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

by

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INTRODUCTION

The timing and volume of spring run-off in a forested watershed is affected by many variables, including forest canopy density, basal area, and tree height, as well as the resulting accumulated snowpack depth, its distribution, and the retention of the snowpack over time. Great variations in the timing and volume of run-off are expected under varying forest structures (primarily canopy density and basal area), such as in areas with no forest, areas with young, low density forests, or areas covered by mature, high density forests. Although previous studies have measured and compared snow accumulation and duration of snow retention in clearcuts and in undisturbed, mature forests (Toews and Gluns, 1988; Wilm and Dunford, 1948 in Troendle, et al.; 1988; Berris and Harr, 1987; Golding and Swanson, 1986; Leaf, 1975), measurements of these variables have rarely been collected nor documented in forests that are recovering from timber harvest activities and that are at young or intermediate growth stages with varying canopy densities. In particular, a data gap exists in regards to the ideal canopy density and/or basal area that promotes increased snow accumulation and provides for a delay in snowmelt and run-off, allowing sustained water flow later into the ablation season. Therefore, the objectives of this research were to measure the effects that varying forest structures, resulting from timber harvest, have on a snowpack's accumulated depth, snow water equivalence, density, and ablation rate.

Because harvesting of forest resources affects the magnitude of a snowpack and the quantity and timing of water availability, the results of this research should be of use to watershed managers. In most mountainous regions, environmental planners should also find these results useful where concern exists for the potential hazards of snowmelt flooding due to changes in the quantity, rate, and timing of snowmelt (Dunne and Leopold, 1978).

STUDY AREA

The study area is within the Hyalite Creek watershed in the Gallatin National Forest, approximately 35 km south of Bozeman, Montana (Figure 1). This watershed yields 57,604,450 m^3 (46,700 acre/ft) of water in a "normal" year (Glasser, 1987) supplying 50-70% of the city of Bozeman, Montana's water (Shields, pers. comm.). The specific study site is within the Lick Creek drainage (at approximately 2085 m elevation). This watershed also contributes significantly to agricultural water supplies and is important economically as timber harvest has continued and expanded here for several decades (Gallatin National Forest Forest Plan, 1987). The forests of the Lick Creek drainage represent several stages of timber harvest and subsequent regrowth, thereby providing tree stands of differing canopy density, basal area, ages and heights. Nearby is a Soil Conservation Service (SCS) SNOTEL site (consisting of snow pillows and thermometers) and the SCS Lick Creek Snow Survey course.

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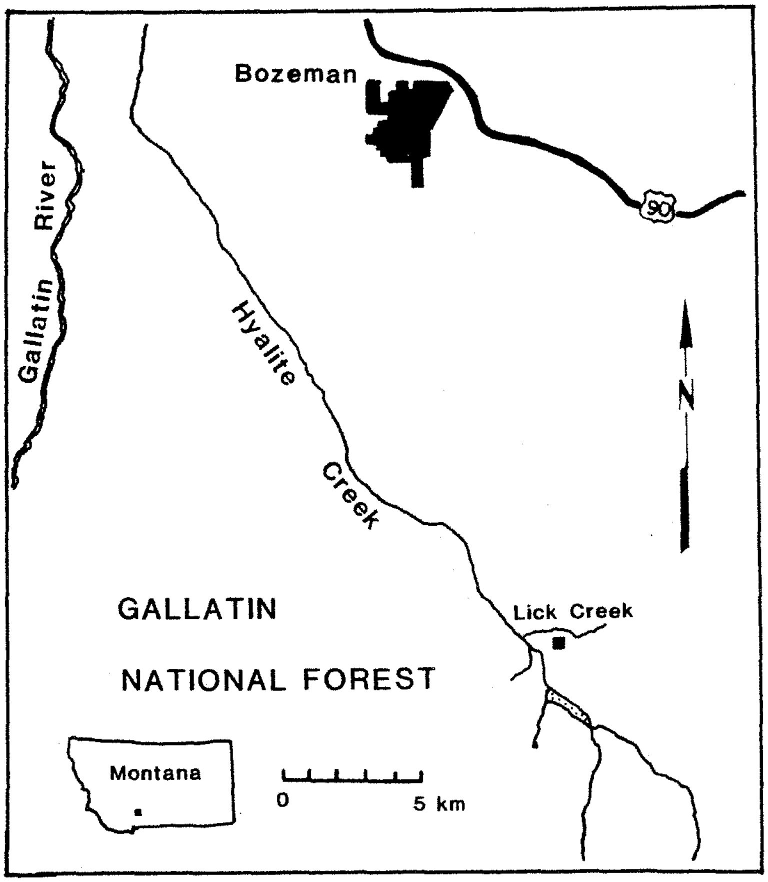

Figure 1. The study area, near Lick Creek, is located within the Hyalite Creek watershed, 35 km south of Bozeman, Montana.

