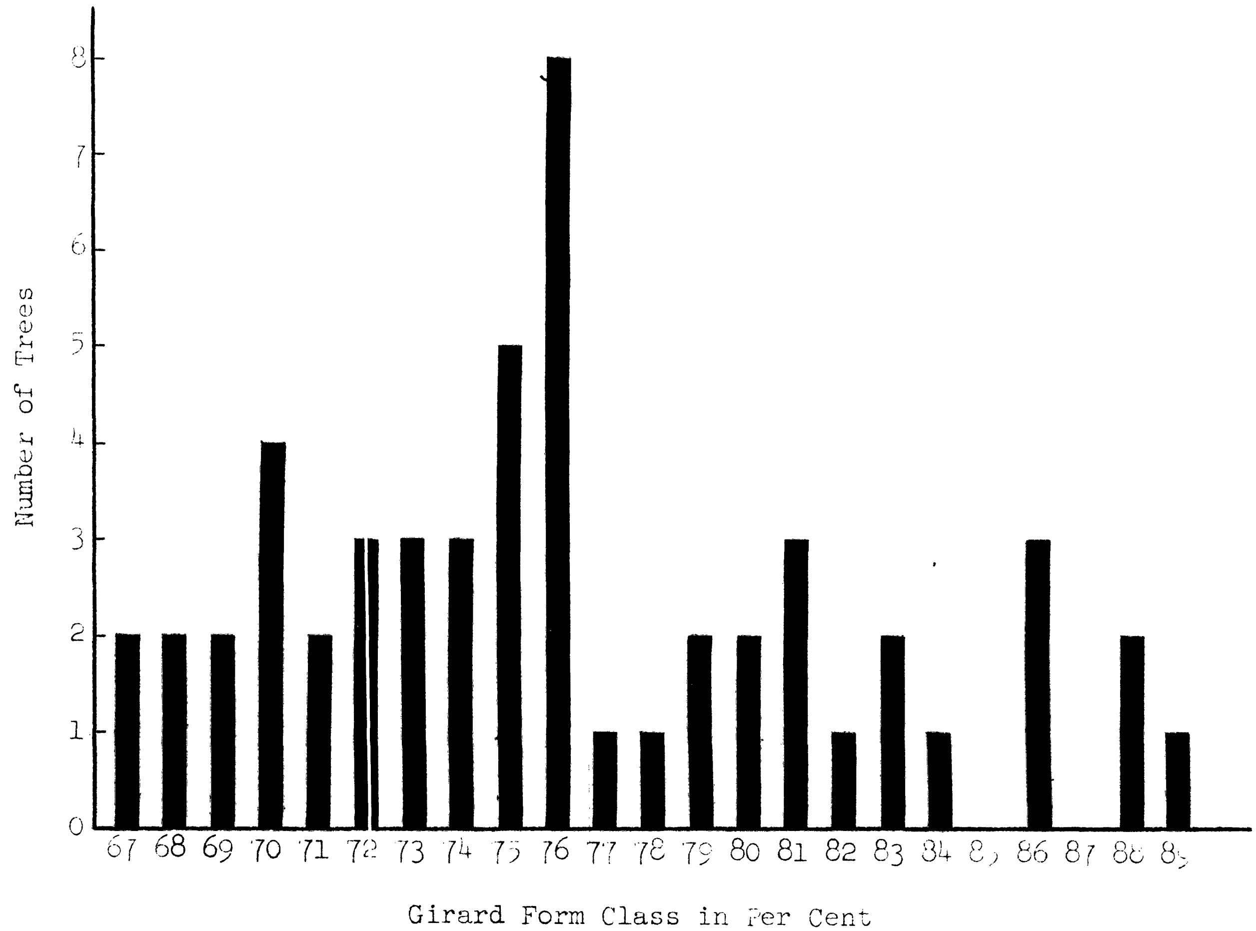

Figure 22. Distribution of Girard form classes among 53 trees.

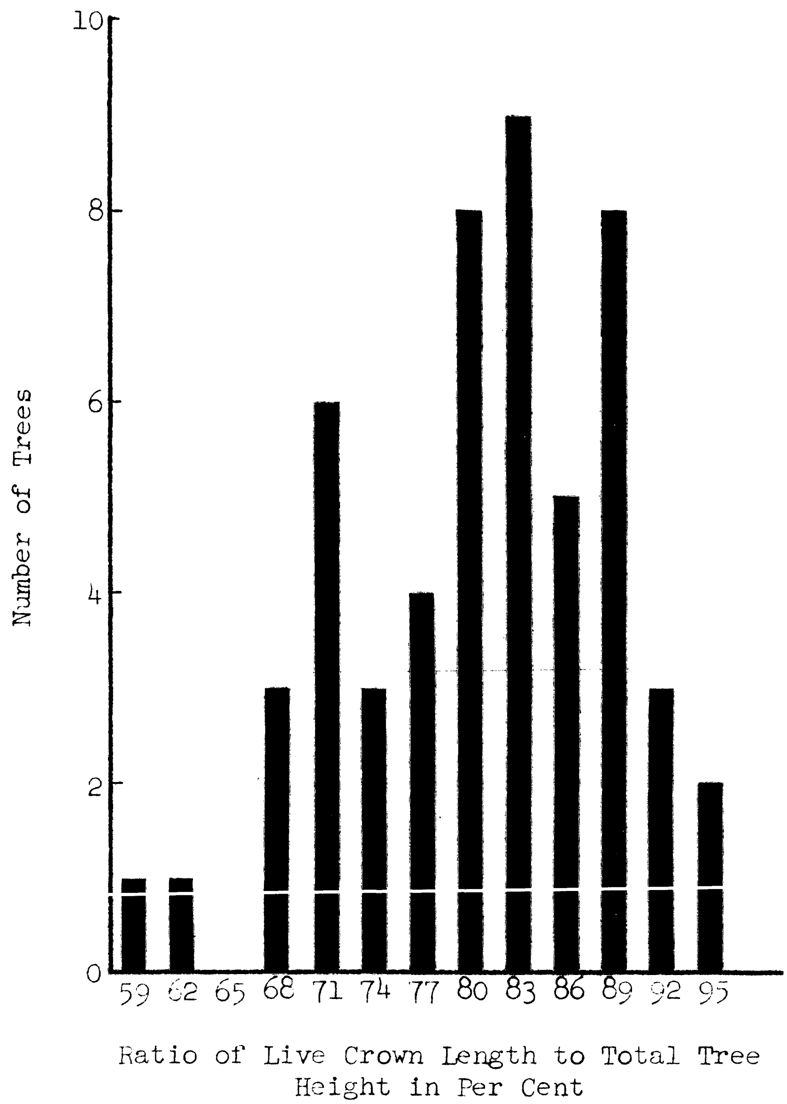

Figure 23. Distribution of crown length to tree height ratios among 53 trees.

