THESIS

FOREST SNOW ACCUMULATION FACTORS IN THE COLORADO FRONT RANGE

Submitted by

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In partial fulfillment of the requirements

for the Doctor of Philosophy Degree

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WE HEREBY RECOMMEND THAT THIS THESIS PREPARED UNDER OUR SUPERVISION BY HENRY A. FROEHLICH ENTITLED FOREST SNOW ACCUMULATION FACTORS IN THE COLORADO FRONT RANGE BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DOCTOR OF PHILOSOPHY DEGREE.

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Permission to publish this thesis or any part of it must be obtained from the Dean of the Graduate School

ABSTRACT OF THESIS

FOREST SNOW ACCUMULATION FACTORS
IN THE COLORADO FRONT RANGE

Maximum snowpack water equivalent is measured at 123 points in the Spring of 1966-1968. These points are distributed over three transects within a four square mile area in the 9,580-10,800 foot elevation zone of the Little Beaver watershed in the Colorado Front Range. Harsh climatic conditions persist through the snow accumulation season with winds of 9.4 m/s estimated for the mean winds during days with precipitation. Average temperatures for these periods were estimated to be -5.2°C. Snowpack water equivalent at maximum ranged from 6.6 to 9.7 inches over the three years of measurement averaged over all points.

Individual points vary widely in their relative accumulation from year to year; the R^2 for 1966 vs. 1968 water equivalent is only 25%. Consistency of snowpack density is noted with snow water equivalent vs. snow depth giving r values of 0.86, 0.90 and 0.73 for the three years respectively.

The single most important variable of those tested in this study is a parameter expressing expanse of and distance from a source area of blowing snow. This source ratio is associated with

40% of the total variance when three years data are pooled and 108 sample points are included. Water equivalent increases an average of 5.0 inches per 1000 feet elevation although only 28% of the total variance in water equivalent is associated with elevation. On the 40 points of mid transect the three topographic variables (source, elevation, and steepness of slope) are associated with 85% of the total variance. However, considering all transects, the topographic variables are effectively supplemented by the use of a canopy variable.

Canopy percentage was estimated with a Lemmon spherical densiometer read to inclued a 114° arc, a 21° arc and crown cover to the windward. Basal area per acre was derived through the use of a cruising prism. These four variables are closely correlated and often interchangeable. The most useful of the four is the 114° arc. About 67% of the total variance is associated with the two major topographic variables (source and elevation) and crown cover in a regression involving 108 points and with the three years data pooled. Crown volume and number of stems or sum of stem diameters do not significantly improve any of the regressions.

Roughness variables were derived from profiles of the canopy drawn with the aid of a Kelsh photogrammetric plotter. The most useful of the roughness variables tested is a coefficient indexing the projection of the first tree upwind from the sample point. This variable was selected as the second most important one on the lower transect. With basal area and Coef. 1, the R^2 was 38%, and with the addition of elevation and the height of trees to the lee of the sample point the R^2 was raised to 58%.

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CHAPTER I

INTRODUCTION

Watershed management to influence the accumulation of the snowpack in the timber-snow zone begins with the management or manipulation of the forest canopy. According to the Select Committee on National Water Resources (1960) analysis of hydrologic data, watershed management in the West can be most productive in the snowpack zone. With ever increasing demands for water from the timber-snow zone it is important to understand the processes involved so that watershed management decisions may have a sound basis. The need for an understanding of the processes involved and a better knowledge of the areal distribution of the snowpack over a watershed are interrelated. Goodell (1959, 1966) and Hoover (1960) note the possibilities for improving total yield and possible changes in timing of the snowmelt runoff through vegetative manipulation.

The differences in maximum snowpack accumulation from year-to-year and the differences in the amount of snow accumulated under various topographic and vegetative conditions have been observed for many years. A large number of studies have been carried out in various geographic regions of the United States and Canada and many of these are summarized by Meiman (1968), Miller (1964, 1966) and Zinke (1967). Each of these reviews cite numerous efforts to evaluate a variety of factors that may influence snow accumulation. However, there seems to be few universally applicable relationships between the topographic, climatic or vegetative variables and snow accumulation. Krutzsch (1864), cited by Miller (1966) as being the first scientist to investigate some of the factors influencing the delivery of snow to paired stations, gave warning even then that his observations were good only for the site where he made them. Early workers in the United States such as Carpenter (1901) and Church (1912) have described variations in the snowpack and attributed them to differences in stand structure. Kittridge (1953) and others have at times considered the differential in accumulation as representing interception losses. Hoover and Leaf (1967) have noted that under certain climatic conditions there may be actually very low losses and the differential redistribution of the snow from the canopy by various forces may account for the differences in accumulation.

The stand structure, topographic or physiographic features, and climatic conditions each may play a part in this snow redistribution. Multiple factor studies such as Packer's (1962) and Anderson's (1967) have included a large array of variables and some of them have shown promise in improving our understanding of the processes involved in this stage of the hydrologic cycle.

However, Meiman (1968) notes that, "After all these years we still cannot explain the physical processes causing these distribution patterns with much precision."

With the relatively recent and exhaustive literature reviews cited above being readily available, only a brief review of the type of factors previously studied will be given here.

Under the general heading of physiographic and topographic features, elevation and aspect (orientation) have been most often evaluated as the basic factors influencing snow accumulation. The apparent effect of elevation on accumulation varies widely. While nearly all of the published papers agree that there is an increase in snow accumulation with an increase in elevation, the reported rate of increase per 1000 feet increase in elevation ranges from 1.8 inches (Court, 1963) to 26.5 inches (U.S. Soil Conservation Service, 1967). The major weather patterns of a given region or individual storm differences are apparently an important factor (Leaf, 1962) (Anderson, 1967). It is also evident that the rate of change varies with the specific elevation zone being considered within a given region.

Aspect appears to be far less influential than elevation in its effect on differences in accumulation and it may be that it is partially a function of the differences of melt rates. Anderson (1967) and Stanton (1966) indicate that the influence of aspect is on a very broad scale although Grant and Schleusener (1961) found strong local effects as well. As with elevation, the reported effect of aspect shows a large variation between studies. Gary and Coltharp (1967) indicate differences of less than an inch of water equivalent in their study in New Mexico while Packer (1962) shows a difference of over 18 inches between north and south aspects in Idaho.

Other topographic features have been mentioned as having some influence such as position on the slope of the ground at the point of study (Anderson, 1967). In the case of slope as well as with aspect, the accumulation may be more nearly associated with the incident solar energy and thus a function of different melt rates.

A large variety of methods have been used to index or describe the vegetative or canopy factors included as an independent variable. Up to now there has not been an entirely satisfactory method developed to characterize a stand or other canopy features. Some of the methods of quantifying the vegetative array being considered are: "size of openings" Anderson and Gleason (1959), Neiderhof and Dunford (1942, 1944) and Miner and Trappe (1957); "forested vs. non-forested or cut vs. uncut stands", Hoover and Leaf (1966), Rothacker (1965), Baldwin (1957) and Berndt (1965); "crown cover percentage", Kittredge (1953), Packer (1962), Anderson (1967); "basal area", Goodell (1952), Weitzman and Bay (1959); "stand size or timber volume", Lull and Rushmore (1960), Packer (1962), Wilm and Dunford (1948). Miller (1966) makes a plea for studies to include additional totalizing measurements such as biomass, surface area of foliage, crown depth and volume.

Until recently, few of the studies included any data concerning the atmospheric conditions during the time of the study. Peck (1964) strongly recommends the use of synoptic weather data in snow hydrology, and Leaf (1962) and Williams and Peck (1962) each have significantly contributed to our understanding of the influence of climatic variables on snow accumulation. Hoover and Leaf (1966) made effective use of air temperature and recorded its influence on the length of time snow is held in a canopy. Anderson's recent study (1967) included such variables as average daily storm winds, average daily dewpoint temperature and average daily solar energy on a north wall of height equal to trees to the north.

Anderson and West (1965) record considerable year-to-year variation in snow accumulation as well as important differences between individual storms. Major and minor physiographic factors probably interact with these climatic variables and thus produce variation in the relative accumulation of snow at a point. The same might be said of the interaction of vegetative variables with the wind patterns of a given storm or over a snow accumulation season.

Thus it may be seen that a knowledge of the areal distribution of the snowpack over a watershed is not easily obtained but that it may be of critical importance in the planning of vegetative manipulation.

Objectives

The objectives of this study are to evaluate a number of topographic and vegetative features thought to be important in snow accumulation in past studies of other regions and to develop new methods of characterizing canopy form and volume to test under these windy, turbulent Colorado Front Range conditions. These may be defined more specifically in the following sections within these objectives:

1) General characteristics of steepness of slope, elevation, crown cover and basal area will be measured and analyzed.

2) A heretofore untried variable measuring the effect of the expanse of contributing areas of wind blown snow and the distance from the source areas into the stand will be developed.

3) On 25 selected points additional crown volume and stem variables will be measured and tested.

4) Through the use of a Kelsh photogrammetric plotter, an aerial view of the canopy will be translated into profiles of the canopy surface and from these profiles several roughness indexes will be developed.

CHAPTER II

DESCRIPTION OF THE LITTLE BEAVER WATERSHED

Physiography

This watershed is located in the Colorado Front Range approximately 70 miles NNW from Denver, Colorado (Figure 1). Its elevational range is from approximately 8,500 feet up to the high point of just over 11,600 feet. The orientation of the 12 square mile basin is nearly east-west with the western end of the watershed occupied by a broad alpine ridge dominated by Crown Point and Crown Mountain. This broad ridge is exposed to the prevailing westerly winds as shown in Figure 2, and is located about 17 1/2 miles east of the Continental Divide.

The terrain runs from relatively broad, flat ridges at the higher elevations to moderately steep slopes at the mid elevations and becoming more gentle in slope at lower elevations. The mean slope of the study points is 26% and it ranges from 10 to 56%. Some slopes in excess of 60% occur on rock outcrops and on some short slopes just above the main drainage. The area is moderately dissected with drainage channels, giving the whole basin a relatively rough appearance.

Table 1

Summary of Climatic Data

Weather Factor	Snow accumulation season 1965-66	1966-67	1967-68
Precipitation caught in recording gage at Pingree Park[1/]	4.38"	6.51"	6.50"
Number of storms[1/]	13	13	14
Mean water equivalent of 108 points in Little Beaver watershed	6.64"	9.74"	9.13"
Estimated mean temperature during days with snowfall[2/]	-5.5°C	-3.7°C	-6.5°C
Percent of storms events occuring at temperatures of 0°C or lower[2/]	82	72	98
Percent of wind speeds over 20 m/s[2/]	1.0	3.0	0.6
Percent of wind speeds 16-20 m/s[2/]	3.7	4.9	4.7
Percent of wind speeds 11-15 m/s[2/]	15.3	26.7	19.1
Percent of wind speeds 6-10 m/s[2/]	49.0	47.6	49.2
Percent of wind speeds 5 m/s or le less[2/]	31.0	17.8	26.4
Mean direction of 25% of events with highest velocities[2/]	296°	279°	283°
Mean wind speed during days with precipitation (m/s)[2/]	8.5	10.3	9.4
Mean wind speed during days without precipitation (m/s)[2/]	7.6	8.9	7.9

1/ Based on data from recording raingage at Pingree Park located 4 1/2 miles SE of the study area and at an elevation of 9,000 feet.

2/ Based on interpolation of 700 mb level data published in Northern Hemisphere Data Tabulation by the U.S. Weather Bureau.

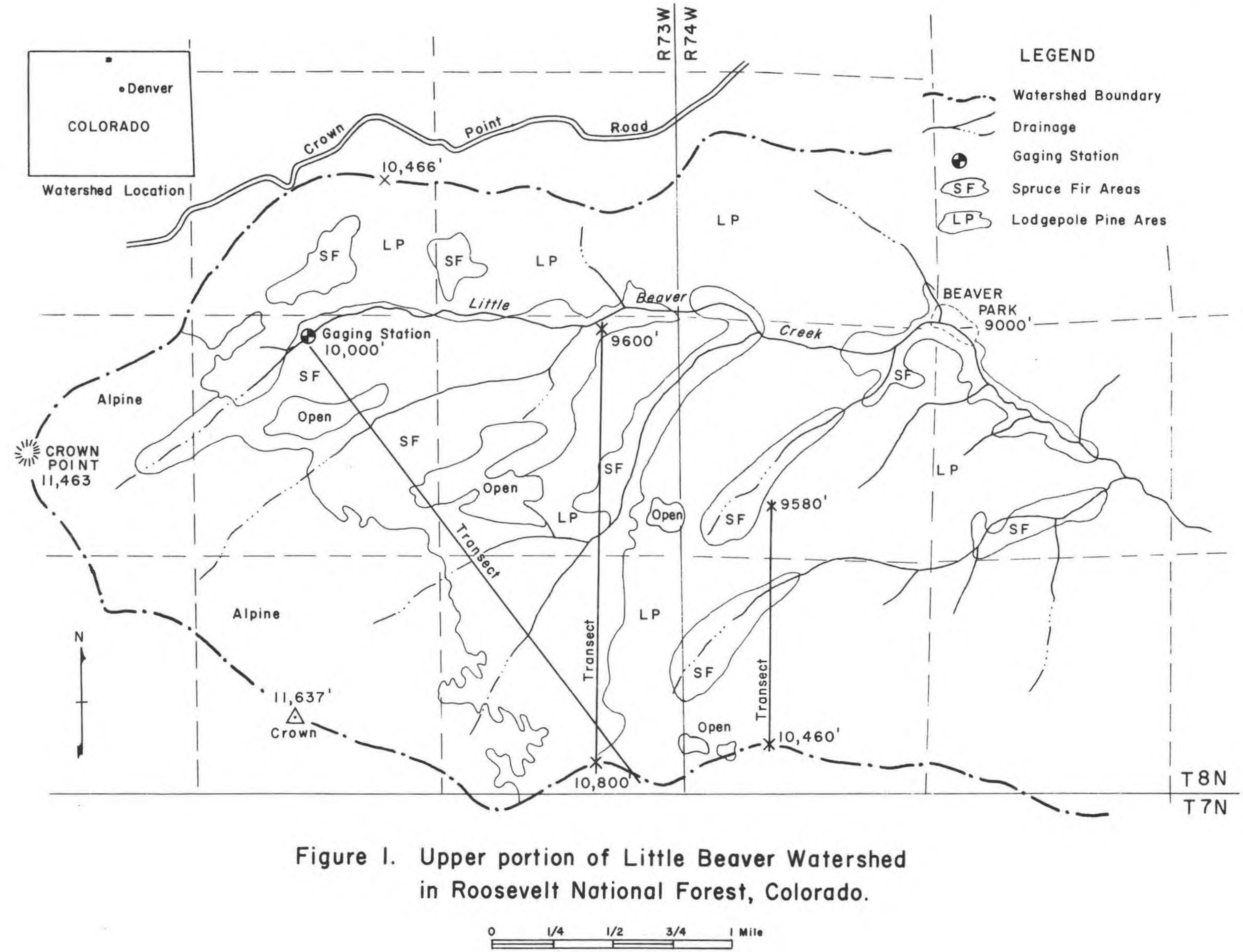
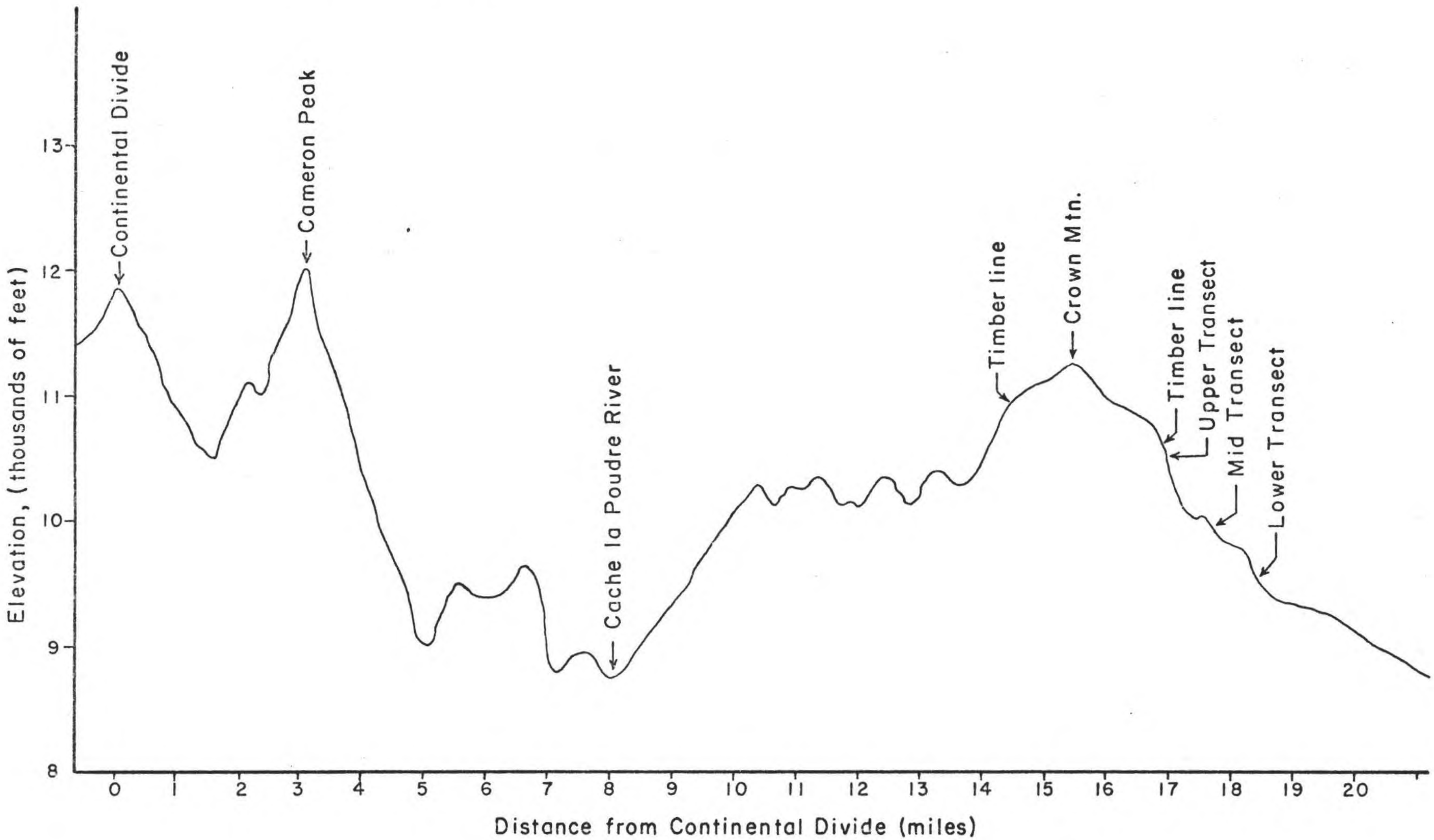


Figure 1. Upper portion of Little Beaver Watershed in Roosevelt National Forest, Colorado.

Figure 2. Profile of terrain from middle of Little Beaver watershed due west to the Continental Divide.