METHODS

Four plots for study were selected to maximize variations in forest structure (Table 1) and to minimize variations in other site factors (slope, aspect, and elevation), which might influence snow distribution patterns (Toews and Gluns, 1986). The mean density of the canopy cover or overstory, expressed as a percentage, was determined from 45 measurements in each plot using a densiometer, as described by Lemmon (1957). A basal area for each plot was determined by measuring the diameter at breast height (DBH) for each tree within the boundaries of the plot. These measurements were converted to areas and summed to give the total area occupied by tree stems per plot. A weighted mean and a range of tree ages for each plot were determined by coring a large number of semi-randomly selected trees (some subjective selections were made in consideration of the range in DBH and species). Tree heights were determined using a Brunton compass to measure height angles (calculated to tree heights) for a number of both randomly selected trees and the tall trees. The logging history of the forests at each plot was obtained from both U.S. Forest Service (USFS) records and discussions with USFS personnel. These characteristics were combined to describe the general forest structure (primarily canopy density and basal area, but including tree age and height). In general, for this study, a low forest structure is used to describe a forest with a low canopy density (0-20%), low basal area (0-10 m^2/ha), and young trees (0-15 years). An intermediate forest structure refers to a forest with a canopy density of 20-60%, a basal area of 10-25 m^2/ha, and tree ages between 20 and 60 years. Finally, a high or full forest structure refers to a mature forest with a canopy density greater than 60%, a high basal area (greater than 25 m^2/ha), and a variety of tree ages (up to 212 years) and species.

Table 1. FOREST STRUCTURE, TREE AGE, CANOPY DENSITY, BASAL AREA, TREE HEIGHTS AND DOMINANT SPECIES FOR ALL PLOTS. Tree species include lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), and subalpine fir (*Abies lasiocorpa*).

SITE	FOREST STRUCTURE	PERCENT CANOPY DENSITY	BASAL AREA (m^2/ha)	TREE HEIGHTS range (m)	DOMINANT SPECIES
A	None (Meadow; 3H in size)	0	0	0	None
B	Low (Young Regrowth Trees; 10-15 yrs.)	6	2.2	0.5-4.0	Pine (100%)
C	Intermediate (Regrowth Forest; approx. 35 yrs.)	56	17.1	10.4-14.0	Pine (86%)
D	High (Mature Forest up to 212 yrs.)	85	36.9	18.6-26.6*	Fir (79%)

* Height measurements are maximum heights.

At all plots a random square grid system was designated with permanent stakes at nine points, 15 meters apart, in a three-by-three, north-south, east-west orientated pattern. Data point spacing was chosen based on previous studies which utilized a range of distances of 10 meters (Toews and Gluns, 1986; Gary, 1979) to 100 meters apart (Daugharty and Dickison, 1982), with the majority of the studies using a spacing of 10-20 meters (McGurk and Berg; 1987, Potts, 1984). Rebar stakes and 1.5 meter, white polyvinyl chloride (PVC) snow stakes marked all 36 points.

Snow measurements were made during the 1988-89 snow season. During the accumulation season (December-March), measurements were collected twice a month; during the ablation season (April-June), considered a critical time as the snowpack was suspected to change rapidly with decreasing snow depth, measurements were collected on a weekly basis. Within each plot, four snow depth measurements were collected at all nine stakes. Using the U.S. Federal Snow Sampler (USFSS), five measurements of depth, density, and snow water equivalence were collected and a mean density was determined for the plot. The mean depth at each stake was combined with the mean density for the plot to determine the total snow water equivalence (SWE) for each stake and for the entire plot. Weather data from the SNOTEL site was accessed via the SCS, Central Forecasting System in Portland, Oregon.

RESULTS AND DISCUSSION

Weather Patterns

According to the SCS SNOTEL data, mean monthly air temperatures (Figure 2), were higher than average during October, November, and December, but by mid-January and all of February air temperatures fell substantially below normal, associated with a shift southwards of the jet stream. March and the entire ablation season (April through May) were characterized by lower than average air temperatures. The snow water equivalence (SWE) stayed consistently below normal for the entire snow season (Figure 2). The maximum accumulation of SWE occurred in early April (April 3-5), and by May 15th the snowpack on the SCS SNOTEL snow pillow was completely ablated.

