# Snow accumulation under various successional stages of lodgepole pine

by Chadwick Arthur Moore

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


Abstract:
Snow accumulation in forested watersheds is controlled by topographic factors and vegetation structure. Conifers affect snow accumulation principally by intercepting snow at the canopy. Different successional stages of a subalpine forest in central Montana were studied to determine if there was a characteristic response of snow to vegetation. Tree canopy cover, basal area, age, and species composition were measured for eight distinct stands. Peak snow water equivalent was measured at systematically located points within eight stands of varying ages and densities. The study was conducted on the Tenderfoot Creek Experimental Forest, administered by the USDA Intermountain Research Station.

Percentage of canopy cover, as measured by the 30° view of the photocanopyometer, was determined to be the principal forest structure variation that affected snow water equivalent on the forest floor. Results show that as a lodgepole pine (Pinus contorta) dominated subalpine forest becomes mature, there is a characteristic decrease in snow water equivalent. A slight increase in snow water equivalent occurs after the intermediate successional stages when spruce and fir (Picea or Abies) begin to replace lodgepole pine in the overstory. Further succession to a climax spruce/fir forest results in a sharp decrease in snowpack.

This non-linear relationship between successional age and snow water equivalent is an inverse of a successional age /canopy cover relationship, except for the 270 year old (LP stage) mature lodgepole pine stand. This study also confirmed a strong inverse relationship between canopy cover and snow water equivalent. A regression analysis of canopy cover explained 51% of the variation in snow water equivalent; snow water equivalent decreased 2.3 cm (6.4 %) per 10% increase in canopy density.

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# Approval

of a thesis submitted by

Chadwick Arthur Moore

The 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

Snow accumulation in forested watersheds is controlled by topographic factors and vegetation structure. Conifers affect snow accumulation principally by intercepting snow at the canopy. Different successional stages of a subalpine forest in central Montana were studied to determine if there was a characteristic response of snow to vegetation. Tree canopy cover, basal area, age, and species composition were measured for eight distinct stands. Peak snow water equivalent was measured at systematically located points within eight stands of varying ages and densities. The study was conducted on the Tenderfoot Creek Experimental Forest, administered by the USDA Intermountain Research Station.

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# INTRODUCTION

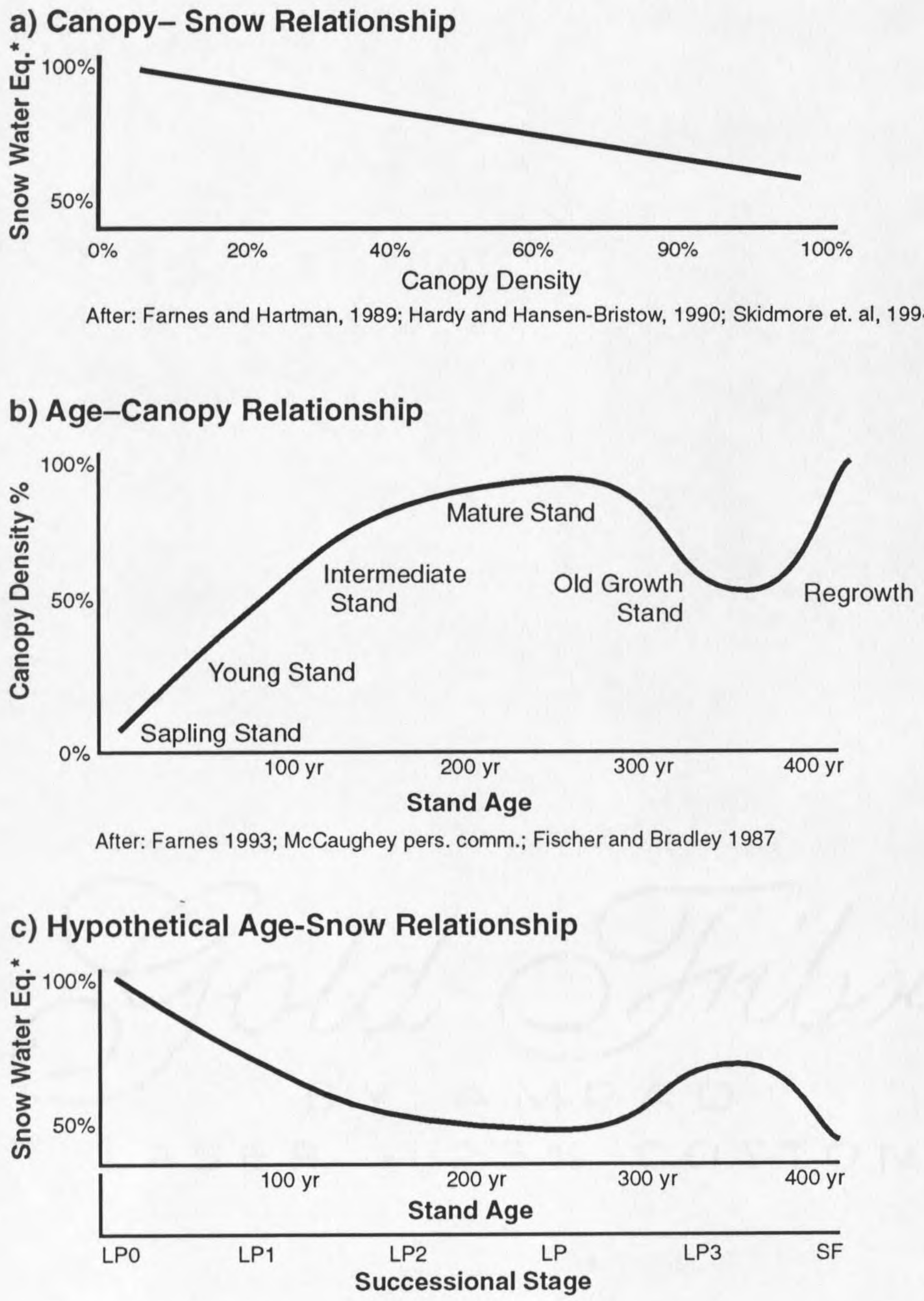
Early studies in forested watersheds noted the variability in snowpack over the landscape, with snow water equivalent varying with climate, elevation, topography, and vegetation (Connaughton 1935; Wilm and Dunford 1948; Packer 1962; Gary 1979; Haupt 1979; Troendle and Meiman 1984; Toews and Gluns 1986; Farnes and Romme 1993). In order to augment water supplies, these studies often manipulated these controlling factors to increase snow accumulation and resultant runoff (Troendle 1983). Research focused on vegetation cover changes because it is the most easily manipulated of the many controlling variables. Paired studies between burned or unburned plots (Farnes and Hartman 1989; Skidmore et al. 1994, Dodd 1995), or clear-cut and forested plots (Wilm and Dunford 1948; Haupt 1951; Packer 1962; Berndt 1965; Gary 1974; Leaf 1975; Gary 1979; Haupt 1979; Troendle and Leaf 1981; Troendle 1983; Troendle and King 1985; Golding and Swanson 1986; Toews and Gluns 1986; Hardy and Hansen-Bristow 1990) were made to determine the potential for water augmentation. The majority of studies found that decreased canopy cover resulted in an increase in snow water equivalent of snowpack (Wilm and Dunford 1948; Haupt 1951; Goodell 1952; Gary, 1974; Leaf 1975; Haupt 1979; Troendle and Leaf 1981; Gary and Troendle 1982; Gary and Watkins 1985; Golding and Swanson 1986; Toews and Gluns 1986; Troendle 1987, Farnes and Hartman 1989; Hardy and Hansen-Bristow 1990, Skidmore et al. 1994), a marginal increase in runoff (Hoover and Leaf 1966; Troendle and Leaf 1981; Troendle and King 1985; Farnes 1993), higher soil moisture (Potts 1984), or a combination of the three.

Most previous studies have quantified differences in snowpack under starkly different vegetation covers. The role of the more gradual growth and seral stage landscape variation upon snow accumulation has not been fully addressed. Fire suppression has altered vegetation structure and canopy on the landscape–scale, which may have influenced the snowpack snow water equivalent (SWE) beneath the canopy. The goal of this research is to determine the influence of successional stage upon SWE in subalpine forests dominated by lodgepole pine (*Pinus contorta var. latifolia*).

Because canopy cover varies with successional stages, it is anticipated that there will be a predictable change in snow accumulation throughout stand successional stages. It is hypothesized that as stands age from sapling to mature forest, the canopy cover increases (Arno et al. 1985), causing a decrease in SWE due to canopy interception and sublimation. Further succession into a post-mature structural stage leads to a thinner canopy (Arno et al. 1985) and greater SWE due to a lack of interception. Later, regrowth of shade tolerant species such as Engelmann spruce (*Picea engelmanni*) and subalpine fir (*Abies lasiocarpa*) increases canopy density (Arno et al. 1985) and decreased SWE. Figure 1a identifies the canopy/SWE relationship quantified by previous researchers. Figure 1b depicts the hypothesized age/canopy relationship that has been described elsewhere in Montana. This study first identifies the variations in canopy density and structure throughout a lodgepole pine forest's seral stages, confirming Figure 1b. It then identifies and quantifies the relationship between successional stage and snow accumulation (Figure 1c), and tests whether this relationship is an inverse function of canopy density (Figure 1b).

If a non-linear relationship between forest successional age and snow water equivalent exists, it will enhance our ability to predict the effect of forest

Figure 1




* as a percentage of an open clearing

succession on water production for lodgepole pine dominated watersheds. Many forests throughout the West are being managed with a fire suppression policy along with a reduction in clear-cutting and with an increase in the use of other silvicultural systems such as seedtree, selection, thinning, and partial cutting (McCaughey pers. comm.). Information from this study will help managers model hydrologic responses due to vegetation manipulations or natural canopy reductions due to insect infestations.

## Previous Research

Past snow studies have focused on the change in peak accumulation of snowpack, the ablation rate, or the resultant runoff from a modified forested watershed. While the increase in snowpack water content and runoff has been noted, the reason for this increase was debated, and still is to a lesser extent. Originally, increases in snow water content were attributed to wind redistribution of snow (Goodell 1952; Goodell 1964; Satterlund and Eschner 1965; Satterlund and Haupt 1967; Hoover and Leaf 1967; Gary 1974; Leaf 1975), while others forwarded the now prevailing thought that reduced canopy interception was responsible for greater snow water equivalent and greater watershed yields (Haupt 1979; Kolesov 1985; Troendle and King 1985; Meiman 1987; Schmidt et al. 1988; Troendle et al 1988; Troendle et al. 1993; Lundberg and Halldin 1994).

### Wind Redistribution

Isolated forest clearings show a substantial increase in accumulation compared to the surrounding forest (eg. Wilm and Dunford 1948; Hoover and Leaf 1967; Gary 1979). However, when this increased localized accumulation failed to result in a significant increase in runoff and watershed water production, researchers began to suggest wind redistribution of snow from one area to another within the watershed as being responsible for SWE increases in clearings. After half of a watershed at the Fraser Experimental Forest in Colorado was clear-cut with no runoff increase, Goodell (1964) called for a reappraisal of the original idea that canopy interception was responsible for snowpack variation. Later studies on snowpack accumulation in and around clearings noted the influence of wind. Research found that the volume of snow gained in a clearing was approximately equal to the decrease in snow around the clearing margins (Satterlund and Eschner 1965; Hoover and Leaf 1967; Gary 1974). Thus the "clearing affect" was attributed to the "robbing" of snow from surrounding forest areas via wind redistribution processes. Also, some early studies isolated the interception process and found it to be insignificant in snowpack budgets. Only 5% of the intercepted mass of snow evaporated and was "lost" under the sub–freezing winter conditions (Sautterland and Haupt 1967).

With time and subsequent research, the wind redistribution theory was tempered. Gary and Troendle (1983) and Golding and Swanson (1986) found evidence of both wind redistribution and evaporation loss through canopy interception to be important factors. Long–term monitoring of the Fraser Experimental Forest eventually produced a statistically significant increase in water production from a watershed that was 40% clear-cut, which could not be the result of wind redistribution alone (Troendle and King 1985). Wind redistribution of snow in and around clearings undoubtedly exists, but more recent research indicates that other forces such as interception and subsequent loss to the atmosphere were responsible for increases in snowpack accumulation associated with less dense forests and clearings.

Canopy Interception

Numerous studies have identified an inverse relationship between snow water equivalent and canopy cover (Figure 1a). Recent research has attributed this variation in snow to the process of interception. Conifers catch the falling snow in branches and needles. The amount intercepted by the canopy is proportional to the canopy density, expressed as a percent of total obscuration of sky. Of the snow that is captured by the canopy, part is sublimated back to the atmosphere and the remainder is eventually added to the snowpack below (Kolesov 1985; Schmidt et al. 1985; Troendle at al. 1988).

Magnitude of Effect. The magnitude of canopy effect on snow varies. Meiman (1970) summarized several early studies and found values ranging from a 0.8 cm increase in SWE per 10% decrease in canopy cover to 6 cm decrease per 10% decrease in canopy cover. Clear-cuts, with distinctly open canopies, have been shown to have up to 70% greater SWE than surrounding forests (McCaughey pers. comm.). These gains must be balanced with losses in forested areas due to wind redistribution (Gary 1979), but still equate to substantial gains in SWE (Troendle and King 1985. Previous studies in Montana, demonstrated 9% to 25% increases in SWE when clear-cuts are compared to surrounding forest (Hardy and Hansen-Bristow 1990; Skidmore et al. 1994). A regression of forest canopy cover with SWE by Farnes and Hartman (1989) yields a slope of 5% increase in SWE for every 10% decrease in cover. The influence of clear-cuts upon snowpack persists for several years after harvests even when the area is regenerated through artificial means such as planting. In one study in northern Idaho, significant increases in SWE in clear-cuts persisted after 34 years (Haupt 1979).

Thinned Forests. Most of these studies dealt with SWE comparisons between clear-cut versus forests. Less research has been done comparing the effect of a range of canopy densities found within a forest upon snowpack. The first investigation to study a range of forest densities, done by Wilm and Dunford in 1948, found that less dense canopies produced more snow than thicker mature canopies. The effect of thinning or of different stand densities was not again examined until 1982 (Gary and Troendle 1982; Gary and Watkins 1985). These investigators found that the canopy–snow relationship (Figure 1a) held for thinned forests as it did for clear-cuts, although the SWE gains were not as impressive due to the more subtle change in canopy cover.

Burned Forests. The Yellowstone National Park fires of 1988 focused attention toward the watershed impact of burned forests. Studies found that burned stands of conifers responded similarly to clear-cuts in how they effect SWE (Farnes and Hartman 1989; Skidmore et al. 1994). The general inverse relationship of canopy with snow accumulation was applicable to burned as well as unburned canopies.

Intercepted Snow. Casual observations of snow falling from trees after storms might indicate that much of the intercepted snow is returned to the snowpack and little is lost to the atmosphere. The sublimation of snow intercepted by the canopy is influenced by wind, humidity, and temperature (Miller 1966; Hoover and Leaf 1966; Schmidt et al. 1988; Lundberg and Halldin 1994). In addition to being sublimated to the atmosphere, intercepted snow may be added to the snow pack by falling from bending branches (Schmidt and Pomeroy 1990), or by falling from wind disturbance, or drip following melt (Meiman 1987). The rate of interception is non-linear; observations indicate a variable curve whereby interception accelerates during a storm as snow becomes lodged in needles. Interception then tapers off as the needle surface area becomes saturated (Hoover and Leaf 1967, Satterlund and Haupt 1967). Proportion of snowfall intercepted has been shown to increase with windier conditions near freezing, with numerous smaller storms, and in areas that receive less precipitation (Schmidt and Troendle 1992). Detailed recent studies with electronic snow particle counters have shown that interception of snow occurs primarily within the upper canopy; and that the post-storm plumes of snow fallen from canopies adds little to the snowpack (Troendle et al. 1988; Schmidt and Troendle 1992). A thorough interception budget study showed that of the 50% of snow intercepted by a forest canopy, 55-60% was sublimated, resulting in a 27-30% decrease in SWE of underlying snowpack (Kolesov 1985). This is in general agreement with the average figure of a 30% decrease in SWE from clearing to dense forest (Meiman 1970).

