



Temporal accumulation and ablation patterns of the seasonal snowpack in forests representing varying stages of growth  
by Janet Phillips Hardy

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences  
Montana State University  
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**Abstract:**

The extent of snow accumulation and timing of spring runoff is affected by many variables, including canopy density and basal area. Prior research on snow distribution patterns in clearcut forests and undisturbed forests, shows that smaller clearcuts result in a depositional increase of the seasonal snowpack and an accelerated average seasonal ablation rate. What has not previously been clarified is the extent of snow accumulation and the timing of ablation in forests representing intermediate stages of growth. To answer this data gap, four plots, each with a different forest structure, were chosen for study within a lodgepole pine, subalpine fir forest of Montana. Plot A is within a small meadow. Plot B is a young regrowth forest with an approximate 6% canopy density, and a basal area of 2.2 m<sup>2</sup>/ha. Plot C is an older regrowth forest with a 56% canopy density and a basal area of 17 m<sup>2</sup>/ha. Plot D is a mixed species forest with a 85% canopy density and a basal area of 37 m<sup>2</sup>/ha. At each plot, snow depth, density and snow water equivalence data was collected throughout the snow accumulation and ablation seasons of 1989 and 1990. Weather data was obtained from the Lick Creek SNOTEL site maintained by the U.S. Soil Conservation Service and located within 0.5 km of each plot. Results of this study during the 1989 snow season suggest: 1. An inverse relationship exists between canopy density and maximum snow accumulation (correlation coefficient = -0.54; p-value < 10<sup>-4</sup>), and 2. A strong inverse relationship exists between canopy density and snow ablation rate (correlation coefficient = -0.87; p-value < 10<sup>-4</sup>). Results from the 1990 snow season imply that a poor inverse relationship exists between canopy density and maximum accumulation (correlation coefficient = -0.14; p-value = 0.4008), while the 1990 ablation patterns support the 1989 data (correlation coefficient = -0.73; p-value < 10<sup>-4</sup>). The results from this research may assist watershed managers in estimating the extent of snow accumulation and the timing of runoff in forests with a history of reduced canopy due to vegetative disturbances such as logging, fire and disease.

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**A thesis submitted in partial fulfillment  
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of

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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## TABLE OF CONTENTS

LIST OF TABLES .....	vii
LIST OF FIGURES .....	viii
ABSTRACT .....	x
INTRODUCTION .....	1
Previous Studies .....	1
Objective of Study .....	4
Location of Study .....	5
Implications of Results .....	5
METHODS .....	8
Site Description .....	8
Study Plot Descriptions .....	8
Site Preparation .....	11
Weather Data Collection .....	13
Forest Studies .....	13
Canopy Density .....	13
Basal Area .....	14
Tree Age .....	14
Tree Heights .....	15
Relationship to Surrounding Forests .....	16
Winter Data Collection .....	17
Accumulation and Ablation .....	17
Transects .....	19
Additional Data .....	21
RESULTS AND DISCUSSION .....	22
Weather Conditions .....	22
1989 and 1990 Snow Seasons .....	22
Comparison of the Two Snow Seasons .....	24
Forest Comparisons .....	26
Canopy Density Comparisons .....	27
Forest Structure .....	29
Snow Accumulation .....	31
The 1989 Snow Season .....	31
Distribution of Maximum Snow Accumulation in Plots .....	33
Statistical Significance of Accumulation Results .....	35
The 1990 Snow Season .....	38
1989 and 1990 Accumulation Seasons Compared .....	40
April 2, 1989 Transects .....	42
Transect Data .....	42
Statistical, Spatial Independence Between Stakes .....	48

TABLE OF CONTENTS--Continued

Snow Ablation . . . . .	48
The 1989 Snow Season . . . . .	48
Discussion of Ablation Patterns . . . . .	49
Statistical Significance of Ablation Results . . . . .	52
The 1990 Snow Season . . . . .	54
1989 and 1990 Ablation Seasons Compared . . . . .	57
Other Patterns of Snow Distribution . . . . .	58
Relationship Between Maximum Accumulation and Ablation Rates . . . . .	58
Snow Density . . . . .	60
Comparison of the Meadow and Young Trees . . . . .	61
Implications . . . . .	65
CONCLUSIONS . . . . .	67
Application of Results . . . . .	68
Further Studies . . . . .	69
LITERATURE CITED . . . . .	71
APPENDIX--Additional Snow Data . . . . .	76

## LIST OF TABLES

Table	Page
1. Canopy Density, Basal Area and Tree Age, Heights and Species for Plots B, C and D .....	27
2. Snow Depth, Snow Density and Snow Water Equivalence for April 2, 1989 .....	34
3. Snow Depth, Snow Density and Snow Water Equivalence for the Entire 1990 Snow Season .....	40
4. Snow Depth, Snow Water Equivalence and Associated Standard Deviations for each Plot as Obtained from Transect Data .....	43
5. Snow Depth, Snow Density and Snow Water Equivalence for the Entire 1989 Ablation Season .....	51
6. Ablation Rate Calculations for all Plots During 1989 .....	52
7. Ablation Rate Calculations for all Plots During 1990 .....	55
8. Snow Density Data for the 1989 Snow Season .....	60
9. Comparison of Maximum Accumulated Snow Water Equivalence and Ablation Rates for the 1989 Snow Season .....	63
10. Snow Water Equivalence and Associated Standard Deviations for the 1989 Snow Season .....	77
11. Snow Water Equivalence and Associated Standard Deviations for the 1990 Snow Season .....	77

## LIST OF FIGURES

Figure	Page
1. Location of Study Area within the Hyalite Watershed . . . . .	6
2. Location of Study Plots within the Lick Creek Drainage . . . . .	9
3. Layout of Stakes in Plots A, C and D . . . . .	12
4. Layout of Stakes in Plot B . . . . .	12
5. Method used to Determine Tree Heights . . . . .	16
6. Snow Density Sampling Pattern . . . . .	19
7. Location of Transects in Plots A, C and D . . . . .	20
8. Mean Monthly Air Temperatures at the Lick Creek SNOTEL Site . . . . .	23
9. Mean Monthly Snow Water Equivalence at the Lick Creek SNOTEL Site . . . . .	23
10. Air Temperature Deviations from the 8-Year Mean . . . . .	25
11. Snow Water Equivalence Deviations from the 25-Year Mean . . . . .	25
12. Tukey Sum-Difference Plot of Canopy Density . . . . .	28
13. Histogram Comparing Canopy Density and Basal Area for Plots B, C and D . . . . .	30
14. Snow Water Equivalence for all Plots During the 1989 Snow Accumulation Season . . . . .	32
15. Scatter Plot of Canopy Density and Maximum Snow Water Equivalence with a Lowess Smooth for the 1989 Snow Accumulation Season . . . . .	36
16. Snow Water Equivalence for all Plots During the Entire 1990 Snow Season . . . . .	39
17. Scatter Plot of Canopy Density and Maximum Snow Water Equivalence with a Lowess Smooth for the 1990 Snow Accumulation Season . . . . .	41

LIST OF FIGURES--Continued

Figure	Page
18. Snow Depth Transect - Plot A .....	45
19. Snow Depth Transect - Plot B .....	45
20. Snow Depth Transect - Plot C .....	46
21. Snow Depth Transect - Plot D .....	46
22. Snow Water Equivalence for all Plots During the 1989 Snow Ablation Season .....	50
23. Scatter Plot of Canopy Density and Ablation Rate with a Lowess Smooth for the 1989 Snow Ablation Season .....	53
24. Scatter Plot of Canopy Density and Ablation Rate with a Lowess Smooth for the 1990 Snow Ablation Season .....	56
25. Plot of the Standardized Values of Maximum Snow Water Equivalence and Ablation Rate .....	59
26. Snowpack Density under Varying Canopy Densities Through Time ..	62

## ABSTRACT

The extent of snow accumulation and timing of spring runoff is affected by many variables, including canopy density and basal area. Prior research on snow distribution patterns in clearcut forests and undisturbed forests, shows that smaller clearcuts result in a depositional increase of the seasonal snowpack and an accelerated average seasonal ablation rate. What has not previously been clarified is the extent of snow accumulation and the timing of ablation in forests representing intermediate stages of growth. To answer this data gap, four plots, each with a different forest structure, were chosen for study within a logdepole pine, subalpine fir forest of Montana. Plot A is within a small meadow. Plot B is a young regrowth forest with an approximate 6% canopy density, and a basal area of 2.2 m<sup>2</sup>/ha. Plot C is an older regrowth forest with a 56% canopy density and a basal area of 17 m<sup>2</sup>/ha. Plot D is a mixed species forest with a 85% canopy density and a basal area of 37 m<sup>2</sup>/ha. At each plot, snow depth, density and snow water equivalence data was collected throughout the snow accumulation and ablation seasons of 1989 and 1990. Weather data was obtained from the Lick Creek SNOTEL site maintained by the U.S. Soil Conservation Service and located within 0.5 km of each plot. Results of this study during the 1989 snow season suggest: 1. An inverse relationship exists between canopy density and maximum snow accumulation (correlation coefficient = -0.54; p-value < 10<sup>-4</sup>), and 2. A strong inverse relationship exists between canopy density and snow ablation rate (correlation coefficient = -0.87; p-value < 10<sup>-4</sup>). Results from the 1990 snow season imply that a poor inverse relationship exists between canopy density and maximum accumulation (correlation coefficient = -0.14; p-value = 0.4008), while the 1990 ablation patterns support the 1989 data (correlation coefficient = -0.73; p-value < 10<sup>-4</sup>). The results from this research may assist watershed managers in estimating the extent of snow accumulation and the timing of runoff in forests with a history of reduced canopy due to vegetative disturbances such as logging, fire and disease.

## INTRODUCTION

The timing and volume of the spring run-off in a forested watershed is affected by many variables, including forest canopy density, basal area, tree height, the resulting accumulated snowpack and its distribution. Previous studies which measured and compared snow accumulation in clearcuts and undisturbed, mature forests have shown that clearcuts typically result in more snow available for run-off than do undisturbed forests (Leaf, 1975; Golding and Swanson, 1986; Toews and Gluns, 1988; Wilm and Dunford, 1948 in Troendle et al., 1988). However, the amount of snow accumulation in forests at young or intermediate growth stages has rarely been measured or documented. Variations in the timing and volume of run-off are expected when comparing areas of differing forest structure (primarily canopy density and basal area), such as is found in areas with no forest, in areas with young, low density forests and in areas covered by mature, high density forests. This issue is further complicated due to water loss by evapotranspiration from trees, soil infiltration and groundwater storage.

### Previous Studies

A variety of studies have compared the distribution of snow accumulation and the duration of snow retention in clearcuts and undisturbed forests, where the volume and timing of water yield during the melt season is of major concern (Gary, 1979; Golding and Swanson, 1986; Toews and Gluns, 1986; Berris and Harr, 1987; Troendle, 1987). Most of these studies were conducted in experimental, mountain watersheds. Clearcut areas are generally thought to increase the volume of snow

available for run-off (Leaf, 1975; Golding and Swanson, 1986; Toews and Gluns, 1988; Wilm and Dunford, 1948 in Troendle et al., 1988). The lack of shading from an absent forest cover, in these clearcut areas, contributes to an earlier and more rapid snowmelt, less infiltration and a less sustained flow later into the ablation season. Late season snowmelt is important in that it allows for more available water when the demand on water supplies is often greatest, such as during the summer months (Lee, 1980).

Potts (1984) investigated snow accumulation and ablation patterns in different stand densities as a result of thinning and found that snow accumulation in lodgepole pine (Pinus contorta) stands was inversely proportional to basal area or canopy density. The basal area of a forest is the total area of the forest occupied by tree stems, as measured at breast height, and expressed in meters squared per hectare ( $m^2/ha$ ); and the canopy density of a forest is defined as the percentage of canopy closure resulting from branches, needles and leaves (Ford-Robertson, 1971). Swanson and Golding (1982) found that snow in thinned forests melted at a faster rate and the snow disappeared 10-12 days sooner than in undisturbed forests. Gottfried and Ffolliott (1980) found that in a mixed conifer forest the higher snowpack water equivalence, total snowmelt runoff and daily ablation rates occurred in sites with low and medium forest canopy densities compared to sites with a high overstory density. Overall, results indicate that the protective canopy cover of a full structured, mature forest contributes positively toward the retention of snow late into the ablation season (Marks and Marks, 1980; Troendle and Leaf, 1981).

Other studies have attempted to determine the optimal timber harvest method, such as strip cutting, to maximize snow accumulation while prolonging snowmelt (McGurk and Berg, 1987). Studies conducted in the 1950's and 1960's found that forest openings are related to tree height (H). Openings of 1H to 2H

result in the greatest accumulation of snow water equivalence at any time (Kattelman, 1982). Similarly, Swanson and Golding (1982) found that on level terrain, maximum accumulation occurred in 2H clearcuts, while slowest ablation occurred in 1H clearcuts. In these small forest openings, it is believed that snowmelt is often delayed because surrounding trees intercept the incoming solar radiation and, at the same time, allow for loss of longwave energy from the snow surface (Marchand, 1987).

The distribution of snow is affected by the interaction of the forest structure and weather factors, such as the nature and frequency of storms, atmospheric winds, temperature, moisture and radiative exchanges (Gary, 1979; Lee, 1980). The forest canopy is an above ground biomass that intercepts snow and makes it vulnerable to sublimation, redistribution by wind or through-fall during and after storms (Gary, 1979). Kolesov (1985) found that 10-15 percent of the total winter snowfall is intercepted by tree crowns and then falls to the surface during wind events or warm weather. Warm, wet and high density snow is deposited when the ambient air temperature is near the melting point, resulting in a snowpack that is more resistant to redeposition than colder, drier and lower density snow. The presence of trees also influences the surface terrain roughness and wind velocity affecting erosional, transportational and depositional characteristics of snow (Gary, 1979). Trees and their forest canopies absorb, scatter and emit radiant energy, profoundly affecting the energy exchange in forests (Bohren, 1972). The effects of both shortwave and longwave radiation are a function of forest canopy structure (Ffolliott et al., 1989). Additionally, areas lacking tree cover are particularly vulnerable to rapid snowmelt for, according to Dozier (pers. comm., 1989), snowpack depths below 0.3 meters may allow incoming radiation to penetrate to the ground, causing warming of the ground surface and enhancing snowmelt.

Few studies have previously measured the effect that various stages of forest growth or structure have on maximum snow accumulation, and on providing protective shading to the snow, which controls ablation. In watersheds with timber harvest activity, there are typically many stands with transitional growth stages and structures. The ability of these transitional structures to accumulate and retain a snowpack is largely unknown. More information is needed regarding the relationship between canopy density or basal area and snow accumulation and snowmelt. Such information is needed to better understand hydrologic changes in watersheds in response to timber harvest and the subsequent regrowth.

#### Objective of Study

The overall objective of this research was to measure the affect forest structure has on snow depth, snow density, snow water equivalence and snow ablation rates (these factors contribute to the volume and timing of spring run-off). Spatial and temporal patterns of snow were compared in forests representing a variety of growth stages. The effects of terrain on snow distribution where not addressed and therefore, were minimized in this study. Specific questions to be addressed in this study included:

- 1) Is there a relationship between the growth stage or structure of a forest and that forest's ability to accumulate a snowpack?
- 2) Is there a stage of growth or structure threshold in which trees provide enough protective shading to substantially delay ablation and retain a snowpack?

### Location of Study

The study area is in the Lick Creek drainage, one of the many drainages comprising the Hyalite Creek watershed, within the Gallatin National Forest, approximately 35 km south of Bozeman, Montana (Figure 1). The Hyalite Watershed yields 57,604,450 m<sup>3</sup> (46,700 acre/ft) of water in a "normal" year (Glasser, 1987) supplying 50-70% of the municipal water for the city of Bozeman, Montana (Shields, pers. comm., 1989). The output from this watershed also significantly contributes to agricultural water supplies, provides a sustained flow for fish populations and is a recreation resource. Additionally, the chosen study area is of economic significance, as timber harvest has continued and expanded here for several decades (Farnes, pers. comm., 1989; U.S. Forest Service, 1987). Although, the study area is not representative of the entire watershed it is representative of the areas being logged. As such, the watershed studied is of tremendous importance to the people in and around Bozeman. The region's dependence on this water source highlights the need to better understand the effects of timber harvest on this critical water supply.

### Implications of Results

In most mountainous environments, the seasonal snowpack and its water content are of considerable concern to water managers in that the resulting meltwater fills reservoirs and controls the amount of water available in a region for municipal use and irrigation (Dunne and Leopold, 1978). Environmental planners are also concerned with the rate and timing of snowmelt due to the potential hazard of snowmelt floods (Dunne and Leopold, 1978). Harvest of forest resources may affect the magnitude of a snowpack and potentially, the quantity of water available.

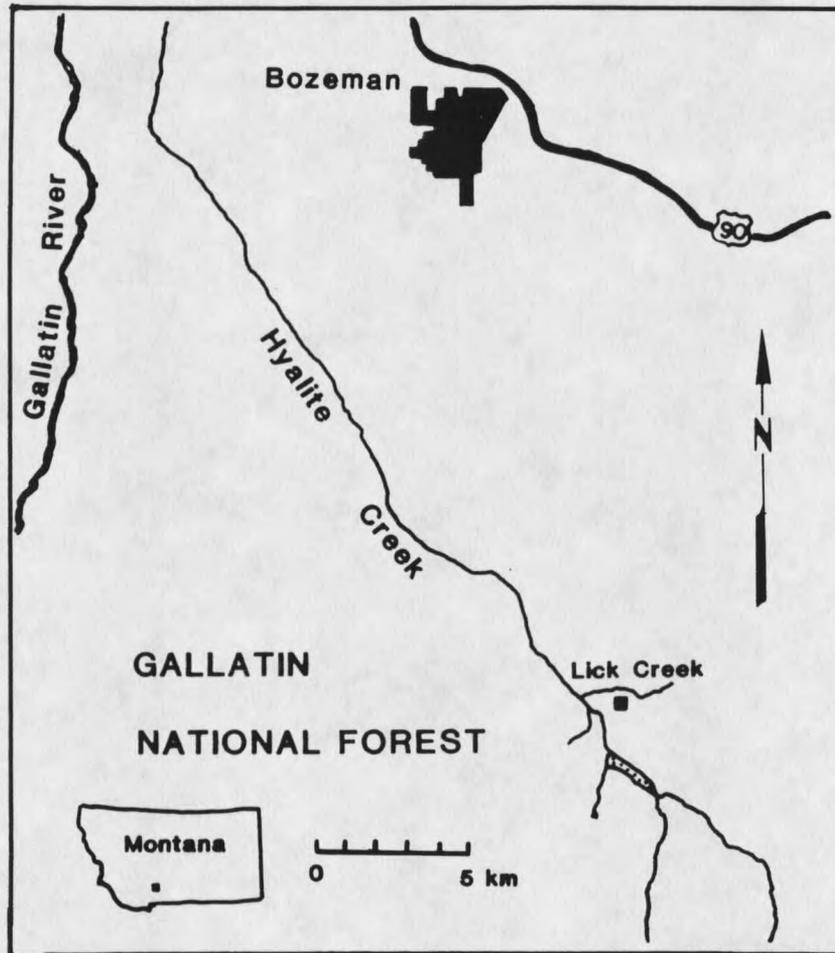


Figure 1. The study area, near Lick Creek, is located within the Hyalite Creek Watershed, 35 km south of Bozeman, Montana.

In many of Montana's watersheds, timber harvesting has occurred in the past and will likely continue into the future. The Gallatin National Forest in southwest Montana is no exception. Therefore, the effects of this timber harvest on the quantity and timing of water available to refill reservoirs is of great importance. According to the U.S. Forest Service (1987), the "water regime for an area harvested by an even-aged management system will generally recover to pre-harvest conditions about 20 years after harvest" (p. IV-41). This research will contribute toward this understanding of the time required, after clearcutting, for the return of pre-harvest snow accumulation and ablation conditions in the Hyalite Creek watershed.