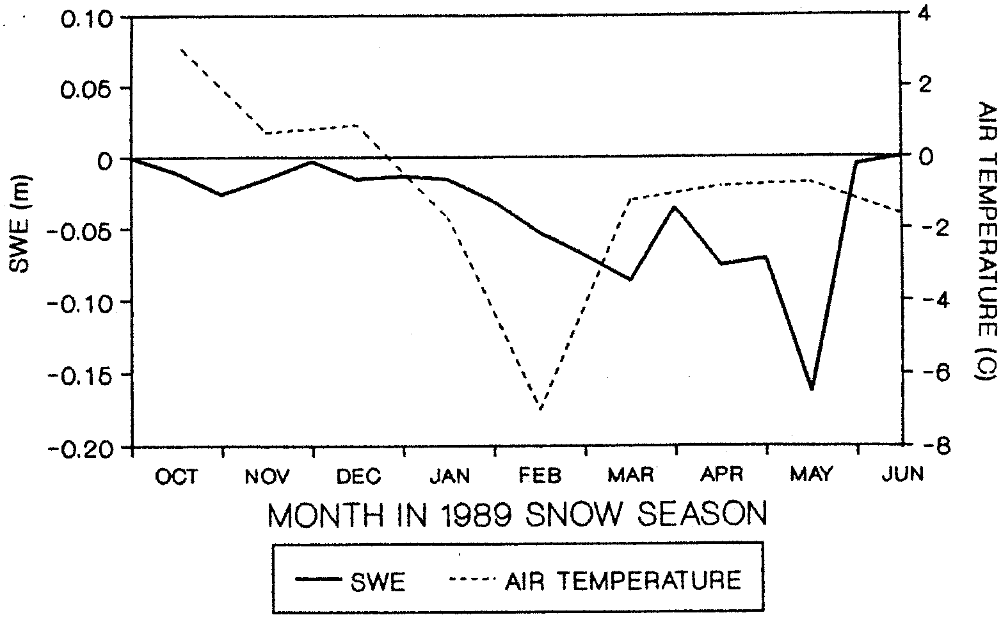

Figure 2. Deviations of temperature and snow water equivalence (SWE) from the mean. Data is from the 1989 snow season (October 1 through June 15; Scaling, 1987). Means are a result of 8 and 25 year averages for temperature and SWE, respectively, as observed at the Lick Creek SCS SNOTEL site.

Snow Accumulation

For much of the accumulation season (from early January; day 8, through mid-March; day 80), plot B with a low forest structure had the highest snow water equivalence (SWE) (Figure 3). The meadow (plot A), with no forest, followed second during this time period, in terms of the amount of SWE. The intermediate forest (plot C) had the third most SWE, and finally the high or full structured forest (plot D) had the least amount of SWE. By late March (approximately day 80) through to the period of maximum mean SWE (early April; day 92), the pattern changed such that the meadow (plot A) equaled and then exceeded the young tree plot (plot B) in SWE. This illustrates the relationship of a decline in maximum SWE corresponding to increasing canopy density, basal area, and tree age (Table 2). The lowest snow depths were measured in the forest with the highest forest structure (high canopy density and basal area) (plot D), and the greatest snow depths were measured in the meadow with no trees. The depths of snow in plots A (no forest) and B (low forest structure) were very similar.

This change in the SWE pattern probably resulted from the late season storms that brought the SWE closer to the average at the SNOTEL site from mid-March to early April (Figure 2). Typically, late season storms are associated with higher temperatures and more moisture, depositing snow with a higher density than the lower temperature and drier mid-winter storms. This higher density snow is often less vulnerable to redistribution by wind, suggesting that much of the snow deposited in the meadow (plot A), free from canopy interception, was not redistributed by wind. The forest canopy is an above ground biomass that intercepts snow and makes it vulnerable to redistribution by wind or through-fall during and after storms (Gary, 1979). Kolesov (1985) found that 10-15 percent of the total winter snowfall was intercepted by tree crowns and then fell to the surface during wind events or warm weather. The presence of trees also influences the surface terrain roughness, decreasing wind velocity and thereby affecting erosional, transportational, and depositional characteristics of the snow (Gary, 1979). The snow intercepted by the young trees in plot B was potentially more vulnerable to sublimation (especially during the warmer months) and more exposed to wind redeposition (being suspended in the aerial environment) than that in plot A, resulting in less snow on the ground in plot B, at the time of maximum accumulation. The high amounts of precipitation in 1989, just prior to maximum accumulation, bringing the

SWE closer to the average (Figure 2), likely contributed positively towards accumulation in the meadow (plot A) while interception and redeposition played a more important role in the plots with trees.