Complexity of Response. The degree to which vegetation influences snow varies. This magnitude of vegetation effect "signal" can be changed by climatic factors as well as the meteorological factors of the storm event. Wind speed, air temperature, and humidity can affect interception and sublimation (Potts 1984; Schmidt and Pomeroy 1990; Schmidt and Gluns 1991; Schmidt and Troendle 1992; Lundberg and Halldin 1994). For example, a stronger wind gives a flatter trajectory for falling snow particles, creating a greater canopy surface area in which to be intercepted (Troendle et al. 1993). Furthermore, some research indicates that these canopy–snow relationships do not hold steady from one year to another (Anderson 1969; Golding and Swanson 1986; Toews and Gluns 1986; Hardy and Hansen-Bristow 1990), probably due to changing meteorological factors which affect canopy interception and subsequent sublimation (Wheeler 1987).

Vegetation

Hardy and Hansen-Bristow (1990) studied the impact of forest growth upon snow accumulation. That study found a significant inverse relationship between age and snow accumulation during one season, but not the following season. My study extends the research Hardy began as a master's student to include a wider range of ages and canopy densities, not solely young and intermediate growth stands. It also incorporates the use of cover types (or successional stages) identified by Despain (1990) and utilized by Farnes and Hartman (1989) to relate to snow accumulation. Very limited research exists comparing the effect of different types of forests upon SWE. Masked within canopy–snow relationships are such factors as species type, overstory structure and height, and stand age.

Canopy–snow relationships are likely to be sensitive to regional climates as well as forest species and habitat type (Farnes and Hartman 1989). The study site, Tenderfoot Creek Experimental Forest, serves to supplement watershed knowledge because of its lodgepole pine (*Pinus contorta var. latifolia*) composition as well as its representativeness of the Northern Rockies. Lodgepole pine habitats cover an estimated 5.3 million hectares in commercially loggable forest (Koch and Barger 1988), and lodgepole pine is the dominant species in 60% of forested communities in Yellowstone National Park (Despain 1990).

Fire

A more subtle human-induced landscape change, and one that can have a significant effect over time and large areas, is the response of the forest to fire suppression. Natural fire occurrences in a subalpine forest typically results in a landscape scale patchwork of different age stands, with each stand differing in age by a small amount (Fischer and Bradley 1987; Despain 1990; Arno et al. 1993). Fire suppression practices may halt this natural fragmenting process and produce a forest with a higher mean age (Fischer and Bradley 1987) that only burns every 150-300 years or more (Despain 1990). Fire may be the sole agent in maintaining a seral stage of lodgepole pine, although in some areas growth conditions are too harsh for other conifer species to thrive (Fischer and Bradley 1987). Fire frequency controls several factors that in turn affect snow accumulation, including canopy density, tree height, forest structure, and species composition.

Radiation Effects

Radiation is another factor influencing snow water equivalent. Dense canopies shade the underlying snowpack from shortwave radiation and radiate longwave radiation to the snow (US Army Corps of Engineers 1956; Bohren 1972; Male and Gray 1981). Snowpack shaded by an overstory has been observed to melt out two weeks later than snowpack in openings (McCaughey pers. comm). Radiation and heat fluxes are difficult to measure and poorly understood within the microclimate of the forest canopy. Increased incoming radiation and trapping of outgoing radiation melts snow, thereby enhancing snow ablation (Dunne and Leopold 1978). Additionally, the degree to which radiation is a factor on snow accumulation is highly dependent on slope and aspect (Haupt 1979; Farnes and Romme 1993; Troendle et al. 1993). The affect of radiation and snow ablation is limited during the winter and early spring until it increases sharply in late spring (Dunne and Leopold 1978). This study limits its scope to the factors affecting peak snow accumulation.

Runoff

Many studies have used watershed runoff as an indicator of increased snow accumulation. If using runoff to estimate snowpack, there are several additional factors including soil moisture recharge and evapotranspiration which must be considered. These factors will typically attenuate any localized increase in snowpack SWE. Such attenuation may be responsible for the marginal 9% gains in runoff noted at the Fraser Experimental Forest after clear-cutting. Runoff efficiency was estimated at 25% of actual SWE increase in a study in the Northern Rockies due to losses such as recharge and evaporation (Farnes and Romme 1993).

## Summary

Previous studies have outlined the factors that affect snow water equivalent of snowpack beneath forested canopies. Principle among these is the influence of the canopy density upon snow interception. Snow dynamics in and around clearings and clear-cuts has been well studied. Little research has been conducted, however, on the influence of various successional stages and corresponding canopy differences upon snow accumulations. The patchwork of different aged stands and species that cover mountain watersheds has been strongly controlled by fire suppression this century. This study examined the role that a range of successional stages in a lodgepole pine forest played in influencing snow accumulation. Peak snow accumulation measured by snow water equivalent is a critical measurement from a watershed perspective, providing an approximate measure of the amount of water that may be added to a basin's precipitation budget from winter snowfall. It was hypothesized that a non-linear curve exists relating successional age to changes in snow accumulation (Figure 1c). This curve is an inverse of the successional age–canopy relationship (Figure 1b).

# METHODS

In order to develop a relationship between successional stage and snow accumulation, snow water equivalent had to be measured under stands of differing ages. Sufficient measurements had to be made at each stand to capture the range of variation and produce a representative mean. Canopy density and basal area were measured for each stand to find the underlying cause behind the variation snow water equivalent between stands. The following sections of this chapter describe where these stands were located and the methods used to measure snow water equivalent and forest variation.

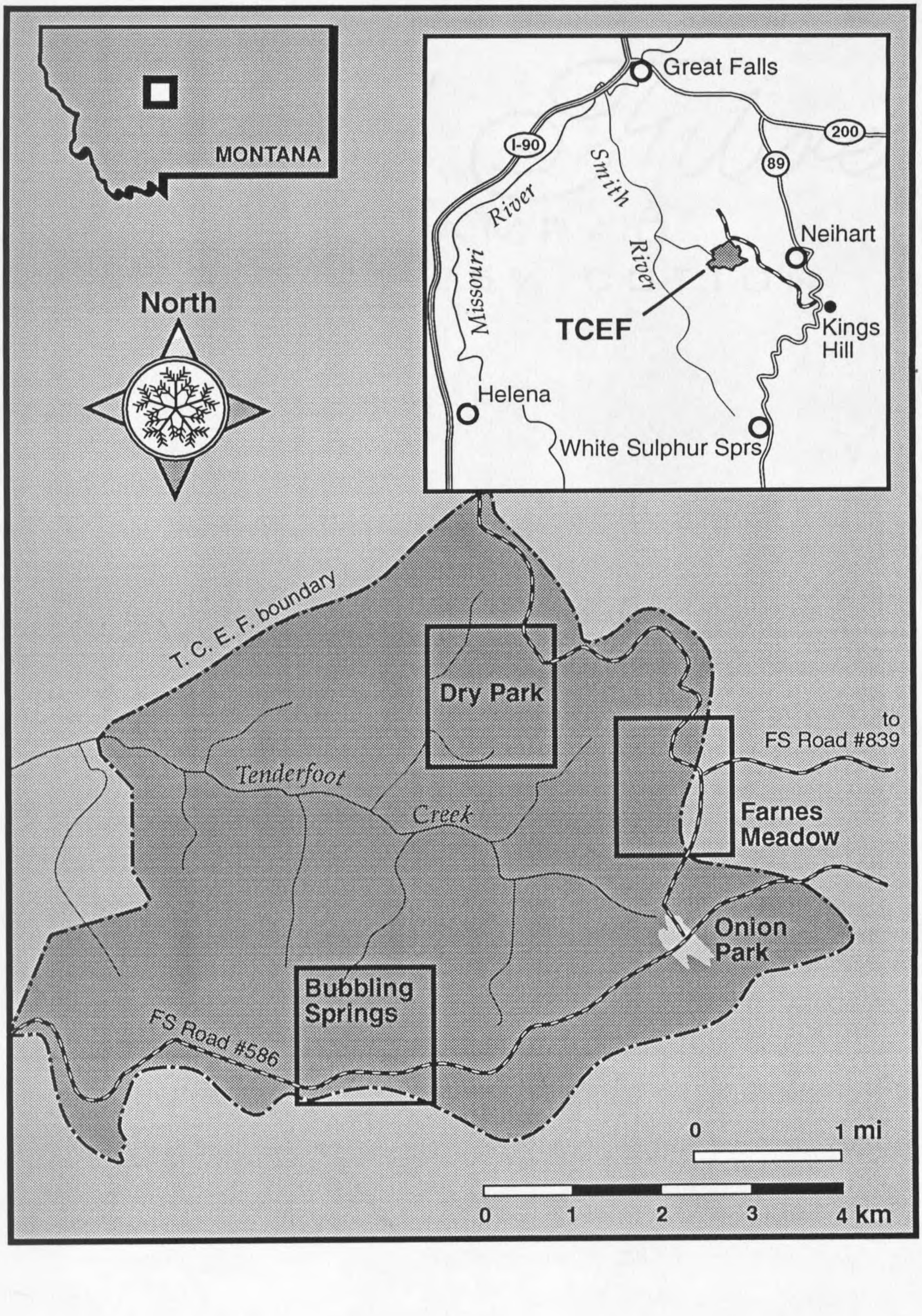
## Study Area Description

### Watershed

This study was conducted at the Tenderfoot Creek Experimental Forest (46° 55′ N, 110° 55′ W), in the Little Belt Mountains, 65 km south-southeast of Great Falls, Montana. The Tenderfoot Creek Experimental Forest (TCEF) is administered by the Intermountain Research Station's Forestry Sciences Laboratory in Bozeman, Montana. The 3,693 ha. (9,125 acre) watershed, part of the Lewis and Clark National Forest, is monitored with instrumentation to measure hydrologic conditions and effects of land use (Farnes et al. 1995).

Tenderfoot Creek drains from the plateau-like crest of the Little Belt Range toward the west–northwest (Figure 2). A steep incised canyon occupies the center of the TCEF, while the tributaries and eight study plots lie in a gentle terrain of 5% to 15% slope. The experimental watershed encompasses the

**Figure 2**
**Map of Tenderfoot Creek Experimental Forest (TCEF)**



headwaters of Tenderfoot Creek, with elevations ranging from 1800 m (6000′) to 2350 m (7800′) (Farnes et al. 1995). The watershed is instrumented with precipitation gauges, stream flow gauges, weather stations and snow pillows.

Climatically, the Little Belt Mountains can be considered an island range of the Great Plains. Snow density is intermediate, lying between the slightly drier snows of the Wasatch and Front Ranges of Utah and Colorado, and the moister conditions found in northern Idaho and northwest Montana (Kosnik 1995). Mean July temperature for the upper part of the watershed is 20.5° C (69° F), while mean January temperatures falls to -0.5° C (-1°F) (Farnes et al. 1995). Snow covers the ground from early October till mid May (McCaughey, pers. comm.).

The watershed is characterized by its lodgepole pine-dominated forests, with a mosaic of different age stands and intermixed with a few natural meadows. TCEF has had no commercial harvesting. The fire history reveals numerous, small burns that have occurred periodically throughout the previous four centuries, with few fires in the last 100 years (Farnes et al. 1995). As a result, the average stand age in the watershed is somewhat higher than it was 100 years ago prior to fire suppression, and old-growth stands are more common than expected in a natural setting where fires are allowed. Studies elsewhere in Montana have shown a marked decrease in lodgepole pine and an increase in subalpine fir associated with the recent infrequency of fire (Arno et al. 1985, Arno et al. 1993).

Study Plots

Snow accumulation was monitored in eight study plots representing five different age classes (Table 1). These plots were contained within three areas of

**Table 1**
**Description of the Eight Stands**

| Area | Stand | Age | %L* | %L/W | %L/S | %S/L | %S | Stage** | Elevation+ | Slope++ | Aspect++ | Est.Precip+++ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BUBBLING SPRINGS | | | | | | | | | | | | |
| | Ba | 123 years | 0 | 0 | 51 | 41 | 8 | LP2.5 | 7390' | 4.5° | 315° | 36.5" (93 cm) |
| | Bb | 415 years | 0 | 0 | 3 | 92 | 5 | SF | 7380' | 3° | 290° | 36.5" (93 cm) |
| DRY PARK | | | | | | | | | | | | |
| | Da | 49 years | 4 | 96 | 0 | 0 | 0 | LP0.5 | 7380' | 7° | 260° | 36" (91 cm) |
| | Db | 123 years | 58 | 0 | 42 | 9 | 0 | LP1.7 | 7460' | 6° | 250° | 36" (91 cm) |
| | Dc | 270 years | 70 | 0 | 30 | 0 | 0 | LP | 7350' | 13° | 270° | 37" (94 cm) |
| FARNES MEADOW | | | | | | | | | | | | |
| | Fa | 75 years | 61 | 0 | 38 | 0 | 0 | LP1.0 | 7440' | 6° | 225° | 37" (94 cm) |
| | Fb | 123 years | 15 | 0 | 85 | 0 | 0 | LP2.0 | 7400' | 6° | 260° | 37" (94 cm) |
| | Fc | 270 years | 0 | 0 | 41 | 58 | 0 | LP3.0 | 7390' | 6° | 280° | 37" (94 cm) |

* Percentage component of different species
L pure lodgepole pine
L/W majority lodgepole pine with some whitebark pine
L/S majority lodgepole pine with some subalpine fir or Engelmann spruce
S/L majority subalpine fir or Engelmann spruce with some lodgepole pine
S pure subalpine fir/ Engelmann spruce

** Lodgepole pine community successional stages (after Despain, 1990)
LP0 recently burned with lodgepole pine colonization
LP1 dense, young stands of small diameter lodgepole
LP2 intermediate age stands with Engelmann spruce/ subalpine fir understory
LP3 ragged canopy with larger component of Engelmann spruce/ subalpine fir
LP climax lodgepole pine in a mature stage, few understory trees
SF climax stands of Engelmann spruce and subalpine fir

\+ Estimate from USGS 1:24,000 topographic map
++ Slope and aspect measured with "Brunton" type compass
+++ Estimated precipitation from 1:50,000 map developed by Phil Farnes (Farnes et al. 1995)

the watershed. All plots have similar elevation, westerly aspect, gentle slopes ranging from 3° to 13° (Figure 3 and 4), and are positioned downslope of the rim of the watershed to minimize the topographic influences upon snow accumulation (Figure 4).

Plots representing the range of forest ages and species compositions were selected based on a fire history map of the watershed (Farnes et al. 1995). The plots included a range of ages, as well as stands of similar age but of different species composition (Table 1). Topographic factors were controlled to the extent possible, thereby isolating vegetation as the snow accumulation variable. Previous research indicates that the minimal topographic variation present in this study may account for up to a 10% variation in SWE (Farnes and Romme 1993).