The research presented here provides information, used in conjunction with other data, that allows watershed managers to estimate the extent of snow accumulation and the timing of spring runoff in forests with varying forest structure. The same knowledge may assist watershed managers in decision-making regarding the amount and timing of timber harvest permitted in critical watersheds. This research additionally applies to basic science in that it contributes to the knowledge base concerning the dynamics of snow deposition, movement and accumulation in environments that modify patterns of distribution.

## METHODS

### Site Description

The study area in the Lick Creek drainage (Figure 2), has a mean annual temperature of 2.0°C (U.S. Soil Conservation Service, 1989) and a mean annual precipitation of 89.9 cm (Scaling, 1988). The forests of the Lick Creek drainage represent several stages of timber harvest and subsequent regrowth, thereby providing tree stands of differing canopy density, basal area, ages and heights.

Near the study area, along Lick Creek, is a SNOTEL (snow telemetry) station (elevation 2085 m) maintained since 1960 by the U.S. Soil Conservation Service (SCS) (Figure 2). The SCS snow telemetry system is used to obtain snow water equivalence, precipitation and air temperature measurements from remote locations. The measurements are then transmitted via radio to a computer data base. The Lick Creek SNOTEL station consists of basic climatic instruments including two snow pillows (1.8 and 3.0 meters in diameter) and two thermometers (both are maximum and minimum thermometers with one connected to the telemetry system). The Lick Creek Snow Survey Course is also located at the SNOTEL site.

### Study Plot Descriptions

Four plots in close proximity (within 0.5 km) to the SNOTEL station, were chosen for study (Figure 2). The study plots were selected to maximize variations in forest structure and to minimize variations in slope, aspect and elevation which might influence snow distribution patterns (Toews and Gluns, 1986). Plot A is

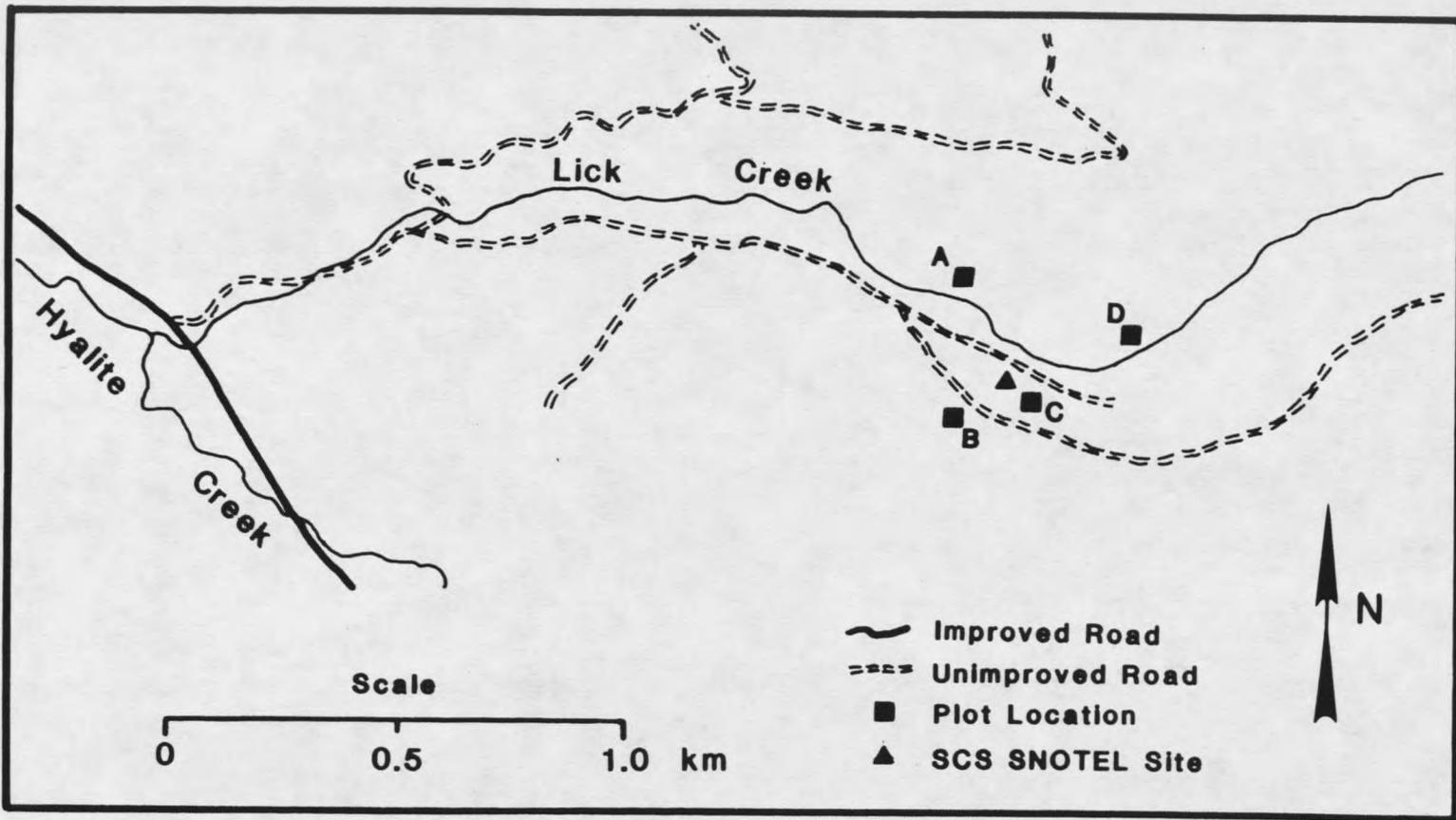


Figure 2. The location of study plots (A, B, C and D) within the Lick Creek drainage.

located 250 meters north to northwest of the SNOTEL site and is an open meadow. The meadow contains two large adjacent lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in the northwest corner of the plot. A mature forest surrounds the meadow. The meadow size, 60 by 65 meters (0.42 hectares), is approximately three times the height of the surrounding trees (3H).

Plot B is within a 19 hectare forest opening located 150 meters to the southwest of the SNOTEL site. The area was clearcut in 1973. Some of the area was replanted in 1981 with two-year-old lodgepole pine seedlings (U.S. Forest Service, 1989). The young trees are now 11-16 years old, one to four meters high, have an average canopy density of six percent (Lemmon, 1957) and a basal area of 2.2 m<sup>2</sup>/ha.

Plot C is located 75 meters to the southeast of the SNOTEL site and is within a lodgepole pine forest (10 hectares in size) undergoing regrowth. The trees of plot C are approximately 35 years old, 10-14 meters high, have an average approximate canopy density of 56% and a basal area of 17.1 m<sup>2</sup>/ha. This area was clearcut in 1950 and later thinned in 1965, allowing for a 2.0 to 3.5 meter average spacing between trees (U.S. Forest Service, 1989). There are no records available that might suggest this stand was replanted, therefore implying natural tree growth initiated in this plot an average of four years after clearing.

Plot D is within a 40 hectare stand, located 300 meters to the northeast of the Lick Creek SNOTEL site. Individual trees in this area were selectively cut in 1953 and replanted in 1964 (U.S. Forest Service, 1989). The plot appears relatively undisturbed, and consists of a mature forest of mixed subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and lodgepole pine. Plot D represents trees with a variety of ages ranging from young saplings to 212 year old

mature trees, heights up to 22 meters, an average canopy density of 85% and a basal area of 36.9 m<sup>2</sup>/ha.

### Site Preparation

Plots at Lick Creek were prepared during the fall of 1988. Data point spacing was chosen based on previous studies, which show point spacings ranged from distances of 10 meters (Gary, 1979; Toews and Gluns, 1986) to 100 meters apart (Daugharty and Dickison, 1982). The majority of the studies reviewed used a spacing of 10-20 meters (Potts, 1984; McGurk and Berg, 1987). At three of the four plots (A, C and D) a random square grid system was established with permanent stakes at nine points 15 meters apart, in a three-by-three matrix with sides oriented north-south and east-west (Figure 3). Limitations in shape and orientation of the fourth plot, B, necessitated a different sampling stake array (Figure 4). In this plot, five points (numbers 1,3,4,8 and 9) were placed 15 meters apart, parallel to the border of the representative area, in a row running approximately 65 degrees east of magnetic north. The remaining four points were placed 15 meters north of the first five points, providing a buffer zone of at least eight meters, or 1H (one times the mean tree height of the surrounding forest), separated the point from the adjacent forest.

Rebar stakes marked all 36 points throughout the study. During the time the ground was snow covered, 1.5 meter, white polyvinyl chloride (PVC) snow stakes also marked the 36 points. A calibrated snowboard was randomly placed half way between stakes five and six in all plots during the 1989 accumulation season to measure snow accumulation at the sites between sampling visits.

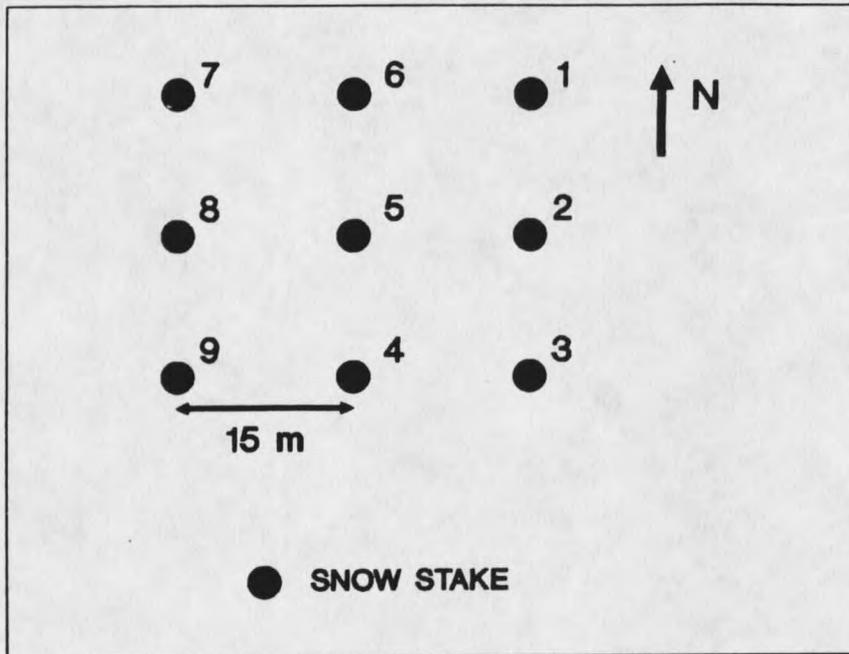


Figure 3. Layout of stakes for plots A, C and D. Each stake was placed 15 meters apart and labeled with a number from one to nine.

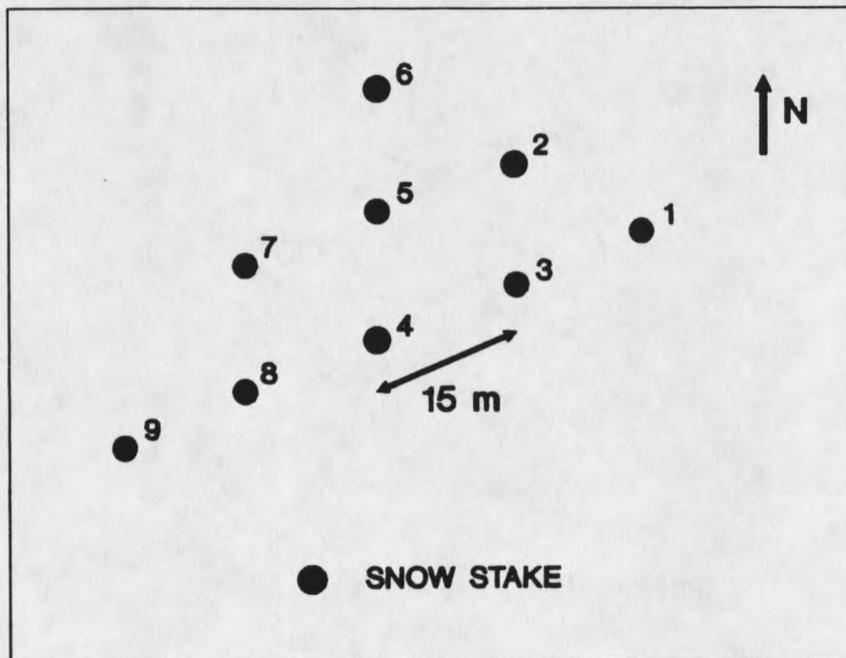


Figure 4. Layout of stakes for plot B. Each stake was placed 15 meters apart and labeled with a number from one to nine.

### Weather Data Collection

Daily weather data from the Lick Creek SNOTEL station was available via computer access from the Soil Conservation Service (SCS) Central Forecasting System in Portland, Oregon. Temperature and snow water equivalence data was obtained from the SCS data base for the two accumulation and ablation seasons of this study. Long-term mean temperature and snow water equivalence summary data was also obtained from the SCS for comparison with the two years of study in 1989 and 1990.

### Forest Studies

During the summer of 1989, characteristics of the forest in plots B, C and D were measured (site A is a meadow and has no trees). The measured characteristics included canopy densities, basal areas, tree ages, tree heights and tree species. The locations and heights of trees outside plots A and B were measured to show the relationships of the surrounding mature forest to each plot (the forests surrounding plots C and D were of similar structure to the forest within the plot boundaries, and therefore were not measured).

#### Canopy Density

The density of the canopy cover or overstory was determined using a densiometer and the method described by Lemmon (1957). Five measurements of canopy density were taken at each snow measurement stake [at the stake, and one meter from the stake in all four compass directions (north, east, south and west)]. The mean of the five measurements was calculated to represent the canopy density at that stake, and the mean canopy density of all the stakes in one plot was calculated to represent the canopy density of that entire plot.

A photo-canopyometer was also used to supplement and compare with the estimation of canopy density as determined by the densiometer. The photo-canopyometer method (Codd, 1959) involved photographing the overstory using a camera, mounted on a tripod at approximately one meter above the ground surface, with a wide angle lens capable of photographing a 90° field of view. The photo negatives were printed on a grid allowing for the calculation of canopy density. For this method, one photograph was taken at each stake in plots B, C and D.

### Basal Area

The basal area representative of each plot was determined to allow better correlation of the results of this study with those of other researchers (Potts, 1984; Ffolliott *et al.*, 1989). In order to calculate basal area, the diameter at breast height (DBH) was measured for each tree within the boundaries of the plot. These diameters at breast height were converted to area measurements and then summed to give the total area occupied by the tree stems. Calculations resulted in a total basal area in m<sup>2</sup>/ha for each plot.

### Tree Age

Two methods were employed to determine the age of the trees within each plot. First, the logging history of the forests at each plot was obtained from both U.S. Forest Service (USFS) records and discussions with USFS personnel in Bozeman, Montana. Second, the tree stem diameter was measured at breast height (DBH) for every tree within the plot boundaries. The sample population of DBH's was then divided into five centimeter classes for each species. For plot D, which has the greatest variability of tree species and age, compared to plots B and C, more extensive sampling was required. In plot D, up to five trees in each DBH class, were cored to determine the age range for that DBH and species. The

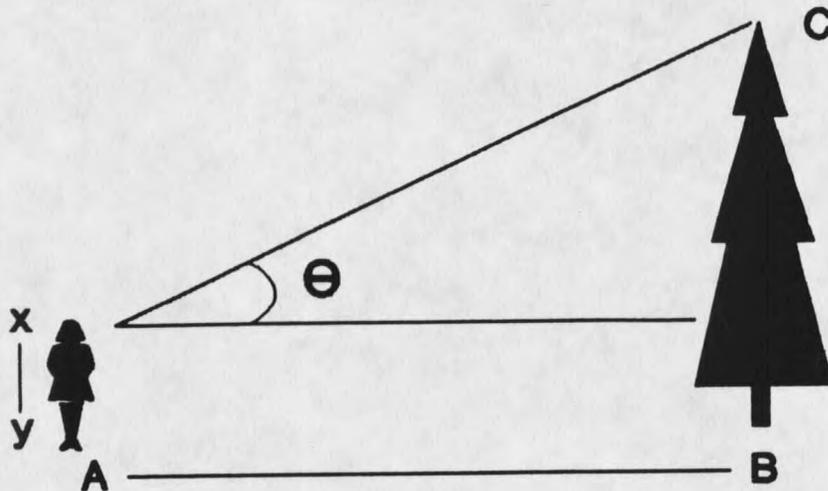
selection of trees to be cored depended on the number of trees within each DBH class. For example, more trees were cored in the 6-10 cm DBH class for fir (of which there were a total of 81 trees available) than in the 21-25 cm DBH class for pine (of which there were only 2 trees available). For plot C, the diameter at breast height (DBH) was determined for each tree within the plot boundaries. Due to the logging history of this plot all trees were similar in age, so as a result, a random sample of ten trees was cored to determine the mean tree age for the plot. Similarly, DBHs were determined for all trees in plot B. Eight larger trees were cored in this plot, while a total of four trees representing the smallest DBHs were cut down (too small to core) from outside the plot, where their absence would not affect snow distribution within the plot. A weighted mean age and range for the trees in each plot were then calculated.

### Tree Heights

Tree heights were determined using field measurements and trigonometric functions (Figure 5). Standing several meters away from the tree, the distance between the observer and tree was measured (line AB). The angle between the observer's eye and the top of the tree ( $\theta$ ) was determined using a Brunton compass. The height from the ground to the observer's eyes (line xy) was measured, and the height of the tree (line BC) was then calculated using standard trigonometry.

Since the heights of the trees vary greatly in plot D, the above described technique was used to measure only a random selection of the tallest trees within the plot (eight trees were measured). A mean tree height in plot D would take into consideration the many young, understory trees that do not contribute significantly, by comparison, to the canopy density of the major overstory within the forest. For plot C, being very uniform in height due to the logging history, heights of eleven,

randomly selected trees were determined. The average of these represented the stand height for plot C. For plot B, the heights of ten trees were measured using a meter stick.



$$BC = AB \tan \Theta + xy$$

Figure 5. Trigonometric method used to determine tree heights in plots C and D.

#### Relationship to Surrounding Forests

Extensive prior documentation indicates that snow accumulation varies with size of the forest opening (Golding and Swanson, 1986; McGurk and Berg, 1987; Troendle *et al.*, 1988). The locations and heights of trees outside plots A and B were measured to determine the relationships of the surrounding forest to the plot. This involved measuring the distance from the stakes defining the plot border to the adjacent forest edge or other definite boundary (i.e. a steep slope). The forests surrounding plots C and D were comparable to the forest within the plots, and therefore, presumably did not influence the snow distribution, so were not measured.

### Winter Data Collection

The "snow season" was the period when the snow pillows at the SNOTEL site had measurable quantities of snow. According to the 25-year record of Lick Creek SNOTEL data, the "snow season" typically lies between October 1st and June 15th (Scaling, 1988). Furthermore, a 25-year summary of the average maximum snow water equivalence (SWE) at the Lick Creek SNOTEL site shows the maximum SWE occurs in early April and the snowpack is completely ablated by mid-June (Scaling, 1988). The date of maximum SWE is the boundary between the accumulation season and the ablation season.

#### Accumulation and Ablation

During the 1988-89 accumulation season (December-March), the study sites were visited once every other week, as long as measurable snow was present. After evaluation of the 1989 data, it was apparent data collection for the 1990 accumulation season could be less frequent. Site visits were reduced to once every 40-45 days in 1990 until the first of April (the time estimated to correspond to maximum snow water equivalence). During the ablation season (April-June 1989 and April 1990), considered a critical time as the snowpack was suspected to change rapidly with decreasing depth, measurements were collected on a weekly basis during both snow ablation seasons.

At each study plot a series of snow depth measurements were taken using a calibrated, one centimeter diameter probe to measure the distance from the surface of the snow to the snow-soil contact. The soil surface was easily detectable with the probe by observing the change in resistance. Four snow depth measurements were taken at all nine stakes, one meter from the stake in each north, east, south and west direction. This gave a total of 36 snow depth measurements in each of

the four plots from which an average depth at each of the nine stakes could be derived.