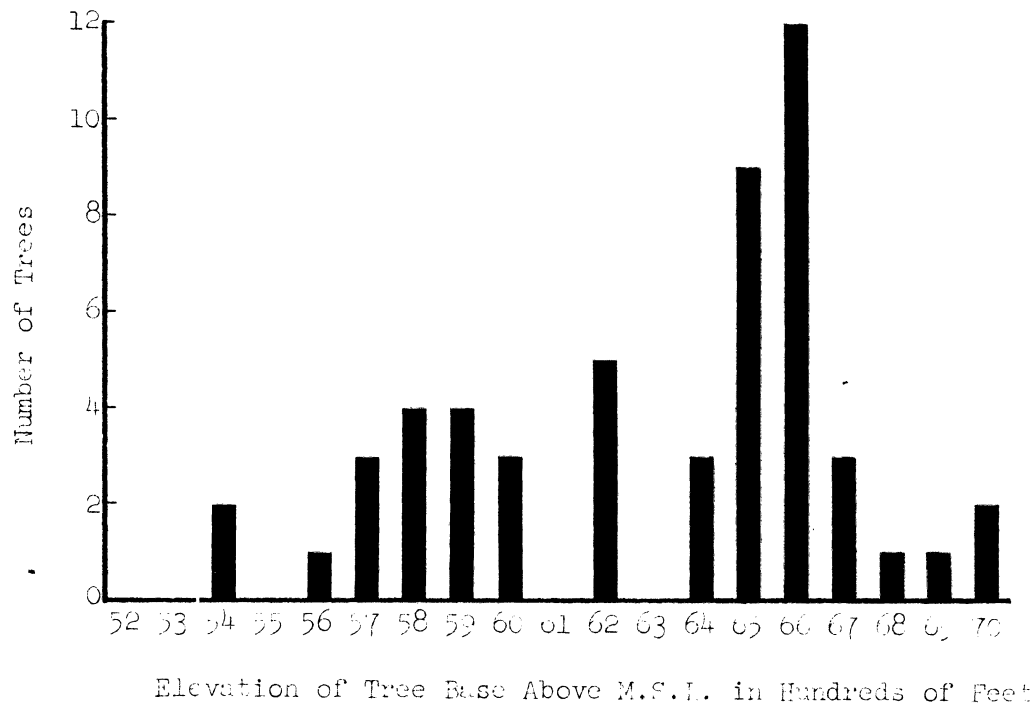

Figure 24. Distribution of elevations among 53 trees.

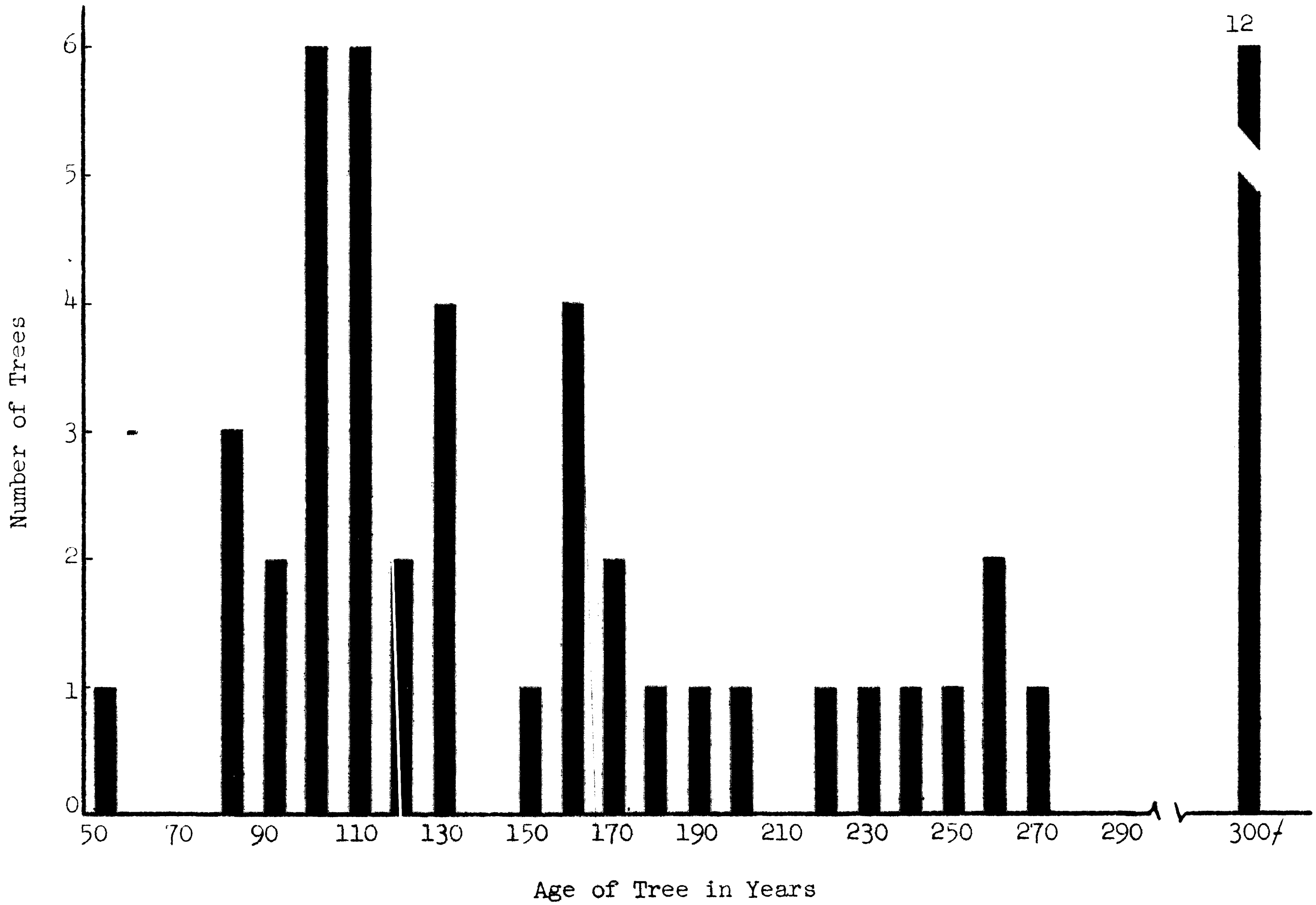

Figure 25. Distribution of tree age among 53 trees.