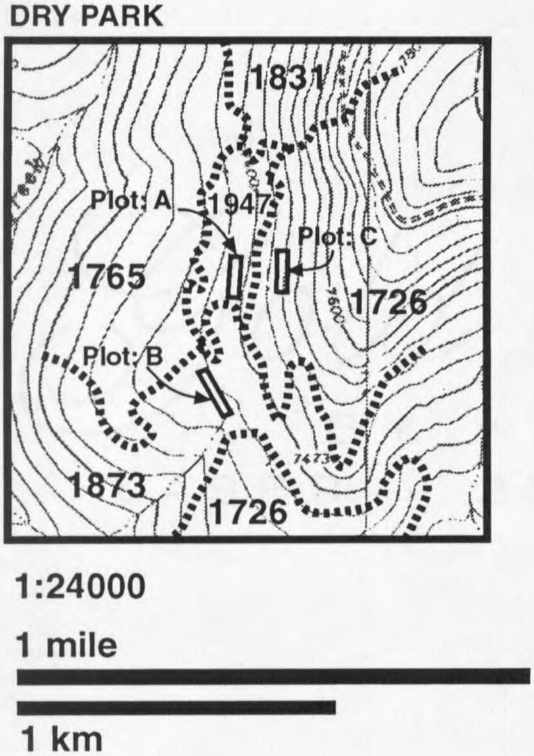
All plots lie near the 90 cm isohyet of annual precipitation, with snow constituting approximately 50% of the total annual precipitation (Farnes et al. 1995). The habitat type is *Abies lasiocarpa/Vaccinium caespitosum* (ALBA/VASC), or subalpine fir/grouse whortleberry phase (Pfister et al. 1977). Subalpine fir is climax in this habitat type, but periodic fire typically maintains a seral stage of lodgepole pine throughout most of the watershed (Fischer and Bradley 1987).

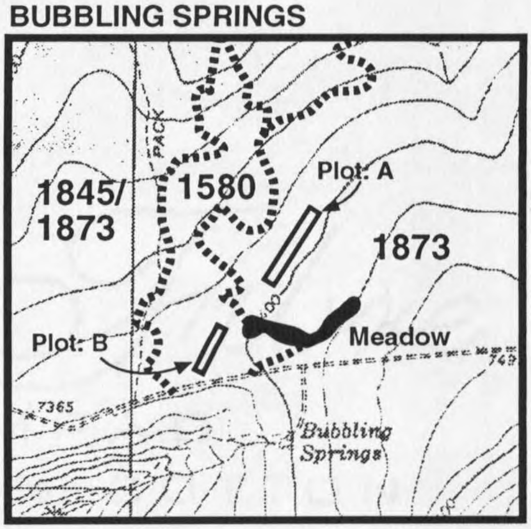
## Study Plot Design

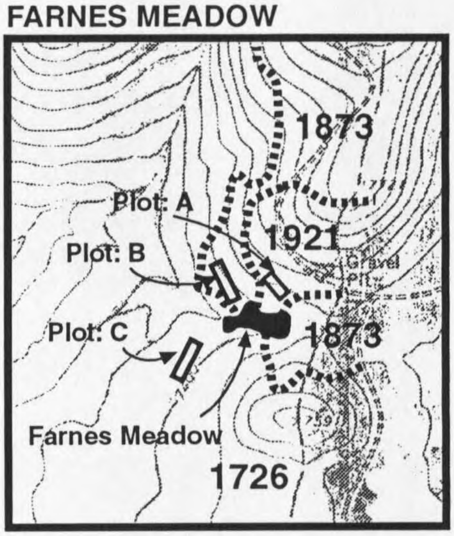
### Plot Establishment

In order to capture and represent the range of variation in canopy and mean canopy structure, a systematic grid was established within each of eight stands. A stand is defined as a contiguous area of trees having the same age and structure. The grid was three sampling points wide by x sampling points long, x

**Figure 3**
**Location of Eight Plots within TCEF**

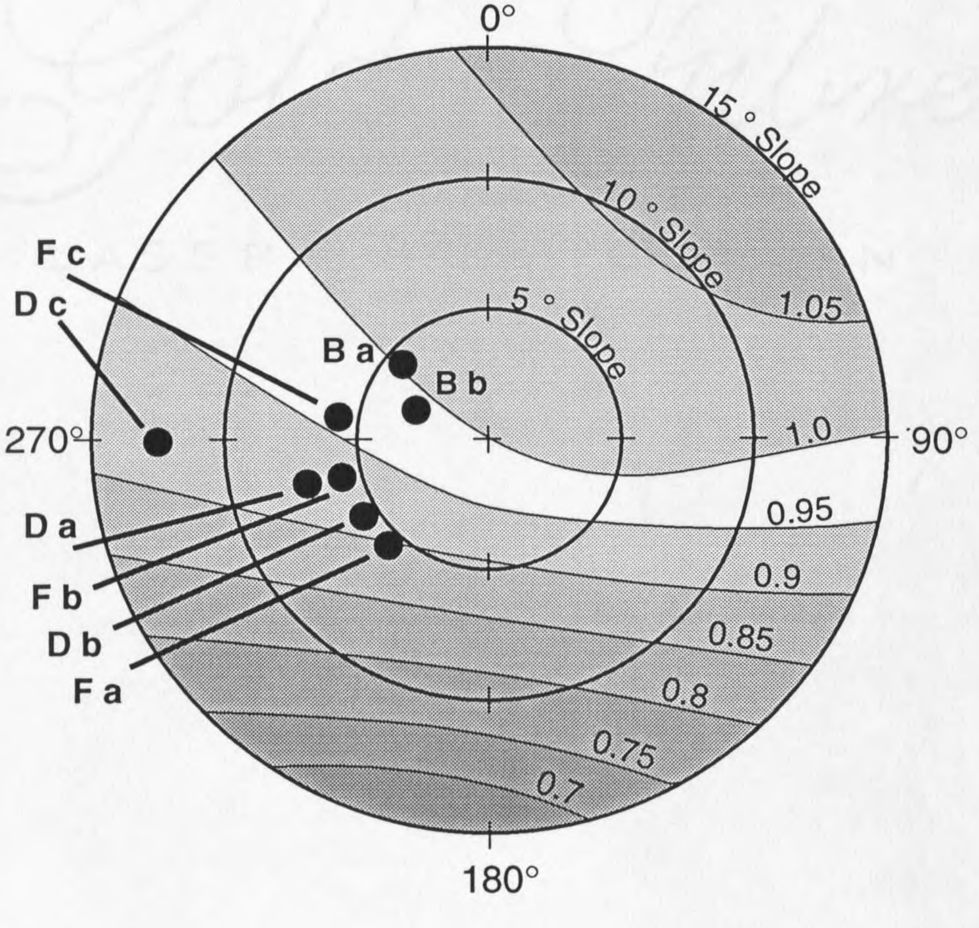



Dashed lines show distinct stands according to a fire history map (Farnes et al. 1995). Bold dates indicate time of last stand-destroying burn.

**Figure 4**
**Aspect of the Eight Stands**

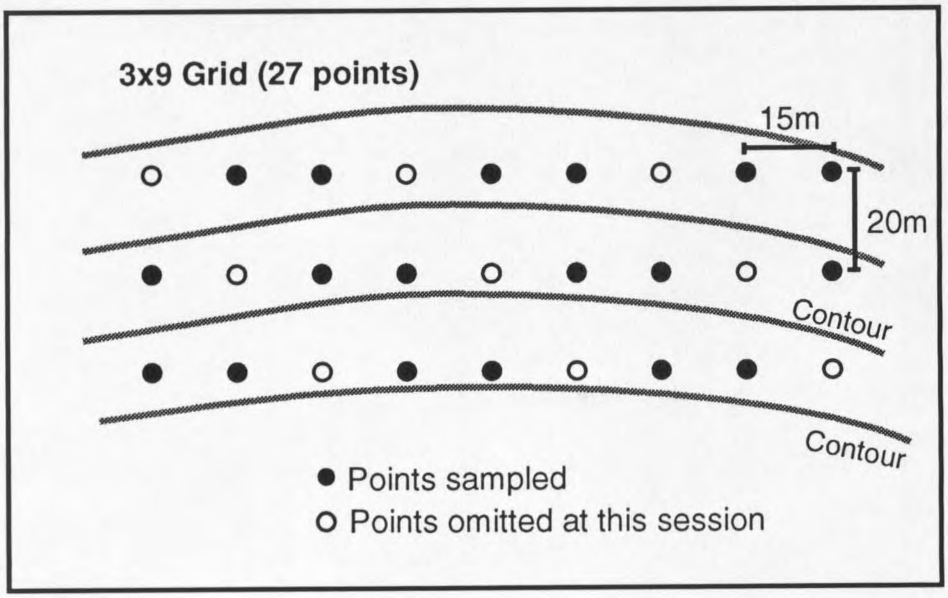



Aspect and slope of the eight study plots (stands) are shown above. Shaded areas represent expected snow water equivalent adjustment factors. Utilizing a snow–topography relationship developed for an area 200 km south of this study area (Farnes and Romme 1993). Based on this relation, topographic variation between stands in this study account for less than 10% change in snow water equivalent. Stands are abbreviated with two letter identifier; see Table 1.

being a multiple of 3. More sample points were used in areas with a higher canopy variance (estimated visually), but typically they were 3 by 9 points to total 27 sample points, with the number of sample points within each plot varying from 18 to 63 (Figure 5).

The three rows of the grid were spaced 20 meters apart and columns were spaced 15 meters apart. Rows were parallel to contour. The spacing dimension was chosen to minimize autocorrelation between points. Toews and Gluns (1986), Hardy (1990), and Skidmore (1994) found that 10 m or greater spacing is required to minimize violating the independence assumption. These were designed to give good statistical power in differentiating minor differences between snow accumulation between stands (Spittlehouse and Winkler 1996). A total of 270 snow sample points were established within 8 grids.

**Figure 5**
**Grid Layout within each Plot**



A buffer area equivalent to two tree heights was delineated just within the perimeter of each stand. The purpose of the buffer was to reduce potential wind redistribution effects from neighboring clearings or stands and thus reduce within stand variability (Gary 1974; Troendle and Meiman 1984). A randomized design element was used for plot layout to avoid statistical bias. A stake was placed at the centroid of the buffered stand. A coordinate pair , for example row 2, column 9, from the grid was randomly chosen for the centroid stake; the remainder of the grid generated out from that stake. Grids were always aligned lengthwise parallel to contours to minimize elevational effects.

Sampling points within the plot were marked by a 0.8 meter re-bar stake driven 0.4 meters in the soil. A 2.0 m PVC pipe marked by bright orange paint was slid over the metal bar. Points of the grid were located along straight lines and equally spaced except where trunks or ground litter interfered with sampling. In such cases, the point was moved perpendicularly uphill until suitable ground existed (usually less than 2 meters).

Stand Characteristics

In addition to the age of each stand, gleaned from the fire history map (Farnes et al. 1993), canopy density, species composition, and basal area were quantified for each plot. These structural measures were as important for interpreting the impact of forest cover upon snow interception. Measurements were made in the summer of 1996, following snow sampling.

Canopy. Two instruments, a spherical densiometer and a photocanopyometer were employed to measure canopy density (or canopy cover). A spherical densiometer was used to estimate canopy cover. It was placed upon a leveled tripod 1 m off the ground. The ratio of dots on the spherical mirror surface obscured by vegetation gives the canopy cover as a percentage. Leveling the mirror and keeping the eye a consistent 30 cm from the instrument was critical for accuracy. The average of measurements from the four cardinal directions was used for analysis. This instrument's cone of measurement has a radius of approximately 45°. Repeating a second measurement for ten different samples yielded values differing by less than 3% in all ten cases.

The second instrument used for canopy cover estimation was the photocanopyometer (Codd 1959). This instrument, placed on the same tripod head as the spherical densiometer, photographs the forest canopy. Aimed a the zenith, the photocanopyometer's view cone is similar to the densiometer's, 45°, but could be masked to more narrow view angles for analysis purposes unlike the spherical densiometer.

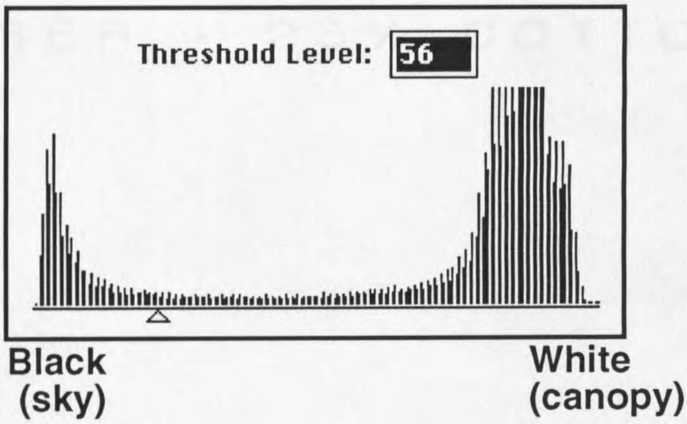
Traditionally, photographs from the photocanopyometer are analyzed with a dot overlay method for evaluating canopy coverage. However, for increased accuracy and precision, a new method of analyzing the photograph was employed. The film negatives were first scanned with a flatbed scanner at 150 dots per inch and manipulated in the image application Adobe Photoshop. The lightest and darkest pixels were saturated to white and black, which adds contrast to the image. A histogram of the image was produced, showing the bimodal distribution of light and dark areas of the image. The low point of the curve between the two histogram modes was used as the criteria for dividing the image into black and white (Figure 6). This resulted in a nominal image representing presence (white) and absence (black) of canopy that accounts for variation in canopy translucence and light reflection.

The images were then duplicated and masked. One was masked to a 45° radius cone, the other to a 30° cone (Farnes, pers. comm., indicated that the 30° cone was a better determiner of canopy that affects snow) (Figure 7). Finally, the pixels in the black and white areas were counted and ratioed to give a canopy cover in percentage. This method was very accurate, within 1%, for dense spruce canopies. Lodgepole pine stands with open canopies often had small openings near and away from the zenith. These open lodgepole pine images were sensitive to the exact placement of the threshold. In worst case scenarios with a poorly exposed photograph, repeating this procedure yielded values ranging within 8%. Such low precision was rare and limited to stands Bubbling Springs A and Dry Park C.

Basal Area. Stem density was measured with a simple "Cruz-All" instrument to determine basal area. A 5 BAF (Basal Area Factor, 5 square feet of basal area per acre) gauge was used to measure individual point basal area. Measurements were taken positioned exactly at the snow stake, as with the other instruments. The number of trees meeting or exceeding the width of the instruments gauge, typically 30-50, were counted and multiplied by the BAF, producing a stem density measurement. Basal area data is spatially autocorrelated, as measurements at each stake counted trees also included at the previous and next sample.

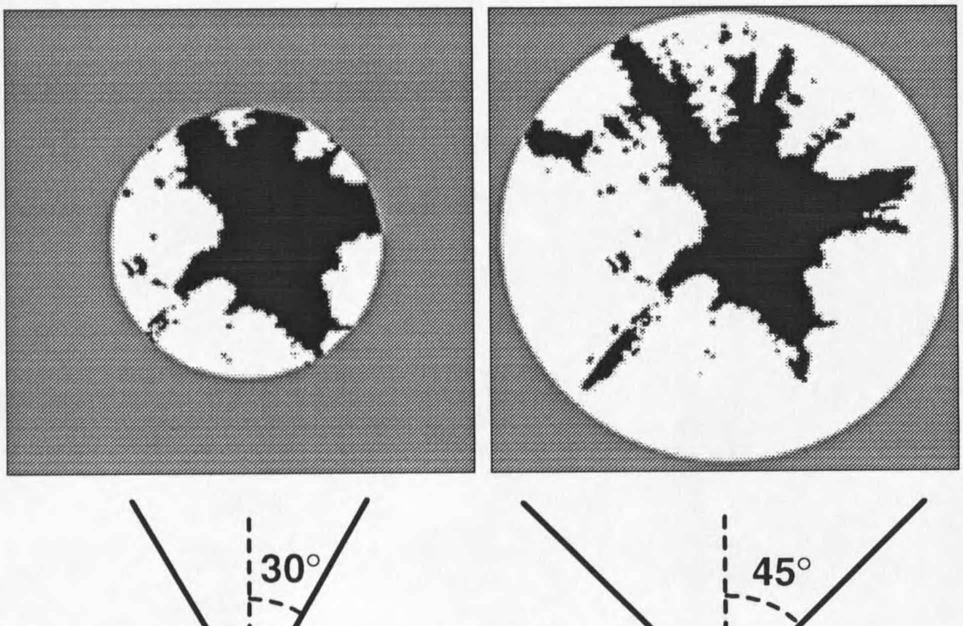
Species Composition. Determining species composition was important because succession in a subalpine fir habitat type involves large changes in species composition as well as canopy cover. Tree species were noted for each tree during basal area measurements.