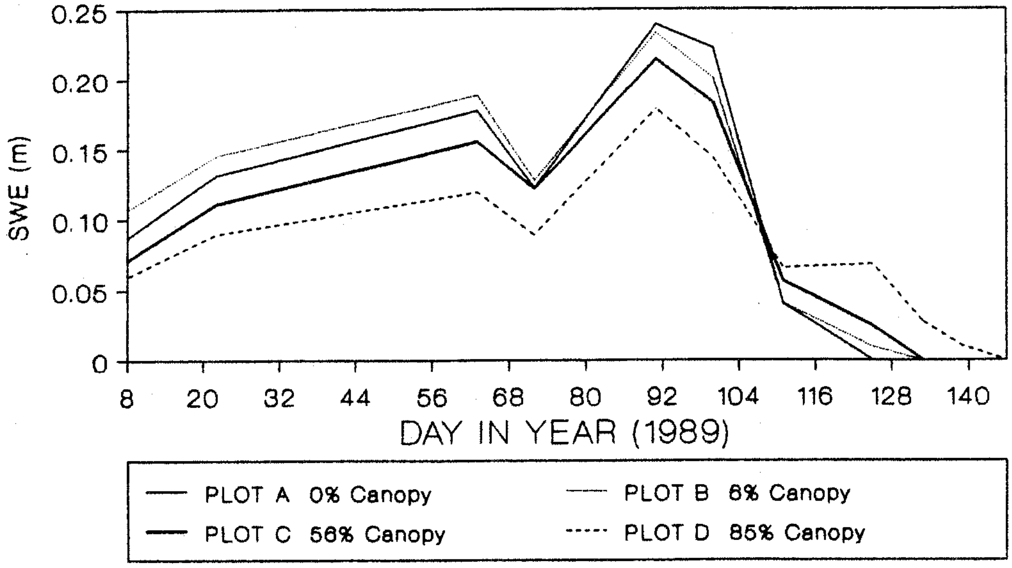

Figure 3. Snow water equivalence (SWE) measured at all plots during the 1989 snow accumulation and ablation season.

Table 2. MEAN SNOW DEPTH, MEAN DENSITY, MEAN SNOW WATER EQUIVALENCE (SWE), AND PERCENT SNOW WATER EQUIVALENCE OF PLOT A ON APRIL 2, 1989 (MAXIMUM ACCUMULATION).

SITE	MEAN DEPTH (m)	MEAN DENSITY (kg/m^3)	MEAN SWE (m)	PERCENT SWE OF PLOT A
A	0.846	283	0.239	100
B	0.809	288	0.233	97.5
C	0.806	266	0.214	89.5
D	0.699	255	0.178	74.5

A similar pattern, to that observed with snow depths, exists when comparing mean snow densities between plots (Table 2) at the time of maximum accumulation. In general, an increase in canopy density negatively correlates ($r= -.96$) with a decrease in snow density. However, an exception did exist in this study, when the snow density was slightly higher (by 5 kg/m^3) in the plot with a young, low density, low structured forest (plot B) than it was in the meadow with no trees (plot A). The lower snow densities as observed in plots C and D, suggest that the higher forest structures in these plots contribute towards a reduction of solar transmissivities (i.e., increased shading) and a reduction of wind-induced redistribution of snow, reducing the effects of these processes on snow metamorphism and therefore, on snow density.

The effect that snow depth and density have on snow water equivalence becomes apparent when these values are compared between plots A and B (Table 2). Although the depth of snow in plot A exceeded that of plot B by 4.6% (0.037 m), the density of plot A was slightly less (1.7% or 5 kg/m^3) than that of plot B. The actual difference in SWE between the plots was only 2.6% (0.006 m) because the lower density snowpack in plot A significantly reduced the snow water equivalence. The SWE accumulated in each plot shows an inverse relationship to forest structure, such that the highest amounts of SWE were found in the plots with the least number of trees. Potts (1984), investigating snow accumulation and ablation patterns in different stand densities as a result of thinning, also found that snow accumulation in lodgepole pine stands was inversely proportional to basal area or canopy density. The canopy density in this study was found to be proportional to basal area (Table 1) such that the snowpack SWE at the time of peak seasonal accumulation was also inversely proportional to the basal area of a site, confirming the results reported by Ffolliot, et al. (1989).