A U.S. Federal Snow Sampler (USFSS) was also used to collect snow measurements. This device is the most widely employed method of manually obtaining snow density and snow water equivalence (SWE) measurements from a snowpack (Gary, 1979; Golding and Swanson, 1986; Toews and Gluns, 1986). With the snow sampler, five measurements of depth, density and SWE were obtained within each plot. The mean of the five measurements of snow density obtained from the USFSS represented the snow density of the plot. The sampling procedure consisted of taking samples in close proximity (within one meter) to the five stakes according to a pre-established pattern (Figure 6). This pattern minimized the probability of sampling the same place more than once. In the event that no snow existed at the prescribed location, a sample was obtained from nearby, undisturbed snow. The mean density obtained from the USFSS combined with the probed snow depth measurements, allowed a calculation of the total SWE for each stake and each plot. Observations in patterns of densification in the snowpack over time was also possible from this data.

During the 1989 snow season, the depth of new snow since the previous visit was measured on a calibrated snowboard. The snowboards were brushed clean of snow after the measurement was taken and replaced on the new snow surface. Additionally, toward the end of the accumulation season and until the snowpack became isothermal (at 0°C), a snow pit was dug in each plot to expose and study the vertical profile of the entire snowpack. Data collected from the snowpack consisted of temperatures (every ten vertical centimeters) to the nearest degree, using a dial stem thermometer, and density of both the new snow and other stratigraphic layers (using a 200 cc triangular density cutter). This procedure was

used to: 1) confirm the snow depths found using the probe; and 2) observe the temperature gradient and recognize when the snowpack became isothermal.

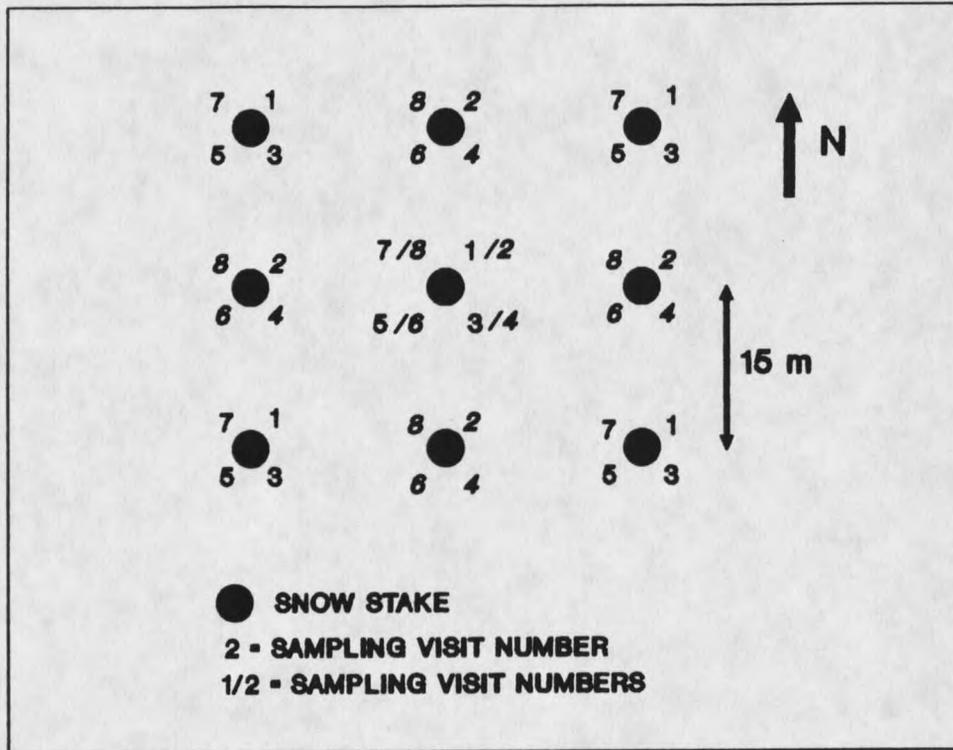


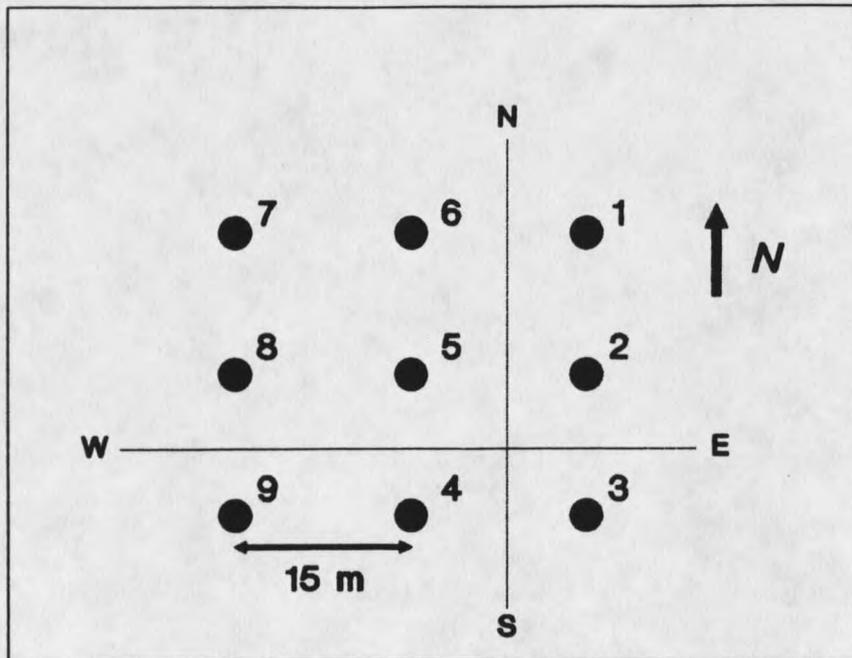
Figure 6. Sampling pattern used with the U.S. Federal Snow Sampler. Each number represents the five sampling locations for a particular visit. For example, on my second visit to the study site, depth, density and SWE measurements with the USFSS were obtained from the five locations marked with the number two.

### Transects

In early April of 1989, two transects (north-south and east-west), established across each plot and into the surrounding forest, facilitated two meter interval measurements of spatial variability of snow depths. The purpose of these measurements was to determine how representative the locations of the chosen plots were relative to the surrounding area, and to determine if individual data collection points (stakes) were statistically independent. To answer these questions,

and due to time constraints at the field site, the depths of snow with the calibrated snow probe, rather than snow water equivalence, were measured in all transects.

In plots B, C and D, the transects were fifty meters long, extending an additional ten meters on either side of the plot into the surrounding forest (Figure 7). However, due to the different arrangement of stakes in plot B, the east-west transect did not extend beyond the plot boundary. In plot A, the meadow, the transects were longer (58 and 78 meters) so as to extend into the surrounding forest. In plots A and B, this transect information was also used to recognize the effects of adjacent larger trees on the distribution of snow in the plot. The forests surrounding plots C and D did not vary from those within the plot, and therefore, it was not necessary to extend the transects further than ten meters beyond the plot boundaries.



**Figure 7.** The location of the April 2, 1989 snow depth transects in plots A, C and D. Snow depths were measured every two meters along the transects. The length of the transects were 50 meters, except in plot A, the transects were 58 and 78 meters long and extended into the surrounding forest.

### Additional Data

In 1989, the SCS conducted monthly snow surveys recording snow depth, density and SWE from January through June at the Lick Creek SNOTEL station. During the 1990 snow season, the SCS only conducted snow surveys from March through June. The SCS data was compared to data of the plots. During each visit observable patterns on the snow surface (i.e. wind scour) or relative to the snow surface and trees (i.e. development of tree wells) were noted. This information aided the interpretation of observed snow distribution patterns.

Since different winters may have yielded significantly varying patterns of accumulation and ablation, observations and data collection at the study site took place over two winters. The methodology for collecting data was derived largely from a variety of studies and is comparable from one year to the next. This similarity allows maximum comparison of results with other studies. Additional snow data for the 1989 and 1990 snow seasons, which is not specifically discussed in the results, is included in the appendix. All raw data collected during both snow seasons is on file in the Department of Earth Sciences at Montana State University.

## RESULTS AND DISCUSSION

### Weather Conditions

#### 1989 and 1990 Snow Seasons

Mean monthly air temperatures at the Lick Creek SNOTEL station, during the 1989 snow season (October 1 through June 15; Scaling, 1988), when compared with the 8-year average (Figure 8), were higher than average during October and November, and near average during December and early January. By mid-January, air temperatures fell below normal, associated with a southward shift in the jet stream which brought cold, arctic air into the region and produced a strong and persistent high pressure system in the area. February's mean air temperatures was 7° C below average. March and the entire ablation season (April through May) of 1989 was characterized by temperatures lower than the 8-year average.

Mean monthly temperatures during the 1990 snow season, when compared with the 8-year average (Figure 8), at Lick Creek were near average during early October followed by consistently higher than average temperatures from mid-October through mid-February. Temperatures remained near average from late February through the rest of the recorded snow season (April 25).

Observed patterns in accumulated snow water equivalence (SWE) at the Lick Creek SNOTEL site (Figure 9), for the 1989 snow season, include a later than average (25-year average) start of the accumulation season (by early November rather than mid-October). The snow water equivalence remained consistently below average for the entire snow season. A slightly earlier than average peak in SWE occurred during April 3-5. The snowpack on the SNOTEL snow pillow was

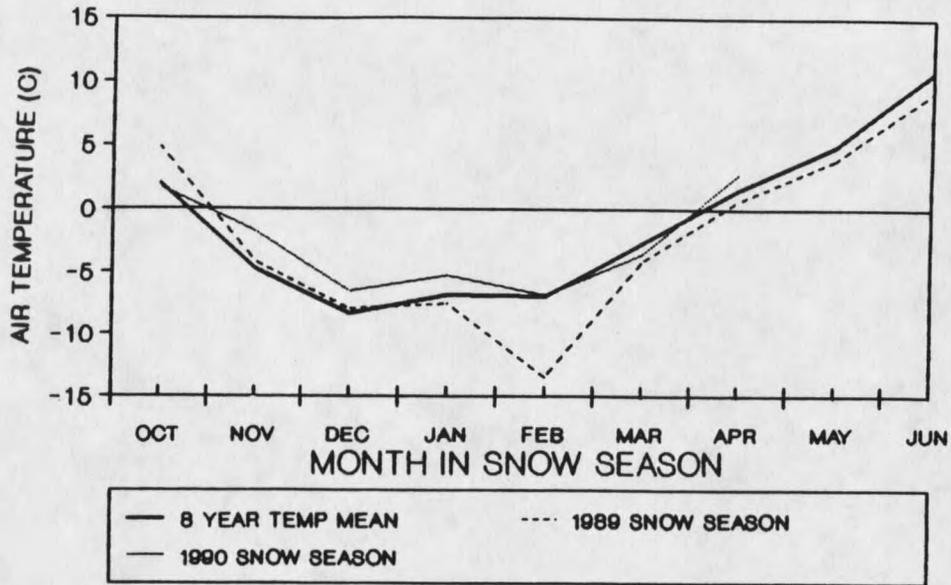


Figure 8. Mean monthly air temperatures from the Lick Creek SNOTEL site for the 8-year mean and the 1989 and 1990 snow seasons. Note the contrasting February temperatures in 1989 and 1990, as compared to the mean.

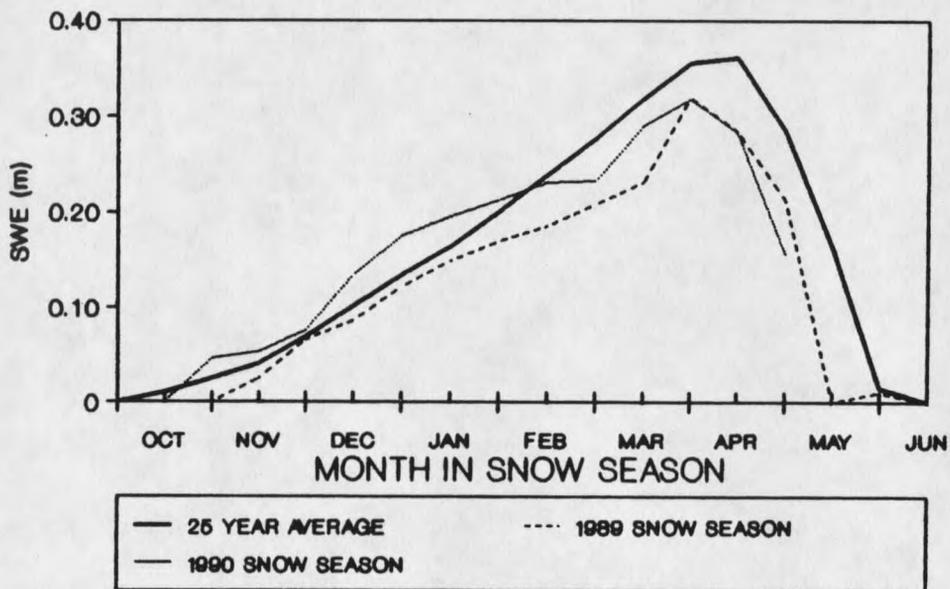


Figure 9. Mean monthly snow water equivalence (SWE) from the Lick Creek SNOTEL site for the 25-year mean and the 1989 and 1990 snow seasons.

completely ablated by May 15th, although, a few low intensity snow storms brought measurable quantities of snow to the pillow site after mid-May.

Precipitation patterns during the 1990 snow season (Figure 9) include an initial accumulation of snow in mid-October (similar to the 25-year average) and a consistently greater than average SWE for the months of October through mid-February. In mid-February, the SWE dropped and remained below the mean throughout the remainder of the data collection period (April 25). Peak SWE was recorded on the snow pillow on March 31, 1990.

### Comparison of the Two Snow Seasons

The deviation from the 8-year, mean monthly air temperature during both snow seasons allows comparison between the two years (Figure 10). During both snow seasons, the mean monthly temperatures were above average throughout mid-December, at which point, the 1989 temperatures dropped well below average, deviating as much as  $-7.0^{\circ}$  C in mid-February. Below average temperatures persisted for the rest of the 1989 snow season. Conversely, mean monthly air temperatures during the 1990 snow season stayed above average through mid-February, with deviations as great as  $+3.0^{\circ}$  C (in mid-November). Temperatures were slightly below average until early April when they again rose to above average for the remainder of the data collection period (through April 25). This resulted in two contrasting January to March temperature patterns for the two years, and generally higher temperatures from November through April for 1990.

The departure from the 25-year mean SWE at the SNOTEL site during both snow seasons allows comparison of SWE between the two snow seasons (Figure 11). In general, SWE during the 1989 snow season stayed consistently below the mean SWE, with the greatest deviations from the mean in early March ( $-0.07$  m)

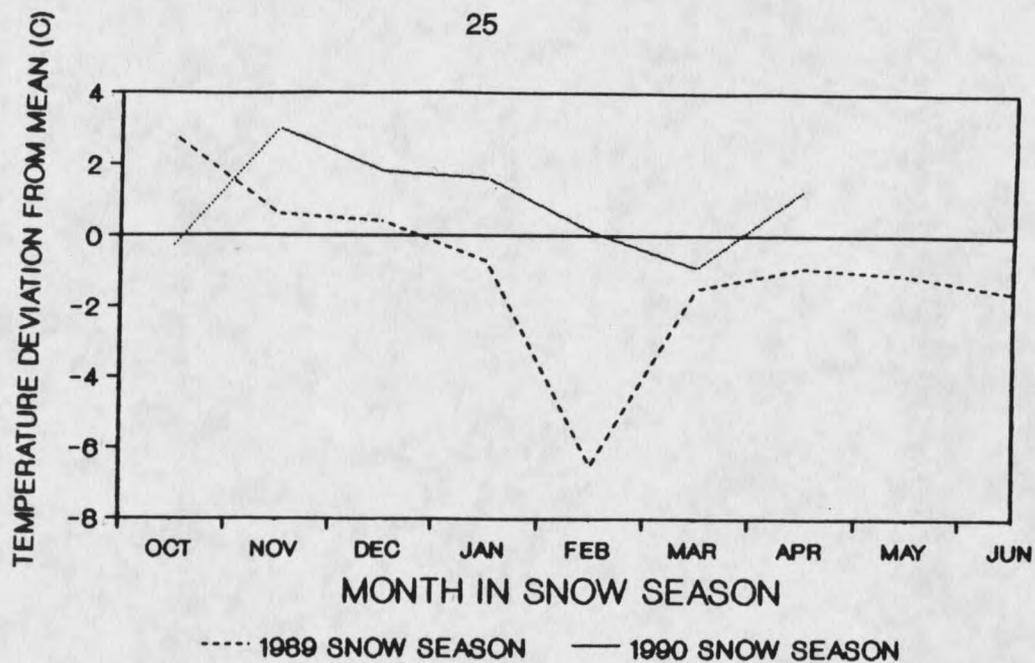


Figure 10. Air temperature deviations from the 8-year mean during the 1989 and 1990 snow season.

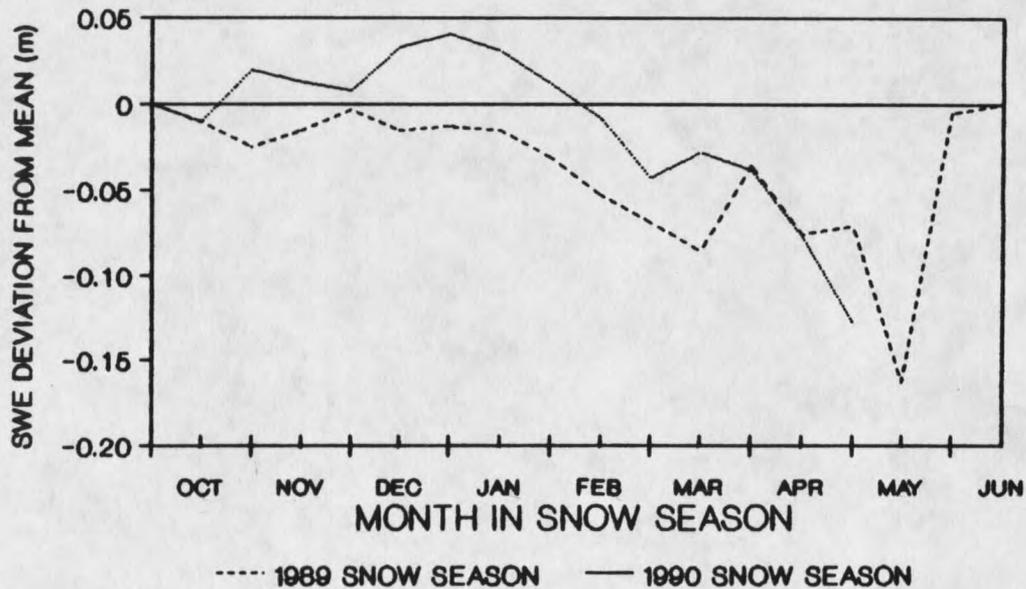


Figure 11. Snow water equivalence deviations from the 25-year mean during the 1989 and 1990 snow season.

and mid-May (-0.16 m). In contrast, snow water equivalence deviations during the 1990 snow season were positive through early February, peaking at +0.04 m in early January. By mid-February, deviations from the mean increased to a low of -0.13 m by April 25th. Near the time of maximum accumulation for both snow seasons (April 1st), the negative deviations from the mean were nearly identical (1989, -0.036 m; and 1990, -0.038 m). In general, ablation at Lick Creek occurred more rapidly in the 1989 and 1990 (until April 25) snow seasons due primarily to the lower accumulation of SWE, as compared with an average spring with wetter weather.

