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

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 Iogdepole 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^2/ha. Plot C is an older regrowth forest with a 56% canopy density and a basal area of 17 m^2/ha. Plot D is a mixed species forest with a 85% canopy density and a basal area of 37 m^2/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^-4), and 2. A strong inverse relationship exists between canopy density and snow ablation rate (correlation coefficient = -0.87; p-value < 10^-4). 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^-4). 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.

TEMPORAL ACCUMULATION AND ABLATION PATTERNS OF THE SEASONAL SNOWPACK IN FORESTS REPRESENTING VARYING STAGES OF GROWTH

by

Janet Phillips Hardy

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APPROVAL

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Janet Phillips Hardy

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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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^2/ha. Plot C is an older regrowth forest with a 56% canopy density and a basal area of 17 m^2/ha. Plot D is a mixed species forest with a 85% canopy density and a basal area of 37 m^2/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 $< 10^{-4}$), and 2. A strong inverse relationship exists between canopy density and snow ablation rate (correlation coefficient = -0.87; p-value $< 10^{-4}$). 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 $< 10^{-4}$). 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^3 (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.

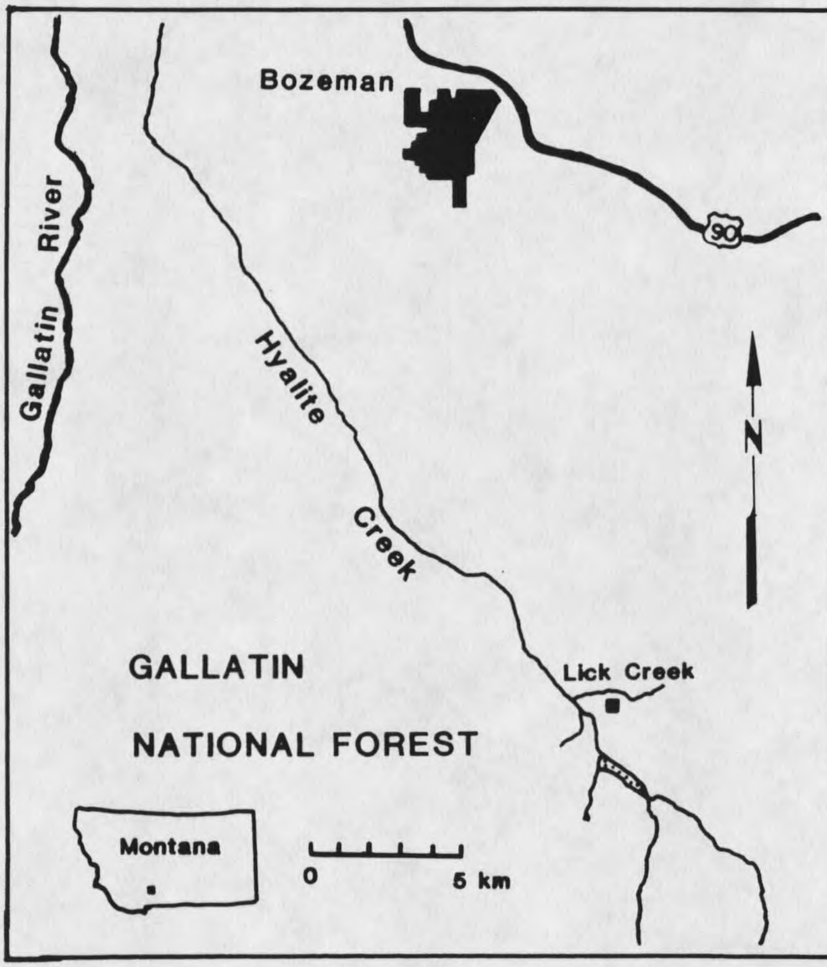


Figure 1. The study area, near Lick Creek, is located within the Hyalite Creek Watershed, 35 km south of Bozeman, Montana.