The relationship between maximum SWE, as observed on April 2nd, and percent canopy density (Figure 4) indicates a good negative correlation (Pearson's correlation coefficient = -.5426; p-value = .0000) (a correlation coefficient of -1 is a perfect negative correlation). When the data are smoothed (f-value = 0.4) and a non-parametric, lowess regression curve is computed (Figure 4), the slope of the curve between approximately 10 and 55 percent canopy density is quite low, suggesting that the extent of maximum SWE is not greatly influenced by these low to intermediate percent canopy densities. At low percents of canopy density, such as in plots A and B, the fluctuations in the curve shown are likely due to the many points representing zero percent canopy densities. These fluctuations may also be due to the influence of the surrounding forests on snow redistribution. The significance of the relationship between maximum SWE and canopy density becomes most apparent in the trend of the curve in areas of intermediate to high percent canopy densities. A sharp break in the slope of the curve at approximately 75-80 percent canopy density suggests that a forest structure with a canopy density at these high percentages will greatly reduce maximum snow accumulation. It should be noted that these high percent canopy densities are reached under a forest dominated by subalpine fir, while the intermediate and low canopy density values occurred in lodgepole pine dominated forests. Although the strength and reliability of the statistical tests are only as good as the extent of the sample size, these results confirm the hypothesis that the extent of maximum snow accumulation is inversely related to forest structure (canopy density and basal area).

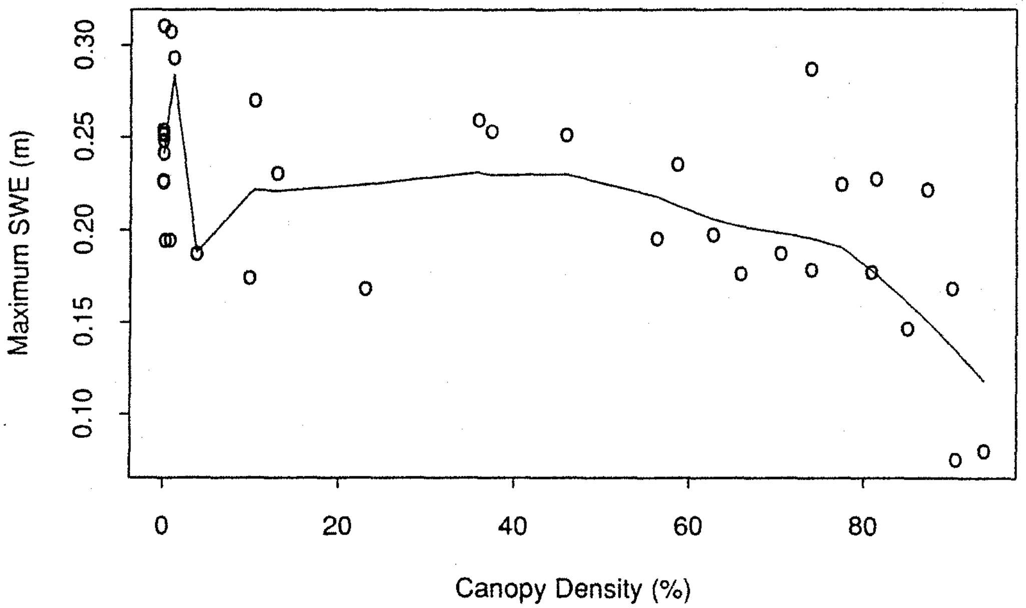

Figure 4. Scatter plot (with lowess smooth) showing the relationship of percent canopy density to maximum snow water equivalence (SWE). The lowess curve was computed using a smoothness parameter of f=0.4; Pearson's correlation coefficient = -.5426; p-value = .0000.

Snow Ablation

Rates of ablation were used to indicate the affect of forest structure on snow retention; for individual trees and the entire forest canopy absorbs, scatters, and emits radiant energy, profoundly affecting the energy exchange within the forest (Bohren, 1972). It was suspected that additional direct solar radiation to the plots with few or no trees would accelerated ablation, compared to plots with shading provided by a high canopy density. As noted by Marks and Marks (1980), as the canopy density increases, as in a high structured forest, less solar radiation reaches the snow surface, reducing the amount of energy input to the snow and slowing the rate of ablation. However, the presence of a forest canopy also diminishes surface wind velocities, reducing the turbulent exchange between the atmosphere and the snow surface (Oke, 1987), resulting in greater net retention of energy by the snow and an accelerated rate of snowmelt. Any vegetation protruding above the snow, including trees, was assumed in this study to have provided additional energy to the snowpack by conduction and by emission of long-wave radiation, as described by Marks and Marks (1980). Clearings the size of 1H (where the diameter of the opening equals the height of the surrounding trees) apparently allow for the slowest ablation rates (Swanson and Golding, 1982) because surrounding trees will intercept the incoming solar radiation, shading the forest opening, and at the same time, the clearing will allow long-wave emission from the snow surface (Marchand, 1987). The degree to which the forest effects short-wave and long-wave radiation is a function of forest canopy structure (Ffolliot et. al., 1989).