Climate

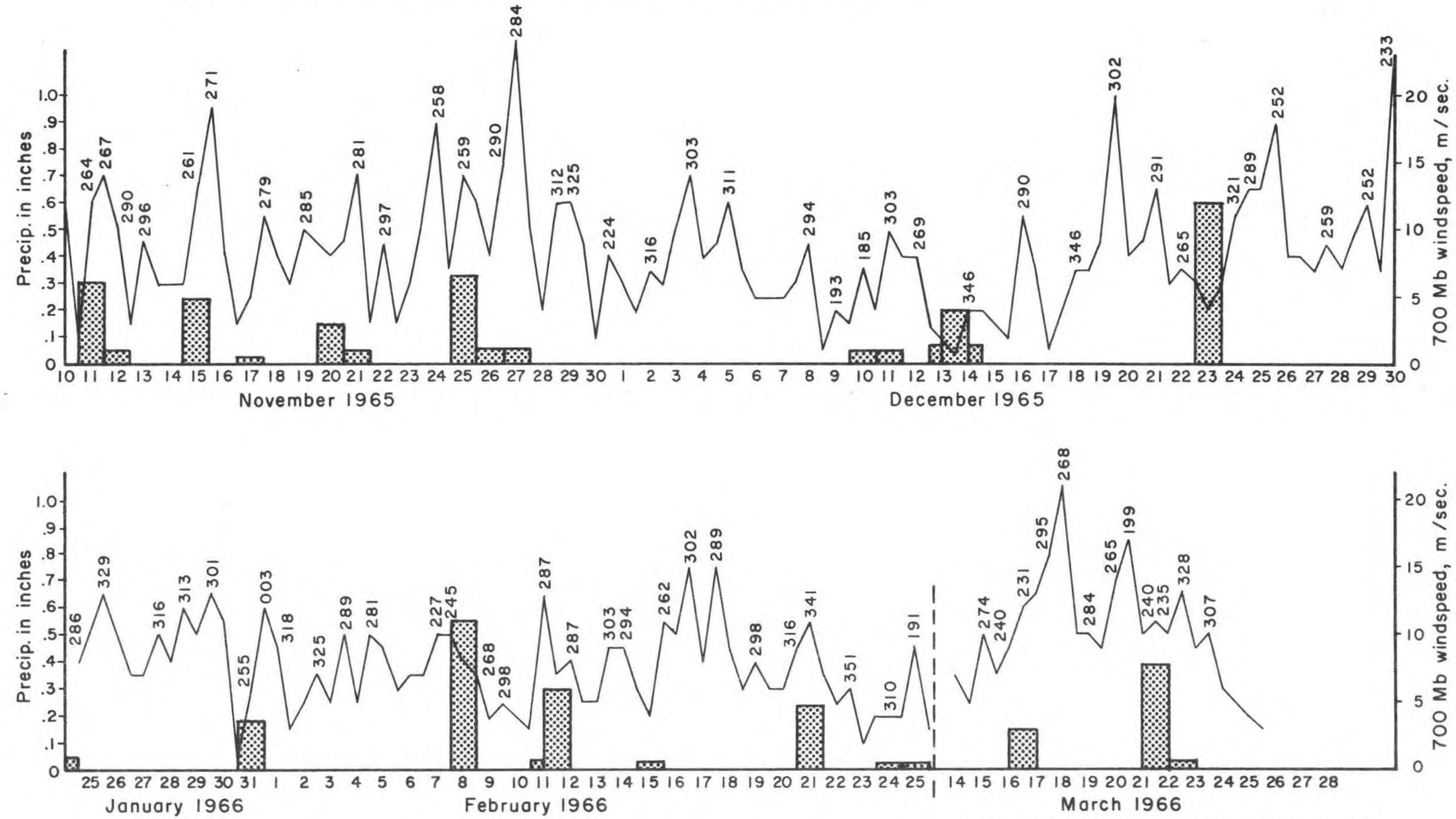
Since there were no weather instruments deployed in the establishment of the study, it was necessary to obtain climatic data from sources that would at least provide a good index to the conditions during the three winter seasons. Two sources of information were used for this, each of which has some limitations and the resulting data must be taken with this in mind.

The nearest source was the weather station maintained by the Watershed Management Unit in the School of Forestry and Natural Resources at Colorado State University. This station is located in a broad meadow at Pingree Park at an elevation of 9,000 feet. Its location is four miles due south of the Little Beaver drainage. The recording rain gage at this station is equiped with an Alter shield and in the snow accumulation season the funnel is removed to prevent bridging over the orifice. It is assumed that there is a good correlation between the timing of storm events at Pingree Park and the study area. It was necessary to know when the events occured so that wind data could be secured for these periods and some year-to-year comparisons be made. Dates and amounts of precipitation at Pingree Park are summarized in Table 1 and shown graphically in Figures 3, 4, and 5.

2 p's.

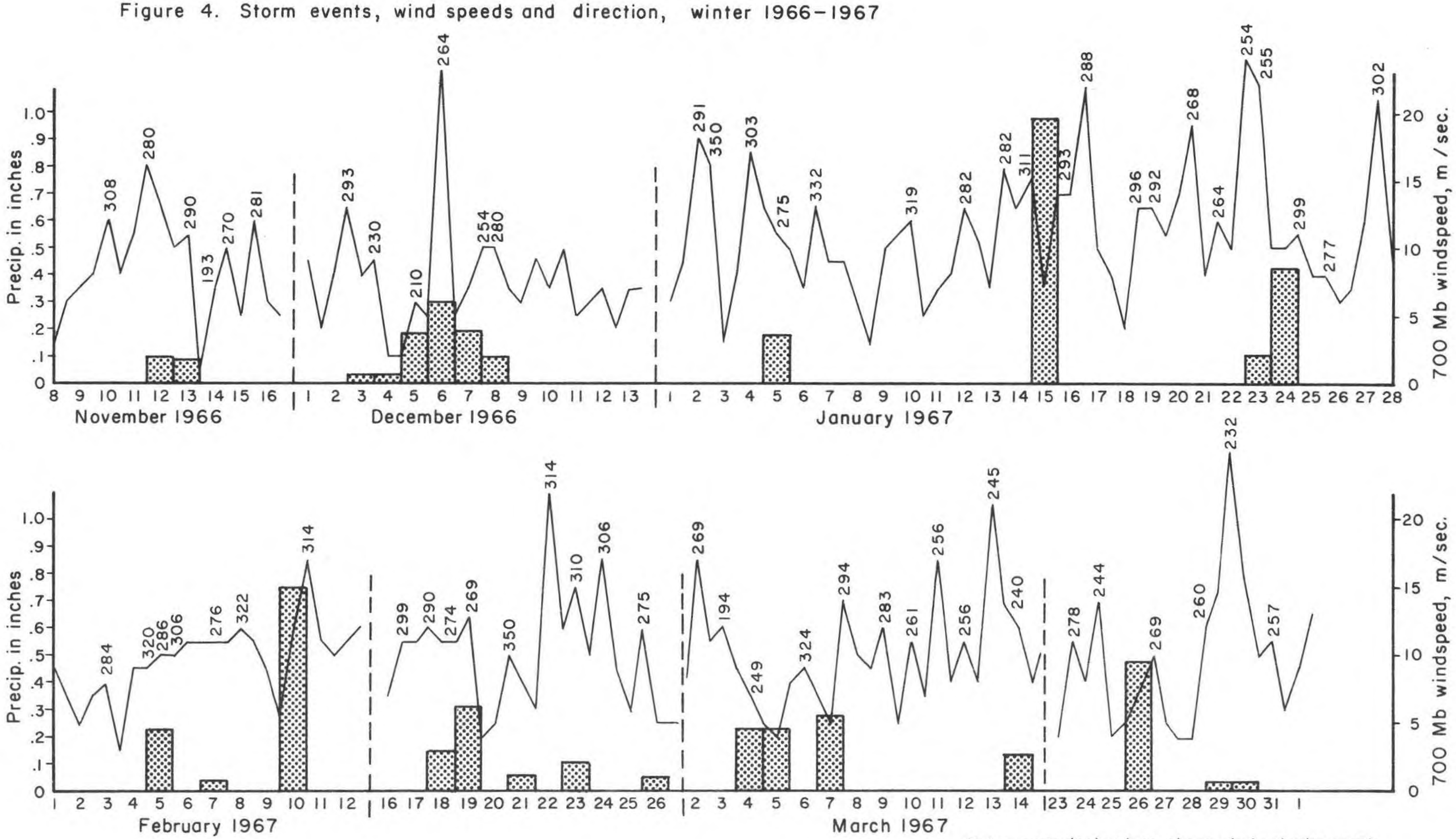
The second source of data used is the Northern Hemisphere Data Tabulation published by the U.S. Weather Bureau. These publications include two readings per day (0000 GCT and 12000 GCT)

Figure 3. Storm events, wind speeds and direction, winter 1965 - 1966



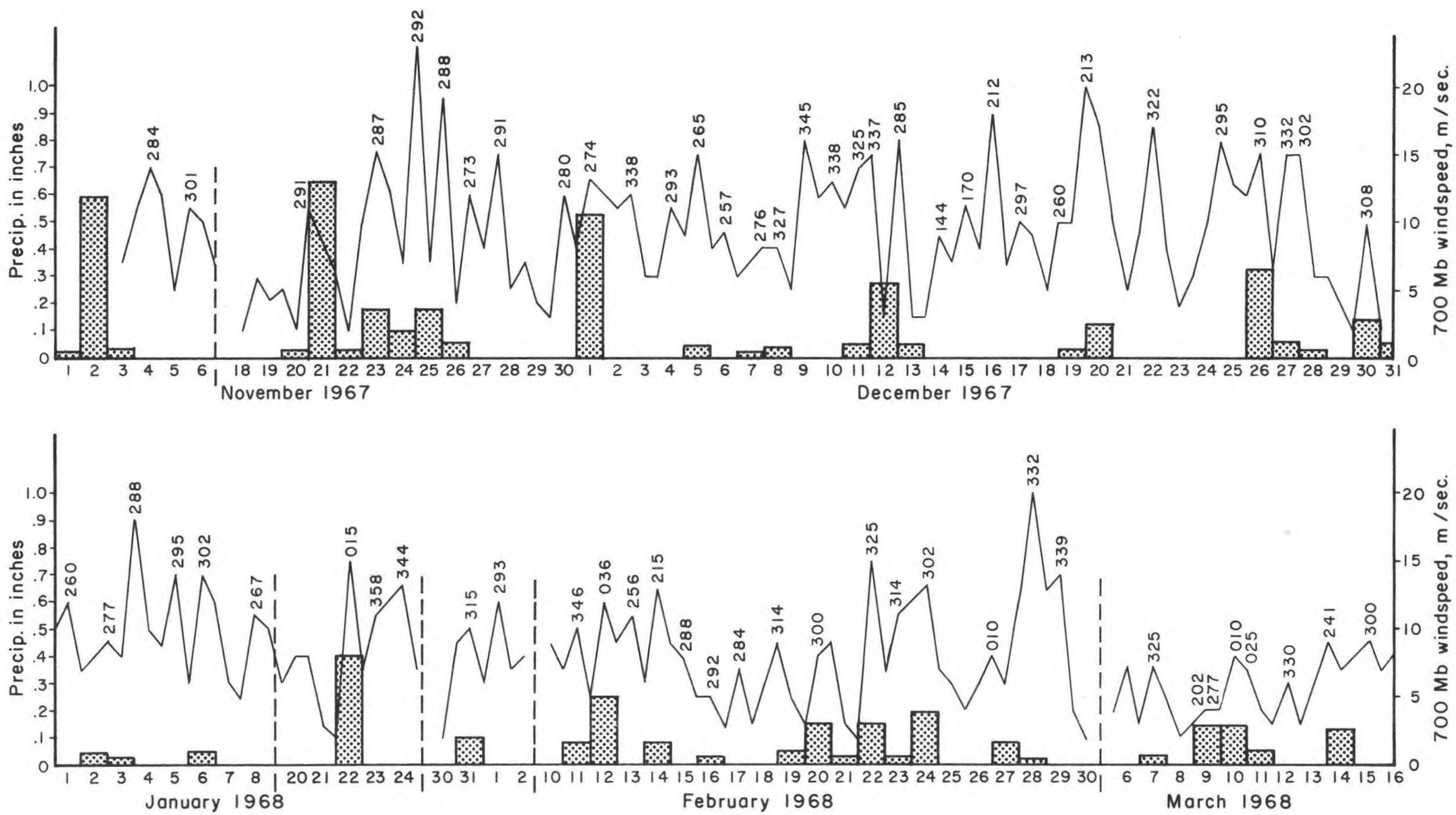
Note: numerical values above wind velocity graph are azimuths of wind direction.

Figure 4. Storm events, wind speeds and direction, winter 1966-1967



Note: numerical values above wind velocity graph are azimuths of wind direction.

Figure 5. Storm events, wind speeds and direction, winter 1967–1968



Note: numerical values above wind velocity graph are azimuths of wind direction.

which record temperature, relative humidity, wind direction and wind speed as measured by radiosonde and rawinsonde instruments. The data for the three snow accumulation seasons was extracted from the records from Denver, Colorado and Lander, Wyoming. The study area in the Little Beaver watershed lies approximately on a straight line between these two stations and, on the assumption that a linear gradient exists between measurements above these two stations, a weighted average was calculated for the atmospheric data to be used. The data from the 700 mb level was chosen in the expectation that this might approximate the conditions found at the mean elevation of the study points. Under stable atmospheric conditions the 700 mb level is approximately 10,000 feet in elevation. The mean elevation of the study points is 10,400 feet. Judson (1965) indicates that there is a better correlation between windspeed in the free atmosphere and ground windspeed than there is for wind direction. Wahl, (1966) as a result of some comparative studies of free atmosphere measurements vs. surface concludes, "The best possible predictor of mountain windspeed could be the flow in the free atmosphere in the vicinity of the particular mountain." He noted that distances of up to 120 km (74.6 miles) did not seriously weaken the relationship if the two points were in the same general windfield.

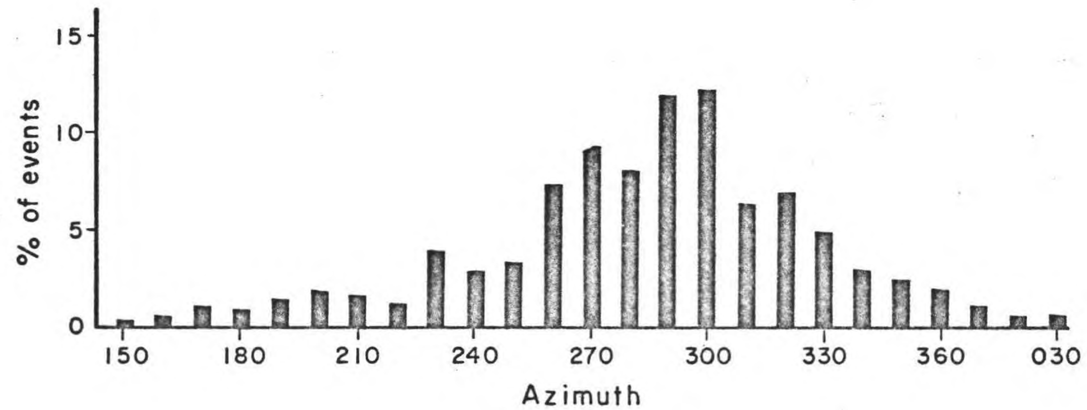
It must be kept in mind that there may be considerable error in the data extracted from these sources, it is expected, however, that they provide a reasonably good basis for a comparison of year-to-year variation in the climatic regime of the study area. There was no adjustment of the data beyond the necessary interpolation, that is, the possible change of direction or velocity as these winds are carried to ground level probably could not be calculated with sufficient accuracy to warrant such a transformation. Wind speeds at the canopy level are probably somewhat less than those in the free atmosphere, but it is also possible that the windspeeds over the exposed alpine areas could be greater than that of the free atmosphere.

The number of storms depositing snow in each of the three winters was about 13, with most of these yielding less than 0.3 inches of water equivalent and only 5 to 6 of these storms yielding 0.5 inches of water equivalent or over. The density of new fallen snow was not obtained, but from general observations one would conclude that the snow fall is typically very light powdery snow. The estimated temperatures during snowstorms is given in Table 1. It was found that most snowfall occurs at temperatures averaging minus five degrees centigrade. While both the 1965-66 and the 1967-68 winters appear to be colder than the 1966-67 winter, the nature of the data does not warrant attaching a strong statistical significance to the mean temperatures. The temperature regime that exists at the time of snowfall would largely determine the ease with which this snow would be re-deposited. It appears that the 1966-67 snow storms probably occured under warmer conditions than the other two years of the study, with only 72% of the temperature readings during days with storms being 0°C or lower. These values must be taken with caution and may only represent a general trend in the temperatures experienced for these three winters.

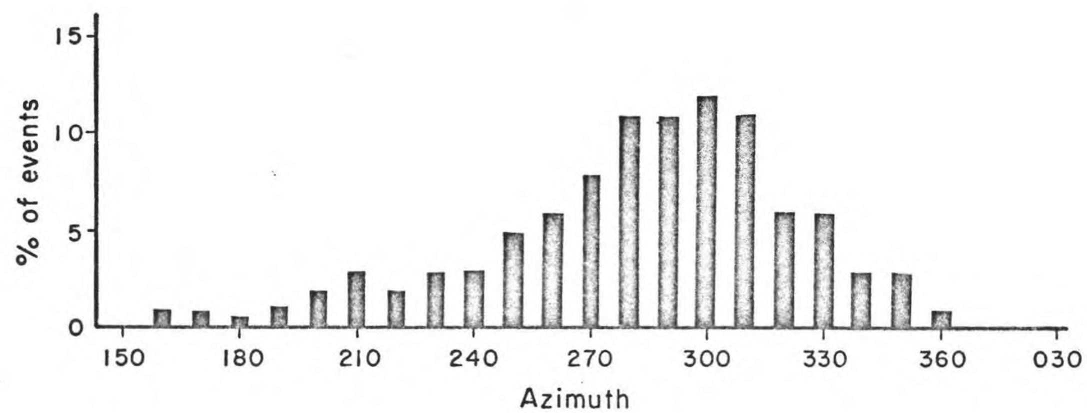
In contrast to several of the published reports on snow accumulation where it was concluded that most snow fell in the absence of wind, the winds of this region are consistent and strong. The data shows that the averaged windspeeds for days with snowfall are consistently higher than for days without snowfall and average about 9 m/s (20 mi/hr.). This compares well with the winter windspeed for Berthoud Pass of 16 m.p.h. reported by Judson (1965). He also notes that on more exposed stations of the Front Range, the winter-month average is considerably higher--20 to 30 m.p.h. Thus wind must be a very important element in evaluating snow accumulation. Figures 3, 4, and 5 illustrate some climatic features of the three winters. Dates and amounts of snow caught in the recording gage at Pingree Park are used to place the several snow storms and the windspeeds associated with these periods are superimposed on the graph. These charts show that during or within three days following a storm, winds usually reached speeds of 12 to 20 m/s (27 to 45 m.p.h.) in the free atmosphere. This is not to say that these velocities were reached at all points within the watershed, but it certainly indicates that snow falls under a strong wind system and that there is a great amount of energy available for the redistribution of snow both from tree crowns and from exposed areas such as the alpine zone or old burns within the watershed.