### Forest Comparisons

Detailed observations of the forest stand characteristics permitted the development of a measure of canopy density, basal area, tree age, tree height and tree species for each plot (Table 1). The characteristics were combined to allow discussion of the plots in terms of their general forest structure (primarily canopy density and basal area, but including tree age and height). Forest structure has been defined as the distribution and representation of age, size (particularly diameter), crown and/or other tree classes (Ford-Robertson, 1971). For the purpose of this study, a low forest structure refers to a forest with low canopy density (approximately 0-20%), low basal area (0-10 m<sup>2</sup>/ha), young trees (0-15 years) and heights less than five meters. An intermediate forest structure refers to a forest with a canopy density of approximately 20-60%, a basal area of 10-25 m<sup>2</sup>/ha, tree ages between 20 and 60 years and tree heights 10-15 m tall. Consequently, a high or full forest structure refers to a mature forest with a canopy density greater than 60%, a basal area greater than 25 m<sup>2</sup>/ha, a variety of tree ages ranging from saplings to 212 years and tree heights up to 26 m tall.

**Table 1. CANOPY DENSITY, BASAL AREA AND TREE AGE, HEIGHTS AND SPECIES FOR PLOTS B, C AND D. Tree species included are lodgepole pine (pine), subalpine fir (fir) and Engelmann spruce (spruce).**

SITE	MEAN CANOPY DENSITY (%)			TREE AGE (years)	
	Densio-meter	Photo-canopy-ometer	BASAL AREA (m <sup>2</sup> /ha)	Mean	S.D.
B	5.6	9.7	2.2	13.4	2.7
C	56.4	60.8	17.1	35.3	2.4
D	84.5	80.2	36.9	78.6	15.3

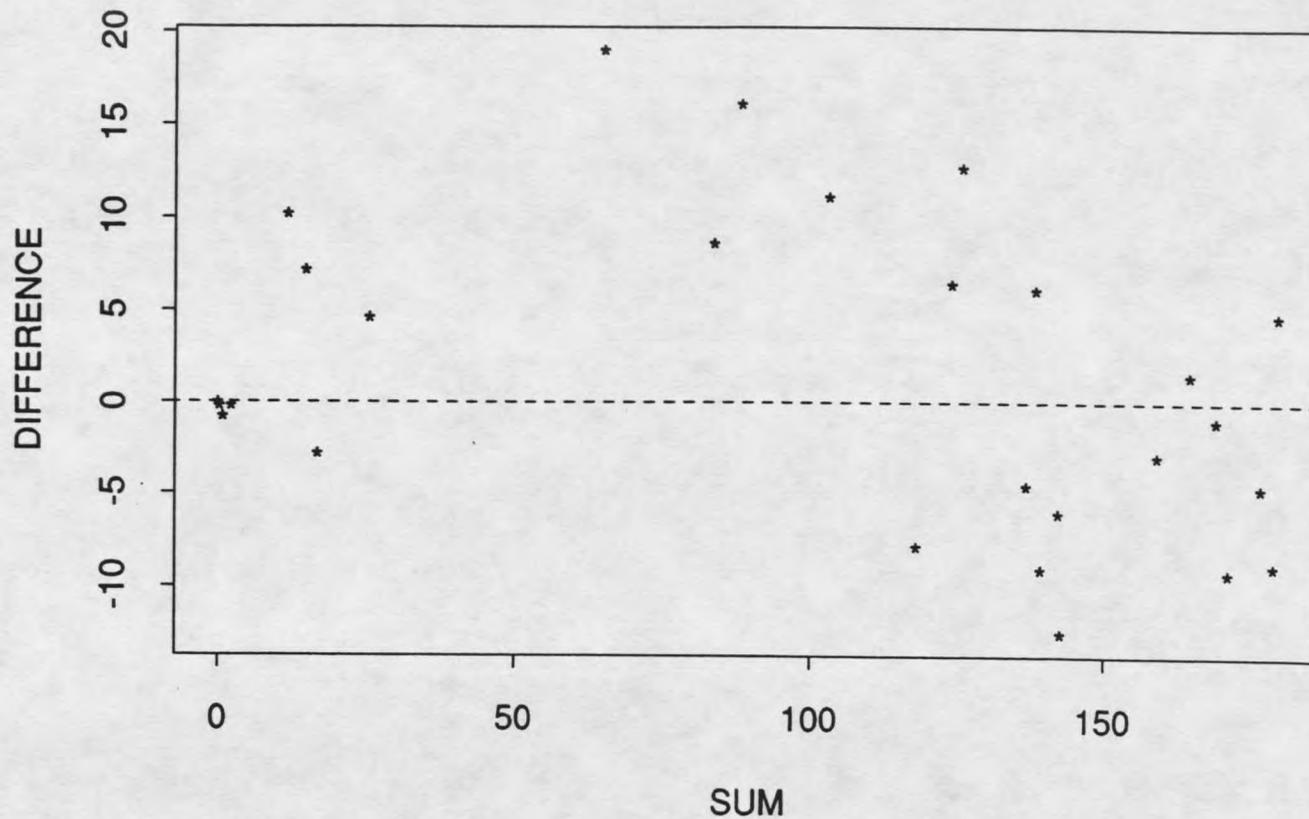
SITE	TREE HEIGHTS		TREE SPECIES		
	Mean (m)	Range (m)	Pine (%)	Fir (%)	Spruce (%)
B	2.5	0.5-4.0	100	0	0
C	12.3	10.4-14.0	86	14	0
D	22.3*	18.6-25.6*	2	79	19

S.D. = Standard Deviation

\* Height measurements are maximum heights.

### Canopy Density Comparisons

The two methods used to obtain a percent canopy density (densiometer and photo-canopyometer) were evaluated to determine how they compared. When measured with a photo-canopyometer, plots B and C showed higher percent canopy densities, and plot D, a lower canopy density (Table 1). This tendency is confirmed by the Tukey sum-difference graph (Figure 12) which assumes the expected values for canopy density derived from the two methods are equivalent, and compares the two methods by looking at the residuals from the expected values (Cleveland, 1985). The x-axis of the graph is the sum of the two canopy densities at each stake while the y-axis of the graph is the difference between the two densities



**Figure 12.** Tukey sum-difference plot of canopy density as determined using the densiometer and the photo-canopyometer. This graph plots the residuals of two independent variables (canopy density as determined by the two methods). The graph displays a pattern in the residuals such that at low to intermediate canopy densities (sum 0-120), the densiometer results in lower than expected values of canopy density, while at high canopies (sum > 120), the densiometer results in higher than expected values relative to the photo-canopyometer.

(photo-canopyometer minus densiometer). The Tukey plot displays a pattern in the residuals which suggests at low to intermediate canopy densities (a sum less than 120), the densiometer results in lower than expected values of canopy density, while at high canopies, the densiometer results in higher than expected values when compared to the photo-canopyometer. The densiometer calculations of canopy density are the mean of five measurements, four of which were taken from the snow sampling points. Because the sampling points of the densiometer were the same as the snow measurement points, the densiometer data was used in all further statistical analysis.

### Forest Structure

Plot A, although a meadow representing a treeless area, contains two logdepole pines inside the plot boundaries, 5.1 and 4.5 meters to the south to southeast of stake seven (Figure 3). These two trees therefore, affect the snow distribution at stake seven. When their combined canopy density (13%) was averaged over the entire plot's canopy density (1.4%) the effect of their presence was negligible. For this reason, the trees were ignored in terms of forest structure descriptions. The trees surrounding plot A are approximately 20.8 m tall, (the dimensions of the meadow are approximately 66 m east-west by 60 m north-south). Thus plot A is an opening approximately three times the height of the surrounding trees (3H).

A comparison of the values of canopy density, as determined by the densiometer, and basal area for plots B, C and D (Figure 13), shows that the plot with lowest canopy density corresponds to the plot with the lowest basal area, as found in the youngest forest (plot B). Plot C exemplifies an intermediate growth structure with an intermediate canopy density and basal area. Forests with the highest canopy density correspond to the highest basal area, as in the mature forest

(plot D). Plots B and C are both regrowth forests following timber harvest, and therefore, their forest structure is more consistent (less obvious variability) than the mature forest (plot D) (Table 1). For plots B and C, the standard deviation of tree age is quite low (2.4 and 2.7 years) compared to plot D (15.3 years). The large range in tree ages, and therefore, in tree heights, and the resultant high standard deviation is expected for an undisturbed, mature forest.

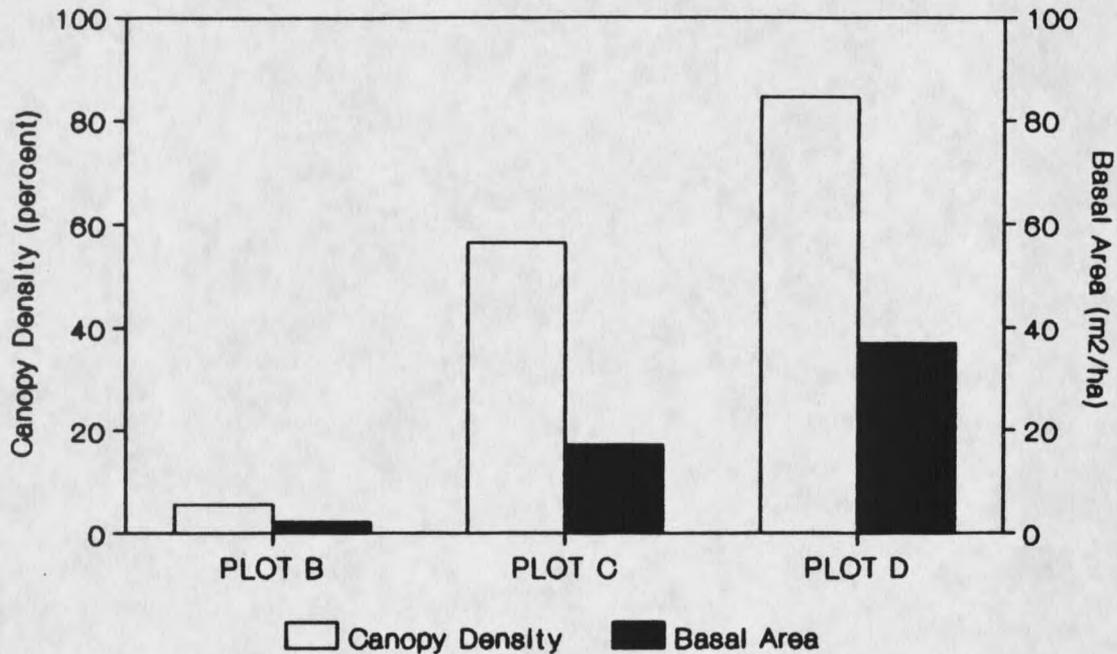


Figure 13. Histogram comparing canopy density and basal area for plots B, C and D.

Plot B is comprised solely of lodgepole pine trees, with low lying debris from past timber harvest activity (i.e. felled logs and remnant, slash burn). Plot C is predominantly (86%) lodgepole pine [diameter at breast heights (DBHs) between 0.15-0.25 m] with only 14% subalpine fir (representing the smallest trees with DBH's < 0.05 m). These fir do not contribute significantly to the overstory canopy density. The greater variety of tree species and near absence of lodgepole pine (only 2%) in plot D is typical of an undisturbed, mature forest with a high percent canopy density,

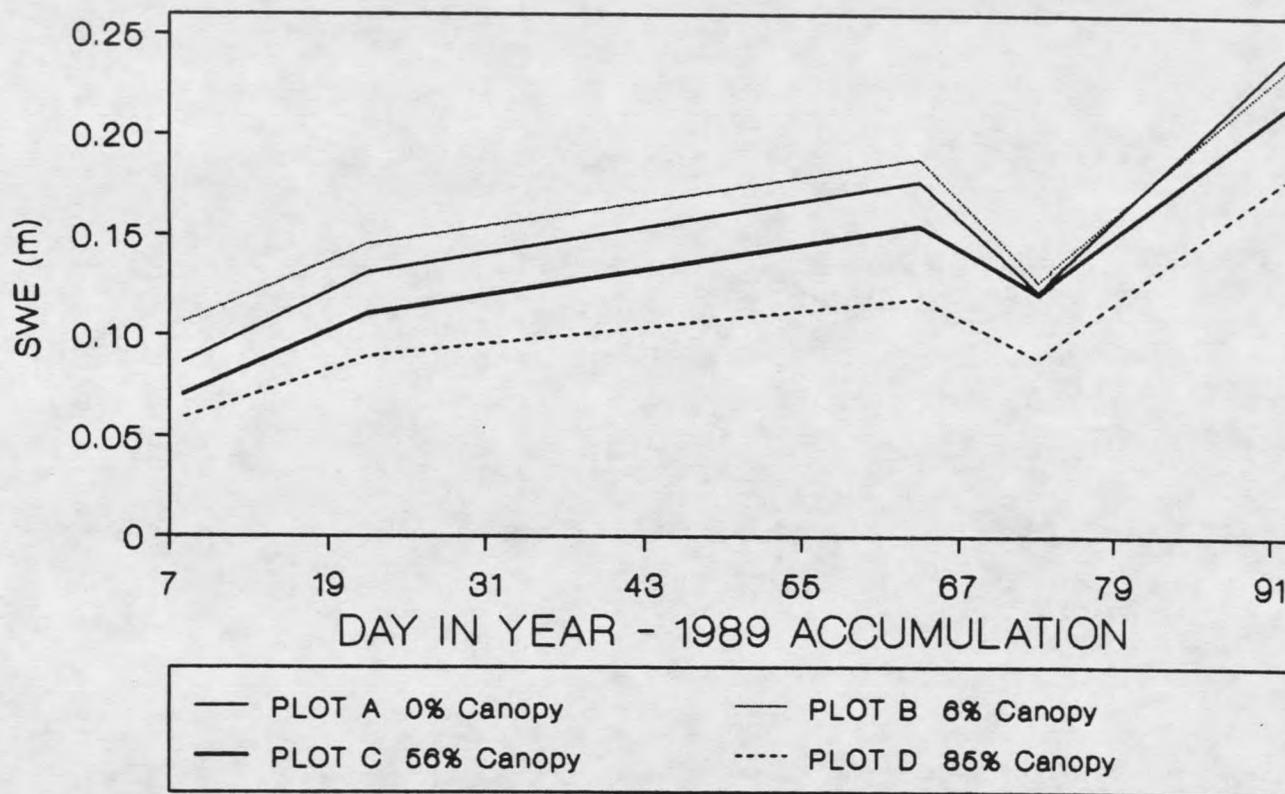
shading out the fairly shade intolerant species (Pfister et al., 1977).

### Snow Accumulation

#### The 1989 Snow Season

The patterns of snow accumulation, during the 1989 season, in forests of varying structures, are evident when snow water equivalence data in the four plots is superimposed (Figure 14). The comparison of the four plots of varying forest structure begins in January and continues until early April. A data gap exists in the collection of snow water equivalence data between January 22nd (day 22) and March 5th (day 64) due to the extreme cold and relatively difficult field-site access during that time. Only snow depth measurements were obtained on February 20th (day 52). For much of the accumulation season (from January through mid-March; day 8 to 80) plot B with the low forest structure had the greatest SWE. The meadow (plot A) followed second during this time period, in terms of the amount of SWE accumulated. The intermediate forest (plot C) had the third most SWE, and finally the mature forest (plot D) had the least amount of SWE. However, by mid-March (approximately day 80) until the period of maximum SWE (early April; day 92), the pattern changed such that the SWE of the meadow (plot A) equaled and exceeded that of the young tree plot (plot B). This produced a relationship corresponding to a decline in SWE with an increase in forest structure (canopy density, basal area and tree ages).

This change in SWE pattern probably resulted from the late season storms that brought the SWE closer to the average at the SNOTEL site from mid-March to early April (Figure 9). Typically, late season storms are associated with higher



**Figure 14.** Snow water equivalence for all plots during the 1989 snow accumulation season. The data point locations can be identified by the break in the slope of the lines. The data collection for the snow accumulation season began on January 8th and continued until the time of maximum accumulation, April 2nd (day 92). Note that at the time of maximum accumulation, the plot with the least forest structure had the greatest accumulation (plot A), and less accumulation was observed under forests with greater structures (plots B, C and D).

temperatures and more moisture, depositing snow with a higher density than the lower temperature and drier mid-winter storms. This higher density snow is often less vulnerable to redistribution by wind, suggesting that much of the snow deposited in the meadow plot (plot A), free from canopy interception, was not redistributed by wind. Also because of the nature of the lodgepole pine needles (long and widely spaced at their ends), snow landing on these needles covers a larger surface area and is more vulnerable to sublimation, evaporation and wind redistribution compared to snow which lands directly on the snow surface. Because of this needle structure, the snow intercepted by the young trees in plots B was potentially more vulnerable to sublimation and evaporation (especially during the warmer months) and was more exposed to wind redeposition (being suspended in the aerial environment), which resulted in less snow on the ground at the time of maximum accumulation than in plot A. In 1989, the higher amounts of precipitation just prior to maximum accumulation, bringing the SWE closer to the 25-year average (Figure 9), likely contributed positively to greater accumulations in the meadow (plot A) while interception and redeposition played a more important role in the plots with trees.

#### Distribution of Maximum Snow Accumulation In Plots

The time of maximum accumulation (marking the end of the accumulation season and the start of the ablation season) in all plots, for the 1989 snow season was approximately April 2, 1989, as determined during the weekly sampling intervals. This date of maximum accumulation coincides with that recorded at the Lick Creek SNOTEL site (April 3-5, 1989) (Figure 9). The amount of snow at the time or period of peak snow accumulation in SWE is the most important criterion in estimating the potential volume of water available for snowmelt runoff.

The pattern of maximum snow depth accumulation in the plots of varying forest structures indicates a decrease in mean snow depth with an increase in forest structure (Table 2). The greatest snow depths were found in the meadow with no trees. The lowest snow depths were found in the forest with the highest forest structure (plot D). The depths of snow in plots B and C were very similar, while the depths in plots A and D represented the extreme accumulations, with plot A having the greatest accumulation and plot D having the least. As other researchers have noted (Gary, 1979; Kolesov, 1985), the forest canopy intercepts the falling snow and results in less accumulation on the forest floor. This intercepted snow is then vulnerable to being redistributed by wind and/or sublimation affecting accumulations in the forest.

**Table 2. MEAN SNOW DEPTH, MEAN DENSITY AND MEAN SNOW WATER EQUIVALENCE FOR APRIL 2, 1989.** Snow depths are the average of 36 measurements per plot. Densities are the average of 5 measurements per plot using the U.S. Federal Snow Sampler. The SWE is the product of the mean snow depth (m) and density ( $\text{g}/\text{cm}^3$ ).