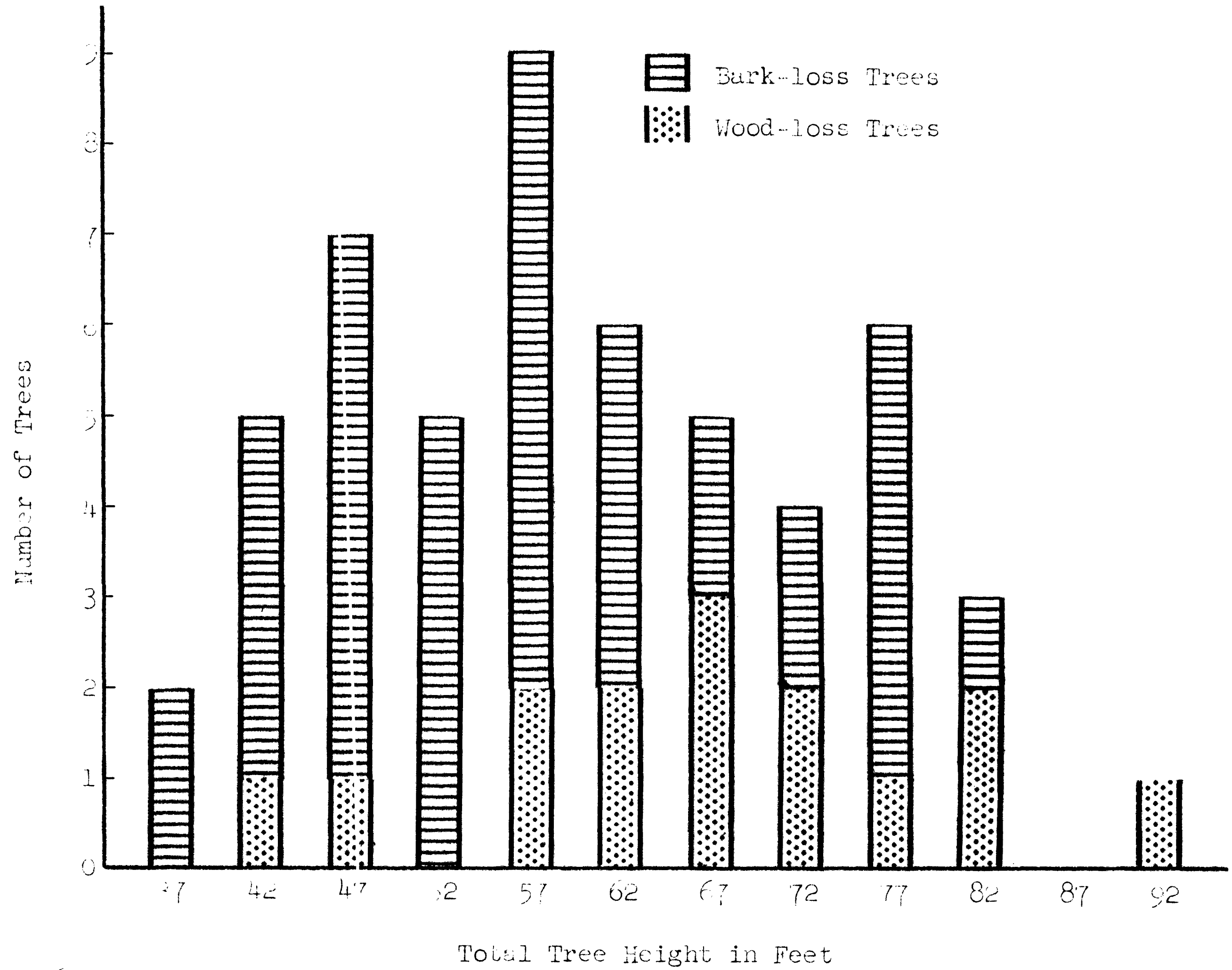

Figure 26. Distribution of tree heights among 15 wood-loss trees and 38 bark-loss trees.

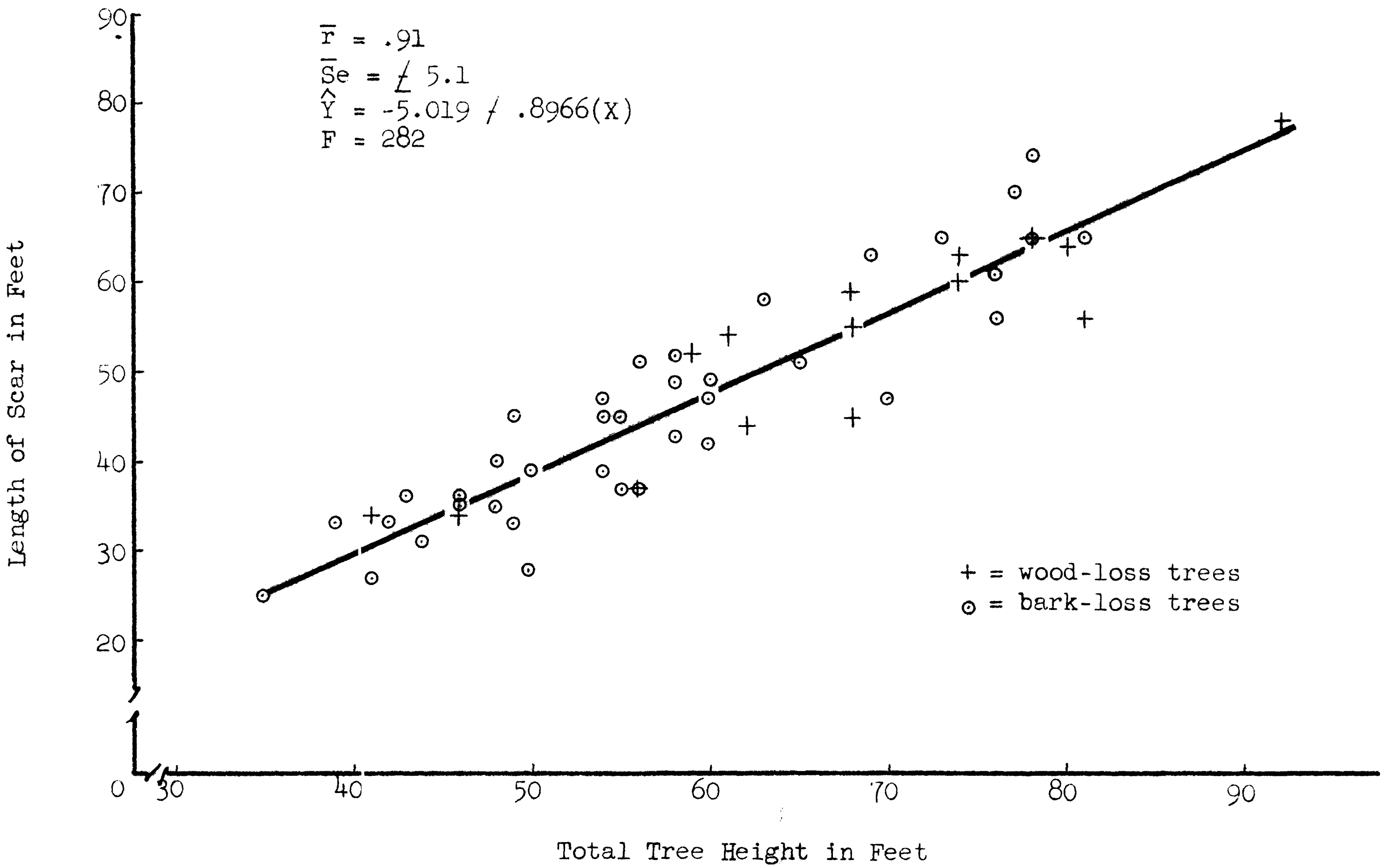

Figure 27. Length of lightning scar over total tree height for 53 trees.