About 75% of the winds come from a 90° sector between 260° and 350° while about 20% of the winds come from directions south of 260° and only about 5% of the winds come from directions north of 350° (Figure 6). When only the highest 25% windspeeds are included, the average direction for each of the three years shows, 296° in 1965-66, 276° in 1966-67 and 283° in 1967-68. This would appear to indicated a higher frequency of storms in 1965-66 with a strong northerly component. This may also be associated with the relative dryness of that particular year. There does not appear to be a significant difference between the direction of the strongest windspeeds of the second and third year of the study. There is no means of independently checking this data, but flagging of trees is quite severe in more exposed positions within the watershed and these indicate that the winds are centered about 280°. Another clue to the wind direction is found on winter aerial photographs which show the striations in the eroded snow surface to be between 270° and 280°. This would seem to indicate that as the wind is brought down from

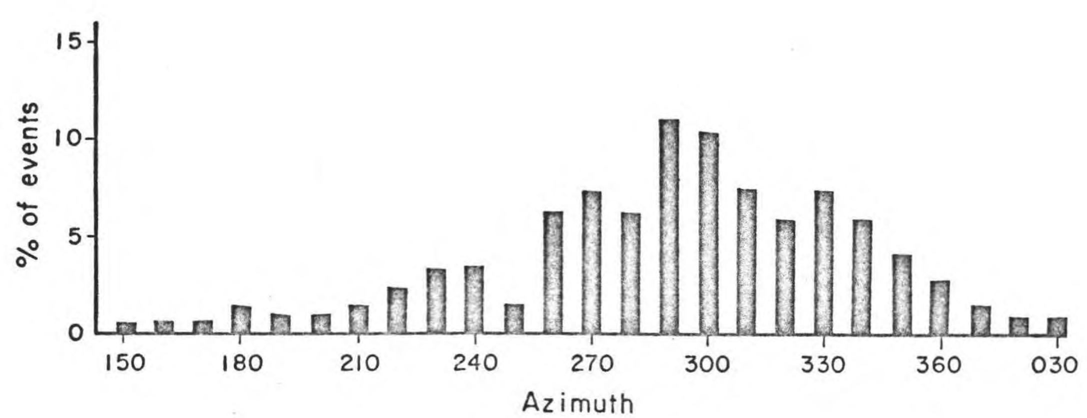
Figure 6. 700 Mb wind directions, November 1 - March 31



1965–1966



1966–1967



1967–1968

the free atmosphere to ground level it tends to rotate counter-clockwise and result in wind at the watershed level with a stronger westerly component.

Vegetative cover

The vegetative cover in the study area is made up of lodgepole pine (*Pinus contorta* Dougl.) over most of the lower elevations within the watershed and averages about 36 feet in height. It varies from small dense stands to open, irregularly spaced stands and in some portions there is a moderate mixture of quaking aspen (*Populus tremuloides* Michx.). In the more moist sites of the lower elevations and over much of the higher elevations, Engelmann spruce (Picea *engelmanii* (Parry) Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) dominate. This latter timber type ranges from large reproduction to merchantable timber size and averages about 50 feet in height. Most of the spruce-fir stands are an all-age mixture with frequent small openings. Fire and insect attacks have caused numerous dead trees and in some of these areas there are large numbers of wind-throw trees.

Crown cover averages 44% for both of these timber types and the basal area for both types averages 134 $ft.^2$/acre. On drier ridges and in some of the old burns limber pine (*Pinus flexilis* James) is present but is always a minor component of the stand.

Above the spruce-fir stands and beginning at about 10,600 feet in elevation, willow (Salix sp.) and spruce-fir krumholtz is present. This lower border is highly irregular and in some very rocky sites, may not appear at all. Above the krumholtz cover the alpine tundra interspersed with occasional large rock fields occupies the site. The krumholtz-tundra extends for more than a mile to the windward from portions of the "high" forest. Figure 1 illustrates the relative positioning of the timber types of the study area within the Little Beaver watershed.

CHAPTER III

PROCEDURE

During the summer of 1965 three transects comprised of a total of 123 observation points were established in the upper portion of the watershed (Figure 1). These are not random samples but rather the transects were positioned to sample the timbered portion of a generally north-facing slope on which timber harvest was under consideration. The points are approximately 200 feet apart along the transect lines. Snow depth and water equivalent were measured each Spring, 1966 through 1968, at a time judged to be near maximum snowpack water equivalent. Actual dates of sampling were 4/16/66, 4/8/67 and 3/27/68. Federal snow samplers were used for all of the snow measurements. All samples were taken approximately one foot downhill from the marker pole, and if a fallen limb or obstruction was encountered sampling was repeated until the ground surface was reached. The poles marking the points extended six to eight feet above the ground and were anchored to angle-iron driven into the soil at the base of the pole.

This set of 123 points used in the preliminary study was reduced to 115 to exclude those points which were found to have a south-facing aspect or were on level, exposed ridgetops. This was further reduced to 108 points prior to the main study to exclude those points which had some possible discrepancy in the data or for which a complete set of data for all variables was not obtained.

Topographic and physiographic measurements

Elevation at each point was measured by barometric leveling and rounded to the nearest five feet. Steepness of slope was measured with a percent abney, reading normal to the contour passing through the point.

Aspect was measured with a staff compass with the points being classified into one of eight-45° sectors, centering about the eight points of the compass. Aspect was not used in the regression calculations since the study was limited to predominantly north and northeast facing slopes. The variation in aspect was limited to very localized topographic features. Snow measurement points which were found to have a south-facing aspect or were on level, exposed ridgetops were later excluded from the statistical analysis.

The effect of contributing areas of blowing snow was indexed by means of a source/distance ratio defined as the length of open, windswept source area under a line drawn to the windward from the sample points over the distance from the sample points to the leeward edge of the source area. Source area was taken here to be openings 300 feet and over in width. The major contributing area is the broad tundra-krumholtz area above timberline. The watershed boundary was arbitrarily taken as the windward limit of this source area. When more than one contributing area fell in the path of the line from the sample point the ratio used was the sum of the ratios computed for each source area under the line. Recent 1:6000 scale aerial photographs were used for the measurements necessary to calculate this ratio.

Canopy measurements

The standard U.S. Forest Service stand size classification methods for this region were used to stratify the stand in a 1/4-acre plot about each point into one of the five classes defined as follows:

6-Non-stocked or deforested (burns, clearcuts)
7-Seedling, sapling, 0 to 4.9 inches d.b.h.
8-Pole, 5.0 to 10.9 inches d.b.h.
9a-Small sawtimber, 11.0 to 20.9 inches d.b.h.
9b-Large sawtimber 21.0 inches d.b.h. and over

The classification was made on the basis of field observations.

Basal area was obtained by Bitterlich cruising prism with a basal area factor of ten. The count of "in" trees times ten was adjusted for slope before being used as an independent variable.

A Lemmon Type-A spherical densiometer was used to estimate the crown cover above each point (Lemmon, 1956). The instrument was mounted on a light tripod and leveled at a height of three feet above each sample point. Prior to being used in the field, the instrument was set up in a room with the ceiling marked off in grids. It was found that with slight variation in positioning of the observer's eye a change in the maximum angle subtended by the reflected field of view occured. With practice, the observer's eye could be held at 18 inches above the convex mirror and at a position so that a specific portion of the observer's head was reflected at a given point marked on the mirror. This combination of eye height and position subtended an angle of 114^{o}. The instrument is meant to be employed by making a count of the number of dots covered by an image of live crown from each of four cardinal directions and these four counts are normally averaged for the canopy cover percentage. With the hypothesis that the crown coverage to the windward (west) of the point would exert an independent influence on snow accumulation, the data was recorded as the crown coverage in each of the four cardinal quadrants and then averaged. These values were initially tested as five independent variables.

To help estimate the effect of crown cover [more nearly vertical] over the snow accumulation point, a second set of readings was made in such a way as to include only 21^{o} of arc above the sample point. This is referred to later as "vertical crown cover." This estimate approximates that used by Packer (1962).

The factors listed above were measured or estimated for each of the sample points in the original three transects. To test other factors, it was found necessary to limit the number of sample points. The additional factors are described below.

Crown volume and stem variables

Because no published tables for such data could be found that would be usable for the species and range of sizes encountered in this watershed, it was found necessary to carry out a preliminary study that would enable a conversion from stem diameters to crown volume.

For this preliminary study, 48 lodgepole pine, 51 Engelmann spruce and 40 subalpine fir were selected within the Little Beaver drainage to sample diameters from 2.0 inches d.b.h. up to 31.8 inches d.b.h. with trees being taken for the sample from locations having a range of elevation from 9,000 feet to 10,700 feet. For each sample tree the following elements were recorded:

1. Elevation
2. Crown class: four classes were defined as follows:
   a. Open - little competition between crowns, 0-15% crown cover.
   b. Crowns touching on one or more sides, 16-30% crown cover.
   c. Moderately closed canopy with crowns frequently touching and with an estimated 31-60% crown cover
   d. Dense stands with extreme crowding of crowns such that crowns touched at several points, over 60% crown cover in the immediate vicinity.
3. Diameter breast height: measured with diameter tape for larger diameters and with calipers for smaller diameters.
4. Crown diameter: this was estimated by fastening a measuring tape to the trunk of the tree and moving out until a plumbline appeared to touch the edge of the crown. This was repeated three times per tree to obtain an average radius and then doubled for crown diameter.
5. Height to crown: this was measured directly where possible and otherwise obtained by the use of an abney and tape.
6. Total tree height: heights were estimated to the nearest foot by the use of an abney and 100 foot tape.

7. Site classification: three classes were arbitrarily designated as dry, moderate, and moist primarily to assure that a range of such sites would be included in the sample.

From approximately 30 photographs of tree profiles plus additional field observations it was concluded that while the shapes of crowns varied greatly, the "typical" crown might be described as having a conical section at the top which has a height equal to 0.3 the crown length and a base diameter equal to 0.7 that of the largest diameter of the crown. A second section is visualized as approximating a truncated cone whose top diameter is 0.7 of the measured crown diameter and whose base is equal to the measured crown diameter. The height of this section is taken as 0.7 of the total crown length.

The space occupied by the top section can be expressed as:

$$V = \pi \left(\frac{0.7D}{2}^{2} \right) \times \frac{0.3L}{3} \qquad (1)$$

or,

$$V = \pi (0.1225\ D^2) \times 0.1\ L \qquad (2)$$

the second or lower section volume is approximated by

$$V = \left[\pi \left(\frac{0.7D}{2} \right) + \pi \left(\frac{D}{2} \right) \right] \times \frac{0.7\ L}{2} \qquad (3)$$

This may be simplified to

$$V = \pi (0.1225\ D^2 + 0.25\ D^2) \times 0.35\ L \qquad (4)$$

the total crown volume then should be the sum of equations (2) and (4) or

$$V = [\pi(0.1225\ D^2)\ x\ 0.1\ L] + [\pi(0.1225\ D^2 + 0.25\ D^2)\ x\ 0.35\ L] \quad (5)$$

or simplified to

$$V = \pi\ L\ D^2\ x\ 0.1426 \quad (6)$$

or finally,

$$V = 0.4478\ L\ D^2 \quad (7)$$

where V = crown volume in cubic feet,
L = crown length in feet
and D = crown diameter in feet

Using equation (7) the crown volume was computed for each of the 139 sample trees. The two-dimensional plotting program of Frayer (1968) was used to graphically portray the data and multiple linear regression methods were used to find a curve of best fit that would enable a direct conversion from stem diameters to crown volume (Figure 7). Because there is a close relationship between stem diameter and crown lenght (r = .71**) and stem diameter and crown width (r = .82**) (Figure 8 and 9) a cubic function would fit the stem diameter-crown volume curve. This was tried but it failed to fit as well as expected. Since a large residual error was apparent in

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**Significant at the .01 level.

Figure 7. Regression of crown volume on tree diameter

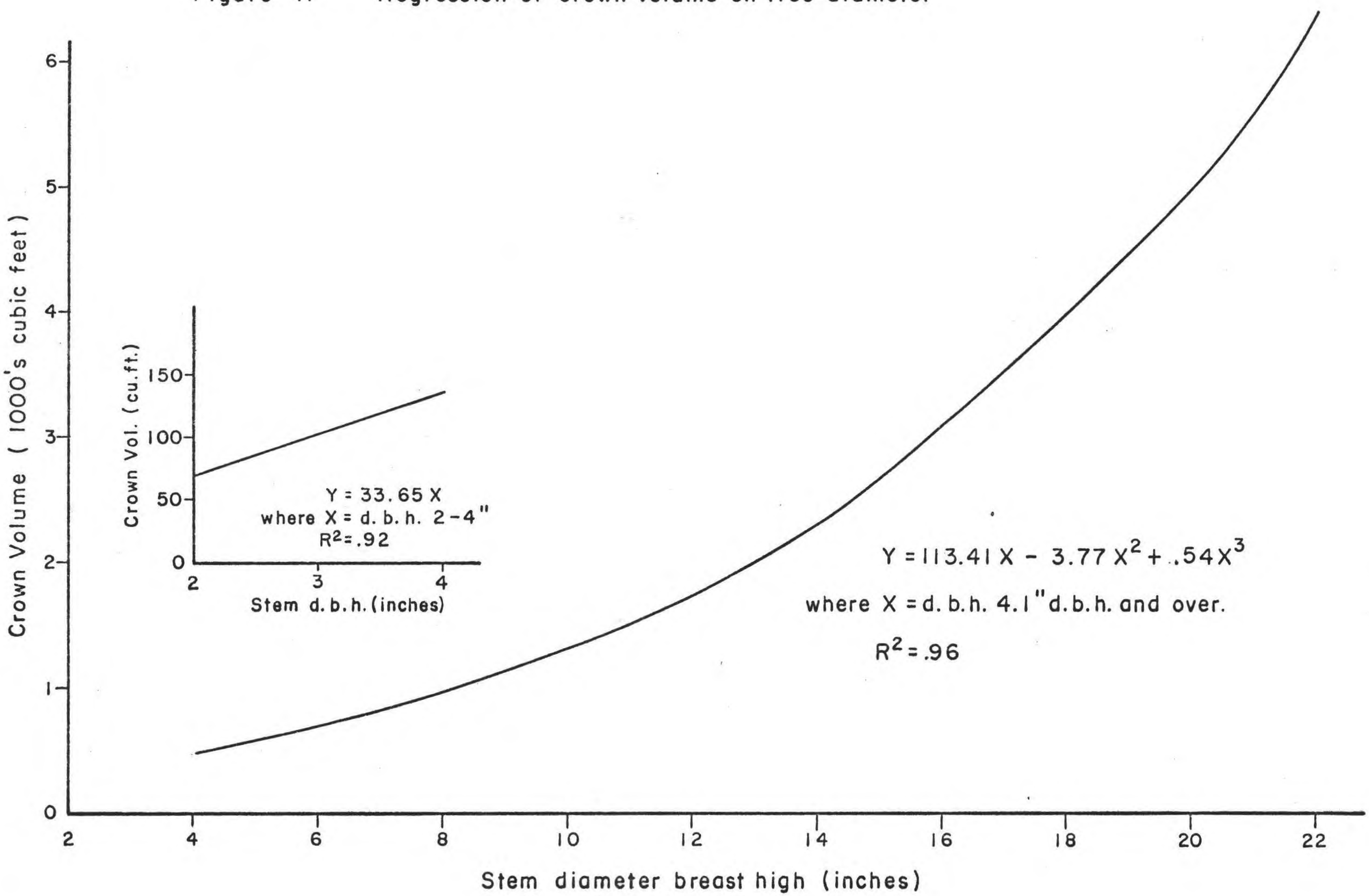


Figure 8. Relationship of crown diameter to stem diameter.

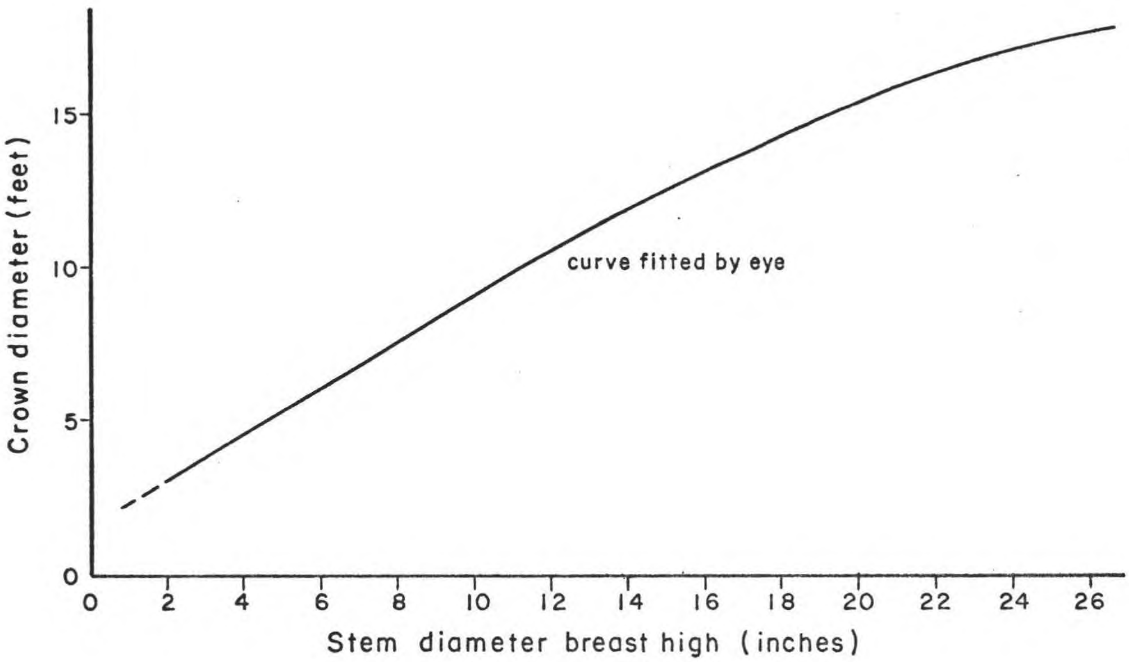
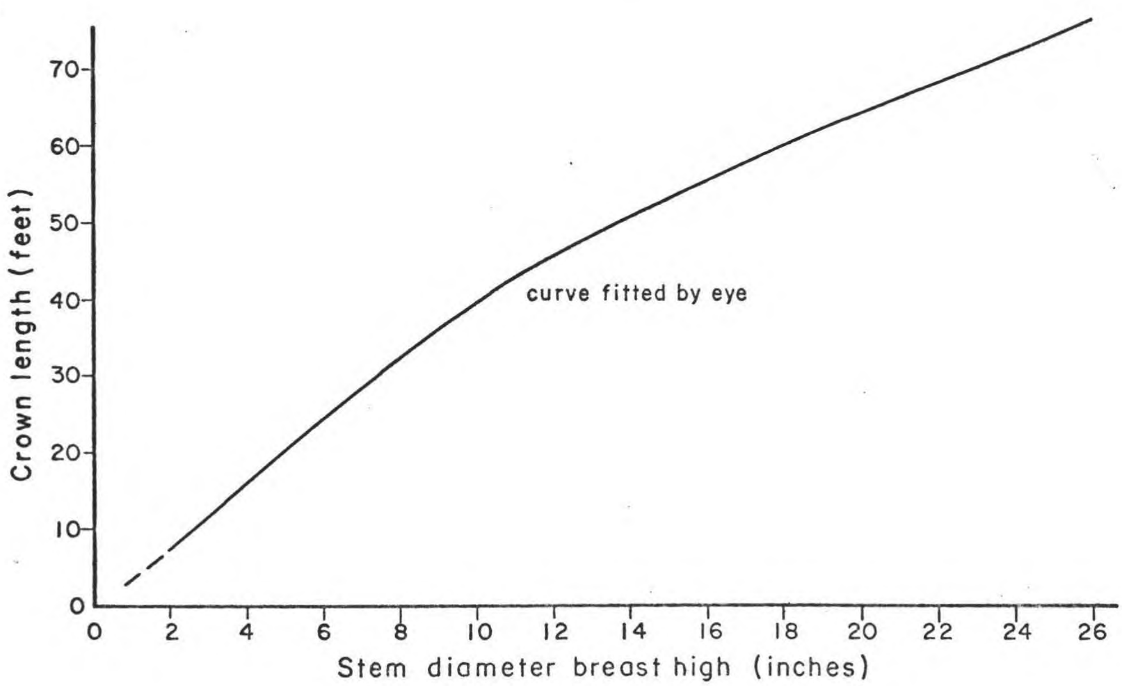


Figure 9. Relationship of crown length to stem diameter.



the low diameter classes these were examined carefully for reasons for the poor fit at the lower portion of the curve. It was observed that there was relatively little change in diameter of crowns in the two to four inch d.b.h. range and that most of the difference was in height. This would give a more nearly linear increase in crown volume through the lower segment. This appears to fit the field observations: where these small stems occured they tended to be in very thick stands with little opportunity for crown diameters to increase. On the basis of these conclusions, the conversion of stem diameters was done through the two equations as follows:

d.b.h. 2 to 4 inches: Crown volume = 33.65 X (8)

where X = stem d.b.h. in inches, (r^2 = .92**) and for d.b.h. 4.1 inches and over:

$$\text{Crown volume} = 113.41\,X - 3.77\,X^2 + 0.54\,X^3 \quad (9)$$

where X = stem d.b.h. in inches, (r^2 = .96**).