**Figure 6**
**Histogram of Photocanopyometer Image**




Small triangle marks the threshold of black to white. The threshold digital number (56 in this case) varied with the shape of the curves. The threshold point was always at the right tail of the left (black) mode. The low noise bridging the two modes was reflected and scattered light from branch ends, and was included in the canopy area.

**Figure 7**
**Photocanopyometer Images with Masks**




At left is the thresholded image with a mask delineating the 30° radius cone. At right is the same image masked to the larger 45° cone.

Five categories were constructed, ranging from pure lodgepole pine to pure Engelmann spruce or subalpine fir (Table 1). The purpose of creating five simplified categories was to speed field data collection of species information. Composition was considered mixed if one or more of another species was present in the basal area count, which typically included 30-50 trees. The majority of sample points were either lodgepole pine dominated or spruce/fir dominated. One category, lodgepole pine dominated with minor amounts of whitebark pine, only occurred at the Dry Park A stand. This sapling-pole stand was the youngest in the study and in the watershed.

Qualitative Description. Primitive field notes describing the soil moisture, soil parent material, tree height, presence of understory growth, and other miscellaneous characteristics were made for each plot. While these qualitative descriptions were not used in the statistical analysis, they were useful in suggesting future research.

## Data Collection

### Snow Measurements

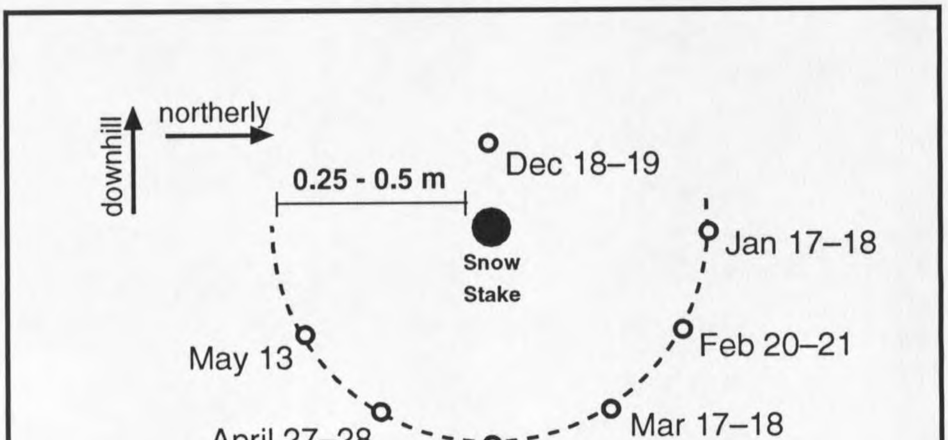
Snowmobiles provided access to TCEF during the winter. Operations were based from the Forest Service cabin at Kings Hill, the summit of Highway 89. All plots were located 0.25 to 1 km from snowmobile trails. Final access to the plots required snowshoes. Access to the three Dry Park plots was more difficult (and sometimes impossible) than the others, due to drifting conditions along the narrow access trail.

Instruments. At each snow survey stake, snow was sampled using a US federal snow sampler. Depth was recorded to the nearest half inch and weight was recorded to the nearest quarter ounce. Accuracy of the federal snow sampler has been estimated at 4% to 11% (Goodison et al. 1981). The 1.49" diameter of the tube is designed such that ounces of weight are equivalent to inches of snow water. Because this method of snow sampling is destructive to a small area of snow, a prearranged pattern was established to avoid repeated sampling of disturbed snow (Figure 8).

Density measurements derived from this data were important in checking the sampling procedure. Density varies little from point to point, thus unusual values indicated instrument or sampler error. Anomalies, such as lack of a soil plug, that may result in large error were noted (Appendix B).

**Figure 8**

**Non-Destructive Sampling Pattern**



Temporal Interval. Seven sample periods were taken throughout the season. Sampling sessions 1 (Dec. 18, 19), 2 (Jan. 17, 18) and 3 (Feb. 20, 21) were intended for pilot studies. Sessions 4 (Mar. 17, 18), 5 (Apr. 9, 10), 6 (Apr. 27, 28) and 7 (May 13) captured the range of peak accumulation. Logistical weather problems prevented a consistent interval between sample sessions. It was also intended that samples be collected between storm events to minimize snowfall driven differences in accumulation between samples within the same session; however, this goal was not always met.

Sampling Type. A hybrid sampling technique utilizing a rectangular lattice and omitting one third of all points was used (Jessen 1975). The pattern of omission rotates systematically at each sampling session (Figure 5). This method is more efficient than a random sampling design and provides a greater spatial coverage of each stand than repeated sampling of the same point. This method improved chances of completion during short winter days and between storms, which was an initial concern.

## Contributing Data

Two adjacent snow telemetry (SNOTEL) stations provided long term averages and were used to construct a record of snow accumulation during the study (Figure 9). The higher elevation Spur Park SNOTEL site and lower elevation Deadman Creek SNOTEL site bracket the conditions found at TCEF. The experimental forest has a snow pillow at Onion Park in both forested and open settings. This instrument should correlate well to conditions at individual plots; but it was only recently established and lacks a long term average (Figure 10).

Figure 9

**1995-96 Snow Season Deviation from Average Based on SNOTEL Stations**

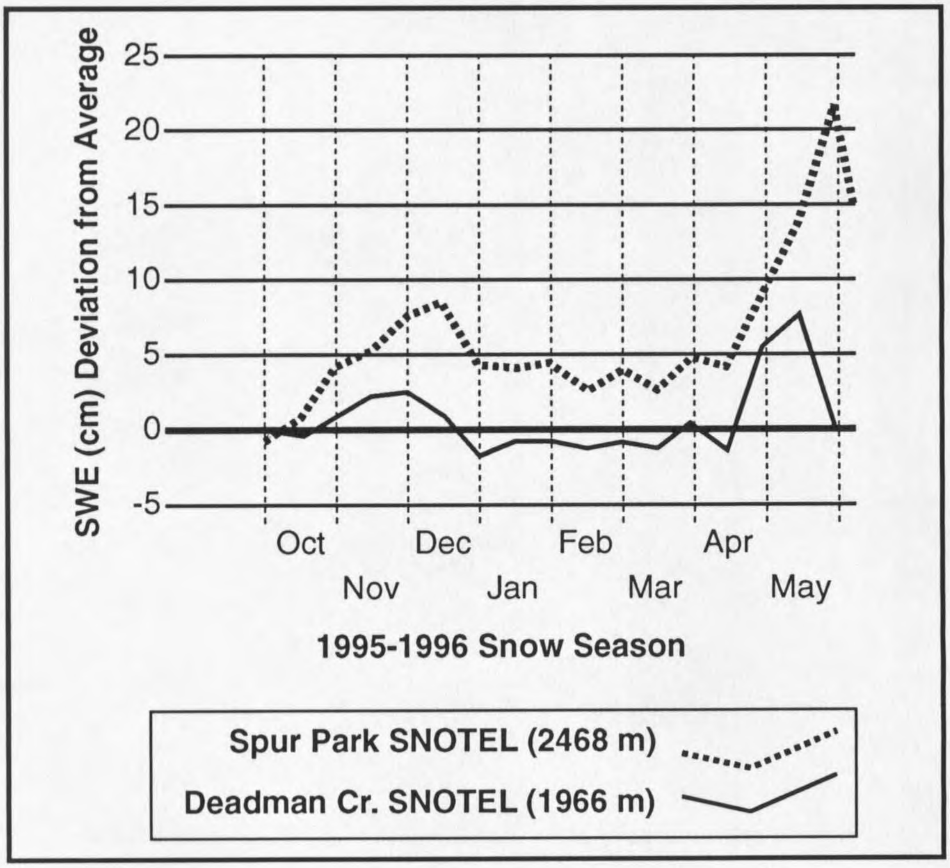
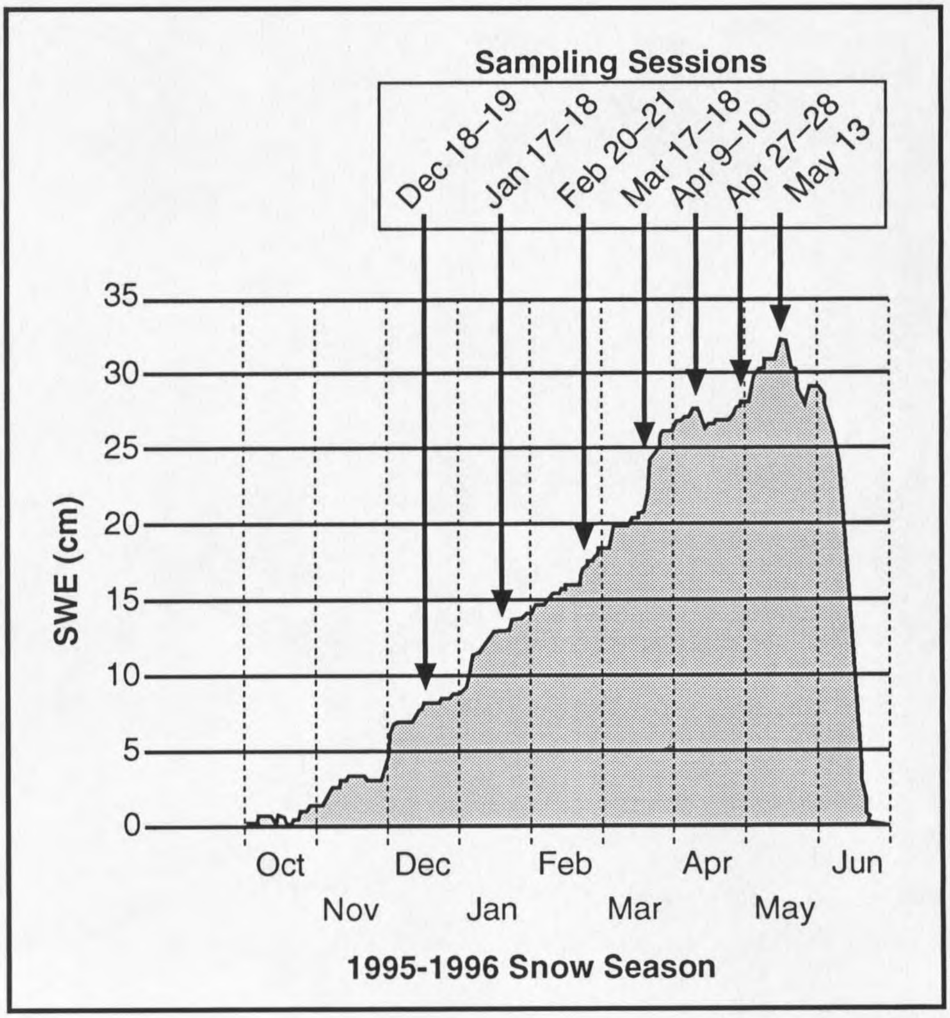


**Figure 10**

**1995-96 Onion Park Snow Pillow (Showing sampling sessions)**



# Data

Snow water equivalent was measured throughout the season, but only one sampling session thought to be the most representative of peak accumulation was used in the analysis. To determine the affects of forest structure upon snow accumulation, I measured basal area and canopy cover to characterize the forest.

## Snow Water Equivalent

### 1995-96 Snow Season

The study season had greater precipitation than normal, based on a 30 year average of the Spur Park and Deadman Creek SNOTEL sites. A small spike around early December and a series of storm events beginning at the end of April resulted in a net snow accumulation of 114% of normal for the higher elevation Spur Park and 102% for the lower Deadman Creek (Natural Resource Conservation Service data) (Figure 9). The conditions at TCEF were likely to be between these two in both snow accumulation and temperature since TCEF is bracketed in elevation by these two instrument stations.

Peak accumulation at TCEF was likely delayed one to two weeks past the average peak; although precipitation records within the forest are not long enough to confirm this. Based on short term data from a snow pillow instrument within the watershed, peak accumulation at TCEF would be expected to occur in early April under forested canopies (Farnes et al. 1995). For most of the 270 snow samples, the last sampling period, May 13th, had the highest snow water equivalents. Some samples, however, showed sharp decreases in SWE as well as snowpack density, indicating that substantial ablation had taken place. Logistical difficulties during the May sample session foiled measurements at all three Dry Park plots. For these reasons, the second April sampling on the 27th and 28th was used to represent peak accumulation. This provided a maximum number of data points as well as avoiding the overlap between accumulation and ablation that created unpredictable results in early May.

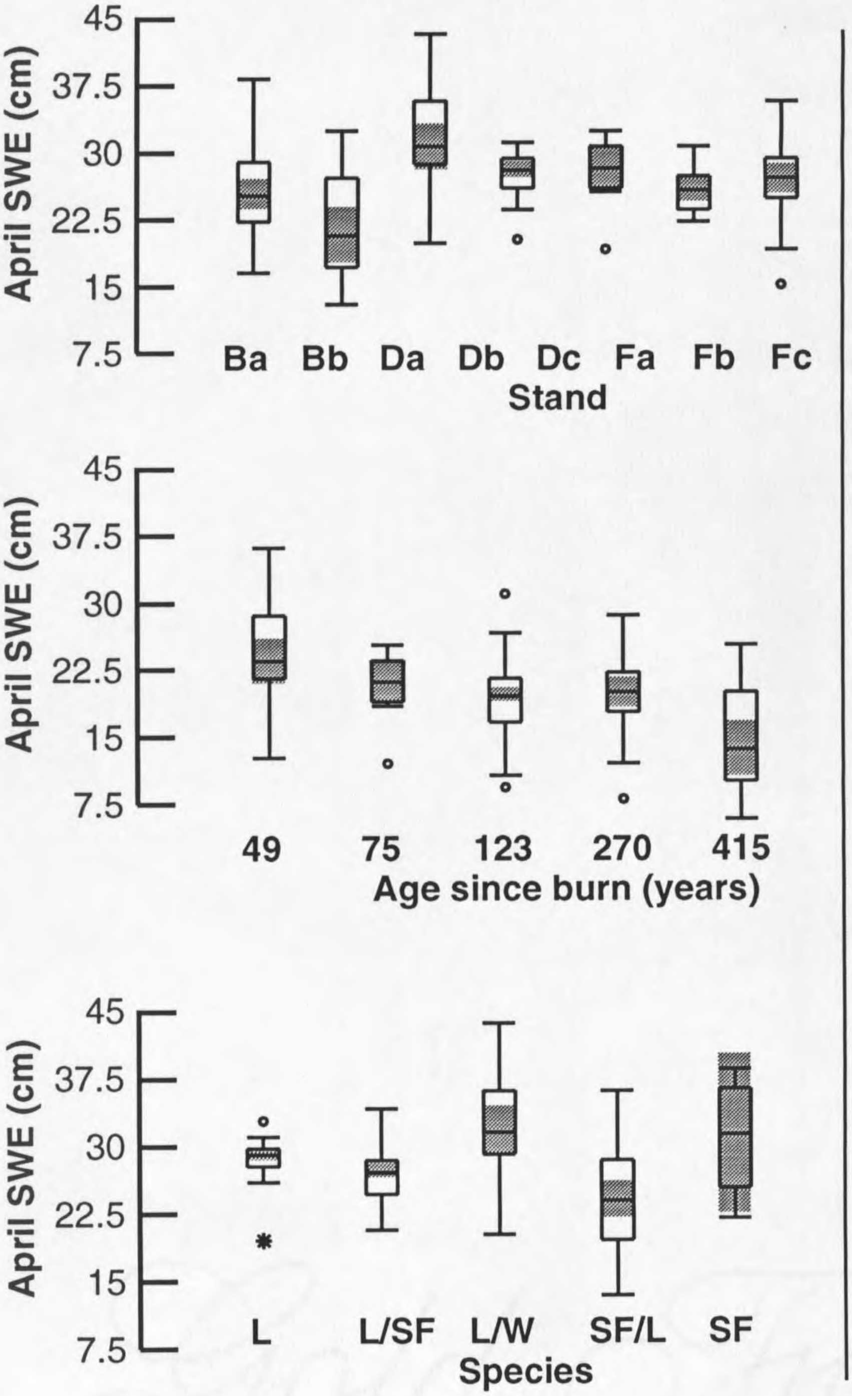
Figure 11 reveals the substantial variation in snow water equivalent measured and compared by individual stands, by age and by species composition on April 27-28. Mean SWE is as low as 22.6 cm and as high as 32.1 cm. A large variation in SWE by age is apparent as are differences between species. The boxplots comparing species may be misleading, since only one stand of a very young age contained the lodgepole pine/whitebark pine (LP/WB) species description, and there are only half a dozen samples defined as pure spruce/fir (SF). This data strongly indicates that snow water equivalent varies between the eight stands representing various stages of growth, composition, and extent of canopy cover. Later, the Analysis and Discussion chapter will explore these underlying factors that are responsible for the variation in snowpack more closely.