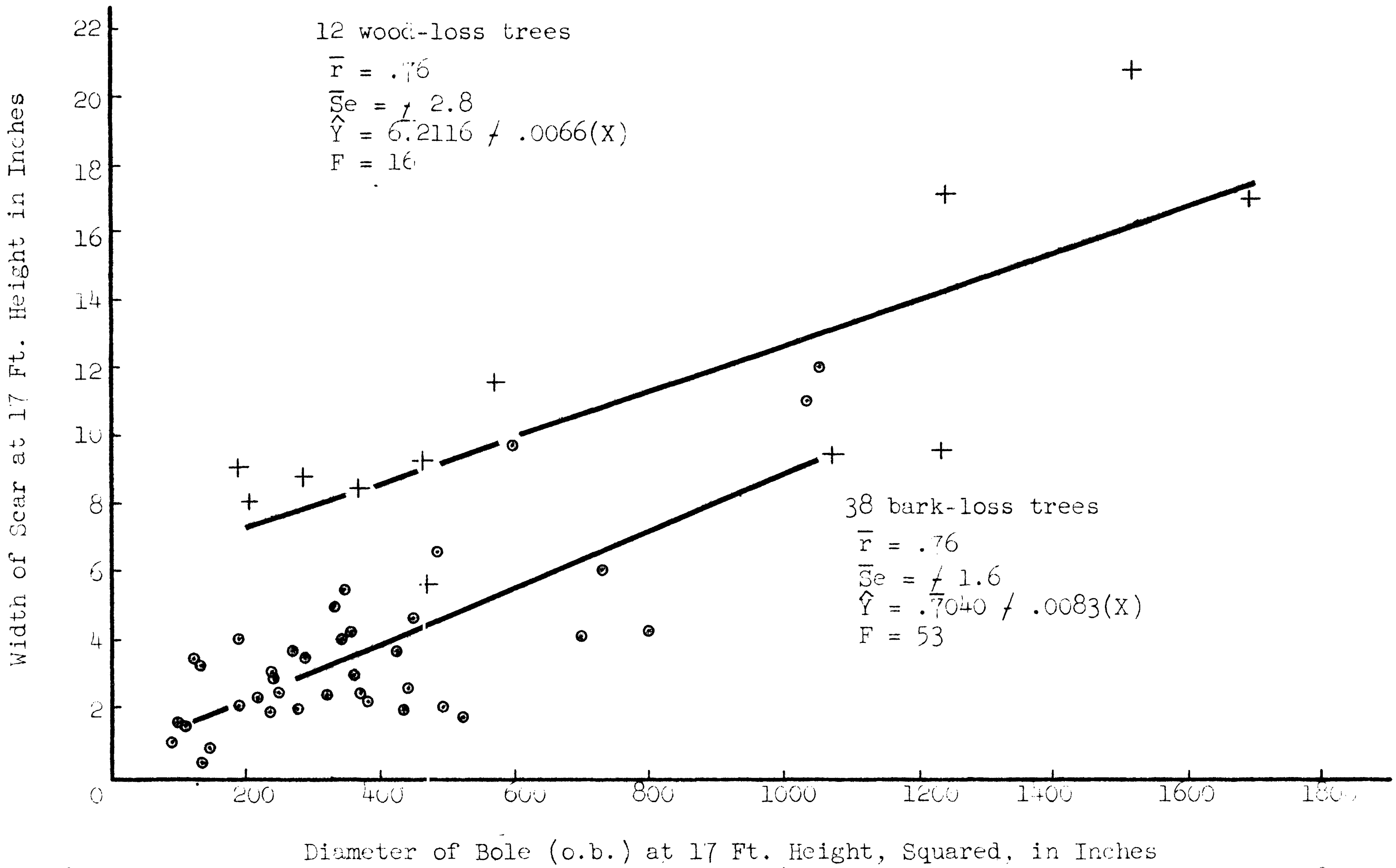

Figure 28. Width of lightning scar over diameter of bole (squared) for 12 wood-loss trees and 38 bark-loss trees.