These equations were tested by species but there was no significant improvement in the regression and it was decided to utilize equations (8) and (9) for all three species without any further adjustment.

Roughness measurements

Black and white, six inch focal length aerial photography was secured in October 1968 and diapositives on .06-inch thick glass

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**Significant at the .01 level.

plates were prepared by a commercial firm. The Kelsh plotter of the Çivil Engineering Department of Colorado State University was made available for this project. The Kelsh plotter allows the enlargement of the three dimensional image by five times so the plot center locations were plotted to a scale of 1 inch = 100 feet and with the aid of enlarged U.S.G.S. Quadrangle maps and known elevations of the targeted sample points, the relative orientation of the diapositives was secured to a satisfactory degree. Since there is very little in the way of good horizontal control in the undeveloped forested areas with rugged terrain, there is probably considerable room for error within this photo analysis. However, measurements were not utilized until there was a relatively close agreement between repeated trials over the same profile. There were some independent checks such as tree heights from the field notes that were used for comparison.

The initial photo measurements consisted of tracing a profile over the canopy surface running from 150 feet windward (270° azimuth) of the snow sample point to 50 feet leeward (90° azimuth). A scale marked off in feet was taped along the desired profile line and the tracing table of the Kelsh plotter was moved along it, keeping the floating dot of the platen in contact with the visible canopy or ground surface of the three dimensional image.

Gears were selected for the tracing table so that elevations of the canopy or ground surfaces could be read directly in feet to the nearest foot. Although the accuracy of the readings could not be directly verified, it is expected that the canopy elevations were within a few feet and ground elevations within ± 2 feet. Tree crowns with narrow, pointed tops are not always resolved on this scale of photography and thus may not be visible in the three-dimensional model. It is expected that the total tree heights are probably consistently low. No corrections were made for this type of error since the data was to be used in a comparative study and the same factors would affect all profiles. The transcribed data was then plotted on 10x10 to the inch cross-section paper and all roughness variables were measured from these plotted canopy profiles.

The following variables were calculated:

1) Profile area to the windward (PA wind.) was taken from the area under the profile in the first 25 foot segment to the windward of the point measured with a polar planimeter.

2) Profile area to the leeward (PA lee) was taken from the area under the profile in the first 25 foot segment to the lee of the sample point.

3) Mean obstacle height to the windward (Wind. ht.) was taken from the first 25 foot segment to the windward from the sample point by averaging the heights of trees or clumps of trees taken as

single units if it appeared they would present a single obstacle to the wind stream.

4) Mean obstacle height to the leeward (Lee ht.) is measured in the first 25 foot segment of the profile to the lee of the sample point and closely clumped trees were taken as a single unit in computing the average height.

5) A measure of the irregularity of the gross surface features in the first 25 foot segment to the windward (Var. 1) was computed by taking the heights of the profile surface at two-foot intervals above a base line drawn below the lowest level of the cross-section. The variance of this array of numbers was then calculated according to the equation

$$\sigma^2 = (y - \mu)^2 / N \text{ where}$$

σ^2 is the variance, μ is the mean, y the height and N the number of observations.

6) The irregularity of the gross surface features of the second 25 foot segment to the windward (Var. 2) was derived in the same manner as Var. 1.

7) The effect of the first obstacle to the windward from a sample point coupled with the distance from the obstacle (Coef. 1) was derived by taking the height of the obstacle minus one-half the mean height of all the obstacles in the first 50 foot segment. This portion of the first obstacle's height was divided by the distance from the

sample point to the base of the obstacle. In choosing the first obstacle to the windward only the major obstacles or trees were taken, that is, a tree whose profile did not extend above a line projected downward at a 45^{o} angle from the next tallest tree would not be used for this ratio.

8) Another coefficient (Coef. 2) was derived in the same manner except that the first obstacle to the windward was omitted and the ratios of height above one-half mean height over the distance from the sample point were summed over the first 100 foot segment to the windward from the sample point.

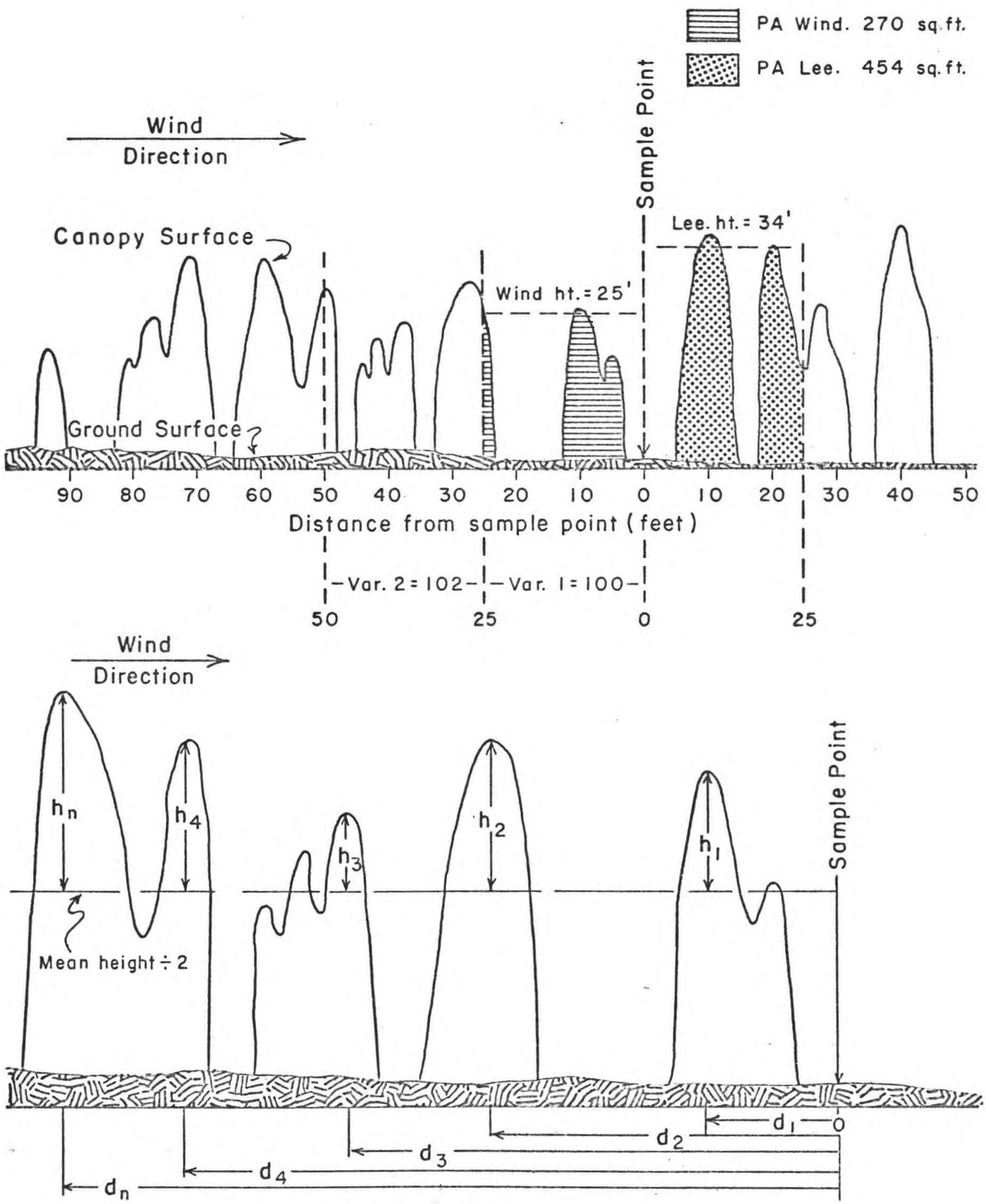
Figure 10 provides an example of the derivation of these variables.

Statistical methods

In the preliminary stages of testing, a linear regression computer program utilizing a method of least squares for fitting a curve to data provided was used (Van Dyne, 1965). Following the preliminary analysis a stepwise multiple linear regression method was used to rank the variables and to evaluate their association with each other (Dixon, 1964).

> This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently it is the variable which has the highest partial correlation with the dependent variable

Figure 10. Example of cross-section of forest canopy taken on lower transect, showing basis for the eight "roughness" variables.



$$C_1 = h_1/d_1$$
$$C_2 = h_2/d_2 + h_3/d_3 \ldots h_n/d_n$$

partialed on the variables which have already been added; and equivalently it is the variable which if it were added, would have the highest F value.

Table 2

Variables, definitions, units and ranges.

Variable	Definition
1966 WE	Water equivalent in the snow pack measured at sample points with Federal Snow Tube, Range 1.5-18.0 inches.
1967 WE	As above, range 4.5-27.5 inches.
1968 WE	As above, range 2.0-23.0 inches.
Elev.	Elevation above sea level measured by barometric leveling, range 9,580-10,810 feet.
Aspect	Orientation of a line normal to the contour as measured by staff compass and stratified into eight sectors.
Slope	Declination of the ground surface as measured with an abney sighting normal to the contour, range 10-56 percent.
Basal a.	Basal area of stand about sample points as measured with a Bitterlich cruising prism in square feet per acre, range 20-315.
CC west	Crown cover to the west of the sample point as measured by a Lemmon spherical densiometer, range 6-74 percent.
Cr. cover	Crown cover as measured by a Lemmon spherical densiometer to include a 114^{o} arc above the instrument, range 10-66 percent.
Vert. CC	Crown cover as measured by a Lemmon spherical densiometer to include a 21^{o} arc above the instrument, range 0-58 percent.
Source	A ratio of the length of open, windswept snow fields, 300 feet and over in width, under a line drawn to the windward from a sample point over the distance from the lee edge of the area to the sample point, range 0.47-20.00.

Table 2 (Continued)

Variable	Definition
Cr. vol.	The calculated space occupied by live crowns within a 1/10-acre circular plot about the sample point, range 15,900-114,800 cu. ft.
Dia. sum	The sum of diameters of all stems 2.0 inches and over d.b.h. on 1/10-acre plot about sample points, range 159-950 inches.
Stems-2"	The number of stems 2.0 inches and over d.b.h. on a 1/10-acre plot about the sample point, range 30-193.
Stems-4"	The number of stems 4.0 inches and over d.b.h. on a 1/10-acre circular plot about the sample point, range 19-107.
PA-lee	Profile area of a 25 foot segment to the lee of a sample point as measured from trace of Kelsh plotter data, range 18-640 sq. feet.
PA-wind	Profile area of a 25 foot segment to the windward of the sample point as measured from trace of the Kelsh plotter data, range 29-565 sq. feet.
Var. 1	The variance in the height of regularly spaced points along the profile of the Kelsh plotter data of a segment 0-25 feet windward of the point, range 7.78-198.52 sq. feet.
Var. 2	The variance in the height of regularly spaced points along the profile of a segment 25-50 feet to the windward of the sample point, range 22.94-225.90 sq. feet.
Coef. 1	A ratio of the height of the first obstacle to the windward over the distance from the sample point to the obstacle, range 0.20-7.00.
Coef. 2	The sum of the ratios of heights of obstacles to the windward from the sample points over the respective distances from the point, range 0.21-2.65.

Table 2 (Continued)

Variable	Definition
Lee ht.	The mean height of obstacles in the first 25 feet to the lee of the sample point, range 8-70 feet.
Wind. ht.	The mean height of obstacles in the first 25 feet to the windward of the sample point, range 13-47 feet.

CHAPTER IV

RESULTS

Snowpack characteristics

Table 3 shows the results of the regression analyses for the data involving all of the points and may be used to get a picture of the snowpack. Figure 11 illustrates the large variability in the water equivalent existing within 200 foot elevation zones and Figure 12 is a plot by years of the general increase in maximum snowpack water equivalent with elevation. There is a large year-to-year variation in the relative values of individual points as emphasized by the relatively low R^2 values for the year-to-year regression. It is not uncommon for a given point to be 20 to 30% below the average for its 200 foot elevation zone in one year and as much above for the next year; many points have even greater variation. Figure 14 illustrates the scatter of points when plotted against elevation. This figure includes only those 108 points retained in the major study after ridgetop, southern exposure, and other points with possible discrepancies were eliminated. Figure 15 illustrates the type of relative variation of snow accumulation between years for all original points on the mid transect.

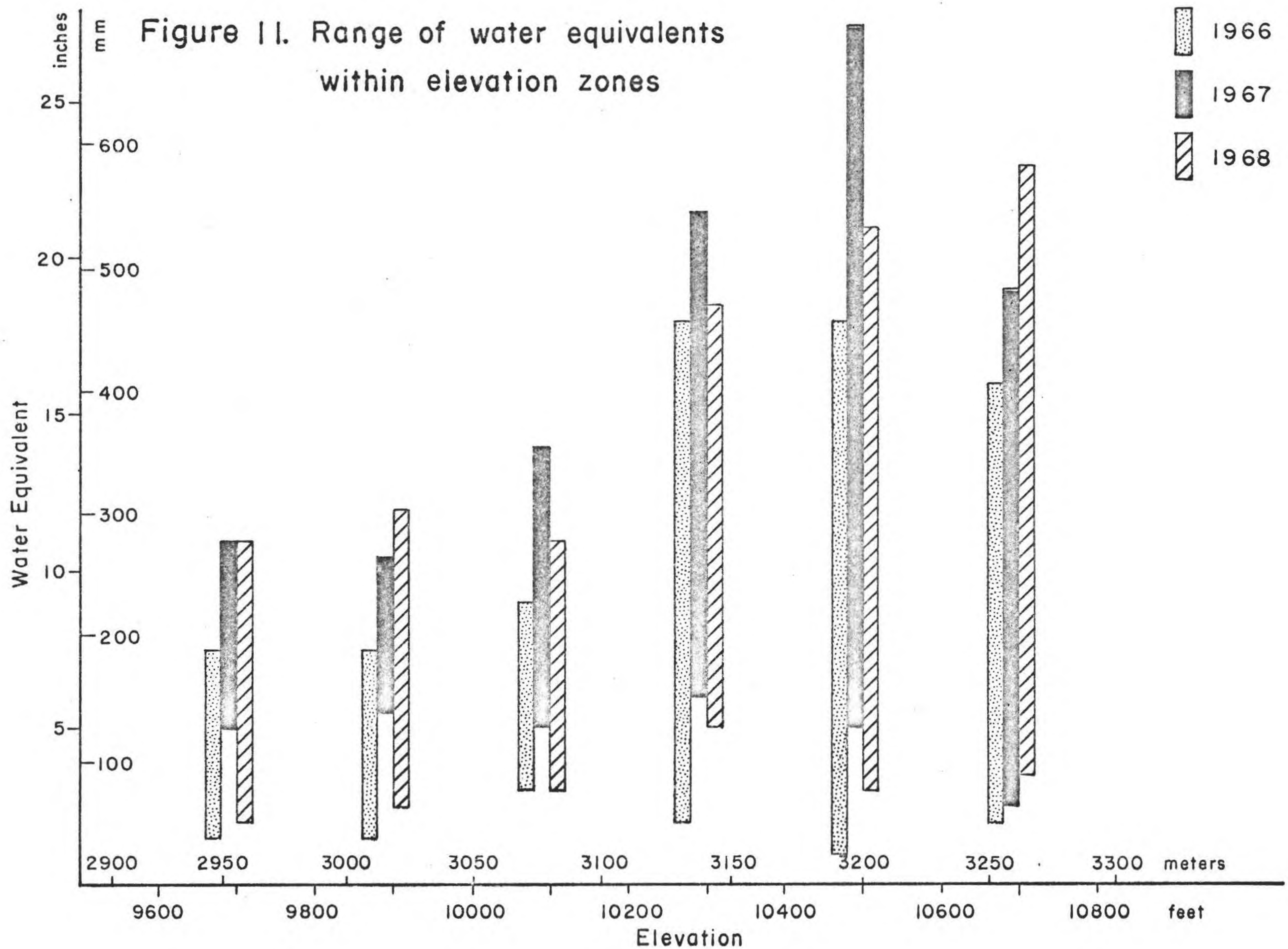


Figure 11. Range of water equivalents within elevation zones

Figure 12. Snowpack accumulation variation by elevation zones and year

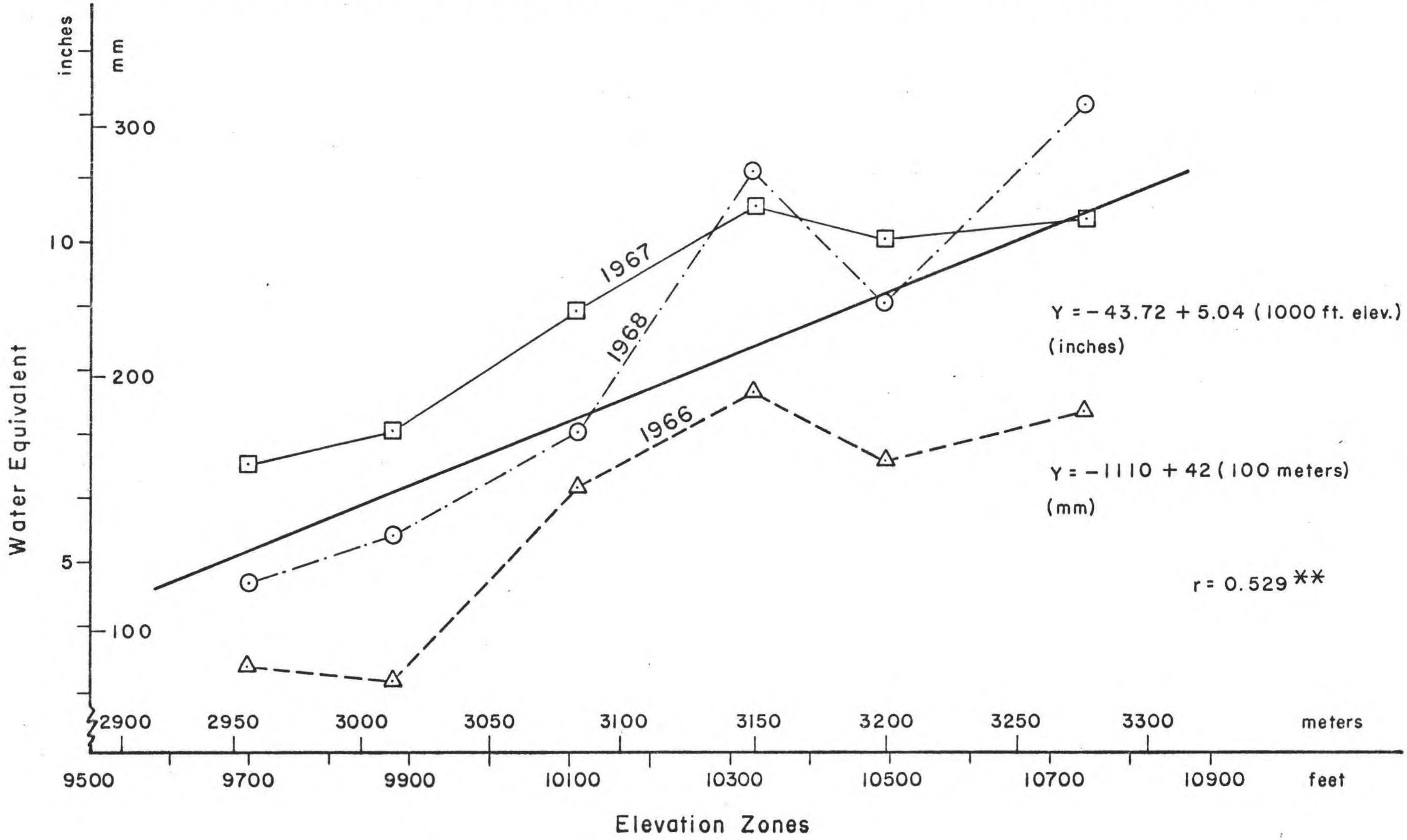


Figure 13. Distribution of snowpack by tree size class and elevation
1967 maximum snowpack