## Canopy Density

### Spherical Densiometer

Measurements of canopy density from the spherical densiometer showed little variation from stand to stand, except for the youngest stand (Figure 12). Mean canopy density values ranged from 47% to 70% for mean stand

**Figure 11**
**Box-plots of Snow Water Equivalent by Stand, Age, and Species.**




First letter of stand abbreviation denotes area (Bubbling springs, Dry park, or Farnes meadow). Second letter is the stand identifier, from youngest ‘a’ to oldest ‘c’.

L= pure lodgepole pine

L/SF= lodgepole pine dominated with some Engelmann spruce/subalpine fir

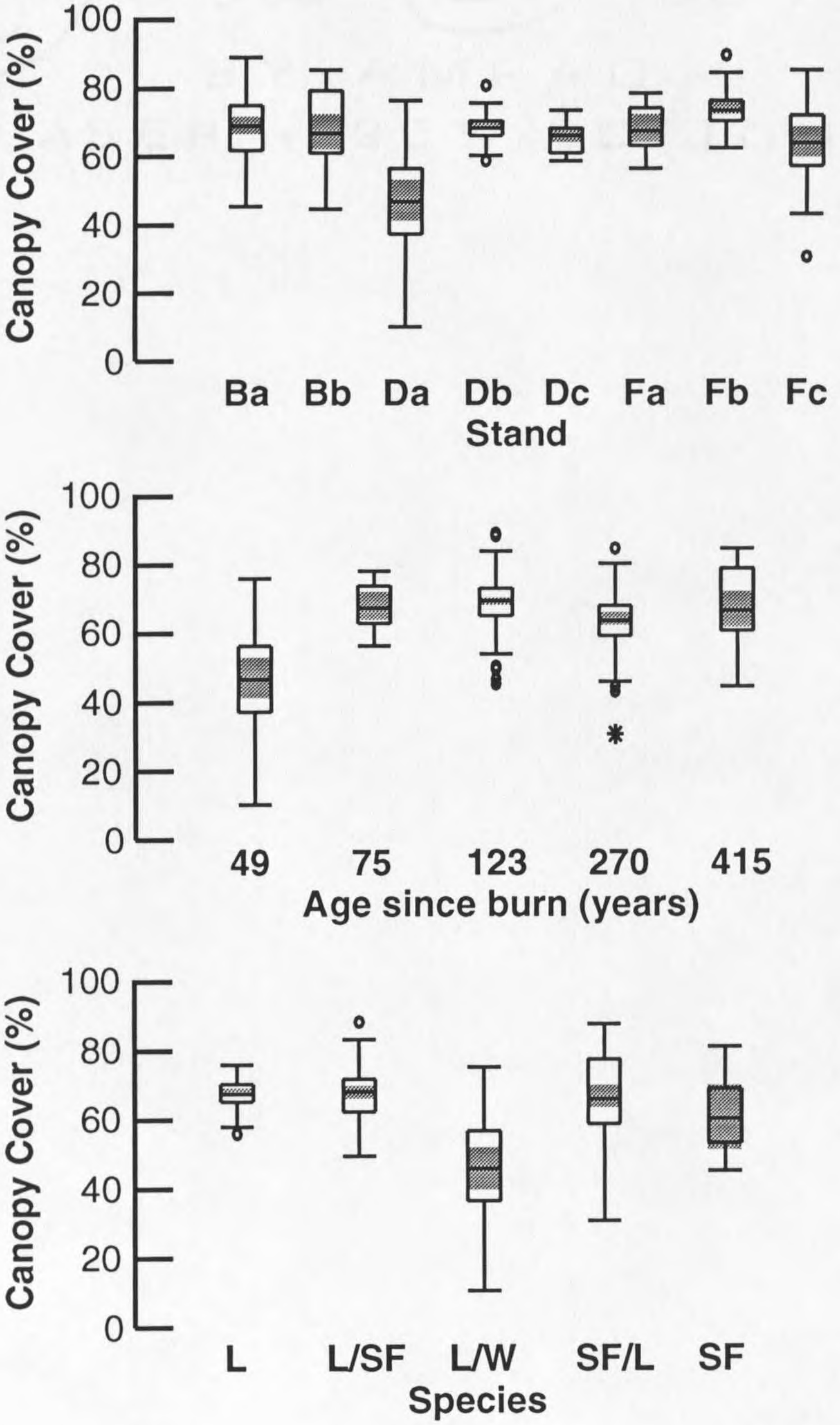
L/W= lodgepole pine dominated with some whitebark pine

SF/L= spruce/fir dominated with some lodgepole pine

SF= pure engelmann spruce/subalpine fir

Boxplots depict median (central horizontal line), 25th and 75th percentile (bottom and top of box) and lowest and highest values (“whiskers”). Outliers beyond the normal distribution of data are shown with circles or asterisks in extreme cases. The shaded portion shows a 95% confidence interval based on medians.

**Figure 12**
**Box-plots of Canopy Density as Measured by Spherical Densiometer.**



measurements. Individual measurements taken at each sampling point ranged from low canopy density (5%) to a very high canopy density (90%).

It was apparent in the field that this instrument was limited in accuracy. Where canopies were thick and dense, as they were with spruce/fir stands, the instrument appeared to have given accurate results; but, fragmented canopies common in lodgepole pine often yielded high values of cover, despite the visual observation that the canopy was comprised of numerous veins and openings. Because of this weakness, the spherical densiometer was omitted from much of the analysis presented here. The photocanopyometer was found to be a better instrument for measuring the canopy, as is discussed below.

Photocanopyometer

The photocanopyometer provided good resolution between stands and more accurately captured the percentage of canopy cover. The eight stands show greater variability in canopy in Figure 13 as compared to Figure 12. Images were masked to both 30° and 45° radius cones of view. Figure 13 demonstrates the variation in canopy density between stands for the 30° view angle of the photocanopyometer. Age and species composition are presented as before.

## Basal Area

Boxplots of the eight forest stands showed substantial variation in stand density between them (Figure 14). Values ranged from 6.0 $m^2$ per ha to 11.2 $m^2$ per ha. Highest median values were found the Dry Park B stand, the 123 years since burn age category, and the lodgepole pine species category. Lowest median values were found in the Dry Park A stand, the 49 years since burn age, and the lodgepole pine/whitebark pine species category (all three of which are the same

**Figure 13**
**Box-plots of Canopy Density as Measured by 30° Photocanopyometer.**

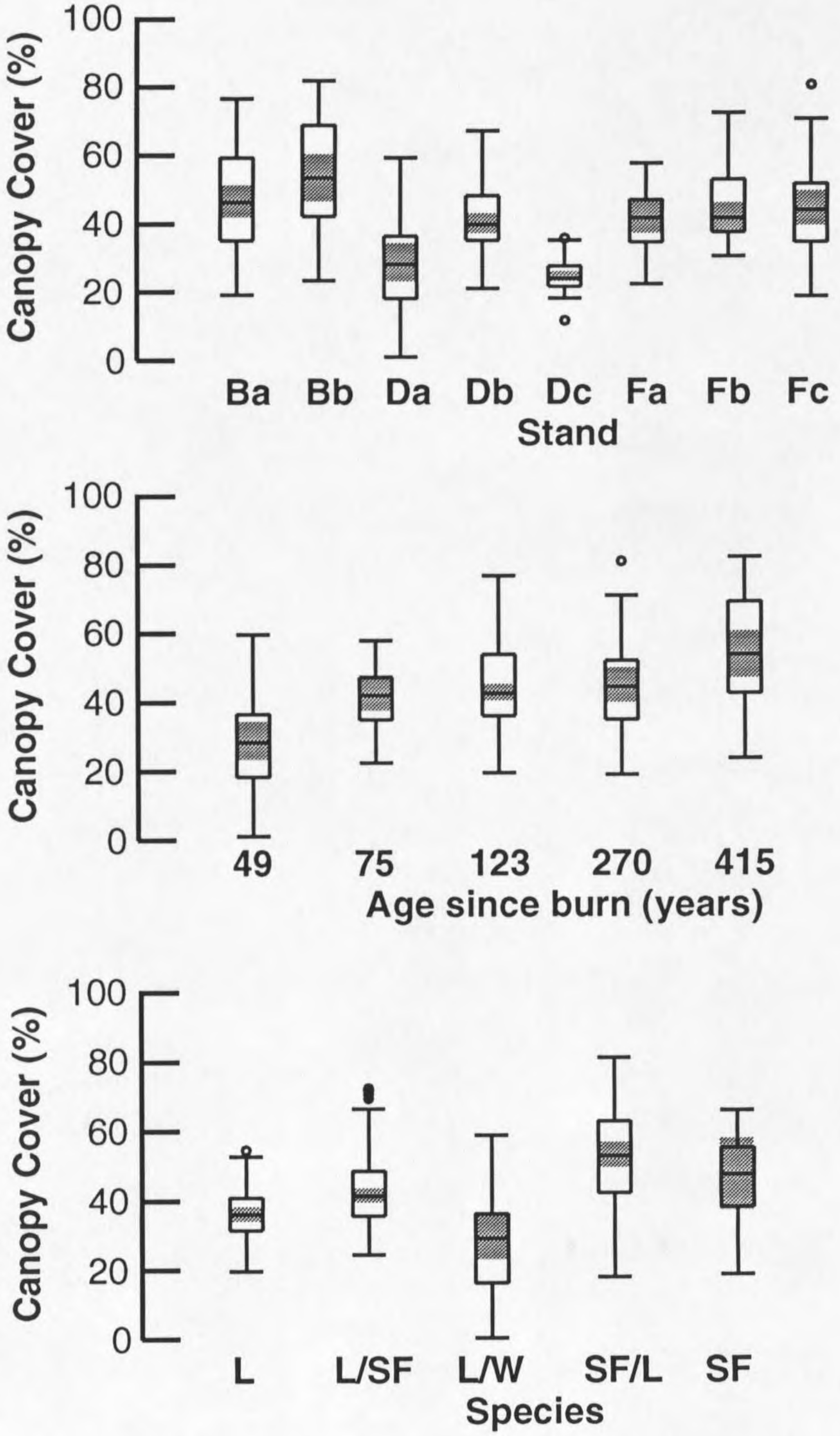
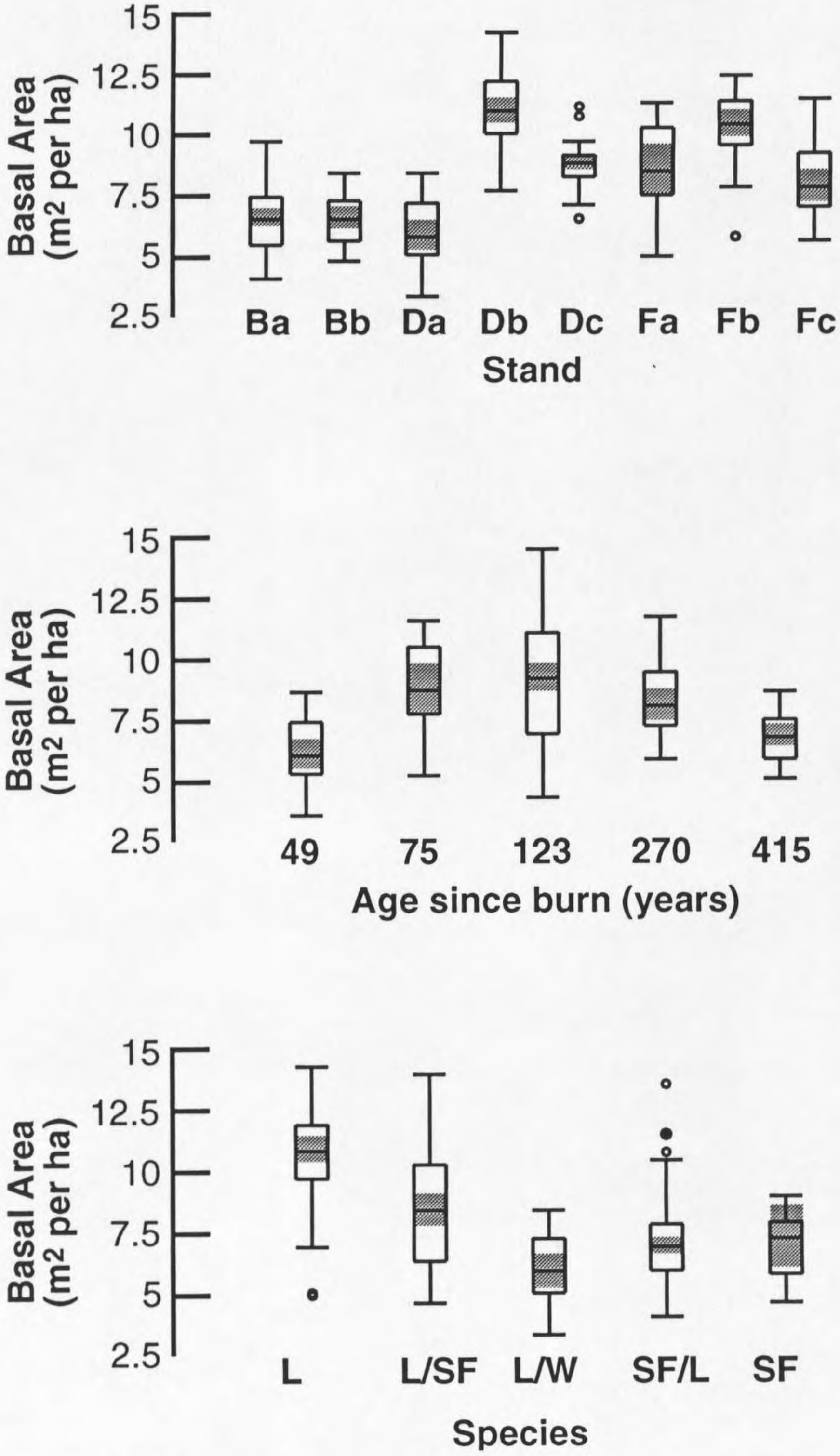


**Figure 14**
**Box-plots of Basal Area by Stand, Age, and Species.**



stand). Highest variability was found at the Dry Park B stand, the 123 years since burn age category, and the lodgepole pine species category. Lowest variability was found at the Dry Park C stand, the oldest 415 years since burn age, and the spruce/fir species category. The Dry Park C stand may have been altered recently by fire, since the adjacent stand downslope was burned intensely in 1947.