Due to the varying forest structure's influence on the environments of the study plots, the length of the ablation season varied between each plot (Figure 3). By mid-April (approximately day 110), once ablation had initiated, the meadow plot (plot A) with no trees had the least SWE, corresponding to the highest ablation rate. This plot was also the first plot to completely ablate. This was followed by a sequence of complete snow ablation in plots corresponding to an increasing forest structure. Plot A was completely snow-free by May 6th, followed by the complete ablation of plots B and C by May 14th, and finally, plot D had ablated completely by May 27th.

The mean daily ablation rate for each plot, determined during a 20 day period when all plots still had a measurable quantity of snow (April 2-22) (Table 3), was highest in the plot with no trees (plot A) and lowest in the plot with a high forest structure (plot D). The average ablation rate, tested against the percent canopy density, suggested a strong negative relationship (correlation coefficient of -.8709; p-value of .0000) (Figure 5). In other words, forests with higher canopy densities have lower snow ablation rates. Using a non-parametric regression fit in order to further understand the relationship between ablation rates and canopy density (Figure 5), a steep downward trend in the ablation rate is noticed at approximately 70-75 percent canopy density. This break in the trend of the slope suggests that canopy densities greater than 70-75 percent are necessary to effectively delay ablation.

Table 3. SNOW WATER EQUIVALENCE (SWE) FOR TWO TIME PERIODS, ABLATION RATES, AND THE ABLATION RATES AS A PERCENT OF PLOT A FOR THE VARYING FOREST STRUCTURES.

SITE	April 2 SWE (m)	April 22 SWE (m)	Difference SWE (m)	Ablation Rate (cm SWE/day)	Percent of Plot A
A	0.239	0.040	0.199	0.995	100
B	0.233	0.040	0.193	0.965	97.0
C	0.214	0.056	0.158	0.790	79.4
D	0.178	0.065	0.113	0.565	56.8

The forests with low and intermediate forest structures (plots B and C) prolonged snowmelt longer than the meadow (plot A), but less effectively than did the mature, full structured forest (plot D). Although the full structured forest accumulated significantly less snow, this forest favored a delay in snowpack depletion. Swanson and Golding (1982) also found that snow in thinned forests ablates at a faster rate and the snow disappears 10-12 days sooner than in undisturbed forests. When the snowpack becomes thin enough (between 0.15 m depth (Oke, 1987) and 0.3 m depth (Dozier, 1989)), solar radiation may be transmitted to and absorbed by the earth's surface, accelerating melt processes at the snowpack's base. Gottfried and Ffolliott (1980) found that in a mixed conifer forest the higher snowpack water equivalence, total snowmelt runoff, and daily ablation rate occurred in sites with low and medium basal areas compared to sites with a high basal area. Overall, results of this study reinforce the results from previous studies (Troendle and Leaf, 1981; Marks and Marks, 1980) by showing that the protective canopy cover of a full structured, mature forest contributes positively towards the retention of snow late into the ablation season.

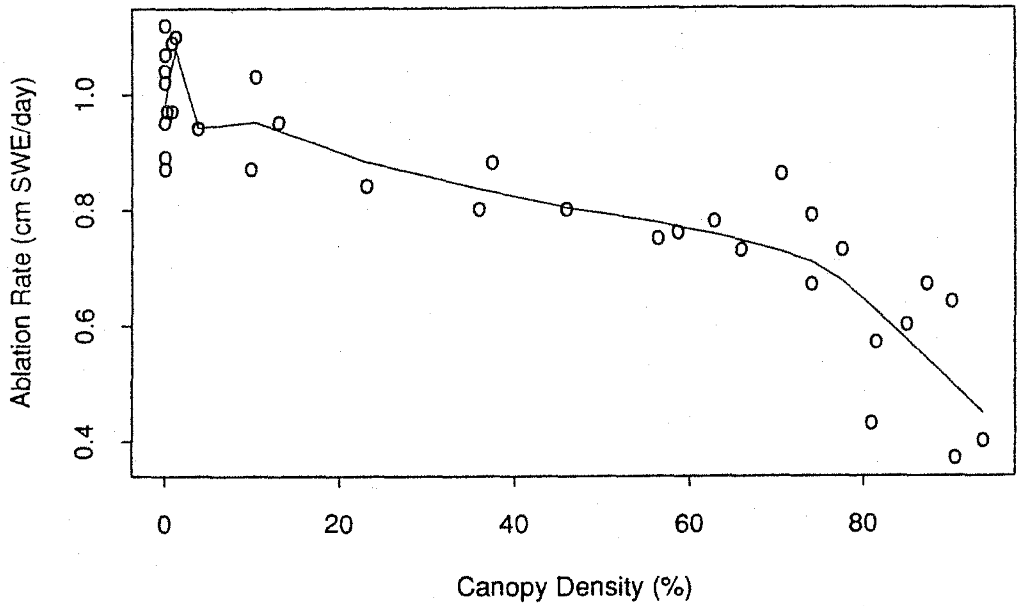

Figure 5. Scatter plot (with lowess smooth) showing the relationship of percent canopy density to ablation rate. The lowess curve was computed with a smoothness parameter of f=0.4; Pearson's correlation coefficient = -.8709; p-value = .0000.