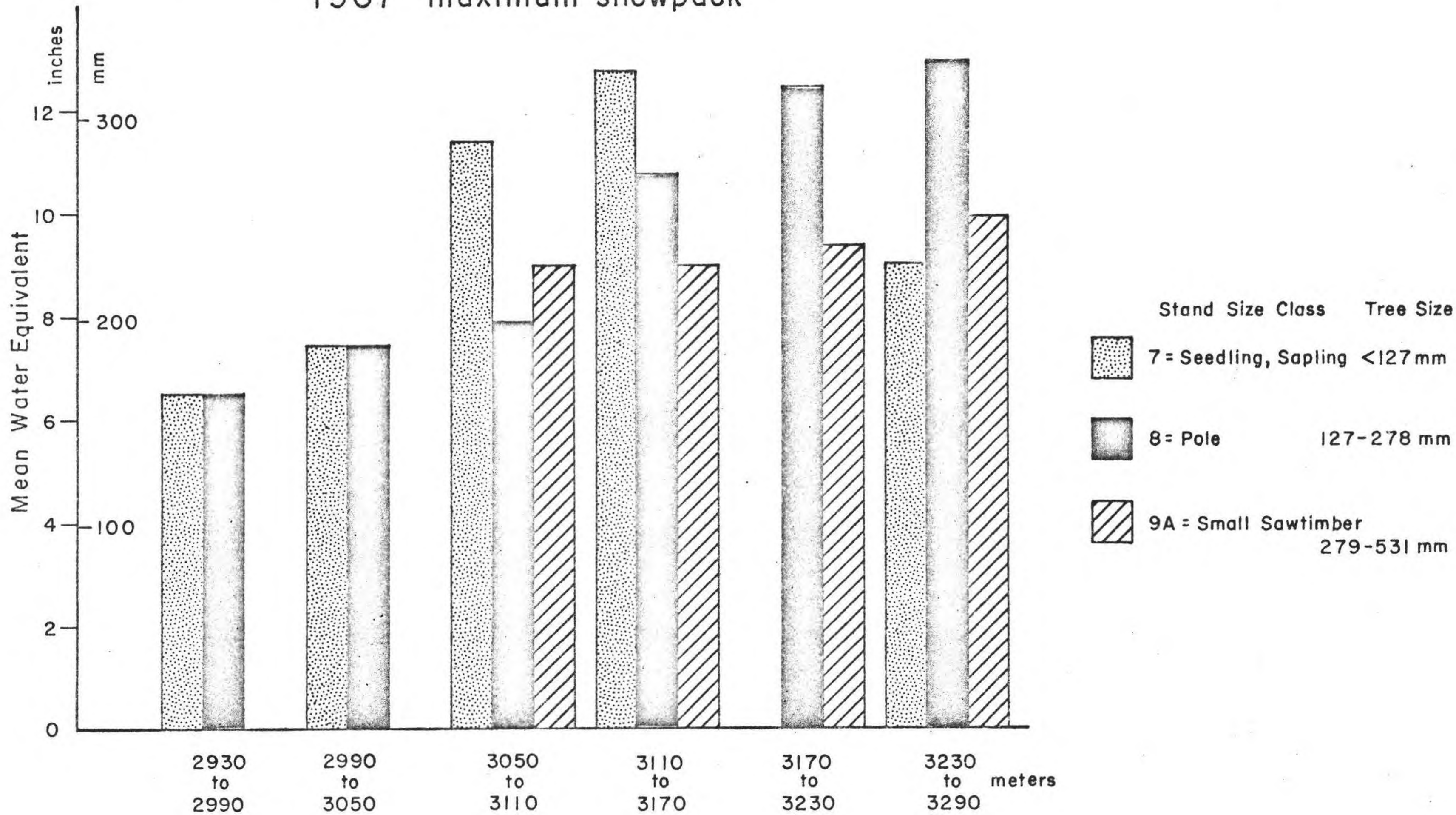


Figure 14. Plot of water equivalents over elevation of 108 points measured April 8, 1967.

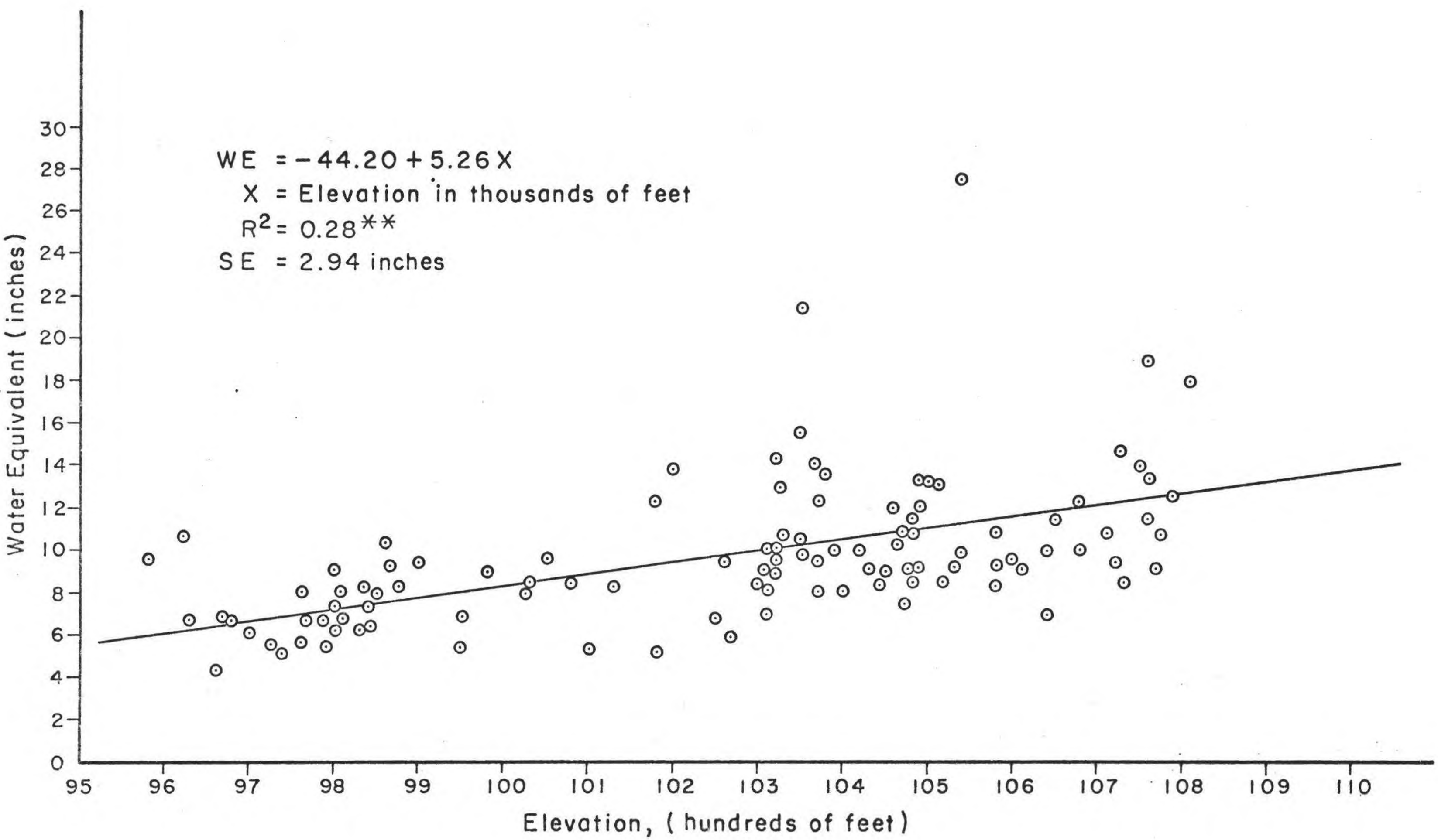


Figure 15. Plot of water equivalent data for each point on mid transect by years

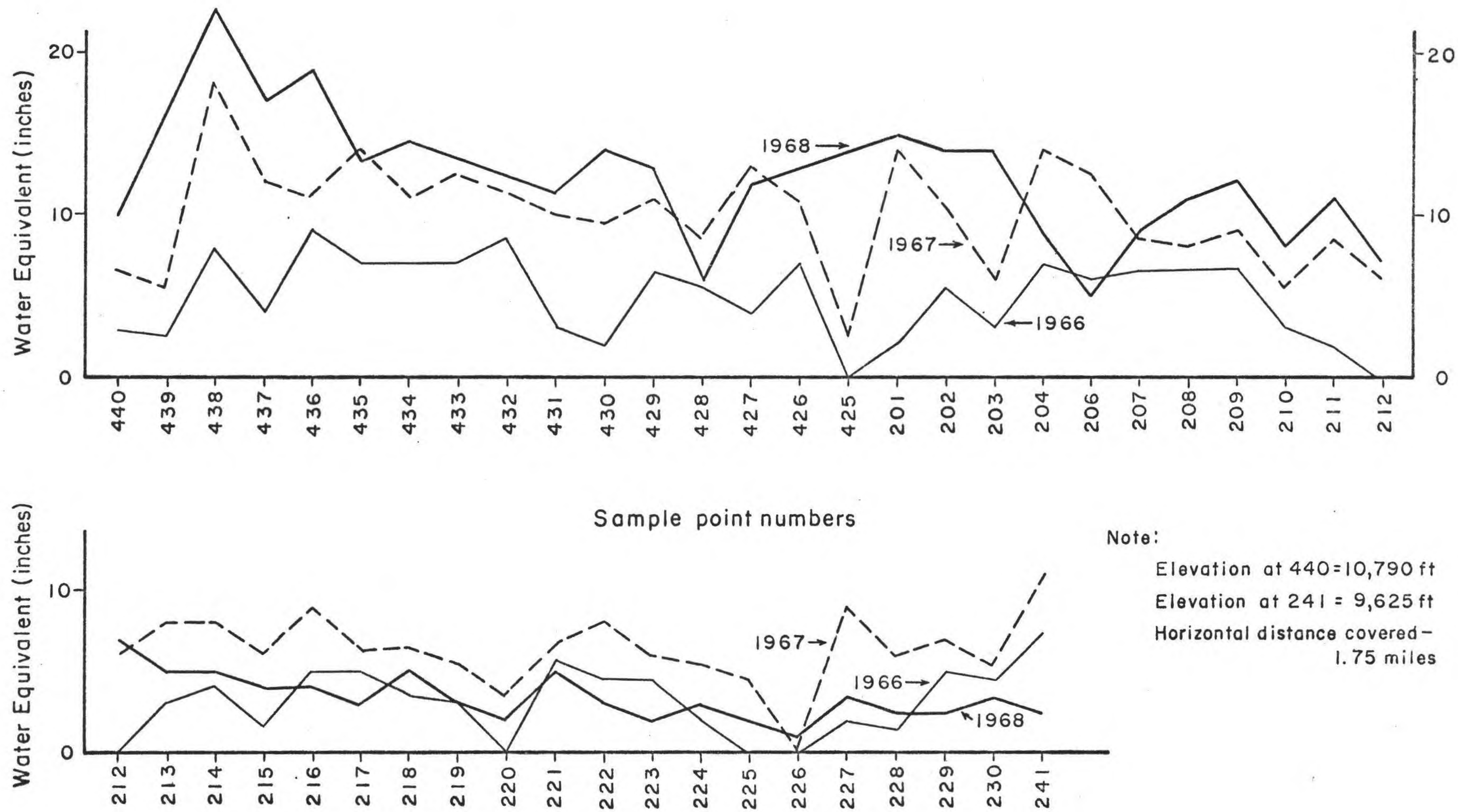


Table 3

Results of regression analyses, general snowpack characteristics over 123 observation points

Independent variable	Dependent variable	R^2	Standard error of estimate
1966 WE[1/]	1967 WE	.48**	2.75 inches
1966 WE	1968 WE	.25**	4.15
1967 WE	1968 WE	.44**	3.58
1966 SD[2/]	1966 WE	.74**	1.73
1967 SD	1967 WE	.80**	1.69
1968 SD	1968 WE	.54**	3.27

1/ WE = Water equivalent of snowpack near time of maximum
2/ SD = Snow depth of snowpack near time of maximum
** Significant at 0.01 level

Phase one

Preliminary tests were run using simple linear regression to estimate the effect of a few of the variables on snow accumulation in each of the three years and also on the sum of the three years water equivalent accumulation for each point (WE sum). In the initial trials all 123 points were used and the results are shown in Table 4. In the first three trials (steps a, b, and c) elevation, crown cover and a combination of the two variables were run. In the fourth step (d) elevation and vertical crown cover were used as the independent variables against each of the three years water equivalent. In step (d) only 115 points are indicated as the vertical crown cover measurements were not made on eight ridgetop stations.

Table 4

Results of regression analysis using three independent variables

Step	Independent variables	Dependent variable	No. of obs.	R^2	Standard error of estimate
a.	Elev.	1966 WE	123	.18**	3.39 inches
	"	1967 WE	123	.16**	3.54
	"	1968 WE	123	.28**	4.05
	"	WE sum	123	.28**	3.03
b.	Cr. cov.	1966 WE	123	ns	----
	"	1967 WE	123	.06*	----
	"	1968 WE	123	ns	----
c.	Elev. & Cr. cov.	1966 WE	123	.20**	3.42
	"	1967 WE	123	.21**	3.42
	"	1968 WE	123	.30**	4.01
	"	WE sum	123	.32**	2.95
d.	Elev. & Vert. CC	1966 WE	115	.16**	3.31
	"	1967 WE	115	.19**	3.42
	"	1968 WE	115	.26**	4.09

* Significant at 0.05 level
** Significant at 0.01 level

Phase two

In the preliminary trials it was found that the variables of stand type and crown cover to the north, east and south quadrants separately were apparently not useful in explaining any of the variation in snow accumulation and these variables were dropped in the following statistical analyses. Also, it was found that data were not available or complete on seven additional points and thus for the following comparisons and regressions, only 108 points are included for the analysis of the following seven variables:

1. Elevation
2. Crown cover (114^{o} arc)
3. Vertical crown cover (21^{o} arc)
4. Source/distance ratio
5. Crown cover to the west (windward)
6. Steepness of slope
7. Basal area

Stepwise multiple regression methods were used here to rank the variables in order of their importance in increasing the coefficient of determination. Four separate stepwise regressions were run on each transect separately by years and then for all transects pooled by years. The results from this phase are presented in Tables 5 and 6.

Phase three

In this phase only those 25 plots on which the crown volume estimates had been made were included. In addition to the seven variables listed in phase two, the following factors were included:

1. Crown volume (Cr. vol.)
2. Sum of diameters of stems over 2.0 inches d.b.h. (Dia. sum)
3. Number of stems 2.0 inches and over d.b.h. (Stems-2")
4. Number of stems 4.0 inches and over d.b.h. (Stems-4")

The results are shown in Table 7.

Table 5

Cumulative coefficients of determination ranking seven variables through stepwise multiple linear regression.