# Analysis and Discussion

This chapter describes and examines the relation of forest canopy, structure, and successional stage to snow. All statistics were generated with the application Data Desk (Macintosh version 5.0, Data Description Inc, Velleman, 1996) with the exception of autocorrelation analysis. A confidence interval of $p< 0.05$ was used throughout.

## Spatial Autocorrelation

Most statistical tests assume independence in samples; therefore analysis of snow data began by testing for spatial autocorrelation (GEOEAS, PC version 1.2.1, Int'l Ground Water Modeling Center, Englund and Sparks 1992). SWE data was analyzed for significant differences between plots. All points within a stand were tested for autocorrelation using the April 27-28 sample session. Spatial variograms of the plots indicated that sample points were independent and that there was not an increased likelihood of similar values at nearer points. Thus, the 15-20 m spacing of the plots was sufficient to avoid the problem of auto-correlation. This result was expected, as previous studies had found 10 m and 15 m spacing under forested canopies to be appropriate for snow studies (Hardy and Hansen-Bristow 1990; Skidmore et al. 1994).

# Snow Water Equivalent

## Between Stand Variation

The data presented in the previous chapter clearly shows variation in SWE from stand to stand. A Mann-Whitney U test of medians was preformed,to compliment the visual interpretation of the SWE data presented by Figure 11 (Table 2). This test of differences between medians shows eight stand–to–stand comparisons that are significant. The Dry Park A stand is significantly different from most other stands, while Farnes Meadow A, Farnes Meadow B, and Dry Park C stands are rarely significantly different from others.

The sampling design was intended to minimize area effects (e.g. one stand receiving more snow than another) and wind redistribution effects. Thus, observed differences in SWE between stands may be attributed to forest age, canopy cover, structure, or species composition. These factors affect snow primarily through the process of interception. Following sections of this chapter will discuss the possible reasons for this stand to stand variation in SWE.

## Snow Water Equivalent vs. Stand Age

Initially, I expected age to be the underlying factor in explaining between–stand differences. The highest SWE occurs at the Dry Park A stand, the youngest of the eight. The Bubbling Springs B stand, the oldest stand at 415 years, shows the lowest SWE. The boxplot of age with SWE (Figure 11) shows a general decline with a plateau between the 123 and 270 year age classes. Within the 270 year age class there are two very different stands; one with predominantly lodgepole pine composition (Dry Park C), the other with a high proportion of spruce/fir (Farnes Meadow C) (Table 1). The complexity embedded in the five age classes lead me to investigate the structural differences between stands, with particular attention to canopy cover and species composition.

Snow Water Equivalent vs. Canopy Cover

The photocanopyometer showed a full range of canopy variation, from completely open to completely obscured canopies. The boxplots of Figure 13 depict the changes in canopy between stands. This measurement also shows the greatest difference between ages and species composition. The photo-canopyometer uses a view angle of approximately a 45° radius. By masking the view cone to a smaller 30° radius, previous studies have yielded a greater relationship between canopy cover and SWE (Farnes, pers. comm.). One of the first analyses was to confirm that the masked 30° view was superior to the wider 45° view.

A regression of the two view angles with SWE shows that the 30° view was superior to the 45° view (Figures 15 and 16). The 30° view of the photocanopyometer explains over half the variation in SWE (51%), establishing this forest structure measurement as the principle factor affecting snow accumulation. This is a stronger relationship than has been found in most previous studies. From this regression equation, I inferred a decrease in snow water equivalent of 2.3 cm (6.4 % of max SWE) occurs per 10% increase in canopy density. This equation approximates work done by Farnes and Hartman (1989) of a 5% decrease in SWE per 10% increase in canopy density.

When points on the scatterplot were grouped by species composition, it became clear that much of the strength of the regression was due to the spruce/fir dominated sites. Two more regression analyses were done comparing

**Table 2**
**Mann-Whitney U Statistics for Snow Water Equivalent between Stands**

Mann-Whitney U test, individual alpha=0.0063, experiment alpha=0.05
Second April Session Snow Water Equivalent

| | Dry park a | Fa | Db | Fb | Ba | Fc | Dc | Bb |
|---|---|---|---|---|---|---|---|---|
| | (LP0.5) | (LP1.0) | (LP1.7) | (LP2.0) | (LP2.5) | (LP3.0) | (LP) | (SF) |
| **Bb** (SF) | **.0001** | .0155* | **.0009** | .0220* | **.0041** | **.0057** | .0221* | ° |
| **Dc** (LP) | **.0028** | .6670 | .0312* | .7222 | .8976 | .7093 | ° | |
| **Fc** (LP3.0) | .0774 | .5365 | .6749 | .1342 | .5204 | ° | | |
| **Ba** (LP2.5) | **.0003** | .1951 | .1526 | .7781 | ° | | | |
| **Fb** (LP2.0) | **.0022** | .1251 | .0122* | ° | | | | |
| **Db** (LP1.7) | **.0039** | .5580 | ° | | | | | |
| **Fa** (LP1.0) | .0731 | ° | | | | | | |
| **Da** (LP0.5) | ° | | | | | | | |

**Table 3**
**Mann-Whitney U Statistics for Canopy Density**
**(30° Photocanopyometer) between Stands**

Mann-Whitney U test, individual alpha=0.0063, experiment alpha=0.05
Significant results are in bold typeface.

| | Dry park a | Fa | Db | Fb | Ba | Fc | Dc | Bb |
|---|---|---|---|---|---|---|---|---|
| | (LP0.5) | (LP1.0) | (LP1.7) | (LP2.0) | (LP2.5) | (LP3.0) | (LP) | (SF) |
| **Bb** (SF) | **.0001** | **.0037** | **.0001** | .0165* | .0343* | .0140* | **.0001** | ° |
| **Dc** (LP) | .2632 | **.0001** | **.0001** | **.0001** | **.0001** | **.0001** | ° | |
| **Fc** (LP3.0) | **.0005** | .6882 | .4189 | .6186 | .3176 | ° | | |
| **Ba** (LP2.5) | **.0001** | .1337 | .0239* | .5942 | ° | | | |
| **Fb** (LP2.0) | **.0001** | .3171 | .1381 | ° | | | | |
| **Db** (LP1.7) | **.0006** | .7842 | ° | | | | | |
| **Fa** (LP1.0) | **.0023** | ° | | | | | | |
| **Da** (LP0.5) | ° | | | | | | | |

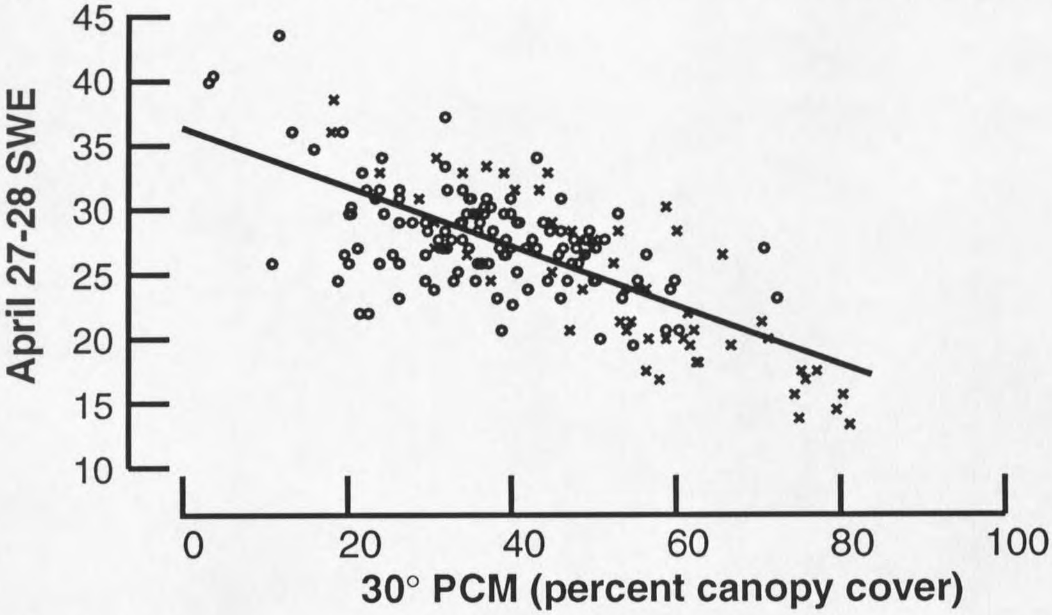
---

Bold values indicate significance at the individual alpha. Asterisked values indicate significance at experiment wide alpha, but failing the individual alpha. Cover types in parentheses are discussed later in the text.

First letter of stand abbreviation denotes area (Bubbling springs, Dry park, or Farnes meadow). Second letter is the stand identifier, from youngest 'a' to oldest 'c'.

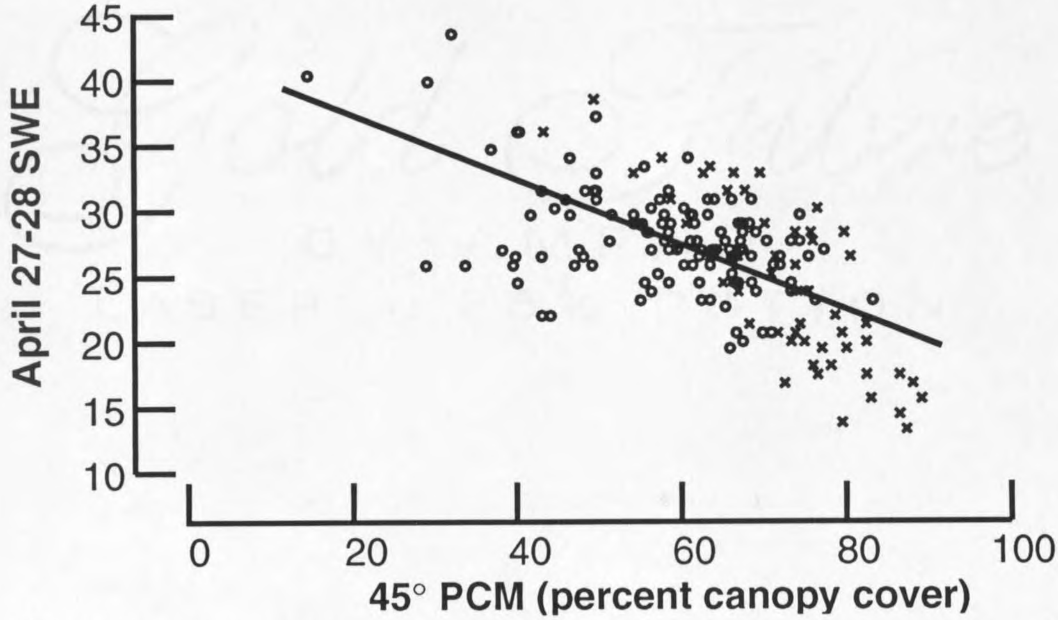
Stands are listed from youngest successional stage (in parentheses) to oldest successional stage.

**Figure 15**
**Regression of Photocanopyometer (30° View) with Snow Water Equivalent**




$R^2$ value for this regression is 51%. Coefficient of regression is -0.23, intercept 36.6, and p<0.0001. Pine dominated samples are shown with a '∘', spruce/fir with an 'x'

**Figure 16**
**Regression of Photocanopyometer (45° View) with Snow Water Equivalent**



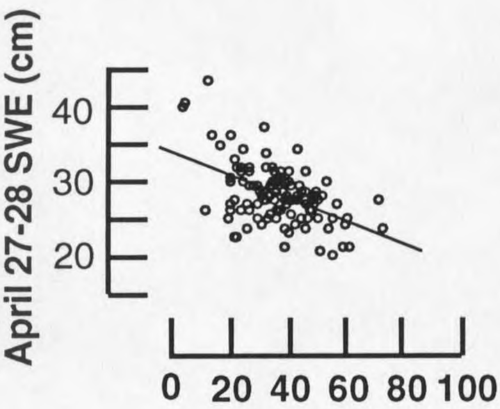

$R^2$ value for this regression is 40%. Coefficient of regression is -0.25, intercept 42.5, and p<0.0001.

different species (Figures 17a and 17b). Snow accumulation for spruce/fir dominant samples (including pure spruce/fir samples) was much better predicted than snow under pine dominated samples. $R^2$ values for the spruce/fir snow water equivalent were 74% for the photocanopyometer–based canopy measurements. On the other hand, regression statistics for lodgepole pine dominated samples were less impressive. The photocanopyometer–based canopy cover could only account for 27% of the variation in snow. These regression analyses confirm the hypothetical inverse relationship between canopy and SWE in Figure 1a, but the slope of the regression is dependent on species composition.

To infer significance between stands, another Mann-Whitney U statistical test for the 30° photocanopyometer view was created (Table 3, page 41). This matrix shows that several stand to stand comparisons have significantly different canopies. Interestingly, the significant pairs are not necessarily the same pairs that were found significant in Table 2, which deals with SWE.

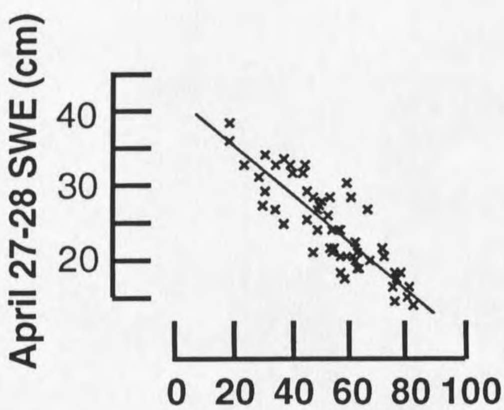
Part of the weakness in regression analysis with pine samples may be due to localized wind redistribution within the stand and under the canopy. Regressions of individual stands indicate that snow sample points under the Farnes Meadow A stand and the Dry Park C stand are very poorly correlated with canopy (Figures 18a and 18b). These two stands have the largest proportion of pure lodgepole pine and have only one vegetative story. Also, they are nearer to the windier rim of the watershed. This may have resulted in eddies and wind within the forest canopy throughout the winter. This effect, if present, may decouple the canopy from the ground beneath it. While the canopy may be exerting influence upon the snow for the entire stand, individual snow sample points are influenced by canopy not at the zenith due to the incidence angle of

Figure 17a
Regression of 30° Photo-canopyometer with Pine Dominated Samples



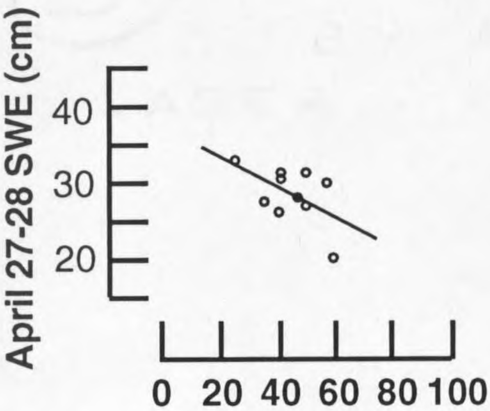

$R^2$ = 27%, coefficient = -0.16, intercept = 34.0, p<0.0001.

Figure 17b
Regression of 30° Photo-canopyometer with Spruce/fir Dominated Samples



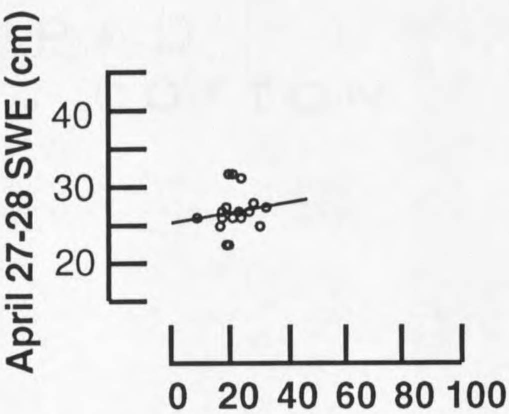

$R^2$ = 74%, coefficient = -0.34, intercept = 42.4, p<0.0001.

