RELATIVE SIGNIFICANCE OF INTERCEPTION AND WIND REDISTRIBUTION IN SUBALPINE FOREST DIFFERENTIAL SNOW ACCUMULATION

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ABSTRACT

In subalpine forests, the relative significance of interception and wind redistribution causing differential snow accumulation varies with species, evapo-sublimation, topography, wind, forest cover density, opening size, and seasonal snow accumulation.

Wind induced differential snow accumulation increases with the intensity of selective or partial cutting. On average, wind redistribution accounts for less than 25 percent of the increased snowpack for lighter cuts to approximately 50 percent for complete removal of forest cover density.

During a near-minimum snowpack year with lower wind energy, reduced interception losses accounted for 62 percent of the differential snow accumulation in a 6 tree height strip cut on Fool Creek at the Fraser Experimental Forest. Thirty-eight percent was attributable to wind redistribution. During a near-maximum snowpack year with higher wind energy, wind redistribution accounted for at least 58 percent of the differential snow accumulation and 42 percent from reduced interception.

Simulated increased snow accumulation using the algorithms developed for reduced interception loss and wind induced redistribution correlate well with snowpack increases observed for various levels and patterns of basal area removal. (KEY WORDS**:** differential snow accumulation, snow interception, wind redistribution, snowpack, subalpine forest)

INTRODUCTION

Our current understanding of the relative roles of wind redistribution and interception in differential snow accumulation at the watershed level is based primarily on inferences made from snow course measurements in partial cuttings, the uncut forest, and clearcut openings. Such measurements integrate the complex processes of interception and wind redistribution. Building on early work and more recently published work which has increased our understanding of processes like (1) the aerodynamics of forest clearings and (2) snow evapo-sublimation since Hoover and Leaf (1967), this paper attempts to present coherent and process-oriented analytical procedures which hopefully bridge gaps in knowledge of the relative roles of snow interception and redistribution in subalpine coniferous forests.

A procedure is presented for making direct computations of interception loss. The analysis of interception loss is followed by partitioning of observed site-specific differential snow accumulation in adjacent six tree height cut and uncut strips on Fool Creek in the Fraser Experimental Forest. Wind redistribution in the strip cut is computed as a residual from direct computation of (a) reduced evapo-sublimation from interception and (b) increased evapo-sublimation loss from the snow surface in the strip cut.

Finally, a procedure is presented for quantifying differential snow accumulation from partial reduction of forest cover density by direct computation of (a) snowpack increases from wind redistribution, (b) reduced evapo-sublimation losses from interception, and (c) increased evapo-sublimation from the snowpack surface according to aspect and forest species.

THE ROLE OF INTERCEPTION IN SUBALPINE DIFFERENTIAL SNOW ACCUMULATION

Part of the increased snowpack observed in natural and man-made clearings is the result of reduced canopy interception losses.

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Maximum canopy storage, which is pertinent for calculating these losses (Miller, 1964), has recently been quantified to a greater extent for subalpine conifer forests by Schmidt and Gluns (1991), whose work was cited by De Walle and Rango (2008). Table 1 contains a summary of the water equivalent of maximum snowfall canopy storage (Sm) for the three primary forest species. It should be noted that observed Sm values by Schmidt and Gluns (1991) are somewhat less than those assumed by Leaf and Brink (1973) which were 7.62 mm and 5.08 mm for Spruce/fir and Lodgepole pine respectively, and by Miller (1964), which was approximately 6 mm for young Lodgepole pine.

Given the estimates of Sm in Table 1, the evapo-sublimation loss from intercepted snow from a given storm event can be written as:

$$\varepsilon_i = \phi \, Sm_i \qquad [1]$$

where

ε_i = evapo-sublimation loss from snow intercepted during a given storm event in mm,

ϕ = the fraction of storm water equivalent lost to evapo-sublimation, and

Sm_i = the water equivalent of maximum snowfall canopy storage in mm.

Equation [1] assumes that snow water equivalent during each storm event is greater than or equal to Sm.

Table 1. Water Equivalent of Maximum Canopy Storage (Sm), Estimated Fraction of Intercepted Snow Lost to Evapo-sublimation (ϕ), and Evapo-sublimation Loss (ε_i) From Intercepted Snow

Species	**Sm (mm)**	**ϕ**	**ε_i (mm)**
Englemann Spruce (Picea Englemanli (Parry))	5.22	0.27	1.409
Lodgepole pine (Pinus Contorta Dougl.)	4.35	0.27	1.174
Subalpine fir (Abies lasiocarpa (Hook) Nutt.)	3.94	0.27	1.064

Schmidt (1994) observed that evapo-sublimation from intercepted snow was not significant during storm events and most of it occurred between 0400 and 1600 each day during non-storm days.