SITE	Mean Depth (m)	Mean Density ( $\text{kg}/\text{m}^3$ )	SWE (m)
A	0.846	283	0.239
B	0.809	288	0.233
C	0.806	266	0.214
D	0.699	255	0.178

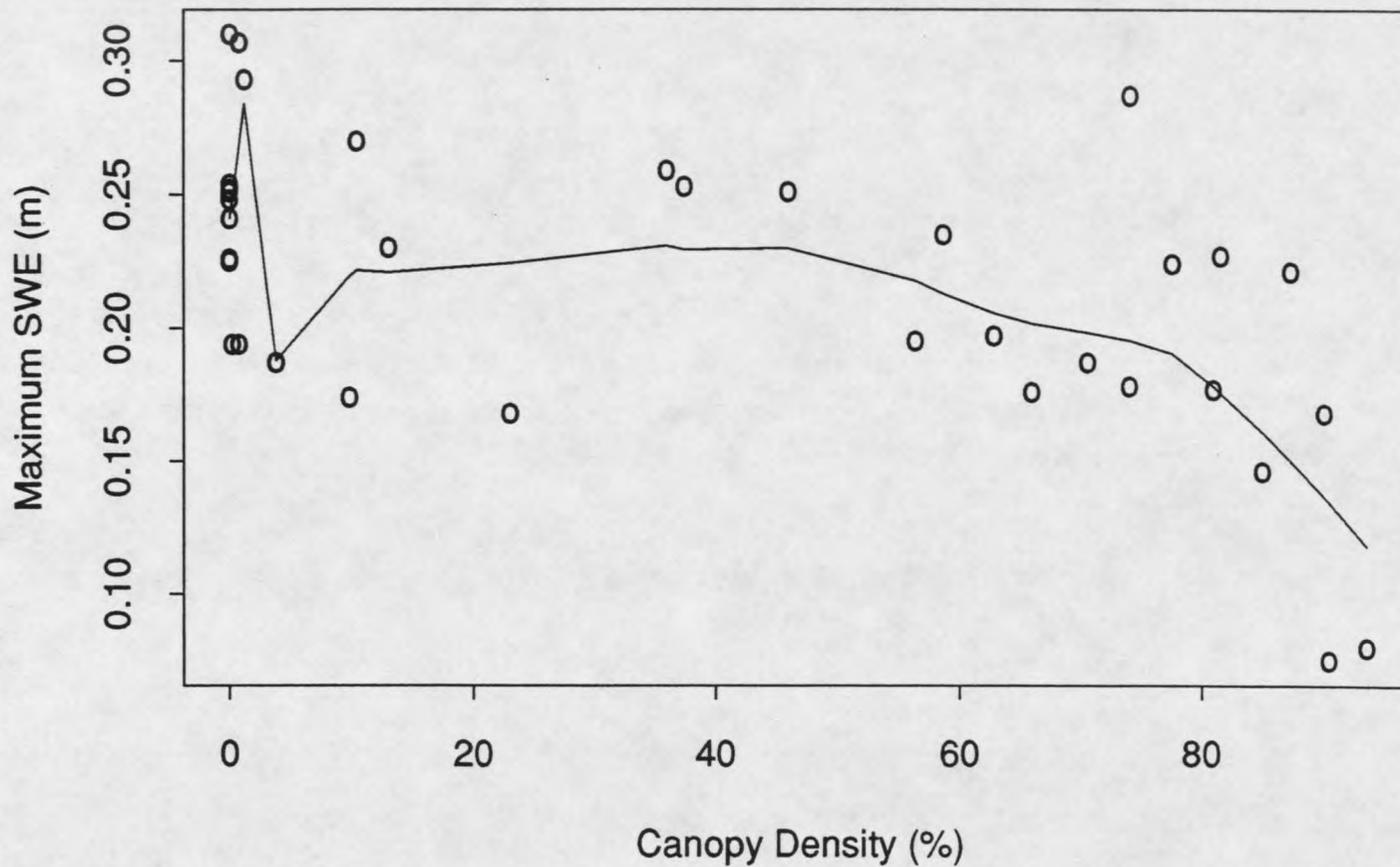
A similar, inverse pattern existed between plots when comparing snow density (Table 2) on April 2, 1989. In general, an increase in forest structure correlated ( $r^2 = -0.96$ ) with a decrease in snow density (regression was calculated

using the mean canopy density and mean snow density for each plot on April 2nd, giving a total of four points). Although the difference is small ( $5 \text{ kg/m}^3$ ), an exception exists in plots A and B, where the snow density was higher in the plot with a low structured forest than in the meadow with no trees. The lower snow densities, as observed in plots C and D, suggest that the higher forest structure in these plots contributed to a reduction in solar transmissivities (i.e., increased shading) and less wind-induced redistribution. These factors probably reduced the effects of these processes on snow metamorphism (crystal changes, melt-freeze and settling), and therefore, on snow density. Additionally, the greater wind velocities in the plots with few or no trees (plots A and B), favor the deposition of wind blown snow, which has a higher initial density, compared to the reduced surface wind velocities in plots C and D with the higher forest structure.

The effect that snow depth and density have on snow water equivalence becomes apparent when values are compared between plots A and B (Table 2). Although, the depth of snow in plot A exceeded that of plot B by 4.6% (0.037 m), the snow density of plot A was slightly less than that of plot B by 1.7% ( $5 \text{ kg/m}^3$ ). The resultant difference in SWE between the plots is only 2.6% (0.006 m) because the lower density snowpack in plot A significantly reduced the snow water equivalence. The mean maximum SWE accumulated in each plot also corresponded to forest structure showing an inverse relationship between mean maximum SWE and forest structure.

#### Statistical Significance of Accumulation Results

The Pearson's product moment correlation was used to test the relationship between maximum SWE, as observed on April 2, 1989, and percent canopy density (Figure 15). The Pearson's coefficient is an indicator of the strength of a



**Figure 15.** Scatter plot of canopy density and maximum snow water equivalence (SWE) with a lowess smooth, for the 1989 snow season. A good negative correlation exists between canopy density and maximum SWE (correlation coefficient = -0.54;  $p$ -value  $< 10^{-4}$ ). The lowess curve was computed with a smoothness parameter of  $f=0.4$ .

relationship between two variables, such that a coefficient of -1 indicates a perfect negative correlation where the increase in one variable results in the decrease of the other (Barber, 1988). In this study, the Pearson's correlation coefficient was used for all subsequent correlations. The relationship between canopy density and maximum SWE indicates a significant negative correlation (correlation coefficient = -0.5426; p-value <  $10^{-4}$ ). Since canopy density was found to be proportional to basal area (Figure 13), the results reported by Ffolliott *et al.* (1989) are confirmed. Snowpack SWE at the time of peak seasonal accumulation is inversely proportional to basal area.

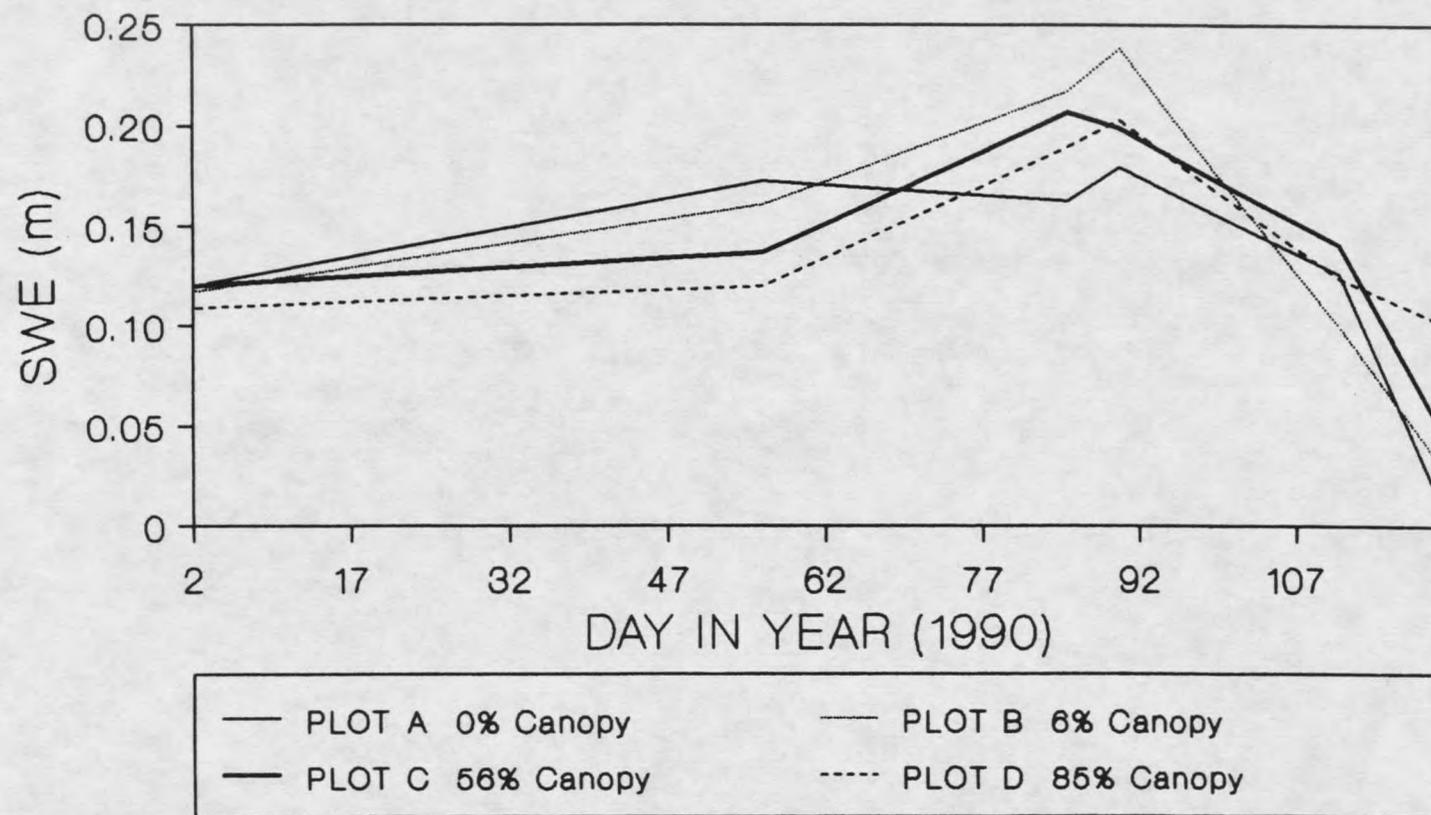
A similar relationship was observed (Figure 15) when the data was smoothed as in a moving average and a non-parametric regression curve was computed (the nature of the population distribution is not assumed; Barber, 1988). An f-value of 0.4, which represents the sensitivity of the smoothing function to the points (a decrease in the f-value results in a increase in sensitivity to the points), was used by the lowess function (Cleveland, 1985) in the statistical programming environment "S" (Becker *et al.*, 1988). At low canopy density, the fluctuations in the curve are likely due to the many points represented by a zero percent canopy density. The data points at low canopy densities are from plots A and B, therefore the wide range of maximum SWE values may also result from the influence of the surrounding forests on snow redistribution at the sample points. The slope of the curve between approximately 10 and 55 percent canopy density is quite shallow, suggesting that the extent of maximum SWE is not greatly influenced by these low and intermediate canopy densities. The significance of this relationship becomes more apparent in the trend of the curve in areas of intermediate to high percent canopy densities. A relatively sharp break in the slope of the curve at approximately 75-80 percent canopy density suggests that a forest structure with a

canopy density at these high percentages will result in a greater reduction in maximum snow accumulation. Although, the strength and reliability of the statistical tests are only as good as the extent of the sample size, these results confirm the hypothesis that maximum snow accumulation (SWE) is inversely related to forest structure (canopy density and basal area).

### The 1990 Snow Season

The snow water equivalence in the four plots, for the data collection period during the 1990 snow season (January through late April), revealed a different pattern than observed during 1989 (Figure 16). The time of maximum accumulation as recorded at the SNOTEL site and at plots A, B and D for the 1990 snow season was March 31, 1990 (Table 3), while in plot C, maximum accumulation occurred on March 25th. In comparing the snow depth, density and SWE on March 31st (day 90), the pattern among the plots was less well defined than during 1989. Plot B, with the low forest structure, accumulated the lowest snow depth of all plots, but had the highest SWE. The mature forest had the second highest SWE on March 31st. The plot with the greatest snow depth (plot C) had a SWE greater only than plot A. Surprisingly, on March 31st, the meadow (plot A) had the lowest SWE of all plots while the snow depth here was the second highest. This result reinforces that snow density, along with snow depth, is an important indicator of snow water equivalence.

The relationship between maximum accumulated SWE and canopy density for 1990 is illustrated through a statistical analysis (correlation coefficient = -0.1444; p-value = 0.4008). This correlation indicates a poor, negative relationship between an increase in canopy density and a decrease in maximum accumulation. Additionally, by plotting canopy density against maximum accumulated SWE and



**Figure 16.** Snow water equivalence for all plots during the 1990 data collection period (January 2nd, day 2 through April 21st, day 111). The data point locations can be identified by the break in the slope of the lines. At the time of maximum accumulation (SWE) on March 31, 1990 (day 90), plot B had the most SWE followed by plot D, plot C and finally, plot A accumulated the least SWE.

adding a lowess smooth ( $f=0.4$ ) (Figure 17), the curve shows no obvious relationship between the variables. At low canopy densities, the fluctuations in the curve are extreme, while the slope of the curve remains relatively flat throughout the intermediate and high canopy densities.

**Table 3. SNOW DEPTH, SNOW DENSITY AND SNOW WATER EQUIVALENCE IN ALL PLOTS FOR THE ENTIRE 1990 SNOW SEASON. The values in bold type are at the time of maximum accumulation (SWE).**

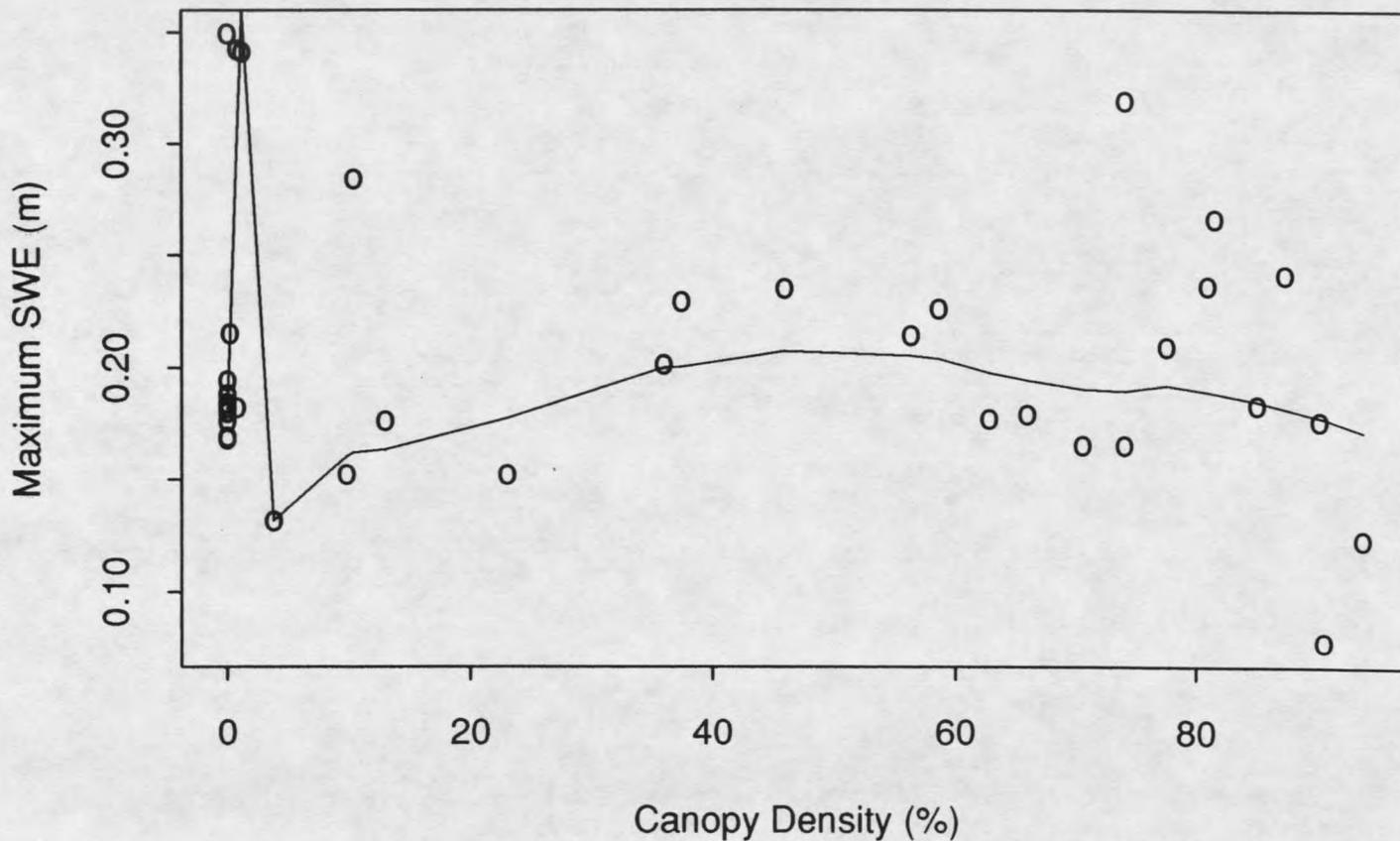
DATE	Depth (m)	PLOT A		Depth (m)	PLOT B	
		Density (kg/m <sup>3</sup> )	SWE (m)		Density (kg/m <sup>3</sup> )	SWE (m)
2 Jan.	0.817	147	0.120	0.778	151	0.117
25 Feb.	0.647	267	0.173	0.594	272	0.161
25 Mar.	0.794	205	0.163	0.742	292	0.217
31 Mar.	<b>0.663</b>	<b>271</b>	<b>0.180</b>	<b>0.616</b>	<b>387</b>	<b>0.238</b>
11 Apr.	0.331	382	0.126	0.284	353	0.100
21 Apr.	0.016	416	0.007	0.066	418	0.028

DATE	Depth (m)	PLOT C		Depth (m)	PLOT D	
		Density (kg/m <sup>3</sup> )	SWE (m)		Density (kg/m <sup>3</sup> )	SWE (m)
2 Jan.	0.558	215	0.120	0.554	196	0.109
25 Feb.	0.545	251	0.137	0.499	241	0.120
25 Mar.	0.728	285	0.207	0.708	269	0.190
31 Mar.	0.668	298	0.199	0.623	326	0.203
11 Apr.	0.483	291	0.141	0.429	288	0.124
21 Apr.	0.142	314	0.045	0.292	345	0.101

#### 1989 and 1990 Accumulation Seasons Compared

Results from the 1989 data, at the time of maximum SWE, showed an increase in forest structure corresponding to a decrease in maximum snow accumulation (Figure 14). A similar relationship was not observed at the time of maximum accumulation in 1990 (Figure 16). The lack of a strong relationship



**Figure 17.** Scatter plot of percent canopy density and maximum snow water equivalence (SWE) with a lowess smooth, for the 1990 snow season. A poor negative correlation exists between canopy density and maximum SWE (correlation coefficient = -0.14; p-value = 0.4008). The lowess curve was computed with a smoothness parameter of  $f=0.4$ .

between forest structure and maximum accumulated SWE, during 1990, is likely a result of three factors. First, the possibility exists that the 1990 data represents the real situation, showing that there is not a strong relationship between the variables. Second, during the 1990 accumulation season, daily SWE data recorded on the SNOTEL pillow as obtained via computer, revealed seven episodes, from November 1, 1989 to March 31, 1990, in which the measured SWE decreased. These periods of ablation, during the accumulation season, presumably had their greatest affect on snow accumulation in the meadow plot due to the lack of protective shading from the overstory. The stratigraphy of the snowpack in the meadow, during March, showed several thin radiation crusts buried beneath the snow surface, confirming the likelihood of intermittent ablation periods. Conversely, during the 1989 snow accumulation period, only one minor (0.003 m) episode of ablation was recorded.

Finally, the accuracy of the density measurements obtained in plot A during March 1990 are in question. During March, a snow pit dug in the meadow (plot A) revealed a top and bottom stratigraphic layer of cohesive, small grained crystals with 0.1 m of loosely consolidated, large grained crystals between the cohesive layers. This situation may result in erroneous measurements by the Federal Snow Sampler. The loosely packed snow can be pushed aside by the snow tube and therefore, would not be considered in the measurement (Gray and Male, 1981). The difficulty in obtaining accurate density measurements was unique to the 1990 snow season and was probably not a significant factor in the 1989 measurements.

#### April 2, 1989 Transects

##### Transect Data

The purpose of the transects was to observe the variability of snow distribution within and adjacent to each plot, and to test for statistical independence

between stakes. Specific questions to be addressed included: 1. Does the variability of snow distribution vary among plots with different forest structure? and 2. Do the snow stakes, 15 meters apart, represent spatial, statistically independent points so that statistical methods can be conducted with the data? Although SWE was not measured across the transect, the usual five measurements of snow density were taken with the USFSS, at the pre-determined location within each plot (Figure 6). This density data was used to determine the mean SWE of the plots from the transect data (Table 4). As later discussed in detail, an observed decrease in snow density was associated with an increase in canopy density, and therefore, could allow for extrapolation of approximate SWE values from forests outside the plot boundaries.

**Table 4.** MEAN DEPTH, SNOW WATER EQUIVALENCE AND ASSOCIATED STANDARD DEVIATIONS FOR EACH PLOT AS OBTAINED FROM TRANSECT DATA. Data is from transects within the plot boundaries on April 2, 1989. Densities are those obtained from the U.S. Federal Snow Sampler.