Figure 18a
Regression of Individual Stand Farnes Meadow A (successional stage LP1.0)




The $R^2$ =30%, coefficient = -0.20, intercept = 36.8, p = 0.1029.

Figure 18b
Regression of Individual Stand Dry Park C (successional stage LP)



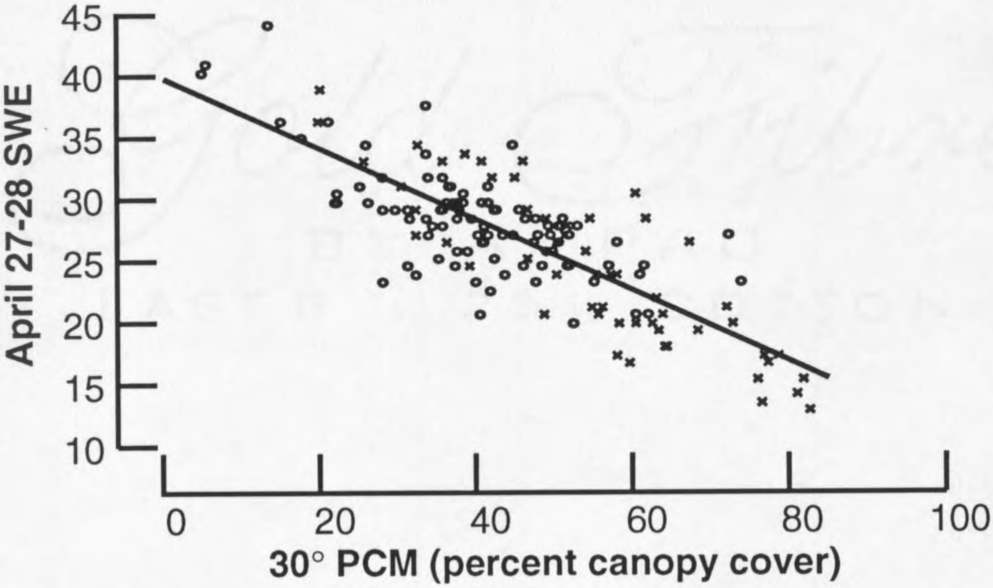

The $R^2$ =2%, coefficient = +0.07, intercept = 25.1, p = 0.5673.

snowfall. Therefore, much of the weakness in regressions of pine samples may be due to the unique behavior of these two plots, and not in a lodgepole pine's lack of ability to intercept snow. Note that with those two stands omitted, $R^2$ values for the 30° photocanopyometer rise from 51% to 65% (correlation coefficient -0.28, t-ratio -16.6; Figure 19). In short, although a regression analysis using only the individual sample points within a single stand is inappropriate, doing so points out the different behavior of this stand compared to all points combined.

## Basal Area

Basal area measures the density and diameter of stems in a forest. High basal area values correspond to a greater number of smaller trees or a modest number of large trees. Greater basal area would logically be correlated to more numerous or larger crowns and canopy coverage. Thus, basal area may be an indicator of interception which in turn affects snow water equivalent, but the stand–by–stand data shows no particular pattern. Regression analysis of basal area and SWE shows no dependence overall, although a slight trend is noticed in the lodgepole pine samples (Figure 20). Basal area varies with age and differs between stands, but it is not proportional to interception and the subsequent snow water equivalent. The poor relationship provided by basal area may be explained by the distinct increase in basal area observed as stands approach an intermediate age of 123 year; followed by a decrease toward the oldest stand. Note the high degree of variance in the intermediate age class (123 years) due to the lower measurements found at the Bubbling Springs A plot. One might expect high basal area variability to be found in the stands that have understory trees

Figure 19
Regression of the 30° Photocanopyometer without Stands Fa (LP1.0) and Dc (LP)




The $R^2$ value for this regression (65%) is boosted with the removal of two stands where wind redistribution under the canopy is suspected.

beneath a mixed species canopy, but stands strongly dominated by lodgepole pine and lacking much of an understory, such as Dry Park B, have a high variability.

The box plots of basal area by species category show the fluctuation in stem density as a stand matures and decays (Figure 14). Also of interest is the sharply lower basal area values at Bubbling Springs A and high values at Farnes Meadow C. One would expect Farnes Meadow C, defined as the most decayed stage of a lodgepole pine stand before it undergoes regrowth by spruce and fire, to have the lowest basal area. Perhaps this is due to small understory trees being calculated in the basal area measurements; using a larger BAF such as 10 square foot/acre might not show this result.

Areas of pure lodgepole pine had the greatest stem density. Stem density decreased with increasing proportion of spruce or fir in the stand. The slight increase in density shown by the pure spruce/fir data may not be important due to the scant number of samples of this category. The low basal area measurement made at the one lodgepole pine/whitebark pine stand (Dry Park A), is due to the young age of that stand, not the species composition.

Previous studies of canopy effects upon snowcover have identified basal area and canopy cover both as suitable predictors of snow interception or net accumulation (Gary 1979; Gary and Watkins 1985). This is not supported by the vegetation data presented here (Figure 21). Lodgepole pine samples tend to have higher basal area and lower canopy density when compared to spruce/fir samples. This is more evidence that suggests that species composition is crucial when applying canopy cover correlations produced in one habitat to another habitat.

Figure 20
Scatterplot of Basal Area and Snow Water Equivalent

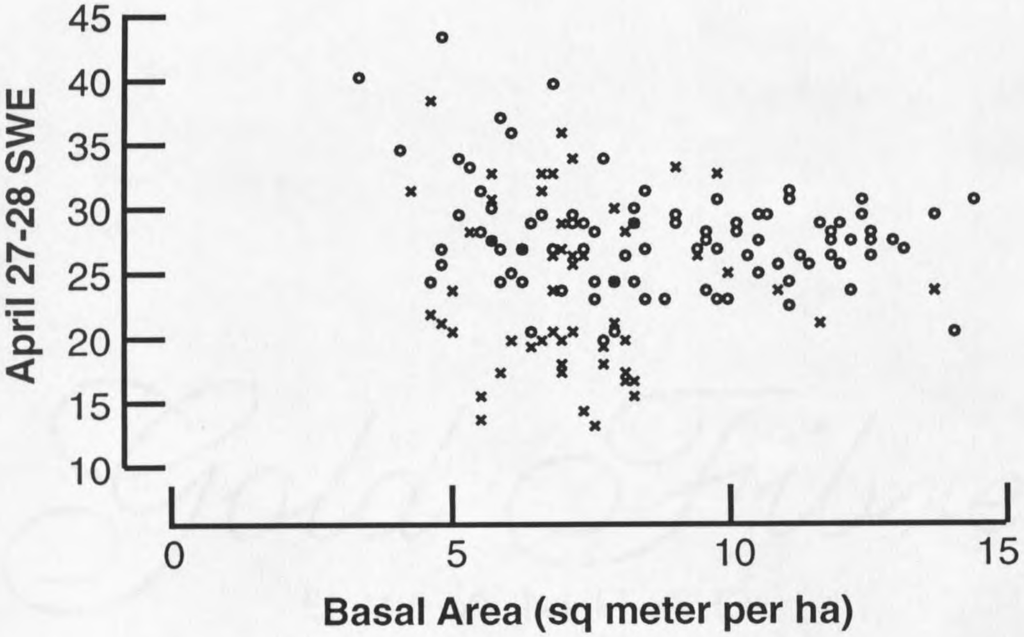
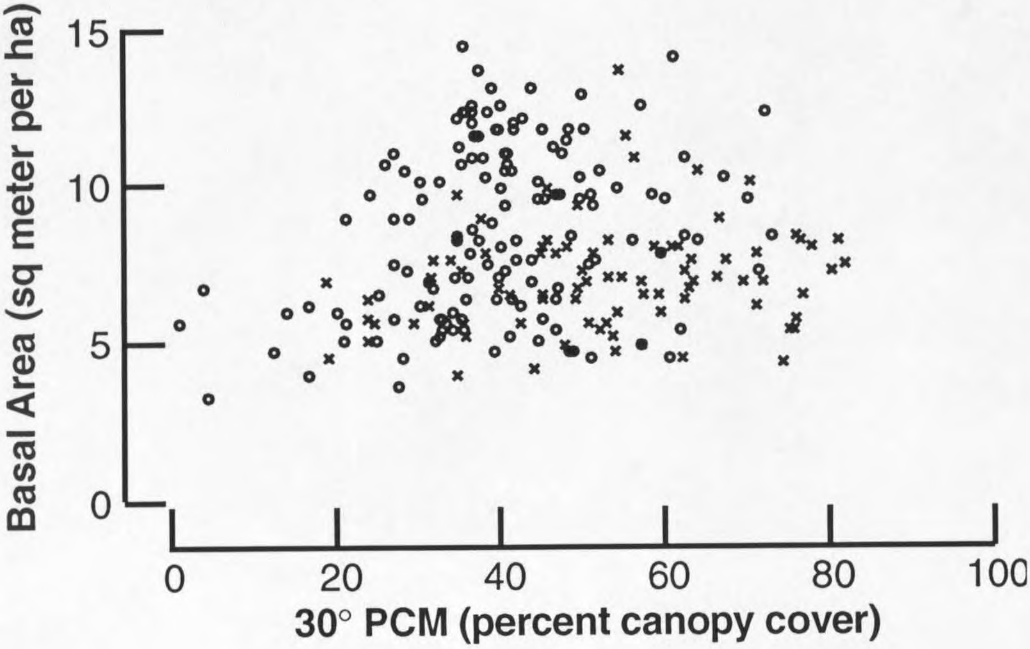



Figure 21
Scatterplot of Basal Area and 30° Photocanopyometer



## Multivariate Analysis

A step-wise multiple regression was used to evaluate the relationship between stand variables and snow water equivalent data. Independent variables included both 30° and 45° view angles of the photocanopyometer, the spherical densiometer, and basal area. These additional variables were added after the 30° photocanopyometer and failed to significantly boost the regression. Furthermore, the test was hampered by multi–collinearity. The two canopy instruments, although there are differences in the data, are essentially measuring the same variable. Basal area was not significantly correlated to SWE. Because of these relationships, multiple regression models are restricted in their applicability. Using qualitative data such as tree height and vegetation story structure as an additional dummy variables yielded little improvement, except that an index of tree height marginally improved the relationship between the photocanopyometer and SWE for lodgepole pine samples. A summary of individual linear regressions are presented in Table 4.

**Table 4**
**Summary of Linear Regression Results**

Different Forest Variables regressed against snow water equivalent.

| Variable | Coefficient | Intercept | T-ratio* | $R^2$ | P value |
|---|---|---|---|---|---|
| 30° Photocanopyometer | -0.23 | 36.6 | -13.6 | 51% | <0.0001 |
| 45° Photocanopyometer | -0.25 | 42.5 | -10.8 | 40% | <0.0001 |
| Basal Area | -0.0 | 27.7 | -0.9 | 0% | =0.5667 |
| Spherical Densiometer | -0.32 | 48.2 | -14.4 | 54% | <0.0001 |

*Degrees of freedom for all expressions is 174

## Predictive Models

Canopy cover, as defined by the 30° view of the photocanopyometer, is a good predictor of snow accumulation in all stands except for the Dry Park C stand. In this one stand, slope, wind dynamics, and ablation due to radiation may be as or more important than canopy cover in determining SWE. Using the regression equation computed for all stands does produce moderately accurate predictions of snow accumulation. The predicted and actual values presented in Table 5 demonstrate the strengths and weakness of the simple linear model of canopy cover with SWE for all successional stages.

**Table 5**
**Predicted vs. Actual Snow Water Equivalents of Stands on the TCEF**

| Stand | Canopy Density | Actual SWE | Estimated SWE | Difference | % Difference |
|---|---|---|---|---|---|
| Dry park a (LP0.5) | | 28.5% | 32.1 cm | 30.1 cm | +2.0 cm |
| +7% | | | | | |
| Fa (LP1.0) | 41.6 | 28.3 | 27.1 | +1.2 | +5 |
| Db (LP1.7) | 40.8 | 28.2 | 27.3 | +0.9 | +3 |
| Fb (LP2.0) | 45.7 | 26.3 | 26.1 | +0.2 | +1 |
| Ba (LP2.5) | 47.3 | 26.2 | 25.8 | +0.4 | +2 |
| Fc (LP3.0) | 44.4 | 27.4 | 26.4 | +1.0 | +4 |
| Dc (LP) | 24.5 | 26.7 | 31.0 | -4.3 | -14 |

Based on the Regression equation of Figure 15

Stands are listed from youngest successional stage (in parentheses) to oldest successional stage.

Using this snow prediction model, the youngest stand (Dry Park A) is underpredicted and the oldest stand, Bubbling Springs B, is overpredicted. The case with the highest error is the mature pine stand, Dry Park C, which was overpredicted. While canopy density alone can explain snowpack variation in most stands, it fails to take into account important structural differences, such as the small young trees of Dry Park A, the dense, highly variable multistory canopy of Bubbling Springs B, or the tall open understory of Dry Park C.

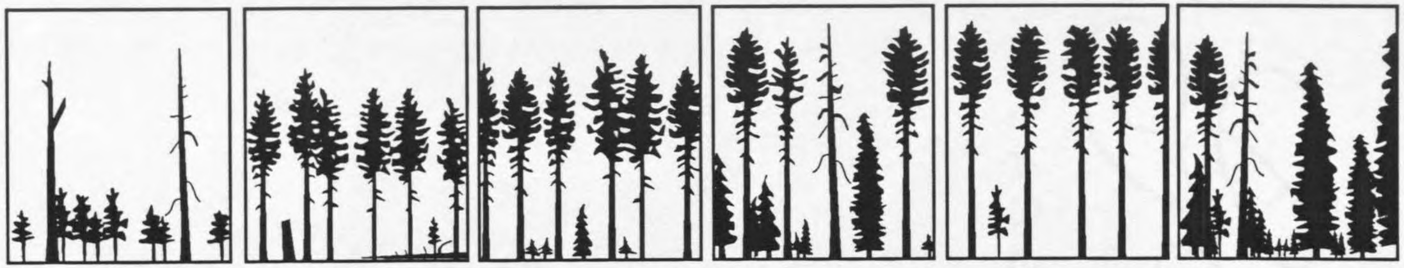
## Successional Stages

Utilizing Despain's (1990) forest cover types developed for Yellowstone National Park, the eight study stands were assigned a successional stage. The Dry Park C stand was reclassified a LP mature stand and the Farnes Meadow C stand was reclassified a LP3.0. Both, species and age are incorporated into a cover type index (Table 1 and Figure 22). This is particularly important when soil moisture, chemistry, slope and other local environmental factors may accelerate or delay the replacement of one species with another, or the growth rate (Despain 1990). Although Woolsey shale underlies all stands and the soil is thin, two stands, the Bubbling Springs B and Farnes Meadow C stands, had much wetter soils. These stands are situated just downslope of wet meadows. The Farnes Meadow C stand reached the LP3.0 successional stage in a relatively short 270 years.

Age alone was shown to be a poor predictor of forest development and change. For example, two stands of the same age, 270 years, show remarkably different structure. One stand, Dry Park C, is exclusively lodgepole pine and has a single story of vegetation. Another stand, Farnes Meadow C, is the same age

**Figure 22 Description of Despain's Successional Stages**

**Forest Structure Diagram**



| Stage | LP0 | LP1 | LP2 | LP3 | LP | SF |
|---|---|---|---|---|---|---|
| Previous Stage | Disturbance such as fire or insect kill | LP0 | LP1 | LP2 | LP2 | LP3 |
| Next Stage | LP1 | LP2 | LP3 | SF | None, sub-dominant climax | None, climax |
| Overstory | Snags from previous stage | Short pole or doghair lodgepole | Closed lodgepole | Ragged lodgepole with some S/F | Thin, tall lodgepole | Spruce and fir multistory |
| Understory | Young saplings, species similar to past stand | Little understory | Beginning of fir and spruce on floor | Dense understory of spruce/fir | Very little undergrowth | Heavy spruce and fir |
| Approx. Age | 0-40 years | 50-150 | 150-300 | 300+ | 300+ | 350+ |
| Fire Liklihood | Moderately comon | Very Rare | Rare | Common | Limited in intensity | Variable, high fuel loading but wet |
| Track | Pine Track S/F Track | Pine Track S/F Track | Pine Track S/F Track | S/F Track | Pine Track | S/F Track |

**Spruce or Fir**

**Lodgepole Pine**

This information closely taken from Despain 1990, pages 107-114 but in advanced stages of fragmentation and species replacement. Several small openings are scattered throughout, and the variation in canopy cover is great.