Depend. var.	1966 WE			1966 WE		
Step	Independ. variable	R^2	SE of est.	Independ. variable	R^2	SE of est.
			Lower transect - 18 points			
1	Cr. cov.	$.17^{ns}$	1.98 in.	Cr. cov.	.28*	1.97 in.
2	Elev.	$.24^{ns}$	1.95	Elev.	.33*	1.95
3	Slope	$.35^{ns}$	1.87	Slope	$.39^{ns}$	1.95
4	Source	$.38^{ns}$	1.90	Basal a.	$.39^{ns}$	2.01
5	Vert. CC	$.39^{ns}$	1.96	Vert. CC	$.40^{ns}$	2.07
6	Basal a.	$.41^{ns}$	2.02	Source	$.41^{ns}$	2.15
7	---	--	--	---	--	--
			Middle transect - 40 points			
1	Elev.	.22**	1.95 in.	Elev.	.53**	2.08 in.
2	Slope	.28**	1.90	CC west	.57**	2.01
3	Source	.32**	1.87	Slope	.59**	1.98
4	Basal a.	.33**	1.88	Source	.61**	1.98
5	Cr. cov.	.42**	1.79	Vert. CC	.62**	1.98
6	CC west	.43**	1.80	Basal a.	.63**	1.97
7	---	--	--	Cr. cov.	.63**	2.00
			Upper transect - 50 points			
1	Vert. CC	.43**	2.80 in.	Cr. cov.	.42**	2.83 in.
2	Basal a.	.47**	2.72	Source	.60**	2.37
3	Source	.49**	2.69	Vert. CC	.61**	2.39
4	CC west	.50**	2.69	Elev.	.61**	2.40
5	Cr. cov.	.52**	2.69	Slope	.61**	2.43
6	Elev.	.52**	2.71	CC west	.61**	2.46
7	Slope	.52**	2.74	--	--	--
			All transects - 108 points			
1	Source	.31**	2.86 in.	Source	.35**	2.78 in.
2	Vert. CC	.37**	2.74	Cr. cov.	.48**	2.48
3	Elev.	.43**	2.62	Elev.	.59**	2.21
4	Cr. cov.	.43**	2.62	Basal a.	.60**	2.21
5	CC west	.44**	2.62	Vert. CC	.60**	2.23
6	Basal a.	.45**	2.62	Slope	.60**	2.23
7	Slope	.45**	2.63	CC west	.60 **	2.24

Table 5 (Continued)

Depend. var.	1968 WE			Pooled WE		
Step	Independ. variable	R^2	SE of est.	Independ. variable	R^2	SE of est.
			Lower transect - 18 points			
1	Basal a.	.29*	2.41 in.	Basal a.	.22*	1.91 in.
2	CC west	.34*	2.39	Elev.	.35*	1.80
3	Vert. CC	.44*	2.29	Slope	$.41^{ns}$	1.78
4	Elev.	$.46^{ns}$	2.32	Vert. CC	$.44^{ns}$	1.80
5	Source	$.48^{ns}$	2.38	Cr. cov.	$.46^{ns}$	1.85
6	Cr. cov.	$.51^{ns}$	2.42	CC west	$.46^{ns}$	1.92
7	Slope	$.51^{ns}$	2.53	Source	$.46^{ns}$	2.01
			Middle transect - 40 points			
1	Elev.	.76**	2.80 in.	Elev.	.76**	1.56 in.
2	Source	.82**	2.46	Source	.80**	1.44
3	Slope	.84**	2.36	Slope	.84**	1.30
4	CC west	.85**	2.36	CC west	.86**	1.24
5	Vert. CC	.85**	2.34	Vert. CC	.87**	1.21
6	Basal a.	.85**	2.37	Cr. cov.	.87**	1.22
7	Cr. cov.	.85**	2.41	Basal a.	.87**	1.25
			Upper transect - 50 points			
1	Cr. cov.	.34**	3.26 in.	Cr. cov.	.51**	2.27 in.
2	Source	.49**	2.90	Source	.67**	1.87
3	Slope	.55**	2.76	Slope	.68**	1.86
4	Elev.	.58**	2.70	Vert. CC	.69**	1.85
5	Vert. CC	.59**	2.70	CC west	.70**	1.86
6	CC west	.59**	2.72	Basal a.	.70**	1.88
7	--	--	--	Elev.	.70**	1.90
			All transects - 108 points			
1	Elev.	.36**	3.80 in.	Source	.40**	2.57 in.
2	Basal a.	.45**	3.53	Elev.	.56**	2.20
3	Source	.51**	3.35	Cr. cov.	.67**	1.92
4	Slope	.52**	3.32	Basal a.	.67**	1.92
5	Cr. cov.	.53**	3.33	Vert. CC	.68**	1.91
6	Vert. CC	.53**	3.34	Slope	.68**	1.92
7	CC west	.53**	3.36	CC west	.68**	1.92

ns-non significant
* significant at .05 level
** significant at .01 level

Table 6

Simple correlation between selected individual variables

Independent variable	Dependent variable	No. of obs.	r
Elev.	Source	108	.41**
Basal a.	Vert. CC	108	.59**
Cr. cov.	Basal a.	108	.78**
Cr. cov.	Vert. CC	108	.73**
Cr. cov.	CC west	108	.79**
Vert. CC	CC west	108	.60**
Basal a.	CC west	108	.58**
Cr. cov.	Cr. vol.	25	.66**
Cr. cov.	Dia. sum	25	.49*
Basal a.	Stems-4"	25	.61**
Basal a.	Dia. sum	25	.70**
Basal a.	Cr. vol.	25	.85**
Cr. vol.	Stems-2"	25	.56**
Cr. vol.	Dia. sum	25	.85**
Cr. vol.	Vert. CC	25	.64**
Cr. vol.	Stems-4"	25	.64**
Vert. CC	Dia. sum	25	.42*
Dia. sum	Stems-2"	25	.86**
Dia. sum	Stems-4"	25	.94**
Stems-2"	Stems-4"	25	.84**

* Significant at 0.05 level

** Significant at 0.01 level

Table 7

Cumulative coefficients of determination ranking 11 variables on 25 sample points selected from the mid and upper transects.

Step	Independ. variable	R^2	SE of est.	Independ. variable	R^2	SE of est.
Depend. var.	1966 WE			1967 WE		
1	Source	.47**	3.40 in.	Source	.49**	3.51 in.
2	Elev.	.57**	3.12	Elev.	.63**	3.06
3	Vert. CC	.62**	3.00	CC west	.72**	2.70
4	CC west	.70**	2.72	Vert. CC	.73**	2.71
5	Dia. sum	.74**	2.62	Slope	.74**	2.75
6	Cr. vol.	.76**	2.58	Cr. cov.	.75**	2.77
7	Stems-2''	.82**	2.30	Vert. CC rem. 1/		
8	Cr. cov.	.82**	2.35	Stems-2''	.76**	2.72
9	Slope	.83**	2.37	Dia. sum	.76**	2.77
10	Stems-4''	.83**	2.43	Vert. CC	.77**	2.82
11	Basal a.	.84**	2.50	Cr. vol.	.77**	2.90
Depend. var.	1968 WE			Pooled WE		
1	Source	.32**	4.94 in.	Source	.55**	3.07 in.
2	Elev.	.46**	4.49	Elev.	.71**	2.52
3	Basal a.	.55**	4.23	Vert. CC	.77**	2.30
4	Stems-2''	.61**	4.03	Stems-2''	.78**	2.29
5	CC west	.62**	4.07	Cr. vol.	.80**	2.23
6	Cr. cov.	.64**	4.04	Dia. sum	.83**	2.16
7	Cr. vol.	.65**	4.12	CC west	.83**	2.17
8	Dia. sum	.70**	3.94	Cr. cov.	.84**	2.22
9	Vert. CC	.71**	3.98	Vert. CC rem. 1/		
10	Stems-4''	.71**	4.12	Basal a.	.84**	2.21
11	--	--	--	Stems-4''	.84**	2.28

** Significant at the .01 level

1/ Variable removed from regression equation

Phase four

The fourth step was to evaluate the roughness factors which had been calculated for the lower transect snow points. The independent variables which were included in the analysis were as follows:

1. Elevation (Elev.)
2. Crown cover in 114^o arc (Cr. cov.)
3. Crown cover in 21^o arc (Vert. CC)
4. Crown cover to the west (CC west)
5. Basal area (Basal a.)
6. Steepness of slope (Slope)
7. Profile area in the lee of the point (PA lee)
8. Profile area windward of the point (PA wind.)
9. Variance of the surface of the profile 0 - 25 feet to the windward (Var. 1)
10. Variance of the surface of the profile 25 - 50 feet to the windward (Var. 2)
11. Ratio of obstacle height to distance windward from the point (Coef. 1)
12. Sum of ratios of obstacle heights to distances to the windward from the point (Coef. 2)
13. Mean obstacle height in the first 25 foot segment to the lee of the point (Lee ht.)
14. Mean obstacle height in the first 25 foot segment to the windward of the point (Wind. ht.)

The results from this phase are presented in Tables 8 and 9.

Table 8

Cumulative coefficients of determination ranking 14 independent variables, by year, on 18 points of the lower transect.

Step	Independ. variable	R^2	SE of est.	Independ. variable	R^2	SE of est.
Depend. var.	1966 WE			1967 WE		
1	Cr. cov.	$.17^{ns}$	1.98 in.	Cr. cov.	.28*	1.97 in.
2	Lee ht.	$.27^{ns}$	1.92	PA lee	.42*	1.82
3	CC west	$.37^{ns}$	1.84	CC west	.55**	1.67
4	Elev.	$.43^{ns}$	1.81	Var. 2	.61*	1.60
5	Slope	.57*	1.65	Coef. 1	.67*	1.55
6	Wind. ht.	.61	1.64	Wind. ht.	.73*	1.45
7	Vert. CC	.71*	1.48	PA wind.	.77*	1.39
8	PA-wind.	.81*	1.26	Vert. CC	.82*	1.32
9	Var. 1	.85*	1.19	Slope	.84*	1.32
10	Basal a.	.90*	1.06	Elev.	.91**	1.02
11	Coef. 2	.96**	0.72	Lee ht.	.92*	1.04
12	Var. 2	.97**	0.72	Var. 1	.94*	0.86
13	PA-lee	.98**	0.56	Basal a.	.96*	0.86
14	--	--	--	Coef. 2	$.97^{ns}$	0.98
Depend. var.	1968 WE			Pooled WE		
1	Basal a.	.29*	2.41 in.	Basal a.	.22*	1.92 in.
2	Coef. 1	.48**	2.12	Coef. 1	.38*	1.76
3	Var. 2	.52*	2.12	Elev.	.52*	1.61
4	Elev.	.57*	2.08	Lee ht.	.58*	1.57
5	Cr. cov.	.63*	2.01	Wind. ht.	.65*	1.48
6	Coef. 2	.67*	1.99	Var. 1	.80**	1.18
7	Vert. CC	.69*	2.01	PA lee	.82**	1.15
8	Var. 1	$.72^{ns}$	2.03	PA wind.	.87**	1.06
9	Lee ht.	$.75^{ns}$	2.01	Vert. CC	.90**	0.86
10	Wind. ht.	.84*	1.72	Cr. cov.	.96**	0.66
11	PA lee	.94*	1.12	Coef. 2	.99**	0.36
12	PA wind.	.96*	1.08	Slope	.99**	0.27
13	CC west	.96*	1.10	Var. 2	.99**	0.29
14	Slope	$.96^{ns}$	1.26	CC west	.99**	0.33

ns non significant
* significant at 0.05 level
** significant at 0.01 level

Table 9

Matrix of simple correlation between variables used on the lower transect, 18 points.

	Basal a.	CC west	Cr. cov.	Vert. CC	Pa wind.	PA lee
Basal a.	1.00	.52*	.71**	.34	-.05	.06
CC west		1.00	.84**	.65**	-.23	-.20
Cr. cov.			1.00	.65**	-.10	.04
Vert. CC				1.00	-.20	-.06
PA wind.					1.00	.82**
PA lee						1.00

	Wind. ht.	Lee ht.	Coef. 1	Coef. 2	Var. 1	Var. 2
Basal a.	-.13	-.14	-.23	.24	.24	-.28
CC west	-.41	-.25	-.28	-.19	-.25	-.24
Cr. cov.	-.27	-.10	-.14	-.17	-.15	-.35
Vert. CC	-.47*	0.08	.20	-.06	-.48*	-.19
PA wind.	.87**	.78**	-.11	.05	.51*	.52*
PA lee	.73**	.86**	-.02	-.14	.38	.34
Wind. ht.	1.00	.70**	-.14	-.05	.69**	.39
Lee ht.		1.00	.02	-.27	.11	.37
Coef. 1			1.00	-.07	-.29	-.18
Coef. 2				1.00	.25	.12
Var. 1					1.00	.13
Var. 2						1.00

* Significant at 0.05 level
** Significant at 0.01 level

Summary of results

The results of this study may be summarized by categories of major influence on snow accumulation.

Physiographic factors

1. The distance to and the extent of potential source areas clearly plays an important role in influencing snow accumulation on this watershed. This variable is relatively unimportant on the lower transect, it helps to increase the coefficients of determination in the mid transect and becomes very important on the upper transect. When the three years of the study are pooled and 108 sample points are included, this variable is associated with approximately 40% of the total variance.

2. There is some degree of interaction between source areas and elevation (r = 0.41*) and when the two variables are used together in a regression on 108 points they are associated with up to 56% of the variation. Elevation when used by itself in a regression using 108 points appears to be associated with up to 28% of the total variance within the limited elevational range of the study area (9,580 - 10,810). The role of elevation also varies markedly from transect to transect, being relatively unimportant in the lower transect, strongly associated with snow accumulation in the mid transect and

becoming least important in the upper transect. A highly significant increase of water equivalent with elevation in all years averaged 5.0 inches per 1000 feet rise in elevation.

3. Steepness of slope appears to exert an insignificant amount of influence on snow accumulation except where there may be some correlation between slope and elevation. Increasing steepness of slope appears to exert a negative influence on snow accumulation in the lower and upper transect, but a positive influence on the mid transect. When the regression on all points and for all years is run the effect of slope is found to be extremely small.

4. The combination of topographic variables exerts an overwhelming influence on the mid transect; the variance associated with elevation, source, and steepness of slope totals 84%. The addition of a vegetative variable adds at the best only 3%.

Vegetative factors

5. The relative importance of the four simple "crown" variables varies considerably and there does not appear to be an important difference between the variables crown cover, vertical crown cover and basal area in their ability to index the canopy influence. Crown cover to the west appears to be the least valuable of the four and is most often ranked last. There does not appear to be any important increase in the amount of variance explained in the regressions by the addition of more than one of the four "crown" variables.

6. When one of the "crown" variables is used in conjunction with the two major physiographic factors (Source and Elevation), 67% of the variance is found to be associated with a combination of the three variables in a regression involving 108 points over all transects.

7. The variable "crown volume", as used here, does not appear to be a useful factor when used in a regression on the 25 sample points. The direct simple correlation with water equivalent is not significant. It is quite closely correlated with basal area (r = 0.85**) and crown cover (r = 0.66**).

8. The three "stem" factors (number of stems 2.0 inches d.b.h. and over, the number of stems 4.0 inches d.b.h. and over, and the sum of the stem diameters) did not appear to strongly influence snow accumulation and, individually, none were significantly correlated with differences in snow accumulation.

Roughness factors

9. In the study of "roughness" factors on the lower transect the range of source ratio values was only .47 - .64; this variable was not included in the stepwise regression. On this lower transect an expression of crown density such as crown cover or basal area was the most important variable. Crown cover alone accounted for 19% of the variation in 1967 and basal area was associated with 20% of the variance in 1968.

10. The use of the ratio of the height of an obstacle over its distance to the windward from a sample point (Coef. 1) was found to be an important factor. When the three years data was pooled, Coef. 1 raised the coefficient of determination from 22% to 38%. In a regression using only the roughness variables Coefficient 1 was ranked as the most important roughness variable.

11. The height of trees to the lee (within 25 feet) of the sample point exerted a positive effect on snow accumulation and was the second most important variable in 1966 and was ranked fourth when the water equivalents for the three years were totaled. Its contribution was to increase the R^2 from 52% to 58% after basal area, Coef. 1 and elevation had been incorporated in the regression.

12. The variables which attempted to quantify the effect of the roughness of the canopy upwind from the sample point were associated with up to 6% of the total variance. In 1967, the variance of the upwind surface was seventh most important variable and in 1968 it was ranked fourth.

13. The variable indexing the roughness of the canopy (over the first 100 feet) to the windward of the point (Coef. 2) was not important in the presence of other roughness variables.

14. The height of the trees to the lee of a sample point coupled with Coef. 1 appear to be the most useful "roughness" variables in the regressions on the 18 points of the lower transect.

CHAPTER V

DISCUSSION

Climatic conditions

It is quite evident that snow falling in this watershed does so in the presence of a strong wind regime and under climatic conditions that produces very low density snow. There may be sufficient variation in the year-to-year wind patterns to account for a large part of the year-to-year relative accumulation at the sample points. The method used to obtain approximate climatic conditions probably leaves much to be desired and on-site measurements would have been preferred. However, such comparisons as could be made with known climatic data and from observations in the stand and on aerial photography provide reason to expect that the extrapolated data provides a good index to the conditions that exist during the three winter accumulation seasons of the study.

There is a distinct contrast between the conditions found here and those reported by Packer (1962) in Idaho where he concluded that snowfall occured most often in the absence of wind. Anderson's (1967) study indicates a range of wind velocities of only .42 to 1.17 m/s at the tree top level. From general field observations during and following snow storms it is noted that snow is usually held in the canopy only a few hours and at the most two or three days. A strong, gusty period possibly associated with the storm front passage may be sufficient to remove nearly all snow from the forest canopy. The turbulence of the air flow is probably quite large in this watershed which is situated in the lee of an 11,000 foot elevation ridge. An observer positioned to view the whole study area can at times observe numerous snow plumes rising out of the timber canopy with a surprisingly strong vertical component. These plumes may rise to a few hundred feet above the canopy and then drift into the canopy downwind.

Hoover and Leaf's (1966) comment about the wind over their study area on the Fraser Experimental Forest, "Prevailing upper level winds do not reach into the valley, but vortices are sheared off when velocities are high and gusts pass down the mountain sides to sweep quickly, but turbulently through the valley", appears to be an exellent description of this phenomena in the Little Beaver drainage also.

The alpine areas of grasses and other low vegetation are fully exposed to the high level winds. Early spring aerial photographs of the snowfields show large differences in accumulation. The surface is deeply eroded in a generally east-west pattern. While snowshoeing across the exposed "source" areas two or three days following a snowstorm large amounts of snow were still being moved in the zone within several feet above the snow surface.

The winter of 1967 appeared to have slightly higher wind speeds than either 1966 or 1968 and the mean direction of winds of the upper 25 percent of the estimated velocities was more nearly out of the west. This could have the effect of changing the extent and the distance to a source area for any particular point, and it might also have a local influence through its interaction with obstacles such as logs, tree trunks or crowns in the close proximity of the sample points. There is considerable opportunity for wind to move through and even under the canopy of the stand in this watershed. At the time of making the snow measurements on the upper transect in March, 1968, snow was observed to be drifting in the first foot or so above the snow surface even in some moderately sheltered sites. The lower transect was found to have the least evidence of drifting snow although even at this distance from the main ridge top (approximately two miles) some of the snow deposition patterns about the sample points suggested a strong wind action on them. Of 32 plots on the upper and mid transects visited in March 1969, 50% of them showed signs of wind influence on the snow surface.

The mean temperatures during snowfall periods compares with those reported by Hoover and Leaf (1966) on the Fraser Experimental Forest in 1964 of being generally below 20 to 30°F with maximums up to 39°F. In the Little Beaver the mean temperatures during days with snowfall over the three year period was 20-25°F. Lows each year were around -5 to 2.4°F and occasionally maximums of 37 to 41°F were estimated. At these temperatures it would appear that there is little opportunity for snow to adhere firmly to the canopy surface, and in the presence of this wind regime, redistribution from the canopy by mechanical wind action is most common.

The snow measured at estimated maximum snowpack, assuming little or no opportunity for melt and minor sublimation losses, at any given point might be a function of the following processes:

1. snow reaching the point directly during initial snowfall
2. snow reaching point blown from adjacent canopies during and shortly after snowfall
3. snow deposited from airborne snow from broad source areas during and for considerable time periods after snowfall
4. snow deposited from local surface drifting throughout snow accumulation season
5. losses from scouring action of local windstreams throughout snow accumulation season

Physiographic factors

It is shown that elevational influence is a common feature throughout regions having a snow accumulation season (Meiman, 1968). Its influence varies widely within and between regions and also may vary with an elevation-year interaction (Packer, 1962). Within this study there are numerous examples of differing rates of increase of snow accumulation with increase in elevation. Over all points (108) and all years (3), the average increase in elevation is about five inches per 1000 feet increase in elevation. This is only valid for the north and northeast facing slopes of the upper elevations and probably does not apply to the south-facing and lower elevations.