SITE	Mean Depth (m)	Standard Deviation (m)	Mean Density (kg/m <sup>3</sup> )	Mean SWE (m)	Standard Deviation (m)
A	0.861	0.03	283	0.244	0.01
B	0.928	0.14	288	0.267	0.04
C	0.722	0.16	266	0.192	0.04
D	0.855	0.27	255	0.218	0.07

The data obtained from the two, west-east and north-south, snow depth transects on April 2, 1989 in each plot were compared (Table 4). Although the mean snow depths and calculated SWE did not decrease with an increase in

canopy density as expected, the associated standard deviations show greater variability in snow accumulation in forests with higher canopy densities and basal areas. In fact, the transect data suggests that mean snow depths in the meadow plot (mean depth of 0.861 m) and the mature forest (mean depth of 0.855 m) were comparable, such that the mature forest (plot D) accumulated 99 percent of the snow depth accumulated by the meadow plot (plot A). However, when the snow density of each plot is taken into consideration and the SWE is calculated, the SWE data show that plot D accumulated only 89 percent of that accumulated by plot A, further reinforcing the importance of snow density measurements when assessing SWE.

The difference in the transect data, as compared to the regular measurements, may result from the method of randomly selecting the location of both the permanent stakes and transect lines. For example, in plot D, there are a few small (approximately 8-16 m<sup>2</sup>) openings in the forest which allow snow to accumulate without canopy interception. However, the adjacent canopy provides extensive shading protection from the incoming solar radiation. These small openings (with relatively deep and shaded snow) resulted in the large variability of snow accumulation in the mature forest (individual snow depths from the plot D transects ranged from 0.17 to 1.28 m). Therefore, the mean snow depth in this plot could have varied significantly, depending on the precise location of measurement points.

The snow depth data from each transect, including the snow depths measured outside of the plot boundary, display interesting graphical fluctuations within both the west-east and the north-south orientations (Figures 18, 19, 20 and 21). Transects in plot A (Figure 18) extended into the surrounding forests. This data reinforced the relationship observed by others (Golding and Swanson, 1986;

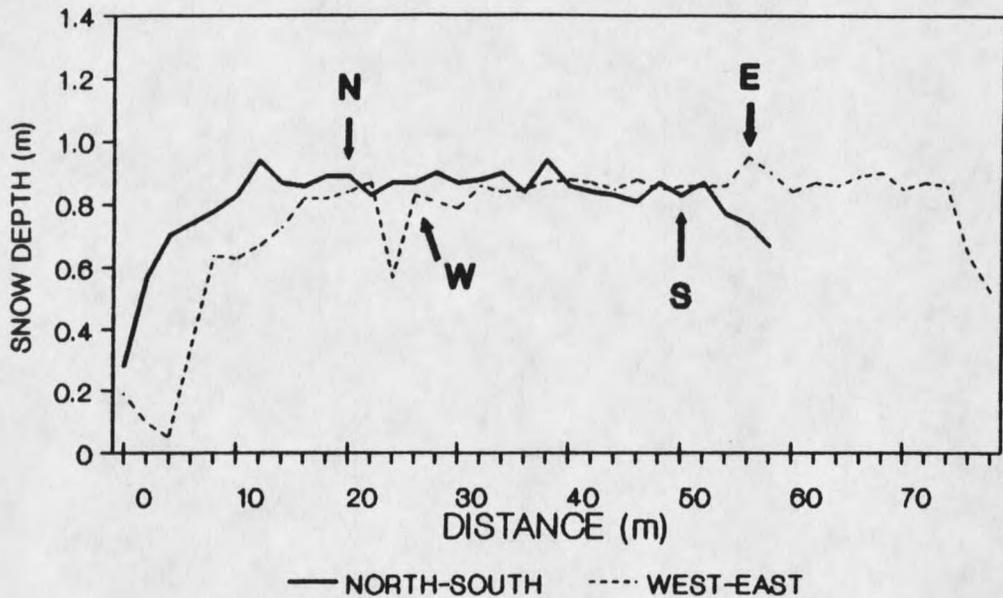


Figure 18. Plot A snow depth transects as observed on April 2, 1989. The graph includes data from both the north-south and west-east transects. The arrows mark the plot boundaries on the respective transect, such that data outside the arrows was collected outside the plot boundary.

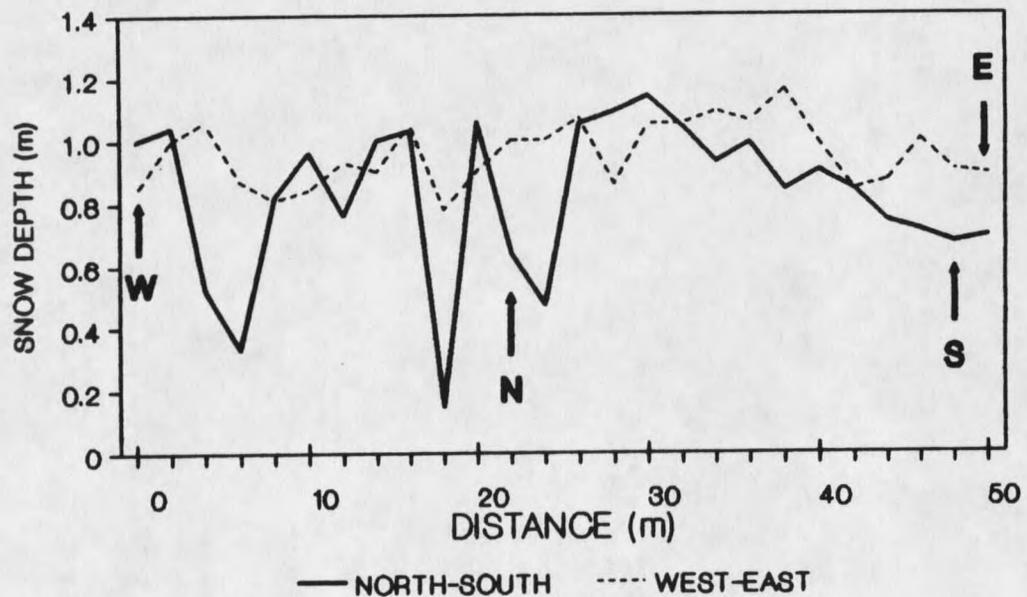


Figure 19. Plot B snow depth transects as observed on April 2, 1989. The graph includes data from both the north-south and west-east transects. The arrows mark the plot boundaries on the respective transect, such that data outside the arrows was collected outside the plot boundary.

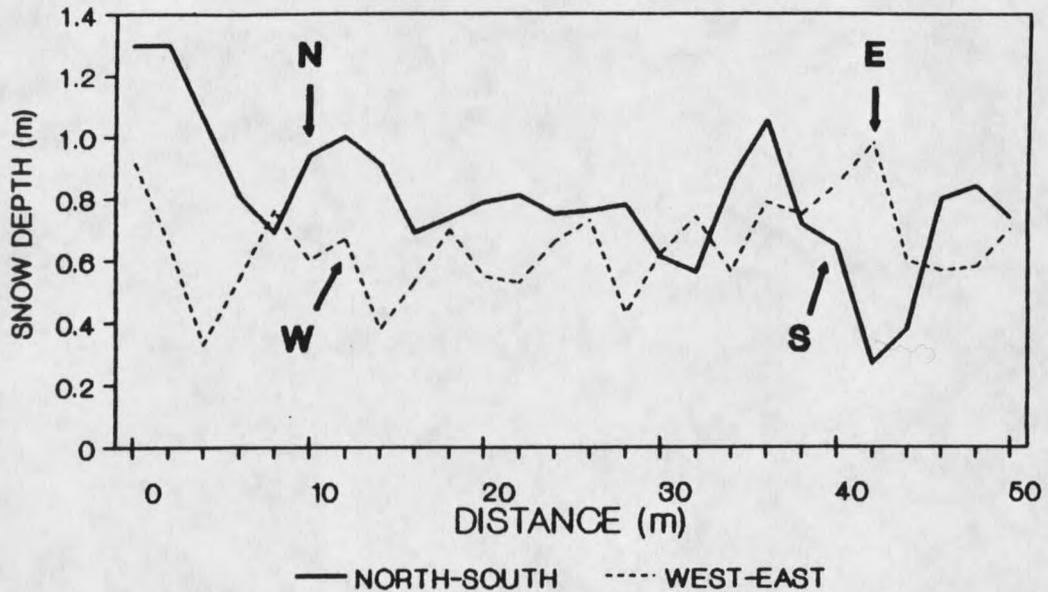


Figure 20. Plot C snow depth transects as observed on April 2, 1989. The graph includes data from both the north-south and west-east transects. The arrows mark the plot boundaries on the respective transect, such that data outside the arrows was collected outside the plot boundary.

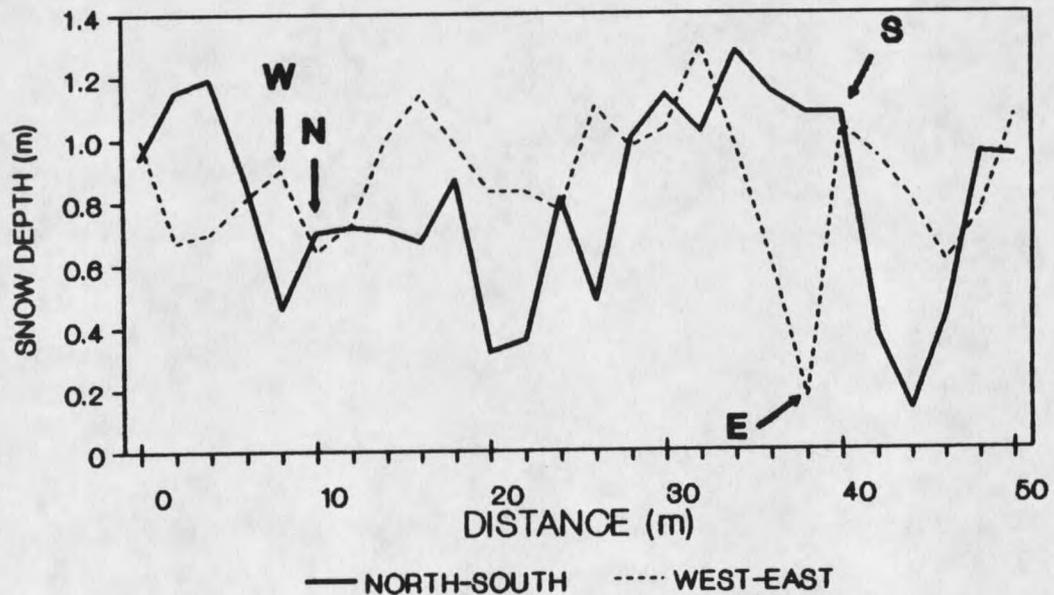


Figure 21. Plot D snow depth transects as observed on April 2, 1989. The graph includes data from both the north-south and west-east transects. The arrows mark the plot boundaries on the respective transect, such that data outside the arrows was collected outside the plot boundary.

Toews and Gluns, 1986; Ffolliott *et al.*, 1989), that interception of snow by the forest canopy results in less accumulation on the forest floor, while more snow accumulates in an adjacent meadow or clearcut. Since the transects began in the surrounding mature forest and extended across the plot, the slowly increasing snow depths for the first 12-16 meters of the transects illustrate the influence of snow interception by the trees. The influence of the trees on snow depth accumulation declined as the transect approached the plot's opening. The depths were relatively constant within the plot opening until, at a distance of 70 meters on the west-east transect, the transect again intersected the adjacent forest boundary. The north-south transect showed a similar pattern of snow depth, also beginning in the adjacent forest, but ending where a south-facing slope was encountered, six meters outside the plot boundary.

Transects of snow depth within plot B showed some variability throughout the west-east transect, but greater variability occurred on the north-south transect (Figure 19). The north-south transect extended 22 meters into the surrounding forest, accounting for the variability at the north end of the transect. The presence of trees in plot B, as opposed to plot A, and the resulting increase in snow depth variability further suggests that an increase in the number of trees will increase the variability of snow depth due to canopy interception, redistribution and shading.

The forest surrounding plot C, as well as plot D, is of similar structure to the forest within the plot boundary, and therefore, the transect did not show changing patterns of snow depth within the plot compared to outside the plot (Figures 20 and 21). However, the graphical presentations of the transect data for plots C and D show more variability in snow depths than do the transects within the boundaries of plots A and B. This is confirmed by the increase in standard deviation of snow depths as the forest structure of the plot increases (Table 4), again due to the

various influences trees have on snow depth distribution (interception, redistribution and shading).

### Statistical, Spatial Independence Between Stakes

Most statistical methods (including regression analysis) assume independence among data points. Spatial data may not be independent when two points that are close together produce essentially the same measure of value. In order to appropriately use statistical methods on this data, the measurements at points 15 meters apart (the distance chosen to separate measurement stakes in all plots) needed to be statistically independent.

Using a variogram analysis (Cliff and Ord, 1981), points as close together as 2 meters showed no evidence of lack of independence. Therefore stakes, 15 m apart in each plot, were assumed to yield statistically independent points. The statistical programming language "S" (Becker *et al.*, 1988) was used to create the variogram plots.

### Snow Ablation

#### The 1989 Snow Season

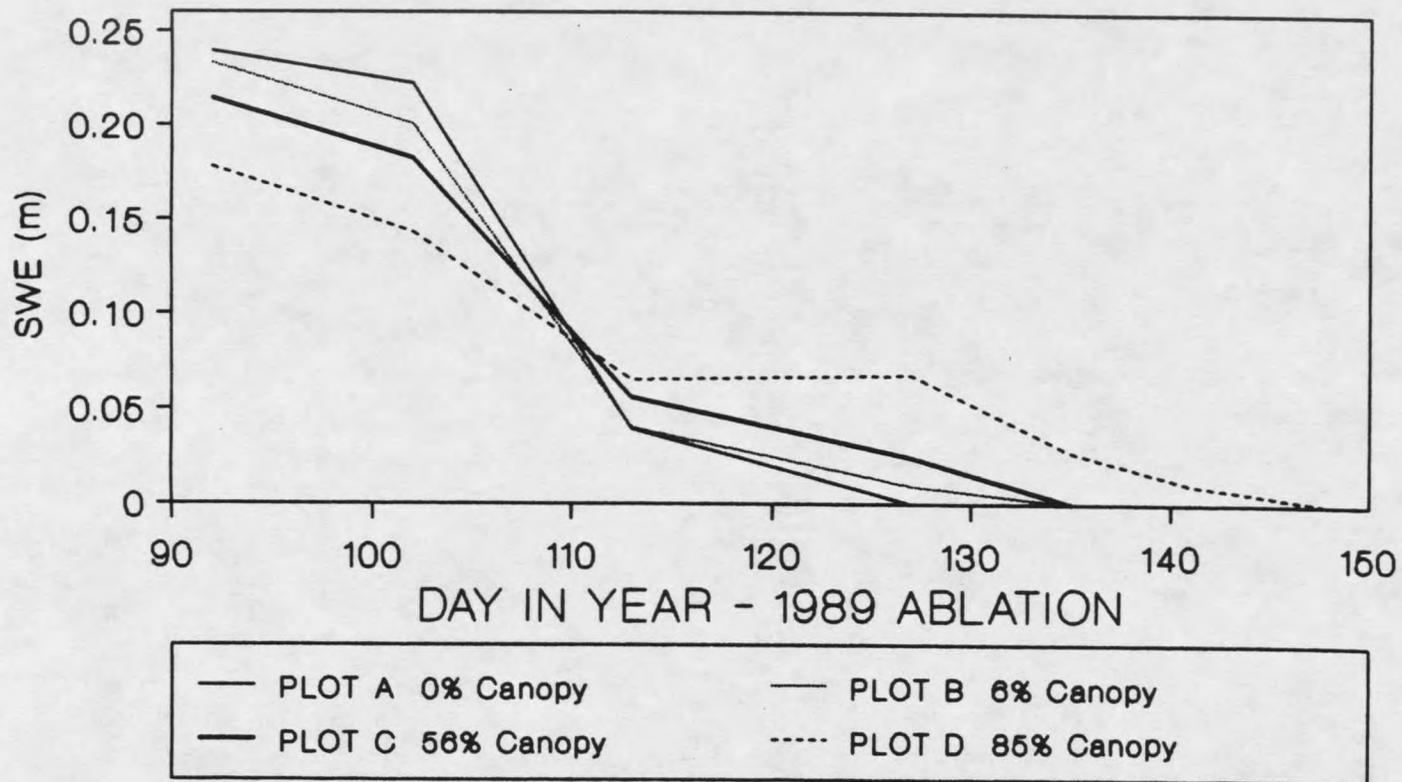
During the snow ablation season, rapid ablation of the snowpack was expected as air temperatures increased and snow depth and snow water equivalence decreased. The rate of snowmelt provided an indication of how the forest structure of each plot affected snow retention. The additional direct solar radiation into the plots with few or no trees was suspected to accelerate ablation, compared to plots with shading provided by a high canopy density.

Due to the variability in the forest structure in the different study plots, the length of the ablation season varied within each plot. As noted by the SWE at the

time of maximum accumulation (Figure 22), the plot with no trees had the most SWE and the plots with older trees and more structure had the least SWE. In mid-April (approximately day 110), this trend reversed such that the meadow plot (plot A), had the least snow water equivalence and was the first to completely ablate. This was followed by a sequence of complete snow ablation in plots corresponding to increasing forest structures. Plot A was completely snow-free by May 6th (day 126), followed by the complete melting of plots B and C by May 14th (day 134), and finally plot D completely melted by May 27th (day 147) (Table 5). The dates of complete ablation of snow in each plot, shown in Figure 22, do not necessarily represent the exact day of ablation since weekly sampling allowed only for the assessment of the correct order of complete ablation between the plots and the exact date of ablation is unknown.

#### Discussion of Ablation Patterns

The presence of trees is known to both accelerate and delay ablation of a snowpack (Marks and Marks, 1980; Oke, 1987). The interception of incoming solar radiation by a forest canopy favors a delay in ablation, while areas with no or low forest structure are not as well protected by shading. Additionally, when the snowpack becomes thin [between 0.15 m depth (Oke, 1987) and 0.3 m depth (Dozier, 1989)], solar radiation reaching the top of the snowpack is transmitted to, and absorbed by, the ground enhancing snowmelt from the base of the snowpack. Any vegetation protruding above the snow, including trees, provides additional energy to the snowpack by conduction and emission of longwave radiation (Marks and Marks, 1980). Also, the presence of trees diminishes surface wind velocities, reducing the turbulent exchange between the atmosphere and the snow surface (Oke, 1987), resulting in more retention of energy by the snow, thereby accelerating snowmelt.



**Figure 22.** Snow water equivalence for all plots during the 1989 snow ablation season. The data point locations can be identified by the break in the slope of the lines. This graph begins at the time of maximum SWE, April 2nd (day 92), and continues until all snow has melted from each plot. The plot with the least forest structure (plot A) was the first to completely ablate, followed by the other plots of increasing forest structure.