For the snow accumulation season (assumed as 152 days between Nov. 1 and April 1),

$$\sum_{i=1}^{n} \varepsilon_i = n\phi Sm_i \qquad [2]$$

where

n = the number of snowfall events

The ϕ coefficient is an elusive parameter which describes the complex interaction between precipitation, canopy morphology, the mechanics of snow interception, the energy balance, gravity, and wind (see DeWalle and Rango, 2008).

Equation [2] provides an areal estimate total interception loss that occurs at varying rates of evapo-sublimation throughout the snow accumulation season.

Miller (1964) and Hoover and Leaf (1967) studied the mechanics of snow interception as did Schmidt (1991) using an artificial conifer. Schmidt (1991) also developed a quasi-empirical sublimation model for simulating snow interception loss from a conifer crown. This model implicitly accounts for the controlling factors of humidity, temperature, wind speed, and radiation, all of which were measured in his experiment. Schmidt developed a tree: sphere quasi-empirical sublimation ratio Z, which is a function of the mass of intercepted snow.

Other empirical evapo-sublimation models which also implicitly account for the controlling factors cited above have been developed. For example, Leaf and Brink (1973) developed algorithms for calculating areal estimates of evapo-sublimation from intercepted snow and from the snow surface beneath the forest canopy as follows:

for intercepted snow:

$$I = V_c = \frac{1}{C_d} E_s \qquad [3]$$

where

I = seasonal intercepted snow evapo-sublimation,
C_d = forest cover density expressed as a decimal, and
E_S = areal evapotranspiration determined from the Hamon Equation (Hamon, 1961).

for the snow surface beneath the forest canopy (V_s):

$$V_s = (1 - C_d)\, E_s \qquad [4]$$

Leaf and Brink (1973) presented a water balance spreadsheet that summarizes canopy and snow surface evapo-sublimation losses between February 20 and April 10, 1967.

From the data presented in this spreadsheet, I = 24.63 mm and V_S = 6.15 mm.

During the same period, snow precipitation was 159.77 mm from 19 storms. Accordingly, the total maximum canopy storage during the interval at this location assuming a mean Sm of 4.78 mm (Table 1) for 50 percent Spruce/fir and 50 percent Lodgepole pine = 19 x 4.78 = 90.82 mm.

The evapo-sublimation loss as a percentage of total seasonal intercepted snow (ϕ) is 24.63/90.82 x 100 = 27.12 percent, almost 5.5 times the evapo-sublimation losses reported by Satterlund and Haupt (1970) for Douglas fir and white pine in northern Idaho, where melting and rainfall dominate the interception process. It should be noted that the evapo-sublimation losses from intercepted snow (ε_i) summarized in Table 1 are within the range reported by Lundberg and Halldin (1994) cited by Stegman (1996) of 0.3 – 3.3 mmd^{-1} for 50 of 250 days during two winter seasons.

The foregoing analysis implies that approximately 73 percent of the intercepted snow not sublimated was mechanically removed as through fall and wind redistribution. This result is supported by Pomerory et al. (1998) (cited in DeWalle and Rango, 2008) who empirically derived a snow canopy unloading coefficient of 0.7 for forests in cold regions.

WIND, PRECIPITATION, AND DIFFERENTIAL SNOW ACCUMULATION ON FOOL CREEK

Figure 1 is an aerial photograph of the classic Fool Creek watershed on which 39 percent of the timber was removed in a system of roads and alternate clearcut strips which varied from one to six tree heights in width.

Cutting patterns were replicated in four blocks. Differential snow accumulation in each block was measured by means of a comprehensive snowcourse network (1224 points) in 1965 and over 600 points in 1966; (Hoover and Leaf, 1967).

Figure 2 shows near-peak snow accumulation across cut and uncut six tree height strips in Block D.

Table 2 summarizes mean water equivalents in the cut and uncut strips observed in 1964-1965 and 1965-1966. Also summarized for comparison are watershed estimates of differential snow accumulation on Fool Creek and Deadhorse Creek North Fork (Troendle and King, 1987) for 1964-1965 and 1980-1981, respectively.