SWE varies considerably within stands of the same age. Three stands identified as being 123 years old have substantially different median snow accumulations as well as different SWE variability. The eight successional stages presented here are not directly correlated to age in years. For example, there are 155 years between LP3.0 and SF in this study, but merely 38 years between LP1.0 and LP 2.5.

Within stands of the same age, canopy variation and SWE variation may be explained by species composition. The average canopy density for pine dominated samples was 37.5%, standard deviation = 13.1, n=184. Canopy density for spruce/fir dominated samples, which were found in the later successional stages, was 52.2%, standard deviation = 15.9, n=86. These differences are significant (two sample t-test statistic = -7.5, p<0.0001). Thus, age and species composition may directly or indirectly affect SWE. What is required is a variable that incorporates these two factors.

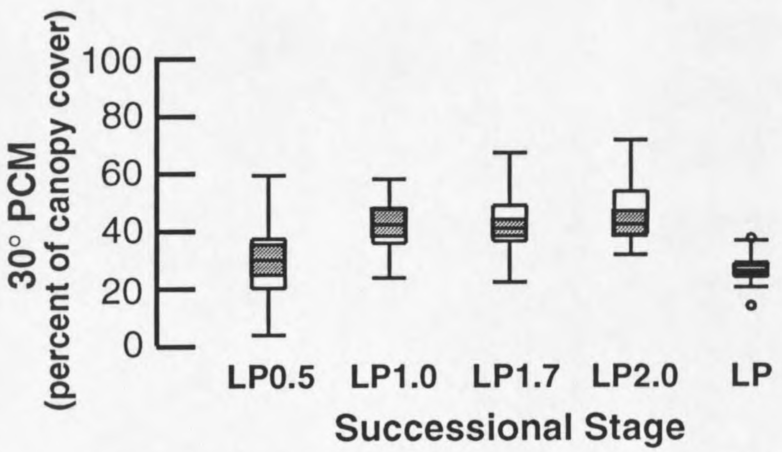
Successional Tracks

The eight stands were arranged into two successional "tracks." The first "pine track" represents forest succession under conditions where spruce and fir would be suppressed. Thin soils or dry environmental conditions as well as periodic fires maintain a sub-dominant lodgepole pine climax scenario. The "spruce/fir track" is the second potential evolution of an ALBA/VASC habitat. Young, fast growing lodgepole pine dominate young and intermediate stands. Slower growing and shade tolerant Engelmann spruce or subalpine fir will succeed the lodgepole during a transition period of pine degeneration and subsequent spruce or fir dominance. Moist soil conditions or infrequent fires favor the spruce/fir track (Despain 1990). These represent two forks of the successional timeline; early stages of succession in a ALBA/VASC habitat may belong to either track, therefore LP0.5 through LP2.0 were included in both tracks in the figures. Figures 23a and 23b examine the difference in canopy between successional stages. Figures 24a and 24b show the variation in SWE found at each of the eight stages.

<u>Successional Stages and Canopy Cover</u>. There is a characteristic curve of canopy density with successional stage when using the 30° cone of the photocanopy-ometer (Figure 23). Both successional tracks include stages LP0.5 through LP2.0, and diverge thereafter. Density increases from the young LP0.5 stand to the LP2.5 stand representing intermediate growth, then canopy density drops slightly from LP2.5 to LP 3.0, as would be expected as a stand reaches the maximal stage of decay. The mature spruce/fir stand, at the climax stage of this habitat type, shows a marked and significant increase in canopy density. This stand had the highest proportion of spruce/fir dominated samples (97%). Spruce and fir were found to generally result in denser canopies. Thus, the progression to a greater percentage of spruce and fir and an older stage resulted in an increase in canopy density as measured by the photocanopyometer.

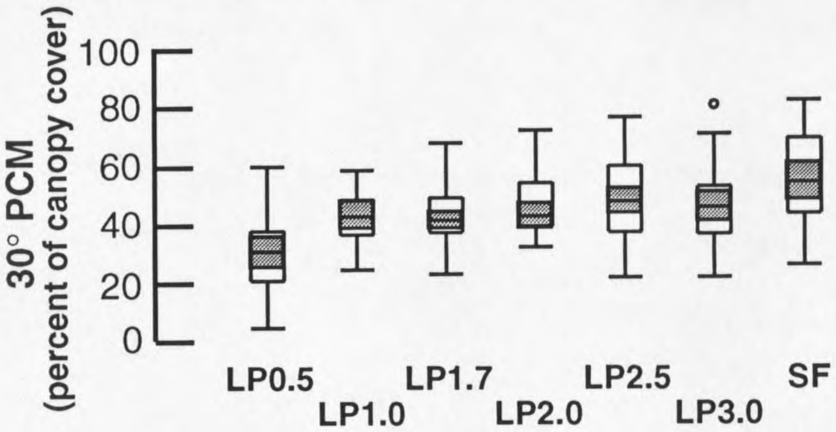
On the other hand, if environmental conditions are dry, or fire frequency is high, a mature lodgepole pine stand is favored and succession follows the pine track (Arno et al. 1985; Despain 1990). After the initial increase in canopy density from LP0.5 to LP2.0, there will be a decrease in canopy density from the LP2.0 stage to the mature lodgepole stage (Figure 23a). Surprisingly, the calculated

**Figure 23 a**
**Canopy Density by Stand (Pine Successional Track)**



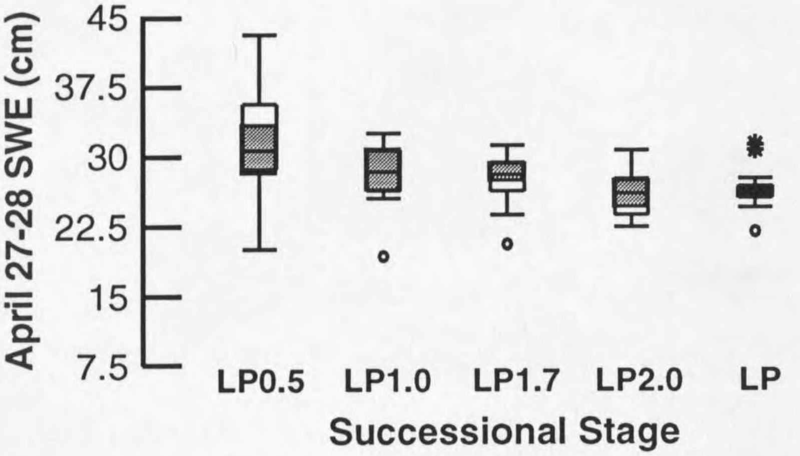

The pine successional track shows an increase in canopy density up to LP2.0, followed by a sharp decrease. The LP stage can be maintained as a sub-dominant climax by frequent light fires or certain environmental conditions. PCM=Photocanopyometer

**Figure 23b**
**Canopy Density by Stand (Spruce/Fir Successional Track)**



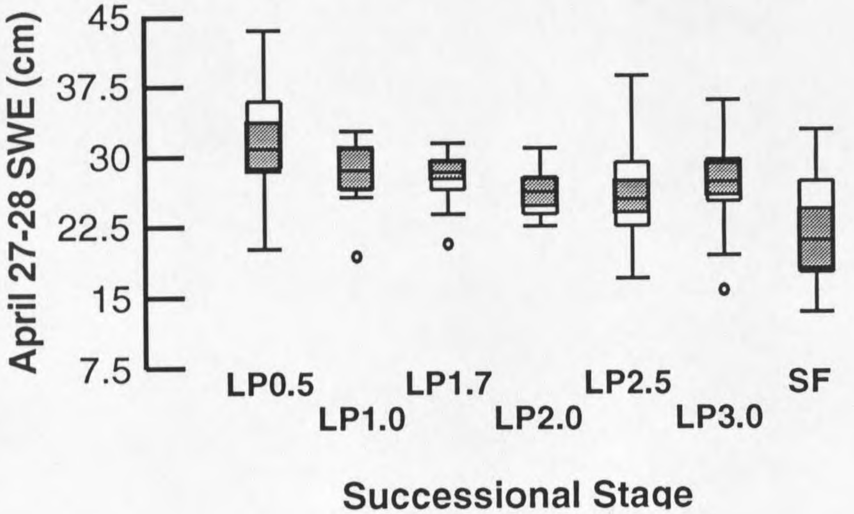

The spruce/fir successional track shows a complex curve where canopy density increases with successional stage until the LP2.5 stage, then decreases slightly as the stand begins to fragment and be replaced by spruce and fir. The climax SF stage shows an increase in canopy density. PCM=Photocanopyometer

**Figure 24a**
**SWE by Stand (Pine Successional Track)**




The pine successional track shows a simple decline in snow water equivalent as the ALBA/VASC succeeds into the LP stage. The LP stage can be maintained as a sub-dominant climax by frequent light fires or certain environmental conditions.

**Figure 24b**
**SWE by Stand (Spruce/Fir Successional Track)**




The spruce/fir successional track shows a complex 's' curve where snow water equivalent decreases with successional stage until the LP2.5 stage, then increases slightly as the stand begins to fragment and be replaced by spruce and fir. The climax SF stage shows a sharp decrease in snow water equivalent.

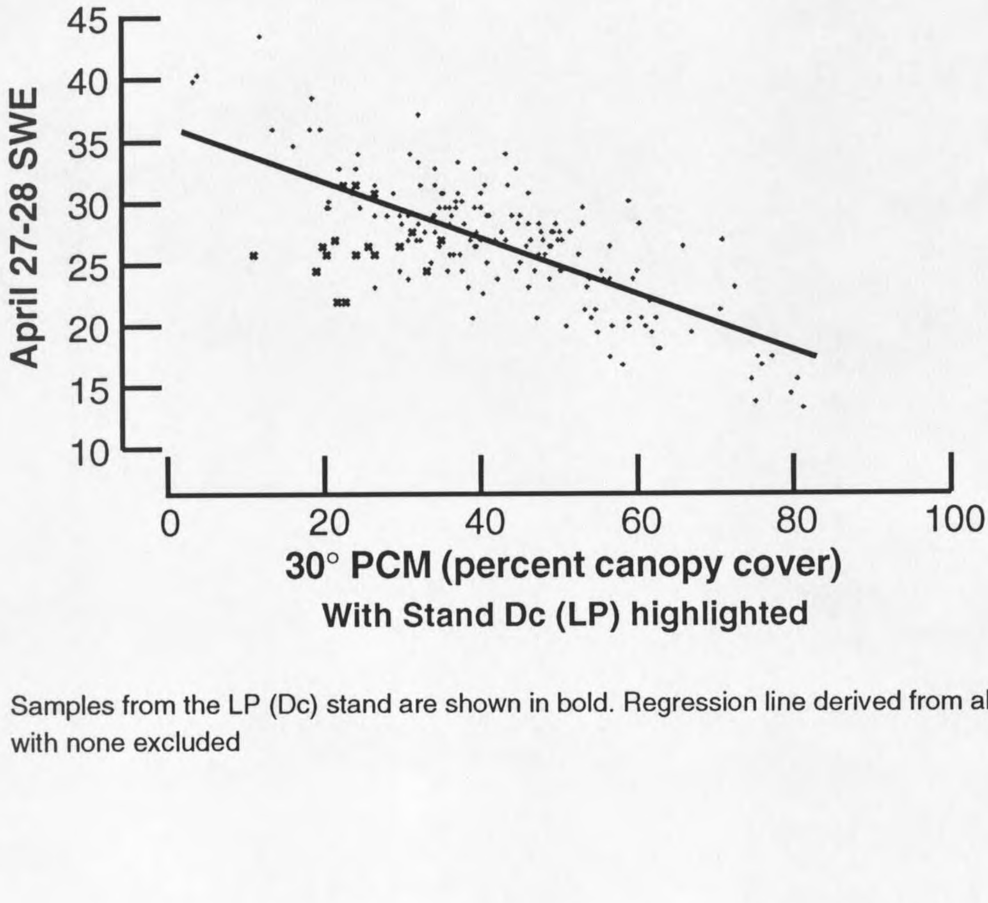
canopy densities for the mature pine stand are lower than the canopy densities for the youngest stand. This drop in median canopy density from LP2.0 to LP is significant ($t=8.6$, $p<0.0001$). The variance in canopy density is roughly equal for all stands except the mature lodgepole pine stand (LP) which has a narrow range of canopy values.

Successional Stages and Snow Water Equivalent. Figure 24a and 24b show the relationship of successional tracks and SWE. The boxplot graph of the pine track shows a decrease in snow accumulation throughout the LP0.5 to LP2.0 stages, becoming less pronounced with age and plateauing at LP. Despite the visible decrease in medians, the only significant differences are found with the LP0.5 stage to the LP 1.7, LP2.0, and LP stages (Table 2).

The spruce/fir track is more complicated, showing a decrease in snow accumulation only up to LP2.5. A slight increase in snow accumulation occurs at the LP3.0 stage, followed by a more pronounced decline at the climax SF stage (Figure 24b). These graphs are almost an inverse mirror image of the 30° photocanopyometer boxplots in Figures 23a and 23b, with one exception. The significantly lower canopy density of the LP stage on the pine track should result in a sharp increase in snow accumulation at this stage, but does not. This unique behavior is noted in a regression analysis. If we identify the LP stage on a scatterplot of canopy density and SWE, (Figure 25) we find that the samples of this stage fall well below predicted values.

The curvilinear relationship between the spruce/fir successional track and snow accumulation shown by Figure 24b follows the same curve form as the hypothetical curve previously show in Figure 1c. While the spruce/fir track follows the hypothesized relationship, the pine track only follows the curve until

**Figure 25**
**Scatterplot of Photocanopyometer with Snow Water Equivalent showing Dry Park C (LP) Stand.**




Samples from the LP (Dc) stand are shown in bold. Regression line derived from all data points with none excluded the mature LP stage where it then continues on a slight downward trend (Figure 24a). The pine successional track (Figure 24a) shows a simple curve, approaching horizontal as the forest matures. Change in canopy density is the underlying process in the reduction in SWE with successional stage. While it is established that canopy density is the primary cause of snow interception, accounting for over 50% of the variation, there are other unexplained factors accounting for the change in snow accumulation. This relationship between canopy density and SWE weakens substantially in certain successional stages. The strength of the regressions change when analyses are grouped into three successional periods. Figure 26a, b and c show regressions between canopy density and snow. These are divided by their position along successional tracks of the ALBA/VASC habitat type. The late spruce/fir track and the four stages that could be grouped into either lodgepole pine or spruce fir both have higher regression coefficients and $R^2$ values than the overall regression, which had an $R^2$ of 51%. The late lodgepole pine track, consisting of one stand (LP, Dry Park C) showed little relationship between canopy cover and SWE. Other canopy measurements and the qualitative stand descriptions did not improve the inverse relationship between canopy density and snow water equivalent for the eight stands.

## Area Effects

Analysis between the eight stands assumed that differences in snow accumulation are due to forest structural differences. External factors such as topography and snowfall were assumed equal. An analysis of regression residuals between canopy density and snow water equivalent indicate that the Bubbling Springs and Farnes Meadow areas were well behaved, with no pattern