Relationship Between Maximum Accumulation and Ablation Rates

The maximum accumulation (SWE) and ablation rates depended on, and had a negative relationship with, the canopy density of the forest. When values of maximum SWE were standardized (such that the mean equals zero and the standard deviation equals one) and plotted against the corresponding standardized ablation rates (Figure 6), the relationship between the dependent variables showed an increase in maximum SWE corresponding to an increase in ablation rate ($r^2 = 0.415$; p-value= .0000). When the two data points at low values of both maximum SWE and ablation rate were removed the strength of the relationship between the variables decreased ($r^2 = 0.203$; p-value= .0038). This implies that maximum accumulation (SWE) corresponded to the ablation rate, as controlled by the forest structure at a particular site. In other words, areas that accumulated large quantities of snow ablated at more rapid rates than those areas that accumulated less snow.

Comparison of Snowpacks within a Meadow, a Clearcut, and a Young Forest

The ability of a young, low structured forest undergoing regrowth following harvest activity, to accumulate and retain a snowpack compared to the abilities of a meadow or a clearcut were analyzed by studying the snowpack dynamics of plots A and B. In terms of maximum SWE accumulation, plot B with the young trees accumulated 97.5% of the maximum SWE accumulated by the meadow (plot A) (Table 2). This suggests that a young, low structured forest will not accumulate substantially less snow than will a meadow. However, notably less snow did accumulate in plot C (89.5%) and in plot D (74.5%) as compared to the meadow. The ablation rates of the meadow (plot A) and the young forest (plot B) were, again, very comparable (0.995 cm SWE/day and 0.965 cm SWE/day, respectively), with the ablation rate of the young forest being 97% as rapid as in the meadow (Table 3). In contrast, the ablation rates of plots C and D were 79.4% and 56.8%, respectively, of the rate of the meadow. These results imply that young, low structured forests (13 years old, in this case) do not prolong snow retention for a substantially longer time than does a meadow.

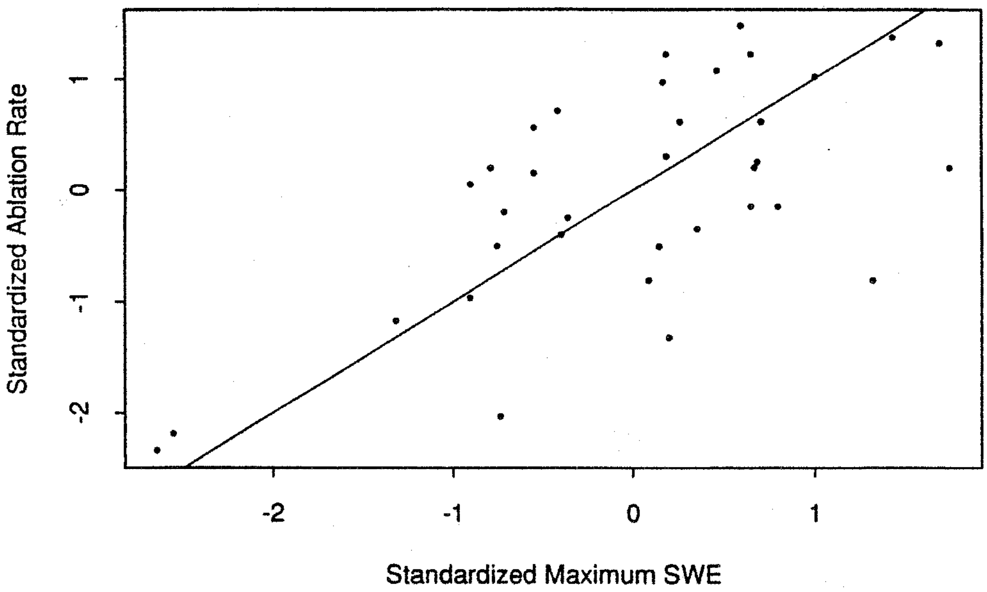

Figure 6. The distribution of maximum accumulation (SWE) and ablation rate are shown by plotting their standardized values (the line extends through the origin with a slope of one) (r^2 = 0.415; p-value = .0000).