**Table 5. SNOW DEPTH, SNOW DENSITY AND SNOW WATER EQUIVALENCE FOR THE ENTIRE 1989 ABLATION SEASON.**

DATE	Depth (m)	PLOT A		Depth (m)	PLOT B	
		Density (kg/m <sup>3</sup> )	SWE (m)		Density (kg/m <sup>3</sup> )	SWE (m)
2 April	0.846	283	0.239	0.809	288	0.233
11 April	0.611	364	0.222	0.574	350	0.201
22 April	0.108	367	0.040	0.114	352	0.040
6 May	0		0	0.027	349	0.094
14 May	0		0	0.002		0
20 May	0		0	0		0
27 May	0		0	0		0

DATE	Depth (m)	PLOT C		Depth (m)	PLOT D	
		Density (kg/m <sup>3</sup> )	SWE (m)		Density (kg/m <sup>3</sup> )	SWE (m)
2 April	0.806	266	0.214	0.699	255	0.178
11 April	0.547	334	0.183	0.481	298	0.143
22 April	0.179	313	0.056	0.246	266	0.065
6 May	0.074	330	0.024	0.212	320	0.068
14 May	0.019		0	0.094	289	0.027
20 May	0		0	0.029	350	0.010
27 May	0		0	0		0

The results of this study imply that the absence of a forest canopy results in more rapid ablation of the snowpack compared to that which occurs within a full structured forest (i.e. high canopy density and basal area). This corresponds to the findings of Marks and Marks (1980), Troendle and Leaf (1981) and Swanson and Golding (1982). Forests of an intermediate structure and age (plots B and C), prolong snowmelt longer than meadows (plot A), but not as long as a mature forest (plot D). Although full structured forests accumulate significantly less snow, these forests favor a delay in snowpack depletion, as observed by the late ablation of plot D. This suggests, as noted by Marks and Marks (1980), that as the canopy density increases, less solar radiation reaches the snow surface, the amount of energy input to the snow is reduced and ablation slows.

**Statistical Significance of  
Ablation Results**

Rates of ablation were used to indicate the affect of forest structure on snow retention. The mean daily ablation rate was determined for each plot during the 20 day ablation period between April 2-22, 1989 (from the time of maximum accumulation to the latest observed date when all plots still had a measurable quantity of snow) (Table 6). As hypothesized, the mean rate of ablation was highest in the area with no trees (plot A) and lowest in the full structured forest (plot D). The ablation rate at each of the 36 stakes (nine per plot) was calculated and tested against the percent canopy density at each stake (correlation coefficient = -0.8709; p-value <  $10^{-4}$ ) (Figure 23). This correlation suggests a strong negative relationship between canopy density and average ablation rate. In other words, forests with higher canopy densities had lower snow ablation rates.

**Table 6. ABLATION RATE CALCULATIONS FOR ALL PLOTS DURING 1989.** The ablation rate was calculated by dividing the difference in SWE for each plot by 20 days (number of days between April 2-22) and then multiplying by 100.

SITE	April 2 SWE (m)	April 22 SWE (m)	Difference SWE (m)	Ablation Rate (cm SWE/day)
A	0.239	0.040	0.199	0.995
B	0.233	0.040	0.193	0.965
C	0.214	0.056	0.158	0.790
D	0.178	0.065	0.113	0.565

The curve on the scatter plot (Figure 23) was generated using a non-parametric regression fit in order to further understand the relationship between the

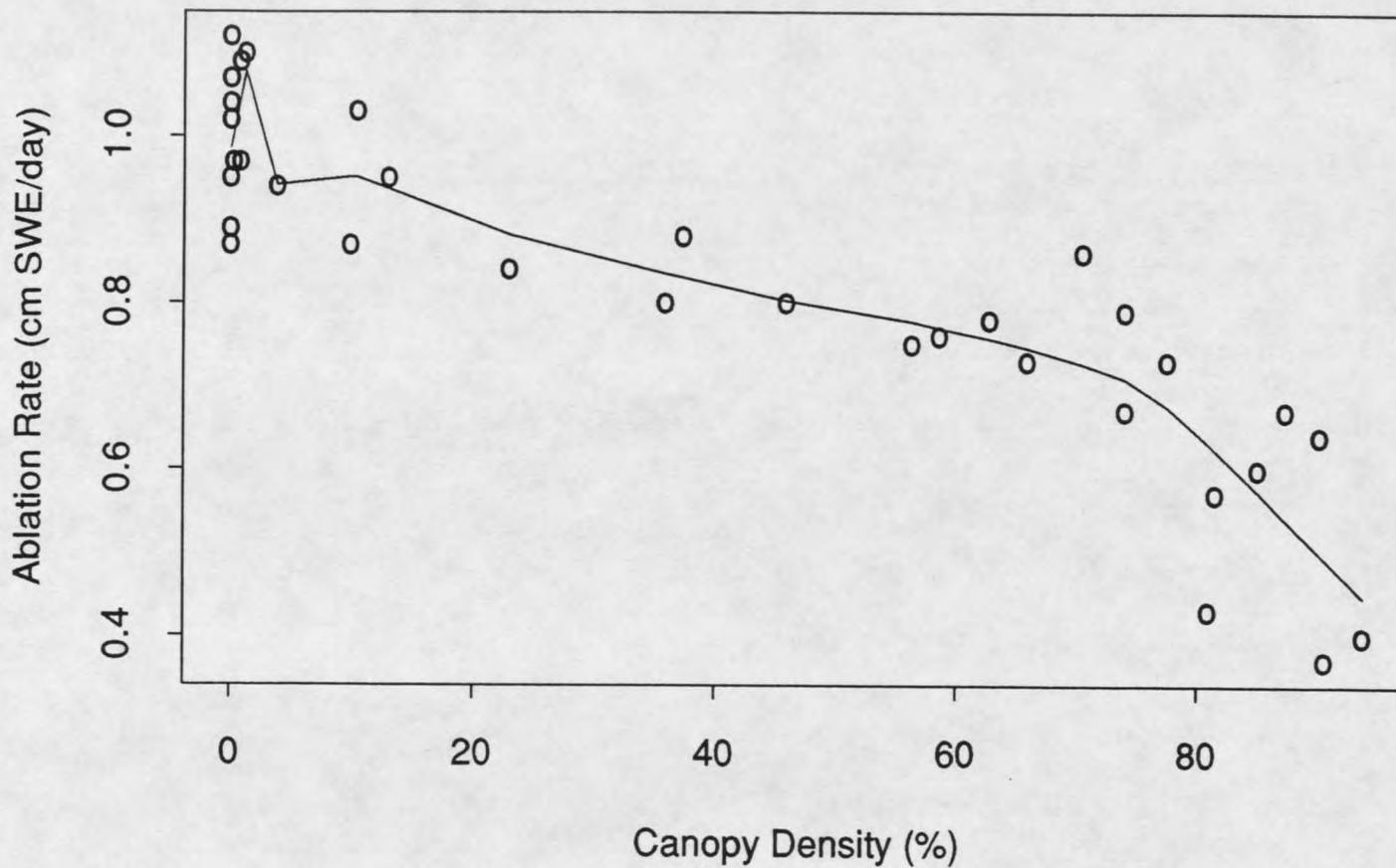


Figure 23. Scatter plot of canopy density and ablation rate with lowess smooth for the 1989 snow season. A strong negative relationship exists between canopy density and ablation rate (correlation coefficient = -0.87; p-value <  $10^{-4}$ ). The lowess curve was computed with a smoothness parameter of  $f=0.4$ .

ablation rate and canopy density. The lowess curve ( $f=0.4$ ) (Cleveland, 1985), displays a pattern similar to the canopy density/maximum SWE graph (Figure 15). The curve fluctuates in response to the several points representing a low canopy density, has a gentle slope throughout the intermediate canopies, and shows a steep downward trend at approximately 75 percent canopy density when the ablation rate falls off steeply. This break in the trend of the slope suggests that canopy densities greater than approximately 75 percent most strongly influenced the ablation rate so as to delay ablation.

The ablation pattern revealed in Figure 23, suggests that ablation rates may be due in part to a result of tree species as well as canopy density. The dominant species in plots B and C are lodgepole pine (100% and 86%, respectively) (Table 1) and collectively, these two plots represent mean canopy densities between 5.6% and 56.4% (Figure 23). The steepening of the lowess curve at approximately 75% canopy density corresponds also to a change in forest composition from lodgepole pine to the fir and spruce forest of plot D, with its mean canopy density of 84.5%. This suggests that not only is the canopy density of a forest a factor in snow ablation rates, but also the nature of a mature, mixed species forest may contribute to snow retention.

### The 1990 Snow Season

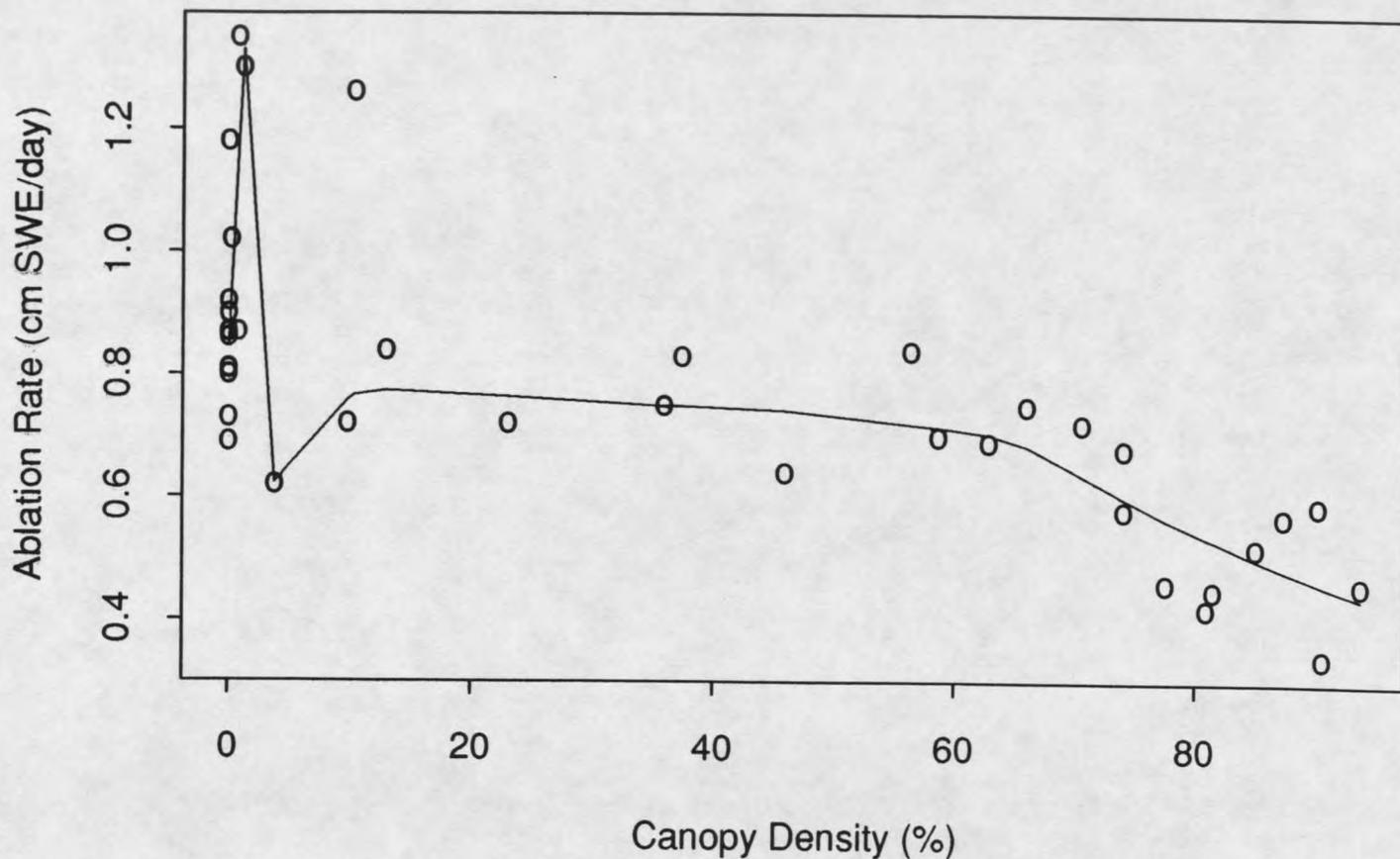
Data collection for the 1990 ablation season began on March 31st, the time of maximum accumulated SWE, and extended until April 21st (Table 3). By late April a positive relationship existed between the amount of snow remaining in the four plots and the forest structure of the plots. The least amount of SWE was found in the plot with the least forest structure (plot A), and the most SWE was found in the mature forest (plot D) (Figure 16). The mean ablation rates in plots C and D for the 1990 snow season revealed a pattern similar to that of the 1989

snow season (Table 7). However, the rates were dissimilar during 1990 in the meadow (plot A) and the low structured forest (plot B). The most rapid mean ablation rate (0.955 cm SWE/day) was observed in the plot with young trees followed by the second fastest ablation rate in the meadow (0.786 cm SWE/day), the forest with intermediate forest structure (0.7 cm SWE/day) was third fastest, and finally, the slowest ablation rate was observed in the mature forest (0.464 cm SWE/day).

Table 7. ABLATION RATE CALCULATIONS FOR ALL PLOTS DURING 1990. The ablation rate was calculated by dividing the difference in SWE for each plot by 22 days (number of days between March 31 and April 21) and then multiplying by 100.

SITE	March 31 SWE (m)	April 21 SWE (m)	Difference SWE (m)	Ablation Rate (cm SWE/day)
A	0.180	0.007	0.173	0.786
B	0.238	0.028	0.210	0.955
C	0.199	0.045	0.154	0.700
D	0.203	0.101	0.102	0.464

The statistical correlation between ablation rates and canopy densities (correlation coefficient = -0.7299; p-value <  $10^{-4}$ ) suggests a strong and significant relationship existed between the variables, such that an increase in canopy density corresponded to a decrease in ablation rate. This correlation coefficient and associated p-value support the findings from the 1989 data. The graphic depiction of this data (Figure 24) with a lowess smooth ( $f=0.4$ ) also reveals a similar trend as



**Figure 24.** Scatter plot of canopy density and ablation rate with lowess smooth for the 1990 snow season. A strong relationship exists between canopy density and ablation rate (correlation coefficient = -0.73; p-value <  $10^{-4}$ ). The lowess curve was computed with a smoothness parameter of  $f=0.4$ .

found the 1989 graph of canopy density and ablation rate (Figure 23). At low canopy densities (0-20%), the variability in the ablation rate (0.62 - 1.35 cm SWE/day) was greater during 1990 than during the 1989 season (0.84 - 1.13 cm SWE/day). The slope of the curve throughout the intermediate canopy densities (20-60%) is shallow, with a steepening of the curve at densities of 65-70%. Therefore, the 1990 ablation data implies that ablation rates are most strongly reduced at canopy densities greater than 65-70%.

#### 1989 and 1990 Ablation Seasons Compared

Mean ablation rates during the 1989 ablation season were higher than mean ablation rates during the 1990 ablation season. This decrease, during 1990, in the mean ablation rates in the plots ranged from 1% (plot B) to 21% (plot A), while plot C decreased 11% and plot D decreased 18%. The slower ablation of snow in 1990, compared to 1989, was not confirmed by data obtained from the SCS SNOTEL site. SNOTEL SWE data (Figure 9) showed that ablation occurred more rapidly during 1990 from the time of peak SWE to April 25th, which was further supported by the higher temperatures recorded during that period (Figure 8). The meadow, with the greatest decrease in ablation rate (21%) from 1989 to 1990, was also the plot where the accuracy of the snow density measurements was questioned. A higher snowpack density, than was actually measured in plot A (271 kg/m<sup>3</sup>), would result in a higher SWE value at the start of the ablation season, and therefore, a higher calculated ablation rate. The 11% and 18% decrease in ablation rates for plots C and D respectively, are more difficult to account for. Unmeasured weather variables such as wind and solar radiation may have played a role in producing this unexpected discrepancy in the ablation data. A one-year growth

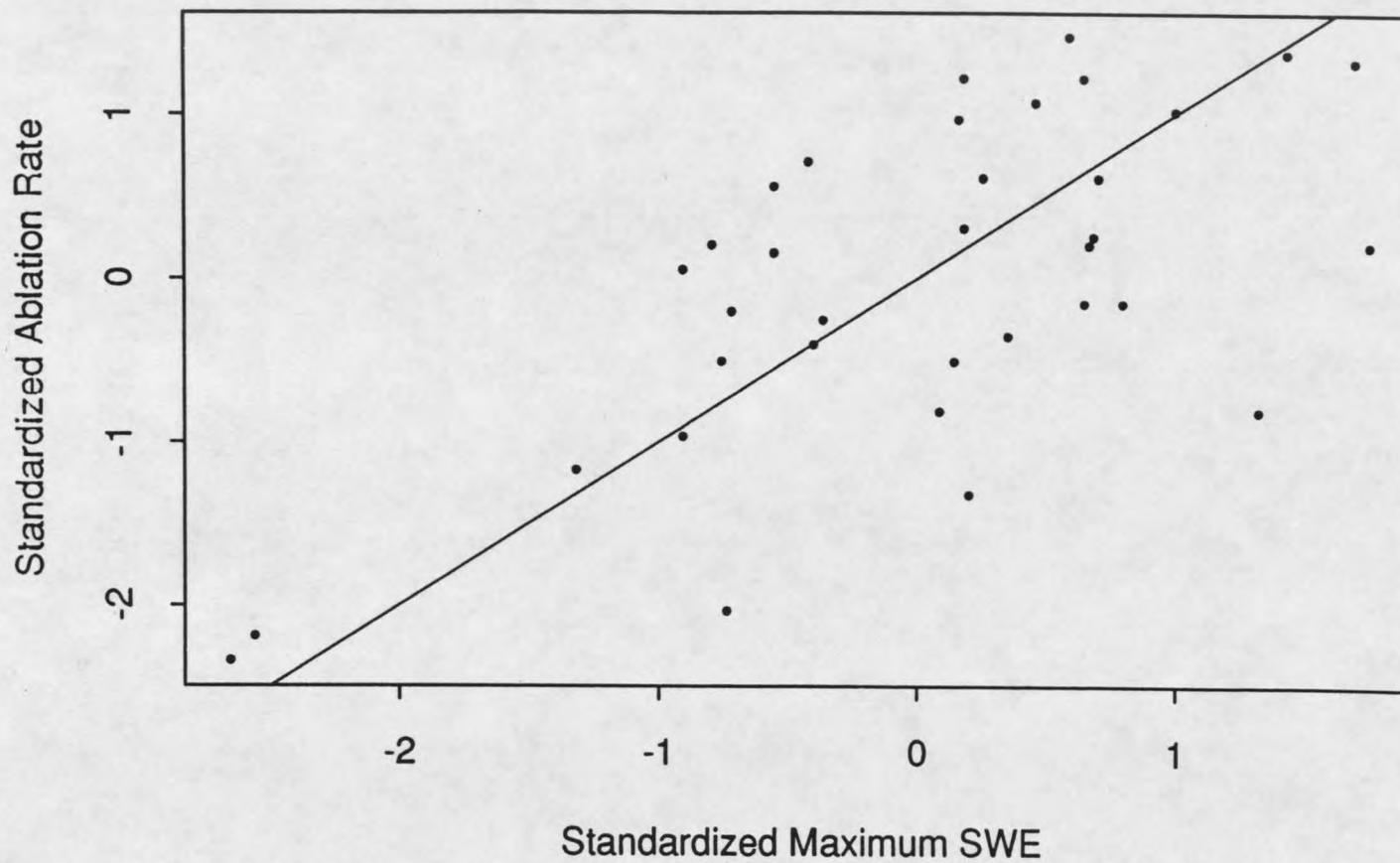
difference in respective forests was probably not significant enough to reduce ablation rates to this extent.

Most importantly, in terms of the ability of a forest to retain a snowpack, is the trend of the lowest curve at high canopy densities (Figure 24). The 1990 data provides support for the conclusions reached based solely on the 1989 data, that forests of a high canopy density (65-75%) correspond to a substantial reduction in the ablation rate of a snowpack.

### Other Patterns of Snow Distribution

#### Relationship Between Maximum Accumulation and Ablation Rates

The distribution of maximum accumulation (SWE) and ablation rates depended on, and had a negative relationship with, the canopy density of the forest. The 1989 values of maximum SWE and their corresponding ablation rates were standardized, using the statistical programming environment "S" (Becker *et al.*, 1988), and when plotted against each other (Figure 25), show that an increase in maximum SWE corresponded to an increase in ablation rate ( $p\text{-value} < 10^{-4}$ ). When the two data points at low values of both maximum SWE and ablation rate were removed, the strength of the relationship between the variables decreased ( $p\text{-value} = 0.0038$ ). Overall, this implies that maximum snow accumulation showed some correspondence to the ablation rate, as controlled by the forest structure at a particular site. Based on the 1989 results from this study, it was observed that the areas that accumulated larger quantities of snow, also ablated at a more rapid rate than those areas that accumulated less snow.