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

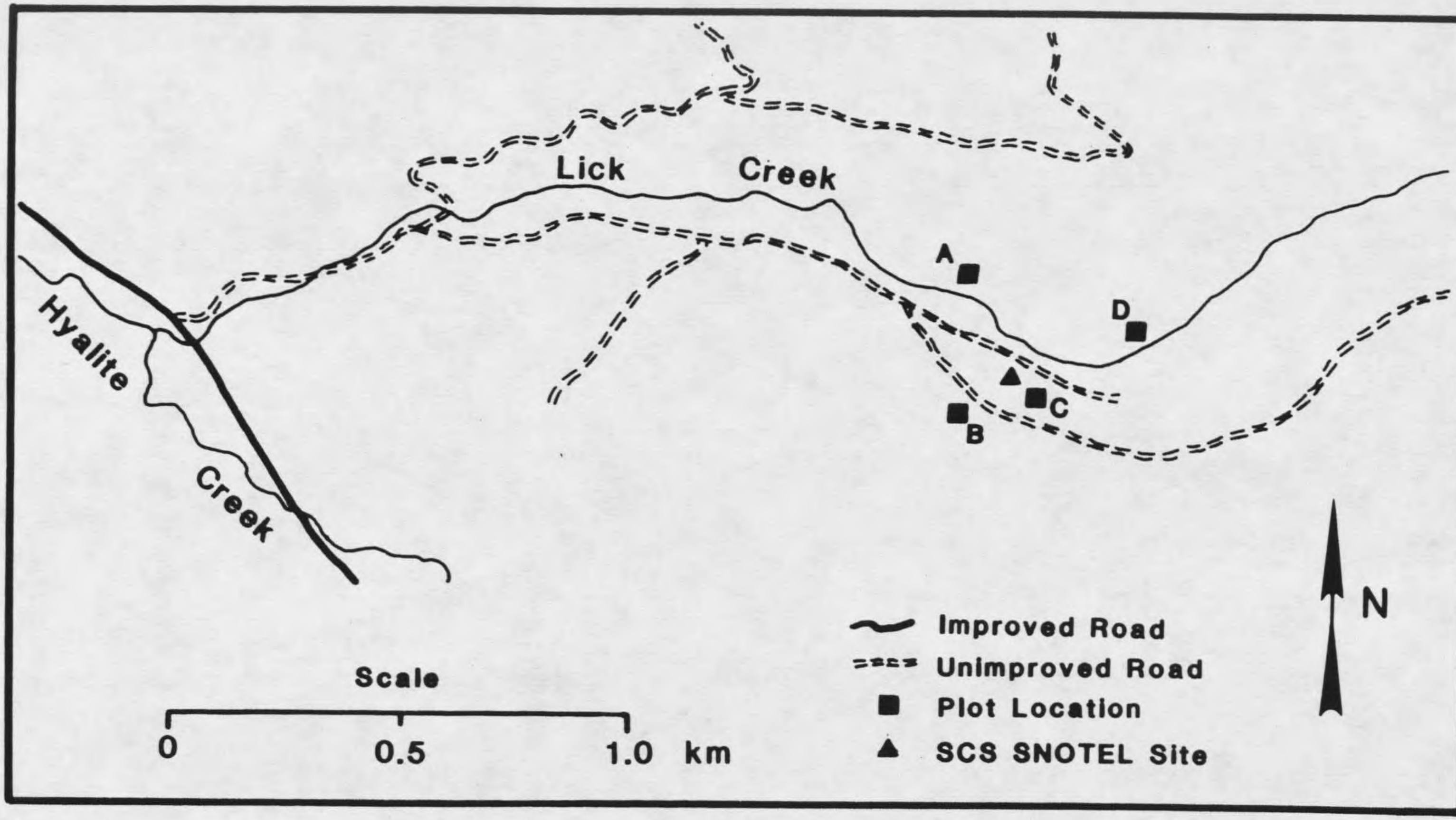


Figure 2. The location of study plots (A, B, C and D) within the Lick Creek drainage.

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^2/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^2/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 logdepole 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^2/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.