Figure 1. Fool Creek, Fraser Experimental Forest, Colorado U.S. Forest Service Photo

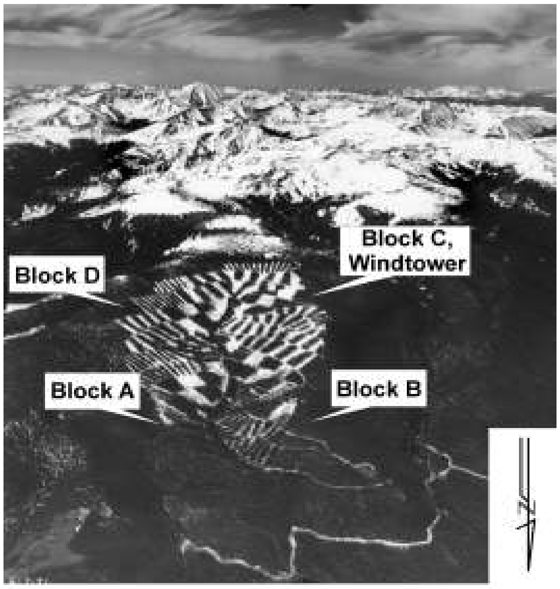


Figure 2. Fool Creek Near-Peak Snow Accumulation Block D, Width 6 Center Transect

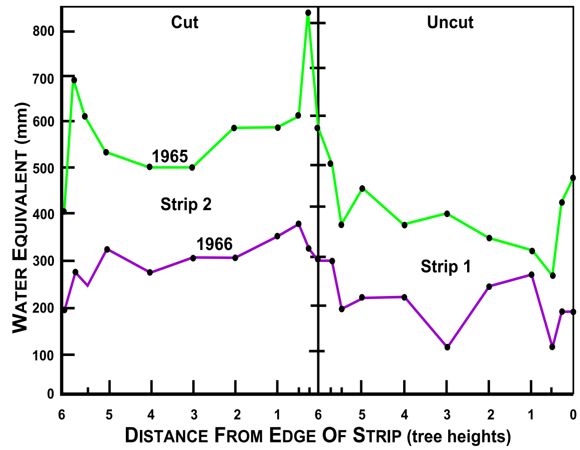


Table 2. Mean Near-Peak Water Equivalent in Forest and Open on Fool Creek and Deadhorse Creek North Fork, Fraser Experimental Forest

Snow Accumulation Season	Mean Water Equivalent (mm)		Ratio: Cut/Uncut
	Cut	Uncut	
A. Block D, 6 Tree Heights on Fool Creek			
1964-1965	560.58	392.43	1.43
1965-1966	278.64	199.90	1.39
Mean	**419.61**	**296.16**	**1.42**
B. Watershead:			
1. Fool Creek all 6 Tree Height Cut and Uncut Strips; Northerly Aspect in Spruce/fir and Lodgepole pine.			
1964-1965	520.70 (487.40)[2)]	349.20 (384.00)[2)]	1.49 (1.27)[2)]
2. Deadhorse Creek North Fork, all 5 Tree Height Opeings and Uncut Forest; Southerly Aspect (Troendle and King, 1987) in Lodgepole pine			
1980-1981	520.00	400.00	1.30

[2)] All cut and uncut strip widths

Table 3 summarizes estimated above canopy wind speed, Ū (Leaf, 2009) and precipitation according to wind direction at Fool Creek Windtower. Wind speed and direction were estimated from correlations with Berthoud Pass Chairlift (Judson, 1977) for the 1964-65 and 1965-66 snow accumulation seasons. The number of snowfall events, as defined in equation [2] was 65 and 52 during the 1964-1965 and 1965-1966 winter seasons respectively.

It should be noted in passing that in order for recently intercepted snow that is loosely bonded to canopy foliage to be transported out of the canopy into adjacent openings, wind speeds must be $\geq 1.75 ms^{-1}$ (DeWalle and Rango, 2008 and Schmidt, 1991). Mean wind speeds summarized in Table 3 exceed the $1.75 ms^{-1}$ threshold from all wind directions.

Table 3. Variation of Above Canopy Velocity and Precipitation with Wind Direction at Fool Creek Windtower During 1964-1965 and 1965-1966 Snow Accumulation Seasons

Wind Direction	1964 - 1965 Ū (ms^{-1})	n	ppt. (mm)	1965-1966 Ū (ms^{-1})	n	ppt. (mm)
North	4.49	21	58.96	4.44	21	57.40
Northeast						
East						
Southeast						
South	5.28	12	64.47	3.33	4	26.42
Southwest	7.00	7	44.00	5.60	4	28.19
West	4.72	25	181.32	4.27	22	89.41
Northwest				4.20	1	3.81
Total		**65**	**348.75**		**52**	**205.23**
Mean	**5.37**			**4.37**		
Std. Dev.	**1.135**			**0.812**		

Table 4. Less Canopy Interception in Block D Width 6 Opening

Season	Mean Sm_i (mm)	Mean ε_i (mm)	n	I (mm)
1964-1965	4.78	1.29	65.25	84.17
1965-1966	4.78	1.29	52.20	67.34
Mean	**4.78**	**1.29**	**58.73**	**75.76**

Interception Loss

Table 4 presents estimates of interception loss for 1964-1965 and 1965-1966 from the data presented in Tables 1 and 3, and equation [2]. Mean Sm_i in Table 4 represents a forest composition of 50 percent Spruce/fir and 50 percent Lodgepole pine determined from a 1948 timber survey.