Figure 17 shows the effect of distance from a source area on snow accumulation, and it may be seen that a broad contributing area can be a major influence up to a 1000 feet away from the source area. This suggests that there should be a massive accumulation in the first forest zone just below the alpine-krumholtz and rockfield areas, and this may be a fruitful site for initial efforts to manage snow accumulation. The exact distance to a source area and the potential for that area to yield snow to downwind locations is not easily measured with precision. Our lack of exact knowledge of the canopy level wind directions and the influence of local topographic features on the snow-air flux makes the calculation of the source ratios somewhat subjective. To know what constitutes a source area requires some degree of familiarity with the terrain. In this study the distances to a source area were taken from 1:6,000 aerial photographs and open areas down to 300 feet in width were included. In a few cases more than one source area lay in the line to the windward and source ratio then became a composite of two or more ratios. The expanse of the snowfield obviously influences

Figure 16. Influence of mean tree height to the windward and leeward of a point on the snow accumulation at average sample point, using equation A, Appendix

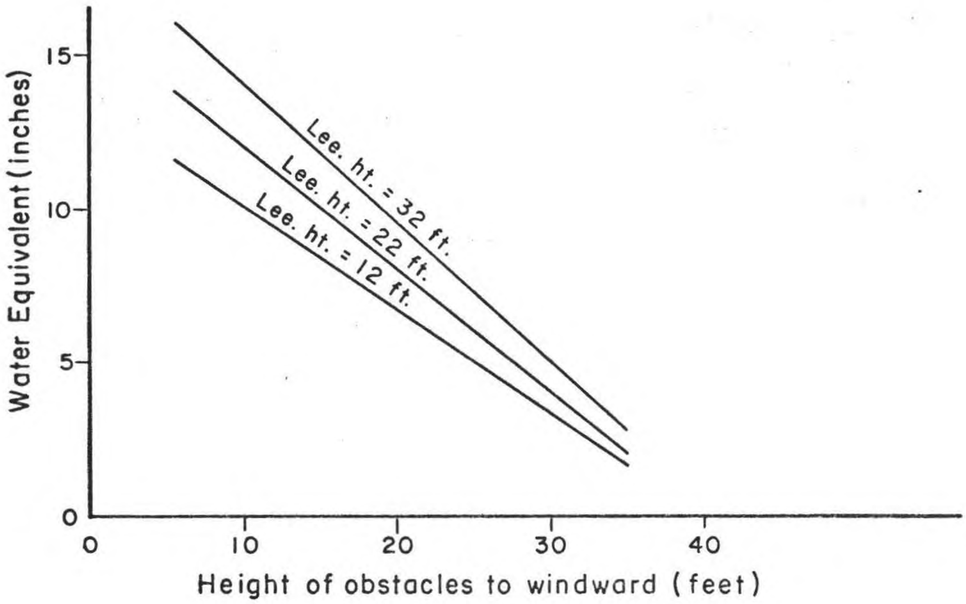
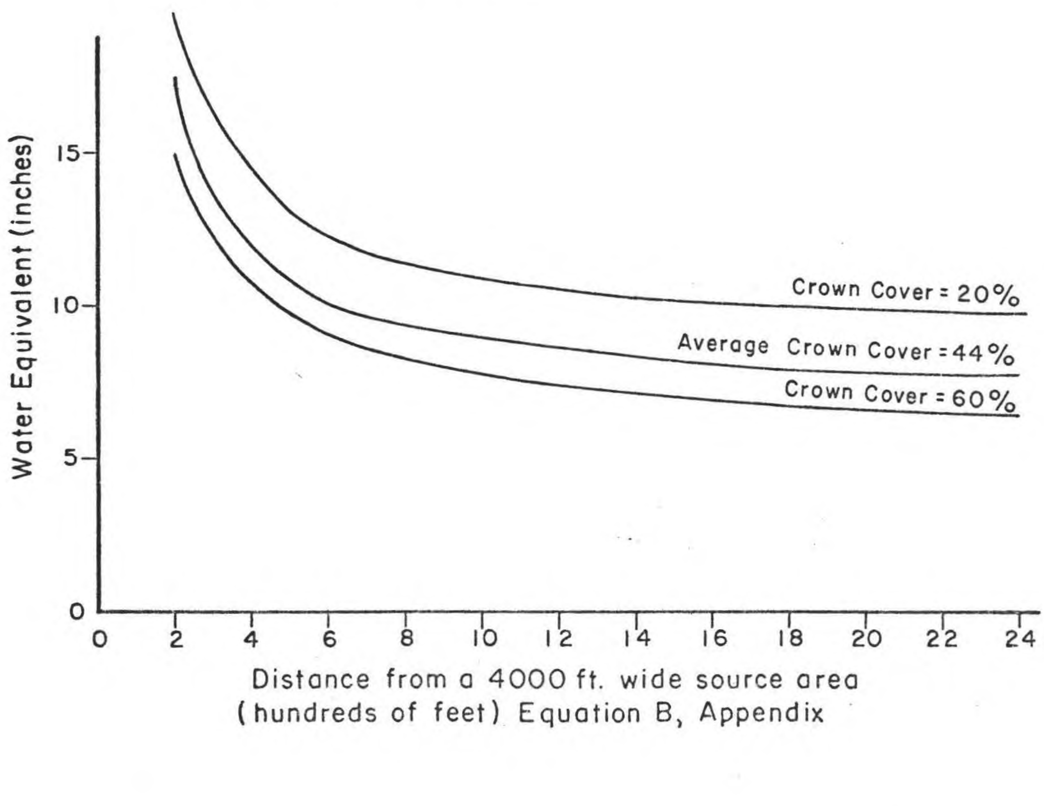


Figure 17. Effect of distance from source area and crown cover on snow accumulation.



its potential for yielding snow (Tabler, 1963). The westernmost ridge top was somewhat arbitrarily chosen as the windward limit of the snow field, although some areas from the west side of the alpine ridge may yield snow for later redistribution into the forested area. That the source-distance ratio was found to be associated with approximately 40% of the total variance of the 108 sample points is indicative of the importance of snow redistribution in this watershed.

There is probably some interaction between source and elevation (r = .41**) and when the two variables are combined in a regression, the coefficient associated with elevation assumes different proportions. The role of both source and elevation changes from transect to transect, but one or the other of them is almost always found among the first two most important variables. The combination of the two variables in the regression using data from 108 points and the three year average water equivalent shows that a highly significant 56% of the total variance is associated with source and elevation combined.

The relatively close correlation between steepness of slope and elevation (r = .77**) on the lower transect may help to explain why it is ranked next to elevation in importance in that area. The fact that an increasing slope exerts a negative influence on snow accumulation on this transect may be due to the apparent increase in exposure to wind on the steeper slopes. It also exerts a negative effect on the upper transect, but not the mid transect. This changing about in importance and direction of influence of slope on snow accumulation with particular sites probably means that there are as yet undetermined interactions between slope and other topographic or even vegetative variables. Over all of the sample points and averaging over the three years, steepness of slope appears to be relatively unimportant in snow accumulation.

Vegetative factors

The influence of vegetative factors on snow accumulation might be examined in two categories, one type of variable that basically indexes the mass of crown and the other type that is indicative of the roughness of the canopy surface. The two are not entirely independent and it is not possible to say that the first type influence only interception and the second only the aerodynamic features. The variables taken here to be primarily an index of mass are crown cover, vertical crown cover, basal area, and crown cover to the west (windward).

These variables are closely correlated (r = .66 to .79) and when used together in a regression are probably somewhat redundant. Crown cover as measured with the Lemmon spherical densiometer is apparently the most useful of the four. When it is used in a regression with source and elevation, the three variables are associated with 67% of the total variance. Crown cover is also the most important single variable in the upper transect (50 points) in two of the three years and in the three year average. When the three years water equivalent are pooled on the upper transect, crown cover is ranked above source and is associated with up to 51% of the total variance by itself. In general a 10% decrease in crown cover would increase snow accumulation by about 0.8 inches. However, on the upper transect it appears that a 10% decrease in crown cover would increase snow accumulation by 1.5 inches for the average point and average year. This represents a range of from 9 to 15% increase in water equivalent respectively with a 10% decrease in cover. The limits of the range of values that this suggested effect would operate are not determinable from the data. Packer (1962) and Anderson (1967) indicate that the effect of crown cover is linear over the whole range of from 0 to 100%, but they report a much smaller canopy effect, that is, approximately 10% change in water equivalent accumulated for a 100% change in crown cover.

It was hypothesized that throughout a winter's snowfall there would be occasions when the angle of incidence of the falling snow would be low and other more calm occasions when there would be a stronger vertical component to the snowfall. If this were the case, then a broad canopy index such as the 114° arc included in the Lemmon spherical densiometer readings would be complimented by a narrow field of view that would be an index to the sky view immediately overhead. To test this the spherical densiometer was modified to include only 21° arc and a second set of readings of crown cover were obtained. This may roughly correspond with Packer's "vertical crown cover" or Anderson's "INT" which was described as the canopy cover in the 10% of the hemisphere above the point. Preliminary trials using combinations of weighting of these two variables did not support the hypothesis. There is a strong correlation between crown cover and vertical crown cover (r = .52**) and there probably is some interaction between them. However, when either one of them was used in a regression in a stepwise fashion, the addition of the second did not materially improve the coefficient of determination. It may be noted that vertical crown cover was selected as the second most important variable in the 1966 regression involving all 108 points, but an examination of the partial correlations prior to the selection of the crown variable revealed that the vertical crown cover variable was only slightly better than the variable "crown cover" in explaining the remaining variance. This would indicate that if vertical crown cover had not been present crown cover would have been selected and it would have accounted for nearly the same amount of variance.

The same may be said of basal area as a crown index variable. It appears that it could be utilized fully as well as crown cover in the regressions and still provide as large or nearly as large a coefficient of determination. This variable is the easiest to obtain and the most consistent value that could be obtained between various observers. Both the spherical densiometer and the Bitterlich prism have the feature of sampling variable radius plots. That is, the taller the trees or the bigger the stem diameters, the larger the area included in the sample. This should be a helpful element when trying to index a stand such as this with a fair range of heights and diameters.

Crown cover to the west appears to be the least influential of these four "crown" variables in its influence on snow accumulation. Anderson (1967) found that the function of canopy in selected quadrants was primarily one of interaction with solar energy. That is, it provided either shade or produced back radiation. It was retained in this study for its possible interaction with the prevailing wind. On occasion, such as the 1967 regression on the middle transect (40 points), it was picked as the second most important variable, but in general its influence varied widely and generally provided little improvement in the amount of explained variance.

It is interesting to note that as shown in Table 4, the first three variables entered in the stepwise regressions account for nearly all (98%) of the variance that is explained by the whole array of variables. Within the first three variables there is always one or both of the two important topographic variables and one of the crown variables. The total variance associated with these three variables in the regression on 108 points and three year average was 67%. This still leaves considerable variance unaccounted for, but it does clearly indicate the relative importance of some of the variables and suggests some areas where further study might be fruitful.

Discussion of crown volume and stem variables

Packer's (1962) work seemed to indicate that a vegetation index such as the sum of diameters might be a useful variable and Miller (1964) has suggested that crown volume, growing space, or other such expression of canopy values might be desireable. To test this the 90 points making up the mid and upper transects were stratified into five snow accumulation classes based on their accumulation over the three years of record. From each of these five classes five points were chosen at random and an intensive inventory was made on a 1/10-acre plot around each of these 25 points. This stratified sampling of the points was used to assure that within this limited number of points the widest range of snow accumulation conditions would be included. The plots chosen also had a wide range of vegetative cover ranging from dense stands of lodgepole pine to merchantable spruce-fir stands. The number of stems 2.0 inches and over ranged from 300 to 1930 per acre.

The new variables produced in this inventory were, number of stems 2.0 inches d.b.h. and over, number of stems 4.0 inches d.b.h.

and over, sum of diameters of all trees on the plot 2.0 inches d.b.h. and over, and crown volume. Table 5 shows that the addition of these variables did not significantly improve the coefficients of determination. This is partially explained by the relatively close correlation between the stem and crown volume variables with the crown cover-basal area variables as shown in Table 7.

Perhaps the most important feature of the method developed for obtaining crown volume is the possibility of its use in estimating the total mass of crown for studies in transpiration losses from the watershed. The computed curve (Figure 7) shows a very similar pattern to that of Cable's (1958) graph of foliage surface area over stem diameters for Ponderosa pine. Also, it is possible that under certain conditions of calm winds such as those reported by Packer in Idaho and Anderson in the Central Sierra Nevada that a crown volume variable would be highly significant. Miller (1955) states that the canopy volume should be the best indicator of transmitted insolation.

In Table 5 it should be noted that probably only the first three variables are the significant ones in the regression. The inclusion of the remainder is not meant to show that these are likely to be used together in a regression equation, but only to indicate the relative ranking of the variables tested in the stepwise method.

Discussion of Roughness Variables

Since it is evident that wind is a major factor in the distribution of snow over this watershed any manipulation of the vegetation of this drainage area to influence snow accumulation should be done with knowledge of what such restructuring of the canopy would have on the wind flow over and through the forested areas. To study the processes some variables must be derived that would index the aerodynamic effect of the canopy structure and its surface.

Some studies of wind movement through forest canopies such as those by Stearns (1965) and Stearns and Lettau (1963) have described the efficiency of obstacles such as Christmas trees in the extraction of momentum per unit silhouette-area. These studies used a similarity parameter to compare obstacle fields in the various studies. This parameter was an expression of the silhouette-area of a given or average obstacle to the projected ground area that it occupies. With such small obstacles as Christmas trees, such measurements were easily obtained by direct measurement. As early as 1928, Zieger (1928) had expressed the desire to obtain a measure of the canopy profile for a variety of purposes but the methods to obtain such data were lacking. Loetsch and Haller (1964) discuss the possibility of using stand profiles or cross-sections and state;

> The arithmetical mean of the areas of all profiles multiplied by the profile spacing gives the so-called

'growing space'. It is necessary that the profile touches the ground at several points so that the surface level can be determined. This variable combines the effects of the stand height and of the stand growing space.

The first problem then in developing a measure of the canopy roughness was to find a suitable means to measure the highly irregular, tall and sometimes dense stands that are found in the Front Range watersheds. Preliminary trials with terrestial photography showed that for stands of this density and height a cross-sectional view could usually not be obtained. Byram (1940) proposed a tree crown profile projector that utilized a sighting device and transparent grid on which the canopy profile could be sketched free-hand. This was taken under consideration but was found to have the same deficiencies as terrestial photography under these conditions.

The Kelsh photogrammetric plotter seemed to offer a possible solution. It has been used for a number of years to measure topography and other gross features and topographic maps for earthwork design had been constructed with it having contours of two foot intervals or less. Cooper (1965) and Smith, Cooper and Chapman (1967) report on the use of the Kelsh plotter for measuring snow depths on 1:6000 photo scale photography with a calculated standard deviation of snow depths of 0.78 feet. Both soil and snow surfaces may be easier to observe accurately in a stereo model than a porous, irregular canopy surface, and certain portions of a tree crown may not be resolved in ordinary photography at a scale of 1:6000. The visible portion of the crown, however, should be subject to observation as readily as any solid surface, and it was thought that for comparative purposes possible errors in absolute measurements would not be a major objection. Consistency of canopy measurement between sample points would be the major objective.

Another instrument that could be utilized for this is the Stereocomparator. A brief trial was made on the stereocomparator at the Foothills Campus of the Civil Engineering Department of Colorado State University. This instrument is much more sophisticated than the Kelsh plotter and allows up to 40x magnification in contrast to the 5x on the Kelsh. It also has the very decided advantage of having the facility of automatically punching computer cards giving the x, y, and z coordinates of the floating dot at any point desired. It was used here primarily to assist in locating the control targets. Operational costs and the initial familiarity of the writer with the Kelsh plotter were the deciding factors in turning to it for this project. The Kelsh plotter was made available through the Civil Engineering Department at Colorado State University. This instrument requires six-inch focal length photography contact printed on 9x9-inch glass plate diapositives.

The lower transect was chosen for this preliminary trial since it is the furtherest removed from the windblown source areas, and was thought to be subjected to nearly the same windfield over its mile-long length. The targeting of only every fourth sample point probably was not sufficient for the control that was desired. Since photography was delayed until October, well past the optimum time for such photography, the recovery of the targets on the resulting photography was quite difficult. A sufficient number of control points was recovered to make it possible to bring the Kelsh stereo-model into reasonably good interior and relative orientation and probably adequate absolute orientation. Independent tests for errors was not possible with the degree of control established, but checks against field notes on tree heights and location of sample points indicate that the profiles obtained were reasonable representations of the canopy surface and were adequate for this preliminary study.

Repeated trials were run over the same profile until consistent traces were recorded and then the remaining profiles were run. The largest single error in tracing the canopy surface is likely to be at the tips of narrow, pointed crowns. In photogrammetric forest mensuration it is common to apply a correction to tree height measurements to obtain a more nearly correct total tree height value. No attempt to adjust the profiles was made on the reasoning that this narrow, pointed tip would not constitute a major influence on the wind stream and that it would be a consistent error and thus not a problem in comparative measurements.

It was theorized that the nearest upwind obstacle (tree or clump of trees) from a point would exert the greatest influence on snow accumulation at that point. Thus a coefficient that might index this influence was sought. Most published studies on a canopy influence on the windstream deal with relatively dense, uniform stands (Reifsnyder, 1955) and do not take into consideration the influence of turbulence that is likely to be generated over such an irregular profile as exists in this study. Area. The large reduction in windspeed within the canopy region is clearly demonstrated. It was expected therefore, that major protuberances above the general canopy level would be the most important factor in bringing the turbulent air-snow flux into the calmer conditions lower in the canopy. Somewhat intuitively rather than on the basis of previous work, the length of crown extending above the level of one-half of the mean obstacle height was used. This height above half of the mean height divided by the distance to the obstacle from the sample point was called Coefficient one. Figure 18 shows the effect of this ratio on snow accumulation and its interaction with height of objects to the lee of the sample point. The shape of the curve is somewhat like that of the snow accumulation behind a 50%-density snow fence when the fence is in contact with the ground. This curve must be interpreted considering that no very large openings were included in the sample and this effect may not continue for a very long distance before a decrease in snow accumulation occurs.