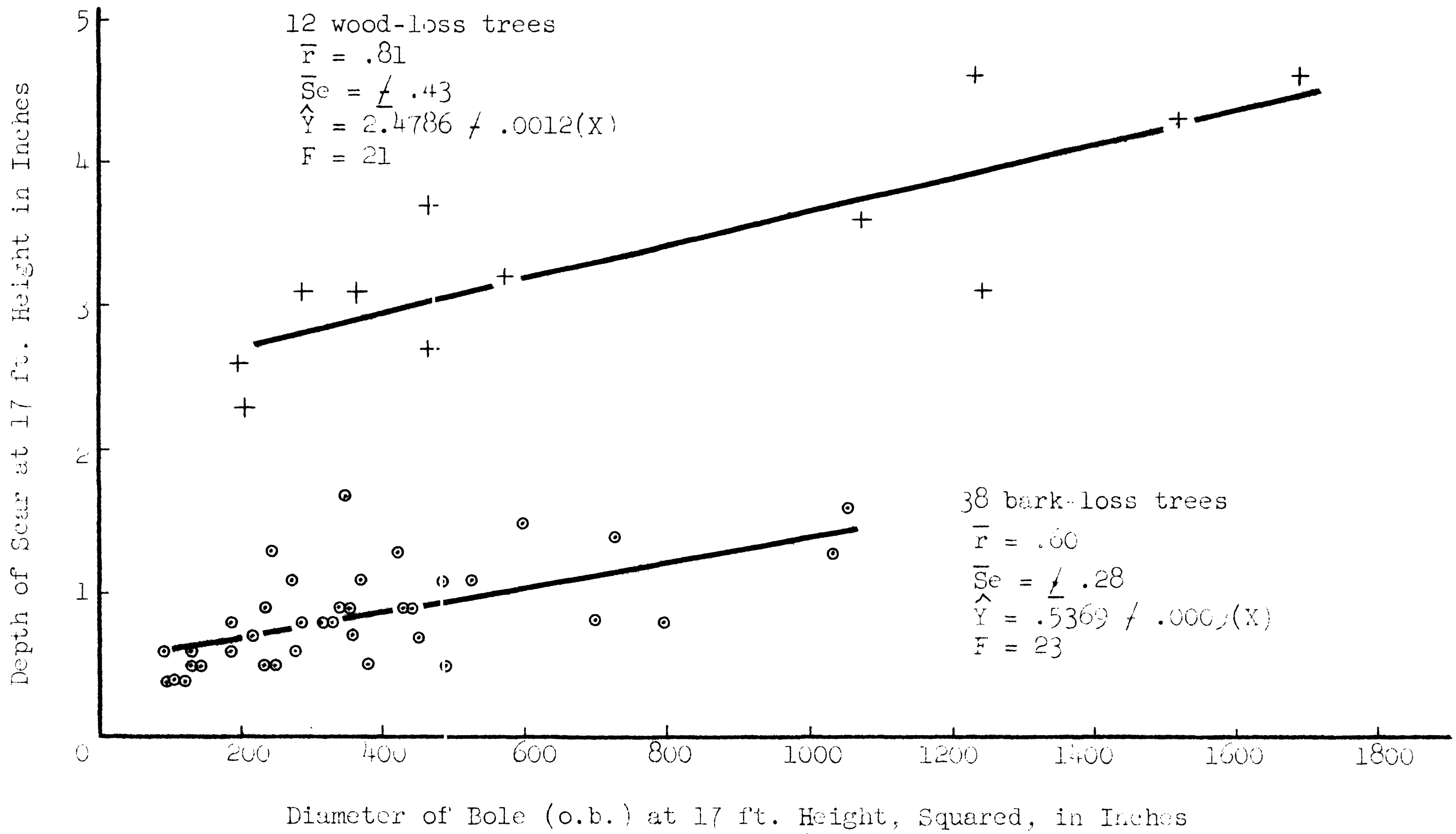

Figure 29. Depth of lightning scar over diameter of bole (squared) for 12 wood-loss trees and 38 bark-loss trees.

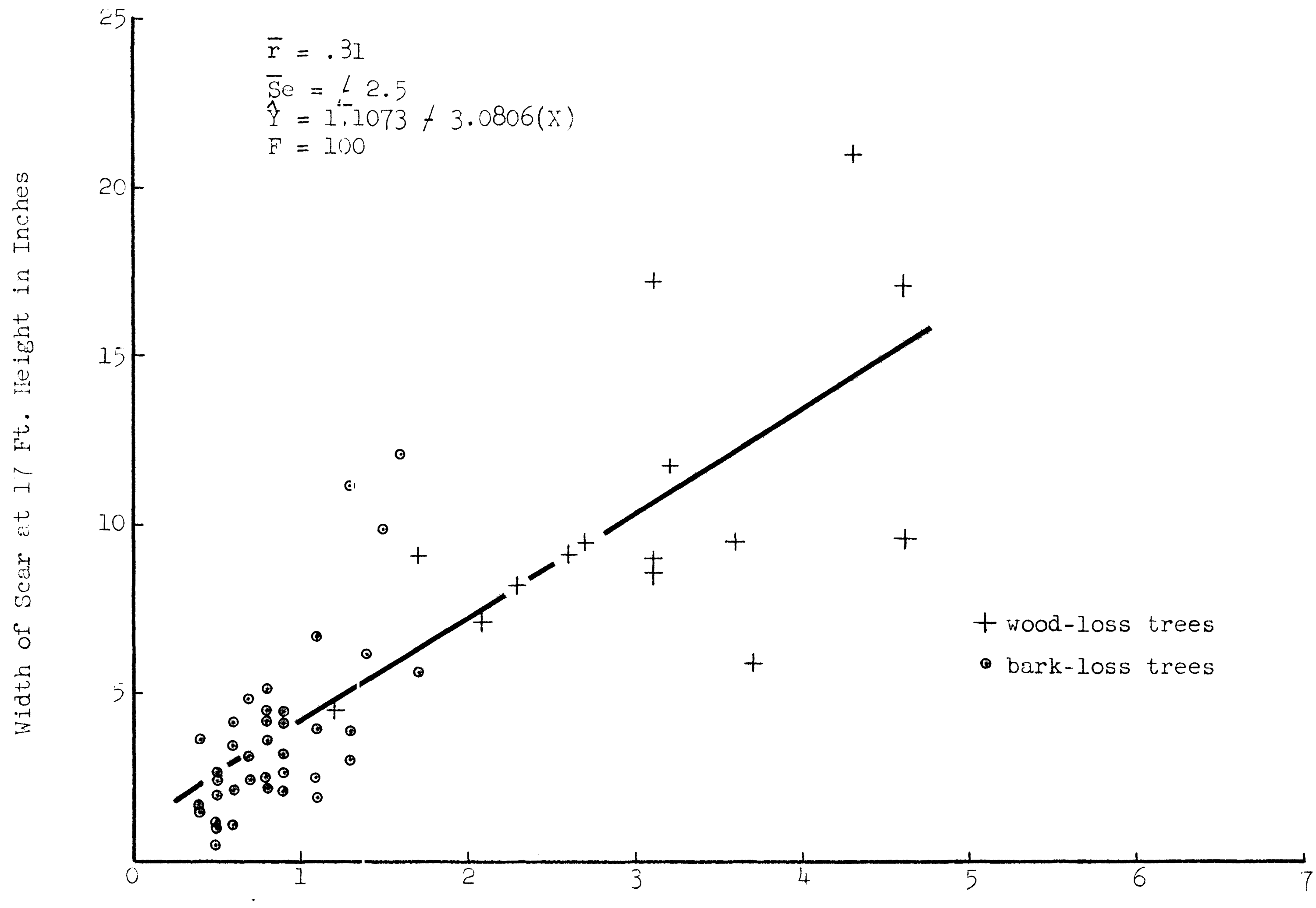

Figure 30. Width of lightning scar over depth of scar at 17 ft. height on bole, for 53 trees.