Protruding vegetation (on a small scale) above a snowpack has been shown to be a better absorber of incoming solar radiation (than is snow), and the subsequent re-radiation provides more energy to melt the snowpack (Marks and Marks, 1980). The many protruding felled logs and slash burn remnants from clearcutting in plot B, likely contributed to a lower albedo in that stand. The similar ablation rate of the young forest to that of the meadow presumably resulted from the combined effects of increased radiant energy accelerating ablation from both the protruding live vegetation and the clearcut debris, and increased snow retention resulting from shading (although minimal) by the forest canopy. Therefore, it is possible that not only a young forest, but also a clearcut with remnant debris above the snow is less able to retain a snowpack than is a meadow.

These snow distribution similarities between the meadow and the plot with the low forest structure (plot B) are significant in that they refute the assumption that the snow, and therefore, the water regime of a cleared forest will return to pre-harvest conditions (i.e. a mature forest) 20 years after harvest (Gallatin National Forest Forest Plan, 1987). Trees in plot B were harvested in 1973 (U.S. Forest Service, 1989), 16 years prior to this study, and the trees now average 13 years of age. According to this study, plot C which was clearcut in 1950 and thinned in 1965 (39 and 24 years prior to the study, respectively) (U.S. Forest Service, 1989) accumulated 20.2% more snow, and ablated at a rate 38.6% more rapid than its' pre-harvest condition (as represented by plot D with a mean tree age of 79 years).

CONCLUSIONS

Under a weather pattern, as observed during the 1988-89 snow season, of low winter and spring temperatures and a less than average snowpack accumulation during the winter, complete ablation of the snow occurred sooner than normal. Forests with varying forest structures (canopy density and basal area) had a definite effect on patterns of snow accumulation and ablation. For much of the initial accumulation period, more snow accumulated in the young, low canopy density and low basal area forest than accumulated in the meadow. Gradually, by the time of maximum accumulation, the meadow's snowpack exceeded that of the young, low structured forested site, probably due in part, to a lack of redistribution by wind of the higher density snow falling later in the snow season. In forests with reduced canopy densities and basal areas (due to a history of timber harvest), 20-34% more SWE was observed at the time of peak snow accumulation than in the undisturbed, higher canopy density and higher basal area, full structured mature forests. Maximum SWE was found to not be greatly influenced by low to intermediate (10-55%) canopy densities; however, a marked reduction in SWE was measured in canopy densities greater than 75-80%.

The plots with the greatest accumulation at the time of maximum SWE also had the highest ablation rates and therefore, the earliest disappearance of the snowpack. Ablation rates (Table 3) of 0.995 cm SWE/day in the meadow, 0.965 cm SWE/day in the low structured forest, 0.79 cm SWE/day in the intermediate structure forest and 0.565 cm SWE/day in the undisturbed, high structured mature forest suggest an inverse relationship between forest structure and ablation rate. Snow ablation rates were not significantly reduced until under a canopy density of 70-75% or greater. The canopy overstory, by shading, is believed to be a critical factor in reducing the radiation input to the snowpack. The effect of reduced radiation decreases the rate and delays the timing of complete ablation.

Within the recently clearcut, young, low structured forest (13 years old with a 6% canopy density), snow accumulation and ablation patterns were very similar to those in the meadow site with no trees. The similarities in accumulation may have resulted from minimal branch interception, and subsequent exposure of the snow to evaporation and sublimation by the relatively few trees. The similarities in ablation rates may have been due to the assumed lower albedo of the protruding clearcut debris (compared to the higher albedo of only snow), enhancing re-radiation and thus increasing ablation rates in the young forest. This refutes the claim that 20 years after a clearcut harvest, a forest will return to its pre-harvest water regime. These results imply that the pre-harvest water regime of a cleared forest will not return until the mean age of the forest is greater than 35 years (age of trees in plot C) and near 79 years (mean age of trees in plot D). The number of years required for complete recovery of the water regime following timber harvest will depend on whether the trees are replanted or allowed to return by natural succession.

With these results, watershed managers may be better able to balance the varying water yields and ablation rates resulting from various forest management strategies and timber extraction practices, so to ultimately sustain or maintain a water supply. The same knowledge may assist watershed managers in decision making regarding the amount and timing of timber harvest permitted in critical watersheds. For example, these results suggest that young trees do not differ significantly from a clearcut in their ability to accumulate or retain a snowpack, and in a watershed where a delayed and sustained water yield is desired, clearcuts and low density regrowth forests should be minimized.

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