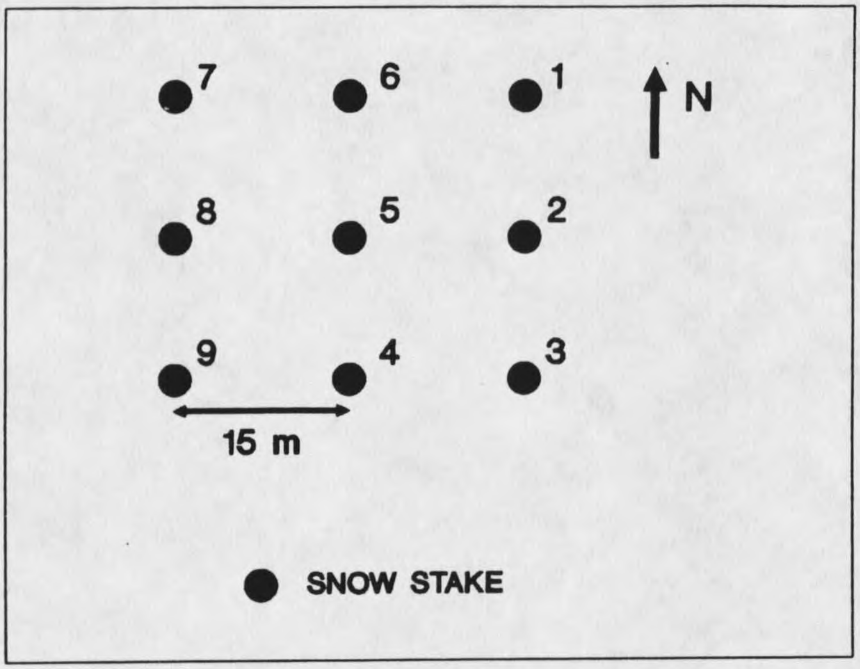


Figure 3. Layout of stakes for plots A, C and D. Each stake was placed 15 meters apart and labeled with a number from one to nine.

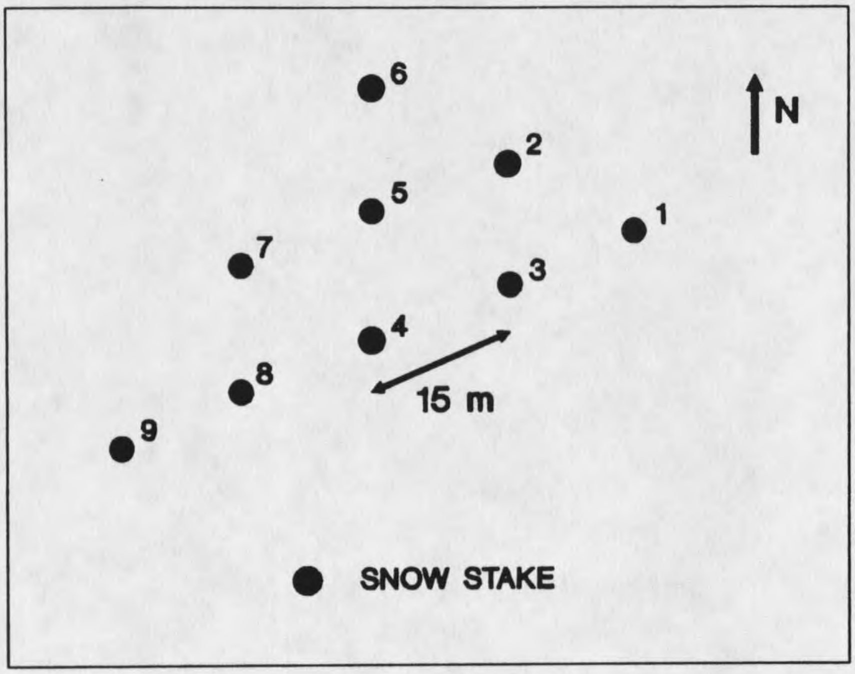


Figure 4. Layout of stakes for plot B. Each stake was placed 15 meters apart and labeled with a number from one to nine.

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^2/ha for each plot.

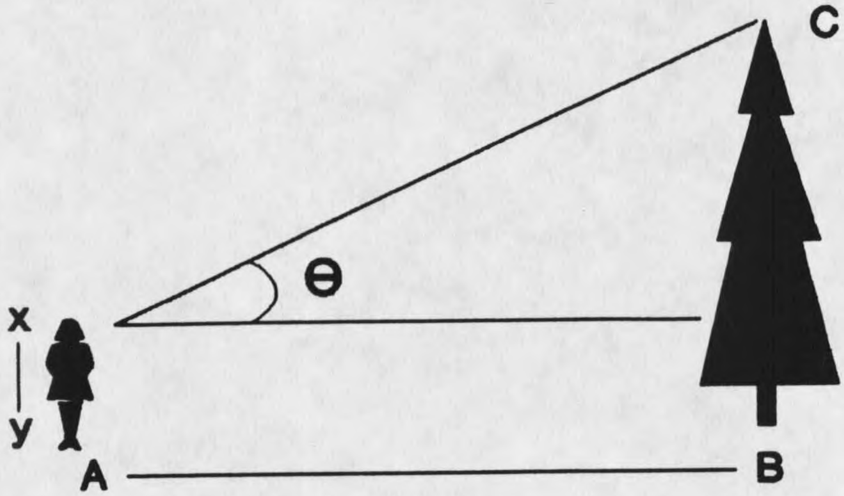
Tree Age

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 (θ) 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