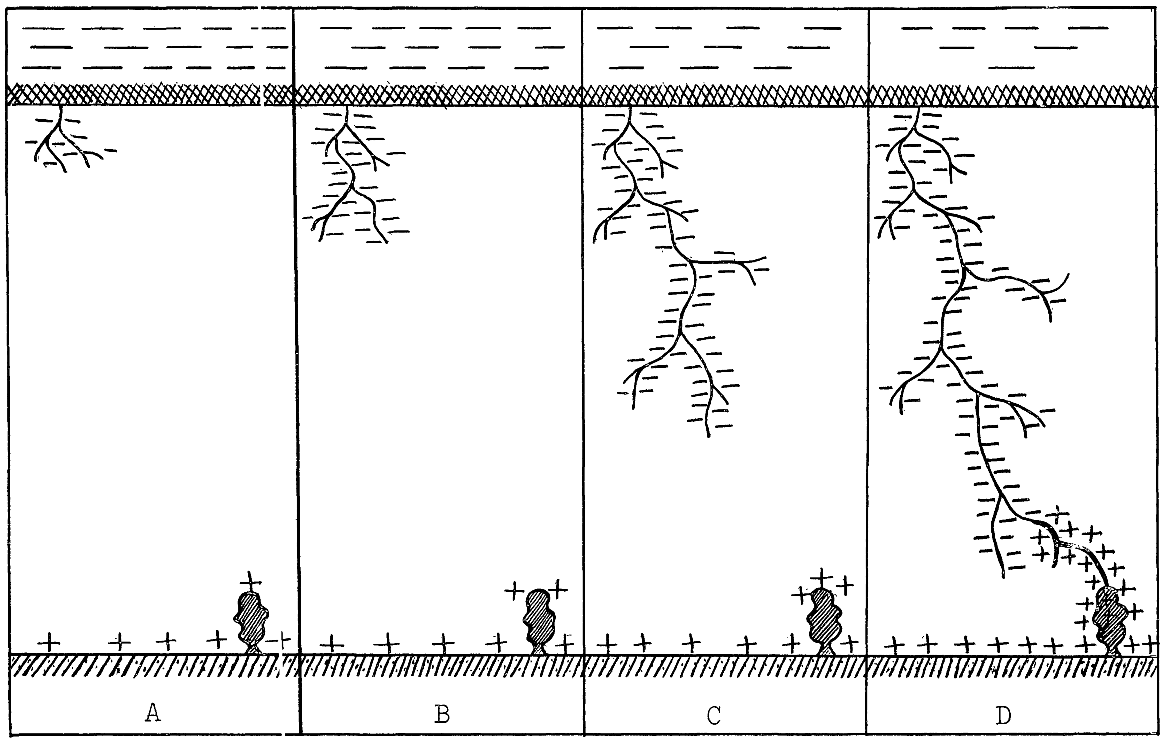

Figure 31. The lightning discharge: A, initiation of downward stepped-leader stroke from cloud, B and C, lowering of cloud charge produces strong electric field between leader and earth, D, positive streamer from tree makes a junction with leader, initiating the return stroke. Maximum current flow is in the return stroke. (From Schonland, 1950.)

APPENDIX B

APPENDIX B

BIMD-06 "MULTIPLE REGRESSION AND CORRELATION ANALYSIS NO. 1" IBM-7090 PRINT-OUT USING SAMPLE SIZE OF 53 WITH 8 VARIABLES EACH, THE DEPENDENT VARIABLE BEING CROSS-SECTIONAL AREA DAMAGE RATIO

Coefficient of Determination	0.1348
Multiple Correlation Coefficient	0.3671
Sum of Squares Attributable to Regression	0.00783
Sum of Squares of Deviation From Regression	0.05026
Variance of Estimate	0.00112
Standard Error of Estimate	0.03342
Intercept (A Value)	-0.13364

ANALYSIS OF VARIANCE FOR THE MULTIPLE LINEAR REGRESSION

Source of Variation	DF	Sum of Squares	Mean Squares	F Value
Due to Regression	7	0.00783	0.00112	1.0012
Deviation About Regression	45	0.05026	0.00112	
Total	52	0.05808		

APPENDIX C

APPENDIX C

STATISTICAL MODELS EMPLOYED IN DATA ANALYSIS

Statistical Model 1. Simple linear regression and correlation; Product Moment Method--ungrouped data.

Step (1) $P = \frac{\Sigma(XY)}{N} - \frac{\Sigma(X)}{N}\frac{\Sigma(Y)}{N}$

(2) $S_x = \sqrt{\frac{(X^2)}{N} - \left(\frac{X}{N}\right)^2}$

(3) $S_y = \sqrt{\frac{(Y^2)}{N} - \left(\frac{Y}{N}\right)^2}$

(4) $r = \frac{P}{S_x\, S_y}$

(5) $Se = S_y\sqrt{1 - r^2}$

(6) $y = r\,\frac{S_y}{S_x}\,x$

(7) $Y-\overline{Y} = b(X-\overline{X})$

(8) $Y = a + bX$

Statistical Model 2. Correction of standard error of estimate and correlation coefficient for small sample size.[12]

---

[12]These corrections adjust r for exaggeration, and adjust Se for an underestimate. They are equivalent to using N-1 in the denominators of steps (2) and (3) in Statistical Model 1.

(1) corrected Se;

$$\bar{S}e^2 = Se^2 \frac{(N-1)}{(N-2)}$$

(2) corrected r;

$$\bar{r}^2 = 1 - (1 - r^2) \frac{(N-1)}{(N-2)}$$

Statistical Model 3. Analysis of variance for linear regression; F test for significance of regression.

Step (1) regression sum of squares;

$$\frac{P^2}{S_x{}^2}$$

(2) residual sum of squares;

$$S_y{}^2 - \frac{P^2}{S_x{}^2}$$

(3) regression mean square;

$$\frac{\text{regression sum of squares}}{\text{1 degree of freedom}}$$

(4) residual mean square;

$$\frac{\text{residual sum of squares}}{\text{N-2 degrees of freedom}}$$

(5) calculated F ratio;

$$F = \frac{\text{regression mean square}}{\text{residual mean square}}$$

(6) comparison of calculated F ratio and tabular F ratio for 1 and N-2 degrees of freedom. (If calculated F exceeds tabular F at prescribed level of significance, regression is significant).

Statistical Model 4. Chi square test for independence; two-by-two tables.

Step (1) construction of table;

	I	II	Total
1	a	b	$a + b$
2	c	d	$c + d$
Total	$a + c$	$b + d$	$a + b + c + d = N$

(2) calculation of Chi square;

$$X^2 = \frac{(|ad-bc| - \frac{1}{2}N)^2 N}{(a+b)(a+c)(b+d)(c+d)}$$

(3) comparison of calculated X^2 and tabular value at 1 degree of freedom. (If calculated X^2 exceeds tabular value at prescribed level, reject null hypothesis of independence between the two variables tested).

Statistical Model 5. t-test for significance of the difference between two means.

Step (1) calculation of standard error of the difference;

$$Sed = \sqrt{\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}}$$

where

S_1 = standard deviation of first sample

S_2 = standard deviation of second sample

N_1 = number of items in first sample

N_2 = number of items in second sample

(2) calculation of sample t;

$$t = \frac{\bar{X}_1 - \bar{X}_2}{Sed}$$

(3) comparison of calculated t and tabular t at $N_1 + N_2 - 2$ degrees of freedom. (If calculated t exceeds tabular t at prescribed level, reject the null hypothesis of no significant difference between the two means).

