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

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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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Statement of Permission to Use

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Date Jan 15 1997

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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.

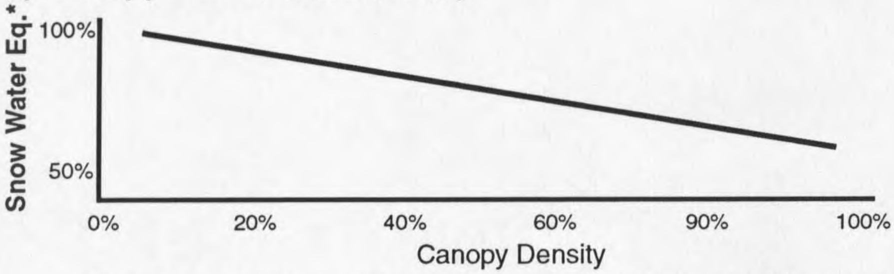
Most previous studies have quantified differences in snowpack under starkly different vegetation covers. The role of the more gradual growth and seral stage landscape variation upon snow accumulation has not been fully addressed. Fire suppression has altered vegetation structure and canopy on the landscape–scale, 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

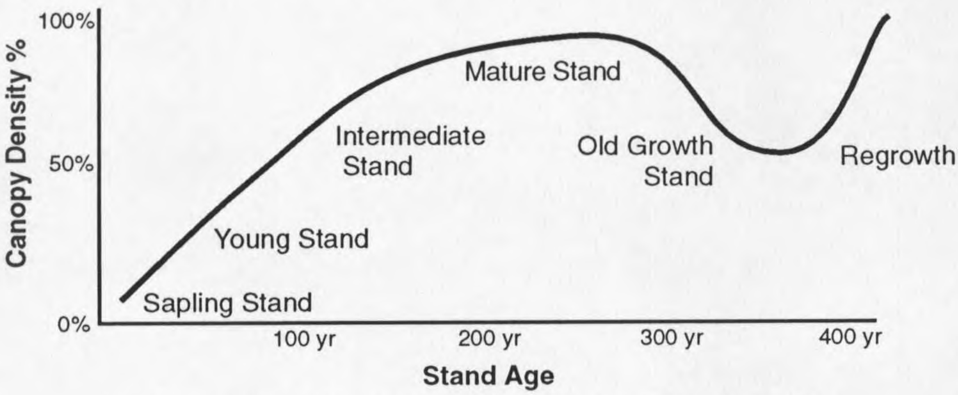
Figure 1

a) Canopy– Snow Relationship



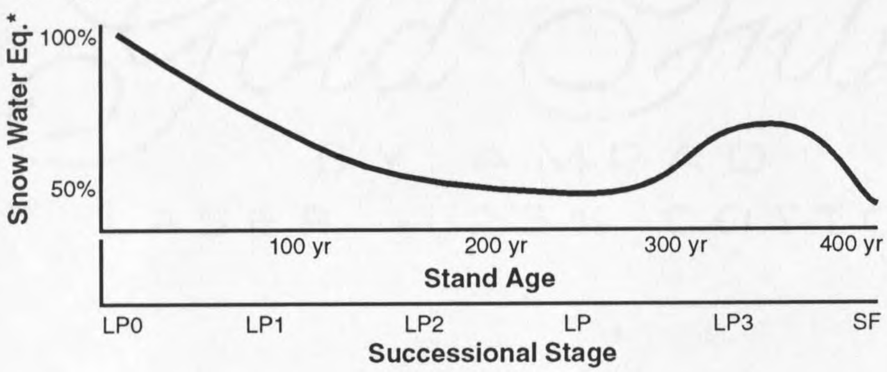
After: Farnes and Hartman, 1989; Hardy and Hansen-Bristow, 1990; Skidmore et. al, 1994

b) Age–Canopy Relationship



After: Farnes 1993; McCaughey pers. comm.; Fischer and Bradley 1987

c) Hypothetical Age-Snow Relationship



* 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