**Figure 25.** The distribution of maximum accumulation (SWE) and ablation rate are shown by plotting their standardized values. The line extends through the origin with a slope of one (p-value = 0.0038).

### Snow Density

Snow density is a critical variable in determining the snow water equivalence of a snowpack because it relates to the ability of the snowpack to hold water and to absorb solar radiation (Colbeck, 1980). A higher density snowpack contains more liquid water per meter of snow than do low density snowpacks of similar depths. Also, a higher density snowpack, with an accompanying lower albedo, will absorb more solar radiation, further enhancing snowmelt (Colbeck, 1980). Snowpack density was expected to increase with time during the ablation season as a result of snowmelt, settling and snow metamorphism. Snow density was expected to be lowest under high canopy densities due to less radiative energy available to the snowpack (Ffolliott *et al.*, 1989). To confirm this expectation, the patterns between canopy density and snow density in each plot throughout the entire snow season were examined (Table 8).

**Table 8. SNOW DENSITY DATA FOR THE 1989 SNOW SEASON.** On February 20, 1989 no measurements of snow density were collected due to time constraints at the field site (- =no data available).

DATE	DAY IN YEAR	MEAN PLOT DENSITY (kg/m <sup>3</sup> )			
		Plot A	Plot B	Plot C	Plot D
8 Jan.	8	181	211	176	187
22 Jan.	22	221	252	227	226
20 Feb.	51	-	-	-	-
5 Mar.	64	242	262	236	217
14 Mar.	73	214	235	231	201
2 Apr.	92	283	288	266	255
11 Apr.	101	364	350	334	298
22 Apr.	121	367	352	313	266
6 May	135	-	349	330	320
14 May	143	-	-	-	289
20 May	149	-	-	-	350
27 May	156	-	-	-	-

In general, the density of the snowpack increased throughout the 1989 snow season (Figure 26) as a result of various snow metamorphic processes. As expected, and because of the typically low density of new snow, the relationship between canopy density and snow density revealed no consistent trend during the accumulation season (January through March). At the time of maximum accumulation (April 2, 1989), a slightly lower snowpack density was evident under higher canopy densities. This trend became more pronounced as the ablation season continued (i.e. data collected on April 11th and 22nd indicated a lower snow density under higher canopy densities). Between April 11-22, the snow density decreased rather than increased as might be expected during the melt season (as evident in the April 22nd data). No new snow was recorded on the Lick Creek SNOTEL pillow between April 11-22 which could account for the decreasing snowpack density. However, late season snowpack densities are known to decrease with a decline, to some critical depth, in snowpack depth (Fames, pers. comm., 1989). With an increase in water volume in the snowpack, smaller grains are replaced by larger grains. When the water volume exceeds that which can be held by capillarity, a sudden release of water can occur by gravity drainage (Colbeck, 1980). This drainage can result in the loss of the snowpack's ability to hold the free water, resulting in water drainage and a decrease in snow density (Colbeck, 1980). This water drainage from the shallower, late season, snowpacks may account for the decrease in snow density as observed in plots C and D in mid-April.

#### Comparison of the Meadow and Young Trees

In order to better understand the ability of a young regrowth forest to accumulate and retain a snowpack as compared to a meadow, specific comparisons

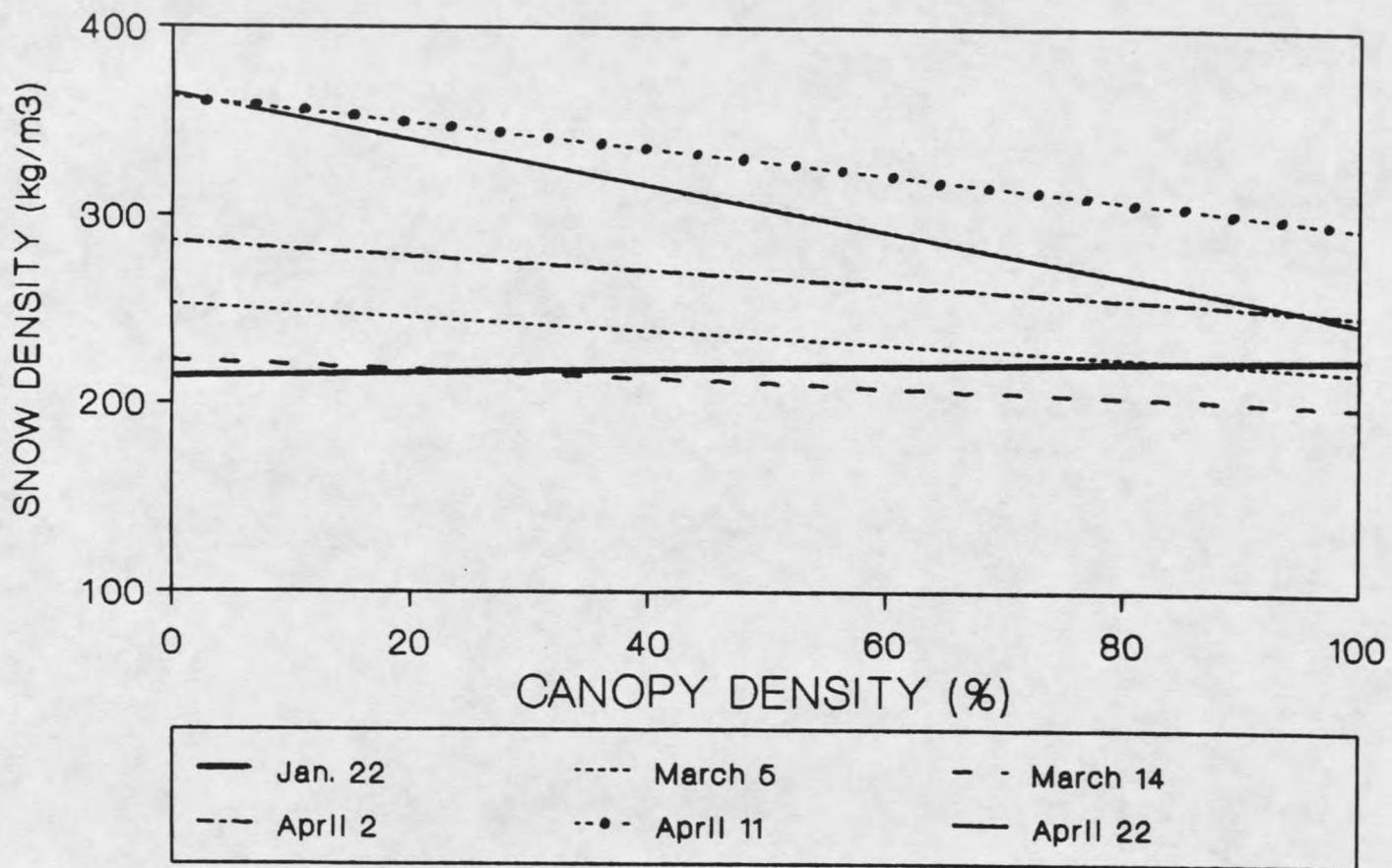


Figure 26. Snowpack density under varying canopy densities through time. This graph shows the regression lines of snow density at six different times during the 1989 snow season. In general the snow density increases through time and decreases with increasing canopy density.

were made. In terms of maximum accumulated SWE in 1989 (Table 9), the plot with the young trees accumulated 97.5% of the SWE accumulated by the meadow (plot A). This represents the greatest similarity between the meadow and all other plots (plots C and D accumulated 89.5% and 74.5% respectively, of the SWE accumulated by plot A). This indicates that a young forest with a comparable forest structure to that of plot B will not accumulate substantially less snow than a meadow.

**Table 9. COMPARISON OF MAXIMUM ACCUMULATED SNOW WATER EQUIVALENCE AND ABLATION RATES OF PLOTS B, C AND D TO PLOT A FOR THE 1989 SNOW SEASON.** Comparisons included the percent of SWE accumulated and ablation rate of each plot to that of plot A. Two sample t-tests were conducted to further compare the mean maximum SWE and ablation rate with plot A.

SITE	MAXIMUM SWE - 1989		ABLATION RATE - 1989	
	Percent of Plot A	t-test p-value	Percent of Plot A	t-test p-value
A	100	-	100	-
B	97.5	0.764	97.0	0.348
C	89.5	0.066	79.4	0.000
D	74.5	0.026	56.8	0.000

A two sample t-test (Snedecor and Cochran, 1967) was conducted on the mean maximum SWE to compare the means of plot A with those of plots B, C and D. The t-test examined the null hypothesis that the mean maximum SWE of plot A equaled, first, the mean maximum SWE of plot B, second, the mean maximum SWE of plot C and third, the mean maximum SWE of plot D. The obtained p-values allowed rejection of the null hypothesis, with at least 95% confidence, if the p-

values were less than 0.05. The null hypothesis was not rejected if the p-values were greater than 0.05. The results of this test (Table 9) were that the null hypothesis was not rejected when the mean maximum SWE of plot A was compared to plot B (p-value = 0.764) and to plot C (p-value = 0.066). The null hypothesis was rejected, with at least 95% confidence, when the mean maximum SWE of plot A was compared with plot D (p-value = 0.026) yielding weakly significant p-values. The two sample t-tests confirmed the previous results (based on percentage differences of mean maximum SWE between plots) that plots A and B were similar in their ability to accumulate a snowpack, but further suggested that plots A and C cannot be considered dissimilar.

The ablation rates of the meadow (plot A) and the young forest (plot B) were very similar (0.995 cm SWE/day and 0.965 cm SWE/day, respectively). The ablation rate of the young forest was 97% as rapid as that in the meadow (Table 9). The comparison of the ablation rates of plots C and D with that of the meadow showed that plot C ablated at a rate which was 79.4% of that of the meadow and plot D ablated at a rate that was 56.8% of that of the meadow. These results imply that young forests (13.4 years old, in this case) do not contribute a great deal towards snow retention.

Two sample t-tests were also conducted to compare the mean ablation rate of plot A with the ablation rates of plots B, C and D (Table 9). Again, results corresponded to the comparison of the percent difference in ablation rates between the plots. The data does not contradict the null hypothesis when comparing the mean ablation rate in plot A with mean ablation rate in plot B (p-value = 0.348). However, when the mean ablation rate in plot A was compared to the mean ablation rates in plots C and D, both t-tests yielded strongly significant p-values (p-value <  $10^{-4}$ ) (Table 9), thereby allowing rejection of the null hypothesis. In all

cases the t-tests confirmed conclusions based on the calculated percentage differences in ablation rates.

### Implications

The meadow plot was initially chosen to represent a treeless area similar to a clearing resulting from timber harvest. However, a comparison of the snow distribution patterns of the meadow with those of the young forest, suggested that a clearcut is less able to retain a snowpack over time than is a meadow. This suggestion originated from the observation that small protruding vegetation above a snowpack is better able to absorb incoming solar radiation (than is snow) and the subsequent re-radiation provides more energy to melt the snowpack (Marks and Marks, 1980). Often, as a result of the method of timber harvest, a clearcut contains many felled logs and slash burn remnants. This situation was observed in plot B, where evidence of slash burn remnants was obvious. The albedo of this debris (often which is blackened due to partial burning) is much lower than snow, therefore absorbing and re-radiating a greater amount of energy than a meadow with minimal or no protruding vegetation. Additionally, the burned and blackened areas (debris and soil) may absorb more sensible heat prior to the accumulation season than a grassy meadow, resulting in less snow retention due to snowmelt at the onset of the accumulation season (Farnes, pers. comm., 1989). The similar ablation rate in plot B and in plot A, likely resulted from the combined effects of increased energy available for ablation from the protruding debris and snow retention resulting from the minimal protection of the forest canopy. Price and Dunne (1976) also found that net radiation was greater at a partially forested site than at an open site. This result was reinforced by the 1990 ablation data, where plot B yielded a higher mean ablation rate than did plot A.

The significance of the snow distribution similarity between the meadow and

the young tree plot is that it refutes the assumption that the snow, and therefore, the water regime of a cleared forest will return to its pre-harvest condition (mature forest) 20 years after harvest (U.S. Forest Service, 1987). The original trees in plot B were harvested in 1973 (U.S. Forest Service, 1989), 16 years prior to this study, and now average 13.4 years of age. According to this study, plot C, which was harvested in 1950 and thinned in 1965 (39 and 24 years prior to the study, respectively) (U.S. Forest Service, 1989), accumulated 20.2% less snow, and ablated 38.6% more quickly, than its pre-harvest condition as represented by plot D.

The results of data collected during the 1989 snow season in the Lick Creek drainage suggest that the snow distribution, and therefore the water regime, of a mature forest is significantly altered by timber harvesting. Additionally, these results imply that the amount of snow accumulated and the ablation rate (important components of the water regime) of a completely harvested forest will not return until the mean age of the forest is much greater than 35 years (mean age of trees in plot C). The return of a pre-harvest snow regime may occur once trees have approached a mean age of 79 years (as represented by plot D). However, the time required for a regrowth, lodgepole pine forest to mature to an older, mixed species forest could be substantially longer than 79 years. Farnes (pers. comm., 1989) observed that 70 years may be necessary until trees are able to influence snow distribution patterns in southwest Montana. Similarly, Troendle and King (1985) estimated 80 years for hydrologic recovery after timber harvest in an experimental watershed in Colorado. The number of years required for complete recovery of the snow regime following timber harvest will depend on whether the trees are replanted or allowed to return by natural succession.

## CONCLUSIONS

Data collected during the 1989 snow season in forests with varying forest structures (canopy density and basal area) revealed a definite pattern of snow accumulation and ablation. In plots with reduced canopy densities and basal area (due to a history of timber harvest), 20-34 percent more snow water equivalence was observed at the time of peak snow accumulation than in the undisturbed, higher canopy density and higher basal area, mature forests. The lowest amount of snow accumulation occurred in the forest with 85 percent canopy density. The increased accumulation of snow in the forests with no trees or a low forest structure was probably due to the absence (or low percentage) of forest cover to intercept the snow and/or to enhance redeposition of the snow by aerodynamic processes.

The plots with the greatest accumulation at the time of maximum SWE also had the highest mean ablation rates, and therefore, the earliest disappearance of the snowpack. Mean ablation rates ranged from 1.0 cm SWE/day in the meadow to 0.57 cm SWE/day in the undisturbed, mature forest. These ablation rates and those of the young forest (0.97 cm SWE/day) and the intermediate aged forest (0.79 cm SWE/day) suggest an inverse relationship between forest structure and ablation rate. Snow ablation rates were not profoundly reduced until a canopy density of approximately 75 percent and greater was achieved. The canopy overstory was believed to be a critical factor in reducing the radiation flux to the snowpack so as to reduce the rate and delay the timing of complete ablation.

The 1990 snow accumulation data indicated a poorer relationship between maximum accumulation (SWE) and canopy density than was indicated by the 1989

data. Differing weather patterns between the two snow seasons and a potential difficulty in obtaining accurate snow density measurements in March 1990 may account for this discrepancy. The 1990 snow ablation season data confirmed the strong inverse relationship between canopy density and ablation rate observed in 1989. There was an observed decrease in mean ablation rates when comparing the 1989 and 1990 data, which could not be accounted for simply by comparing weather patterns. The results from the 1990 data collection period confirmed the importance of weather variability on the distribution of the seasonal snowpack.

### Application of Results

The results from this research may assist watershed managers in further understanding the effects of timber harvest on water yield. These results suggest that the positive effects of timber harvest on the water supply, primarily increased snow accumulation which is then available for runoff, may continue for 35 years (age of intermediate plot C). The negative effects of timber harvest as relevant to this study, predominately an enhanced ablation rate due to less shading and higher radiation receipt, emphasizes the importance of mature forests in delaying ablation, thereby providing more snow available for runoff late into the ablation season.

With these results, watershed managers may better balance the positive effects (greater water yield) and the negative effects (early ablation) of timber harvesting, to enhance water yield and to retain snow late into the ablation season, when the demand is often the greatest. An optimal percentile distribution of varying canopy densities for the watershed may then be developed. The results presented here suggest that young trees do not differ significantly from a clearcut in their ability to accumulate or retain a snowpack. Therefore, in a watershed where maximum attainable water yield is desired, and snow retention may be relatively

unimportant, a larger area of clearings and low structured forests could be allowed. In a watershed where a delayed water yield is desired, clearcuts and low density regrowth forests should be minimized. Different effects on the seasonal snowpack, than were observed in this study, will occur dependent on elevation, slope and aspect of the site.

### Further Studies

A controversy exists among forest hydrologists as to the predominant reason for the greater snow water equivalence in clearcuts as compared to forests. Most researchers (Kolesov, 1985; Wheeler, 1987) attribute the increased SWE to the combined effect of the lack of forest interception (and subsequent sublimation and evaporation losses) and redeposition. A better understanding of the role these effects have on snow distribution in the Hyalite Watershed of Montana is important because while forest interception reduces the amount of snow deposited on the forest floor, which eventually produces water runoff, redistribution of the snow results in the same quantity available in the area to recharge the reservoir.

Additional studies in the Hyalite Watershed could involve a correlation of stream discharge and run-off data with timber harvest activity and a soil moisture/infiltration study. A study correlating long-term stream discharge data on Hyalite Creek with the amount and timing of forest removal could reveal relationships between water yield and timber harvest, as well as the extent of sublimation and redepositional processes. A study which compared soil moisture and infiltration in the forests of varying structures would provide information valuable to further understanding the water balance in soils under different canopies and its relationship to runoff.

Most importantly, the results from this two year study suggest that varying weather patterns do play an important role in the distribution of snow in forests. For this reason, this research would benefit from the continuation of data collection in the forests of varying structure as established in the Lick Creek drainage of the Hyalite Watershed of Montana.

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**APPENDIX**  
**ADDITIONAL SNOW DATA**

**Table 10.** Mean snow water equivalence (SWE) with associated standard deviations (S.D.) from each plot on every day of data collection during the 1989 snow season. Each number was calculated from a sample size of 36 (n = 36).

DATE	<u>PLOT A</u>		<u>PLOT B</u>		<u>PLOT C</u>		<u>PLOT D</u>	
	MEAN		MEAN		MEAN		MEAN	
	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)
1/08/89	8.7	0.6	10.6	2.3	7.1	1.6	5.9	3.1
1/22/89	12.5	0.8	14.6	3.3	13.5	2.4	8.9	4.3
3/05/89	17.7	0.9	18.8	5.4	15.5	2.8	11.9	5.3
3/14/89	12.2	1.1	12.7	4.3	12.1	3.0	8.8	5.3
4/02/89	23.9	1.6	23.3	6.6	21.4	4.6	17.8	9.7
4/11/89	22.2	1.7	20.1	8.1	18.3	5.7	14.3	10.0
4/22/89	4.0	2.6	4.0	5.7	5.6	4.4	6.5	6.8
5/06/89	0	0	1.0	2.0	2.5	3.4	6.8	7.9
5/14/89	0	0	0	0	0	0	2.7	4.0

**Table 11.** Mean snow water equivalence (SWE) with associated standard deviations (S.D.) from each plot on every day of data collection during the 1990 snow season. Each number was calculated from a sample size of 36 (n = 36).

DATE	<u>PLOT A</u>		<u>PLOT B</u>		<u>PLOT C</u>		<u>PLOT D</u>	
	MEAN		MEAN		MEAN		MEAN	
	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)	SWE (cm)	S.D. (cm)
1/02/90	12.0	0.8	11.7	1.8	11.6	1.9	10.8	4.5
2/25/90	17.3	1.4	16.1	4.0	13.7	2.3	12.0	5.2
3/25/90	16.3	1.5	21.6	7.2	20.7	3.9	19.0	8.4
3/31/90	18.0	1.5	23.8	10.2	19.9	3.8	20.2	9.9
4/11/90	12.6	2.3	10.0	8.2	12.7	4.7	12.4	8.4
4/21/90	0.7	1.5	2.8	4.2	4.5	4.0	10.1	8.5

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