APPENDIX D

APPENDIX D

EXPLANATION OF TABLE II.

Table II gives values of the original field observations on 24 tree and damage characteristics for 53 lightning-damaged trees. All of the curves and frequency distributions presented in this paper may be reproduced from the values in Table II.

The key to all qualitative entries is shown below. In each instance, the column heading is given first, followed by the table entry and its meaning. Blanks in the table indicate that the category was not applicable to that tree.

Tree Characteristics

1. shape of top: rou (round); poi (pointed); fla (flat).
2. crown class: dom (dominant); cod (codominant); int (intermediate.)
3. aspect of slope, in degrees: R (ridge top); B (bottom land).

Damage Characteristics

1. scar alignment: str (straight); obl (oblique); spi (spiral).
2. direction of spirality: L (ascending to the left); R (ascending to the right).
3. bole crack: Y (bole crack present); N (bole crack absent).
4. cambium strip: Y (cambium strip present); N (cambium strip absent); U (tree not examined for cambium strip).

TABLE II

ORIGINAL FIELD OBSERVATIONS ON 24 TREE AND DAMAGE CHARACTERISTICS FOR 53 LIGHTNING-DAMAGED TREES

	TREE CHARACTERISTICS											DAMAGE CHARACTERISTICS												DAMAGE RATIOS	
	Tree I.D. number	Diameter b.h. in.	Crown-height ratio	Girard form class	Age yrs.	Shape of top	Elevation, MSL	Crown class	Total height ft.	Diameter, 17 ft.ht. in.	Aspect of slope, degrees	Scar length, ft.	Scar depth, in.	Scar width, in.	Upper deficit, ft.	Lower deficit, ft.	Scar align.	Direction of spiral	Number of spirals	Scar age yrs.	Bole crack	Cambium strip	Aspect of scar, degrees	Length-loss ratio	Cross-sectional area damage ratio
Wood-loss trees	963	43.2	.88	.89	300/	rou	6200	dom	92	41.1	R	79	4.6	17.0	11	2	str			3	Y		067	.28	.06
	958	30.9	.83	.72	175	rou	6200	dom	59	23.9	164	53	3.2	11.7	5	1	obl	L	0.25	3	Y		164		.08
	953	20.8	.84	.86	110	poi	6400	cod	68	19.1	279	56	3.1	8.6	12	0	spi	L	1.00	1	Y				.09
	234	25.1	.88	.76	130	poi	6600	cod	68	21.5	181	60	2.7	9.4	7	1	str			2	Y		160	.48	.07
	945	19.4	.89	.77	90	poi	6400	dom	56	16.9	268	38	3.1	8.9	17	1	obl	L	0.50	5	Y		025		.12
	929	18.1	.70	.70	230	rou	6500	dom	46	14.3	210	35	2.3	8.2	9	0	obl	L	0.25	5	Y		271		.12
	970	40.2	.81	.74	300/	rou	5800	dom	78	32.7	056	66	3.6	9.5	12	0	spi	R	2.00	4	Y				.04
	937	38.3	.77	.86	300/	poi	6600	dom	74	35.2	091	61	3.1	17.2	13	0	spi	R	1.00	4	Y				.05
	942	43.4	.74	.81	350	poi	6400	dom	81	39.0	174	57	4.3	20.8	21	3	obl	R	0.50	1	Y		304		.07
	964	37.6	.85	.88	300/	rou	6200	dom	80	35.1	R	65	4.6	9.6	15	0	obl	R	0.25	0	Y		194	.24	.05
	244	27.3	.88	.76	170	rou	6500	dom	68	23.6	260	46	2.1	7.2	21	1	str			1	Y		128		.03
	949	22.4	.81	.78	160	poi	5800	dom	74	19.0	291	64	1.7	9.1	10	0	str			1	Y		185		.05
	969	24.2	.68	.76	160	rou	5700	dom	62	20.3	029	45	1.2	4.5	14	3	obl	L	0.25	3	Y		029		.02
	235	15.6	.85	.80	240	poi	6600	cod	41	13.9	R	35	2.6	9.2	6	0	spi	R	1.00	2	Y			.29	.16
	943	27.6	.79	.67	200	fla	6500	cod	61	21.6	176	55	3.7	5.8	3	3	spi	R	1.00	5	Y				.06
Bark-loss trees	980	17.4	.62	.76	160	poi	6500	cod	58	14.6	R	53	0.7	2.4	5	0	obl	R	0.25	4	Y	Y	121		.01
	981	22.9	.89	.76	80	poi	6800	cod	54	18.9	R	40	0.7	3.1	8	6	spi	L	1.00	4	Y	Y			.01
	965	14.6	.95	.69	50	poi	5400	cod	44	11.3	052	32	0.6	3.4	12	0	spi	L	1.00	3	N	Y			.02
	983	14.1	.95	.72	90	rou	7000	dom	41	10.9	161	28	0.4	3.6	13	0	obl	R	0.25	3	Y	Y	120		.02
	951	25.4	.87	.75	260	rou	5900	cod	46	20.9	161	37	0.9	2.7	9	0	spi	L	1.00	1	N	Y			.01
	959	27.1	.92	.73	100	rou	5800	dom	50	21.9	074	40	1.1	6.7	9	1	obl	L	0.50	1	N	Y	265		.02
	971	22.8	.59	.81	325	rou	6700	cod	63	19.4	209	59	0.5	2.3	4	0	spi	R	3.00	1	Y	Y			.00
	957	23.5	.84	.71	220	poi	6600	dom	56	18.4	258	52	0.9	4.1	4	0	spi	R	2.00	0	N	Y			.01
	960	31.9	.74	.83	300/	rou	5800	dom	76	28.2	131	62	0.8	4.4	12	2	spi	R	1.00	0	N	Y			.01
	979	28.8	.81	.86	300/	rou	5600	dom	78	26.4	B	75	0.8	4.2	3	0	spi	L	1.00	0	N	Y			.01
	975	12.8	.67	.75	250	poi	6600	dom	54	10.4	242	46	0.4	1.6	8	0	spi	L	2.00	0	N	Y			.01
	973	23.5	.88	.72	100	poi	6600	dom	48	18.7	R	36	0.9	4.4	12	0	spi	L	1.00	0	Y	Y			.01
	935	23.8	.79	.75	80	poi	6200	dom	81	20.5	204	66	1.3	3.8	15	0	obl	L	0.50	2	N	U	160		.01
	972	27.7	.72	.74	300/	rou	6600	cod	58	22.8	133	44	1.1	1.9	8	0	obl	R	0.25	4	N	N	298		.01
	940	11.9	.71	.69	175	rou	6500	cod	35	9.4	320	26	0.6	1.1	6	3	spi	R	1.00	1	N	U			.01
	236	13.2	.69	.79	190	rou	6600	cod	39	11.4	310	34	0.5	0.5	3	2	obl	L	0.50	1	N	U	260		.00
	237	15.2	.83	.82	120	rou	6600	dom	42	13.6	341	34	0.6	4.2	3	5	obl	L	0.75	1	N	U	108		.02
	967	14.7	.77	.74	110	poi	5700	cod	48	11.9	R	41	0.5	0.9	7	0	obl	L	0.50	1	N	N	034		.00
	944	18.6	.78	.76	100	rou	6000	dom	54	16.4	124	48	1.1	3.8	6	0	spi	L	1.00	4	Y	U			.02
	941	18.9	.88	.70	100	poi	6600	cod	60	15.5	180	50	1.3	3.0	10	0	obl	L	0.50	5	Y	U	032		.02
	956	21.8	.74	.76	270	poi	6600	cod	69	18.1	232	64	0.8	5.1	5	0	spi	R	2.00	1	Y	N			.02
	950	23.9	.92	.88	130	rou	5900	cod	60	22.1	309	43	0.5	2.1	16	1	spi	L	1.00	4	Y	U			.00
	951	18.9	.92	.75	80	poi	6500	int	66	15.2	073	54	0.5	2.0	12	0	obl	L	0.50	4	Y	U	018		.01
	974	20.6	.82	.79	100	rou	6500	cod	65	17.8	316	52	0.8	2.5	9	4	spi	L	1.00	4	Y	N			.01
	978	20.3	.79	.76	130	poi	7000	dom	58	16.6	R	50	0.6	2.1	6	2	obl	L	0.25	3	Y	N	333		.01
	247	22.4	.71	.68	260	poi	6500	cod	70	18.6	036	48	1.7	5.6	22	0	obl	R	0.12	2	Y	U	126	.24	.04
	910	30.2	.80	.71	150	rou	6600	dom	77	24.4	180	71	1.5	9.9	6	0	obl	R	0.25	2	Y	U	035		.03
	966	35.0	.83	.84	300/	rou	5400	dom	76	32.1	021	57	1.3	11.1	18	1	str			3	Y	N	265		.02
	968	27.7	.84	.68	130	rou	5700	cod	56	20.7	179	38	0.9	2.1	17	1	obl	L	0.25	3	Y	N	253		.01
	947	36.2	.90	.81	300/	poi	5900	dom	73	32.4	205	66	1.6	12.1	7	0	str			2	Y	U	122	.10	.02
	962	34.2	.84	.70	300/	rou	6000	cod	49	26.9	R	34	1.4	6.2	12	3	obl	L	0.25	3	Y	N	132	.33	.02
	952	18.6	.72	.73	110	poi	6500	cod	43	15.3	023	37	0.9	3.2	6	0	spi	L	1.00	2	Y	U			.02
	982	12.4	.70	.73	110	poi	6900	int	50	9.9	163	29	0.4	1.7	21	0	obl	L	0.50	4	Y	N	160		.01
	955	26.2	.87	.75	160	poi	6700	dom	60	21.1	148	48	0.7	4.8	12	0	obl	L	0.25	3	Y	U	321		.01
	946	17.2	.83	.70	110	poi	6700	dom	46	13.6	108	36	0.8	2.2	9	1	obl	L	0.50	4	Y	U	324		.01
	939	18.3	.78	.80	100	poi	6200	cod	49	15.7	219	46	0.5	2.6	3	0	spi	L	2.00	1	Y	U			.01
	954	21.6	.80	.83	120	rou	6000	dom	55	19.1	B	46	1.1	2.5	5	4	spi	L	2.00	5	Y	U			.01
	948	22.9	.85	.67	110	rou	5900	cod	55	16.9	342	38	0.8	3.6	14	3	str			4	Y	U	089		.01