Figure 18. Effect of distance from windward obstacle and leeward obstacle height on snow accumulation. Based on average of three seasons, 18 points, using equation A, Appendix

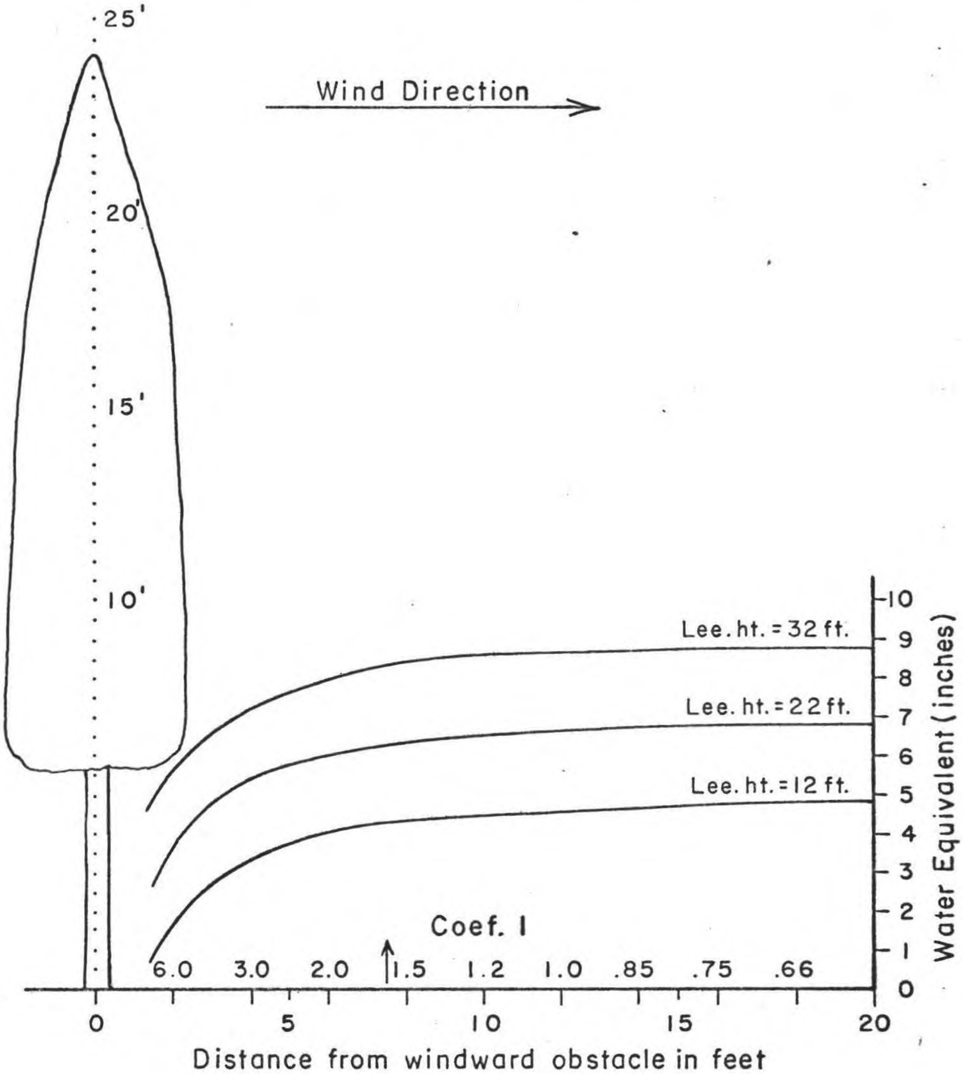


Table 8 shows the results of the stepwise regressions utilizing the roughness variables along with the general variables used in the larger study. Both in 1968 and when the water equivalents for the three years are totaled, Coefficient one is ranked as the second most important variable and when combined with basal area, 38% of the total variance is found to be associated with these two factors. This is slightly better than when only basal area and elevation are used. When basal area, elevation and Coefficient one are used in a regression on these 18 points, about 52% of the total variance is explained, significant at the .05 level. This is some improvement over the regressions shown in Table 5 (lower transect) since in that case the results using three variables (basal area, elevation and slope) were non-significant.

There is, of course, a large amount of variance left unexplained, but it does indicate that the roughness coefficient may be a step in the right direction to indexing the effect of canopy configuration. Since only one profile per point was run, and that under rather difficult circumstances, it may be that better technique would assist in improving the variable. Also, the value of the variable might have been improved if it were based on more than one transect intersecting the canopy within several feet of the sample point. That is, measuring the roughness of a wider path possibly up to one-half tree height in width.

The second most important variable is simply the average height of the trees or clumps of trees in the first 25 feet down wind from the sample point. The evidence is far from conclusive since one cannot be certain that the addition of a fourth variable in a regression of only 18 points is meaningful. The fact that this variable was ranked second in the 1966 data and fourth in the regression on the pooled water equivalents may be a clue that this is an important factor. It may be that the greater the projection of the obstacle into the windstream the larger the opportunity for directing the snow-air flux into a location conducive to snow deposition. Figure 16 illustrates the interaction between lee height and windward height. According to equation A (appendix), the effect of the trees to the windward is approximately twice that of the leeward tree heights. The fact that lee height was selected before windward height in the stepwise regression is possibly due to the fact that Coefficient one had already indexed this effect.

The R^2 values listed in Table 8 beyond the third or fourth variable are probably unrealistically large and no conclusion should be drawn from them. In an effort to test the roughness variables in the absence of other known effective major variables, a set of stepwise regressions was run using only the eight roughness variables. The results of this test shows that no single roughness variable used nor any combination of them was significantly correlated with snow accumulation. The relative ranking of the roughness variables remained about the same with the variable Coefficient one generally the most important one followed by lee height.

A brief search for the "problem" points was made by calculating the percentage of the mean water equivalent for each point for each year. These ranges for each point over the three years were used as a dependent variable in a stepwise regression. This showed that the "problem" points are inversely correlated with both slope and elevation. This may mean that in the lower transect and at the lower elevation points there may have been some opportunity for melt in some years thus creating an unusually high variation from year to year.

Table 9 lists the simple correlations that exist between these crown and roughness variables. It is observed that "Lee ht." and "PA lee" are strongly correlated and that "Wind. ht." and "PA wind." are similarly correlated. "PA-lee" was picked as the second most important variable in 1967, but an inspection of the partial correlations after crown cover had been entered in the equation showed that the difference between these two variables was very small. Since the height measurement is more easily obtained it is suggested that this is the most logical downwind variable to consider in future studies.

The "variance" variable was expected to show the influence of the roughness of the canopy upwind from the point, but it apparently is not a very sensitive method and generally ranks quite low, and the variance in the 25 to 50 foot segment upwind generally ranks lower than the variance in the first 25 foot segment. This relative ranking is not conclusive due to the nature of the test and interaction between variables, but the fact that these two are fairly consistently low probably indicates that they are not very meaningful expressions of the canopy surface. As calculated, the variance does not take into consideration the spacing between obstacles and some visibly different profiles had quite similar variance values.

The variable "Coefficient two" was designed to take into account the relative spacing of the obstacles and in addition give a weighting to the obstacles nearest the sample point. The results are disappointingly low, and any of the other windward variables account for more variation than this roughness coefficient.

Possibly the most important feature of this phase of the study is that it does demonstrate the canopy can be characterized by such photogrammetric means and that variables both to the windward and leeward are probably important when in close proximity to any sampling point.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Results from measurements of maximum snow water equivalent in 1966 - 1968 on a Colorado Front Range watershed together with measurements of selected physiographic and vegetative factors were analyzed to evaluate the effect of these factors on snow accumulation. The forest cover is very heterogeneous relative to age, stand density, and spatial distribution. Elevation of the observation points ranged from 9,580 to 10,810 feet. The area is often subjected to very strong winds during and after snowfall. An analysis of data from radiosonde and rawinsonde atmospheric data published by the U.S. Weather Bureau for Denver, Colorado and Lander, Wyoming were interpolated using the 700 mb level to represent the approximate level of the Little Beaver study area. This data showed that free atmosphere winds have an average velocity of 9.4 m/s on days with precipitation and about 8.1 m/s on days without precipitation. An average of about 13 snow storms occur during the November to April snow accumulation season. Mean temperature during snowfall is about minus 5.2°C. The mean snowpack water equivalent near maximum accumulation was 6.6 inches in 1966, 9.7 in 1967 and 9.1

in 1968. The wind is predominantly from the west but with some differences in the mean wind direction from year to year.

A stepwise linear regression was run with three sets of variables against water equivalents for each year and for the sum of the three year's water equivalent. From these stepwise regressions it was observed that in general the source/distance ratio is the single most important variable found in the study. When the three years of the study are pooled and 108 sample points are included 40% of the total variance was found to be associated with this ratio.

Elevation is the next most useful variable and when used by itself over the 108 points and the three years water equivalent pooled it appears to be associated with up to 28% of the total variance. The role of elevation also varies markedly from transect to transect, but there is a highly significant increase in snow accumulation with elevation. For the three years of the study the rate of increase of water equivalent averaged five inches per 1000 feet of increase in elevation within the narrow elevation range studied (9580 - 10,810 feet). While at times the variable of steepness of slope seemed to be important, over all the effect of slope was found to be very small. The combination of the three topographic variables, source, elevation and slope, was found to be associated with 84% of the total variance in a regression involving the 40 points of the mid transect. Elsewhere in the study area the topographic variables were enhanced by the addition of a vegetative variable.

There is a close correlation between the four crown variables, but crown cover as measured by the Lemmon spherical densiometer to include a 114° arc appears to be the most useful. It is practically interchangeable in the regression equations with basal area as measured with a 10-basal area factor Bitterlich cruising prism. When one of the crown variables is used in conjunction with source and elevation, 67% of the total variance can be associated with them in the regression involving the 108 sample points and the three years pooled data.

The crown volume and stem variables did not prove to be very useful in the regression equations. The highly significant correlation (r = 0.85**) between crown volume and basal area indicates that the simpler and easier to obtain variable is a more efficient way to index crown mass.

The fourth objective of the study was to develop an index for forest roughness. The lower transect was used which had always given the poorest correlations with any of the variables tried up to this time. That is, it always had the largest unexplained variance over its set of points. Coefficient one was developed which is briefly defined as the ratio of the height of the first object to the windward from the sample point, minus one-half the mean obstacle height of the first 50 foot segment to the windward, over the distance from the sample point to the obstacle. Lee height was used and it is simply the average of all obstacles in the first 25 foot segment to the lee of the point. These two roughness variables, Coefficient one and Lee height, were the two most promising roughness variables. In the absence of the previously used topographic and vegetative factors, these roughness variables did not significantly account for the variance of the data from the 18 sample points. However, in the presence of basal area and elevation, Coefficient one brought the total variance associated with the three variables up to 52% when the three years data was pooled. The addition of lee height to the regression brought the R^2 up to 58%. The effect of the other roughness variables varied from year to year, but were generally of much less importance.

It appears that a photogrammetric method of indexing the canopy has considerable potential. The technique developed in this study is indexing some of the factors not included in other variables and helps to explain more of the variance about this lower transect than had been explained by previous sets of variables. It appears that further refinement of the technique and types of measurement that index the influence of the canopy on the wind-snow flux is warranted.

Snow management possibilities seem especially good in the zone of a few thousand feet distance leeward from the alpine source areas. Cutting patterns in this or other portions of the watershed must consider the influence of wind on snow redistribution.

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APPENDIX

APPENDIX CONTENTS

Table A

Selected multiple regression equations and standard error of estimates.

(a) Regression equation including roughness variables as used on Lower transect, 18 points.

Y = average of three years water equivalent

Variable	Coefficient
Constant	2.20213
Elev.	0.00132 (ft.)
Basal area	-0.04685 (sq. ft./acre)
Wind. ht.	-0.40703 (ft.)
Lee ht.	0.19596 (ft.)
Coef. 1	-0.55557
Var. 1	0.04069 (sq. ft.)

Multiple R = 0.8926
F ratio = 7.186**
SE of estimate = 1.18 in.

(b) Regression equation including three variables most effective over all 108 points.

Y = average of three years water equivalent

Variable	Coefficient
Constant	-33.60658
Elevation	0.00428 (ft.)
Crown cover	-0.07613 (%)
Source	0.49579

Multiple R = 0.8177
F ratio = 69.942**
SE of estimate = 1.92 in.

Table A (Continued)

(c) Regression equation including seven variables produced by seven steps in the stepwise regression method, 108 points.

Y = average of three year water equivalent

Variable	Coefficient
Constant	-35.21264
Slope	-0.01959 (%)
Elevation	0.00445 (ft.)
Basal a.	-0.00572 (sq. ft.)
Crown cover	-0.04114 (%)
Vertical CC	-0.01831 (%)
Source	0.47950

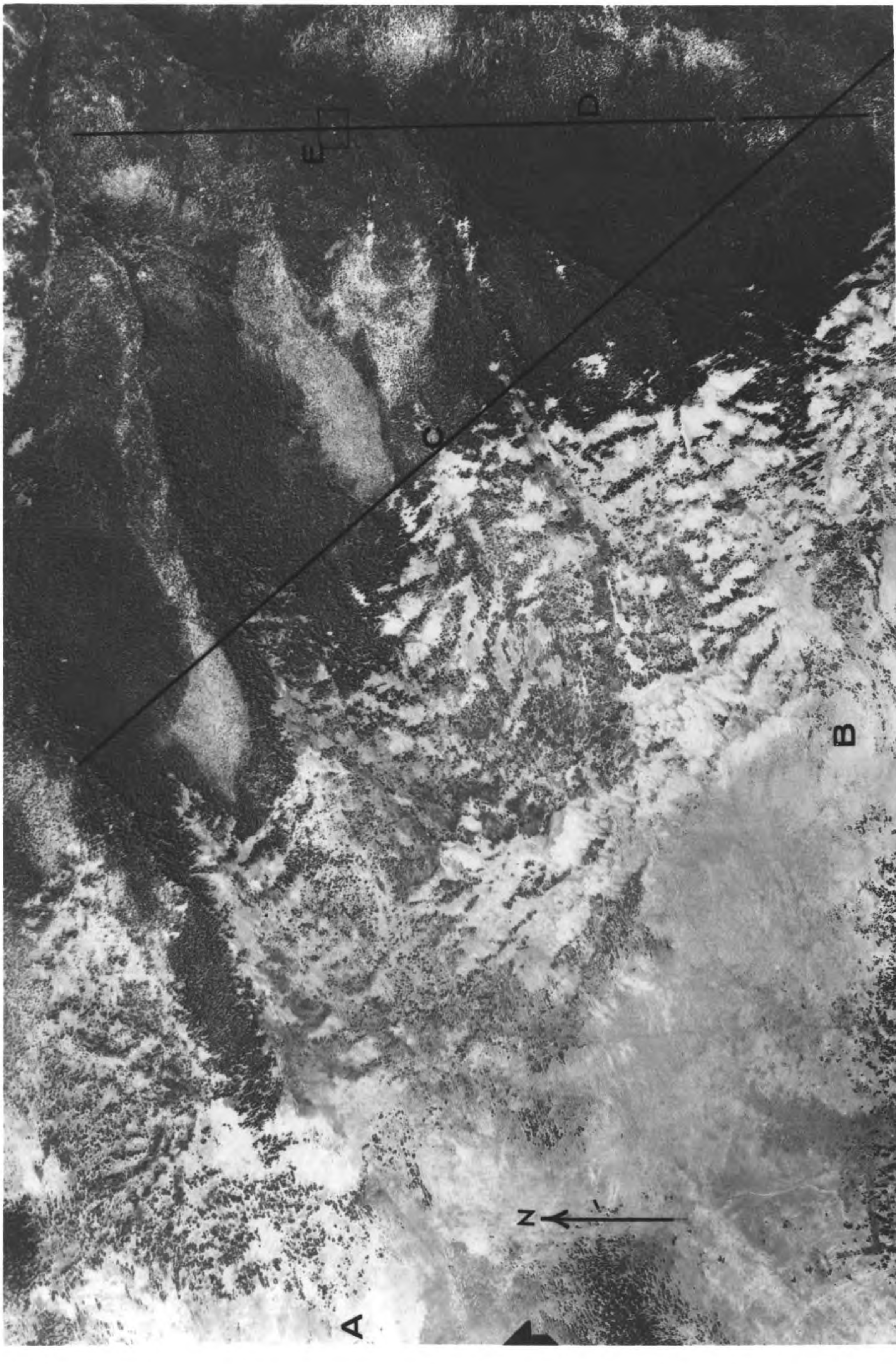
Multiple R = 0.8248
F ratio = 30.405**
SE of estimate = 1.92 in.

(d) Regression equation including crown volume variables on 25 points selected from the mid and upper transect.

Y = average of three year water equivalent

Variable	Coefficient
Constant	-57.90996
Elevation	0.00636 (ft.)
Vertical CC	-0.02149 (%)
Stems-2 in	0.03348 (count on 1/10 acre)
Crown vol.	-0.06499 (cu. ft.)
Source	0.66579

Multiple R = o.8971
F ratio = 15.675**
SE of estimate = 2.23 in.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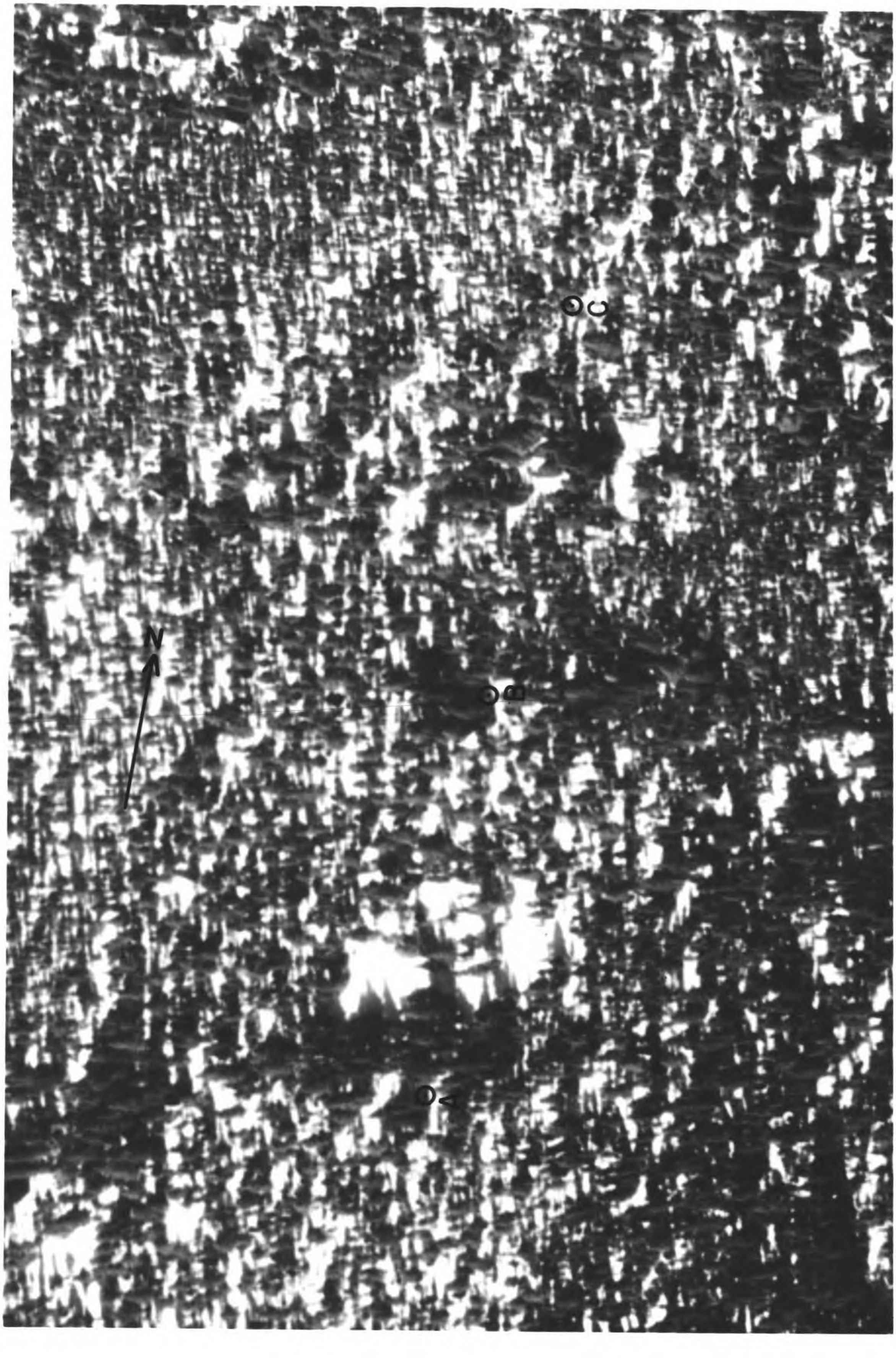
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