SAMPLE RECORD FORM

A sample punch card record form is shown on page 85. Each study tree was assigned a card. Entries were made on the face of the card in ink at the time of measurement. The proper holes were hand-punched in the office.

7 4	2 1	7 4	2 1	7 4	2 1	7 4 2 1
88 87	86 85	84 83	82 81	80 79	78 77	76 75 74 73
R.CH.	ALIGN.	TOP	L.L.	ASPECT	ELEV.	

TREE IDENTIFICATION No. (1–12)

X-SEC. AREA DAMAGE RATIO (13–24)

DOM. (25–27)

IGNIT. (28)

X-sec. ratio

1. Dia. o.b. 17 ft. above sfc.________
2. X-sec. area, sq. ft.____________
3. Scar dimen.____w.______d.________
4. Scar X-sec. area, sq. in.______ft.____
5. $r = \frac{\text{X-sec. scar}}{\text{X-sec. total}} =$ ____________ = ________
6. Spiral cor.______cor r=_________

L-L ratio

1. Height after length loss__________
2. forked (yes) (no) act. broken L._____
3. Length of stem removed____________
4. Total height before damage__________
5. $r = \frac{\text{length removed}}{\text{total height}} =$ ________ = _______

Form

1. D.B.H. o.b.______Dia. 17 ft. i.b._____
2. $r = \frac{\text{Dia. 17 ft. ib.}}{\text{D.B.H. o.b.}} =$ ________ = _______

Age

1. Actual ring count______+5=________
2. Damage age=____Tree age at time "0"____

Crown

1. Total ht. before dam.____live crown L.____
2. $r = \frac{\text{live crown length}}{\text{total ht.}} =$ ________ = _______

El.

1. Tree elev., b.h.______—L.P.______=_____

Check-list

1. Ignition (no) (yes) where?______
2. Scar aspect_____Tree aspect_________
3. Scar alignment (straight) (oblique) (spiral)
4. Direction of spiral—plan view—(cw) (ccw)
5. Lower reach of scar______________
6. Dominance class ______________
7. Shape of top (pointed) (rounded) (flat)
8. Length loss (yes) (no)
9. Tree I. D. number______________
10. Legal description Twp.____R.__¼__S.__
11. Date of measurement____________
12. Photo number______________
13. Hor. dist. to closest tree of same or greater height______________
14. Remarks ______________

GIRARD FORM CLASS (61–72)

TREE AGE (53–60)

LENGTH-LOSS RATIO (45–52)

CROWN-HEIGHT RATIO (29–36)

D.B.H. o.b. (37–44)

7 4	2 1	7 4	2 1	7 4	2 1	7 4 2 1
44 43	42 41	40 39	38 37	36 35	34 33	32 31 30 29