Wind Redistribution

The wind-induced component of increased snow accumulation was calculated as:

$$R = \Delta we - I + \Delta E_s \qquad [5]$$

where

R = the wind-induced component of increased snow accumulation in mm,
Δwe = the observed differential snow accumulation in 1965 and 1966 (Table 2) in mm, and
ΔE_s = the increased surface evaporation in the clearing in mm.

Schmidt, et al. (1998) cited research which indicates that E_s in openings can be up to twice that in the adjacent forest.

Leaf and Brink (1973) assumed that surface evaporation in the open expressed as a ratio to surface evaporation beneath the forest canopy varies as:

$$\frac{1}{(1-C_d)}$$

where C_d is the forest cover density (see equation [4]). In Block D on Fool Creek, C_d was estimated to be 0.5, therefore, $E_s = 2.00\ V_s$. This compares with $E_s = \frac{V_s}{0.69} = 1.45\ V_s$ from an ice sphere model developed by Schmidt, et al. (1998).

Table 5 compares estimated daily surface evaporation in the strip cuts (e_s) and surface evaporation beneath the forest canopy (v_s) with e_s and v_s measured by Wilm and Dunford (1948). The seasonal mean e_s is comparable to Bernier and Swanson (1993) who reported that surface evaporation in 6 tree height openings was approximately 0.35 mmd^{-1}. These long-term seasonal means are also comparable to Doty and Johnston (1969) who reported 0.30 mmd^{-1} with a range of 0.02 – 0.76 mmd^{-1} in openings and 0.14 mmd^{-1} with a range of 0.07 – 0.17 mmd^{-1} beneath mixed conifer forest. Surface evaporation beneath the forest canopy can be significantly higher (up to 0.5 mmd^{-1}) for short periods during the snow accumulation season as reported by Schmidt, et al. (1998).

It is also interesting to compare estimates of interception loss proposed herein with measured Lodgepole pine plot data (Wilm and Dunford, 1948). Assuming that I = 64 x 0.27 x 4.78 = 82.90 mm from equation [2]. For an assumed 152-day snow accumulation period, mean interception loss = 0.55 mmd^{-1}.

From Table 5, it is seen that mean daily evapo-sublimation loss from intercepted snow is approximately 4 to 4.5 times that from the snow surface beneath the forest canopy.

Table 5. Estimated Surface Evaporation Loss Rates (v_s) and (e_s) in Block D of Fool Creek Compared with Lodgepole Pine Harvest Plots for Average Year

Location	v_s mmd^{-1}	e_s mmd^{-1}
Fool Creek Block D, Width 6 Strip Cut	0.125	0.279
Lodgepole pine Harvest Plots (Wilm and Dunford, 1948)	0.134	0.334[3)]

[3)] measured quantity

RELATIVE SIGNIFICANCE OF REDUCED INTERCEPTION AND WIND REDISTRIBUTION

Table 6 summarizes the relative significance of seasonal gains from reduced interception and redistribution in the six tree height strip cuts in Block D of Fool Creek. The gross wind redistribution was calculated as a residual from equation [5].

Table 6. Relative Significance of Seasonal Gains from Reduced Interception and Wind Redistribution in Block D Width 6 Opening

Season	Δwe	I	ΔE_s	R	Ratio $\frac{I}{\Delta we + \Delta E_s}$	Ratio $\frac{R}{\Delta we + \Delta E_s}$
	(mm)	(mm)	(mm)	(mm)		
1964-1965	168.15	84.20	30.40	114.35	0.421	0.576
1965-1966	78.74	67.36	30.40	41.76	0.617	0.383
Mean	123.44	75.78	30.40	78.06	0.493	0.507

The analysis summarized in Table 6 shows the relative significance of seasonal gains from reduced interception and wind redistribution on the north-northeast facing aspects of Block D in Fool Creek. During 1964-1965, a near-maximum snowpack year with higher wind energy (Table 3), 42 percent of the increased snow accumulation was derived from reduced canopy interception and 58 percent from wind redistribution.

During 1965-1966, a near-minimum snowpack year with less wind energy, 62 percent of the differential snow accumulation was from reduced interception, and 38 percent was from wind redistribution. For the average year, the ratios are 49 percent and 51 percent for wind redistribution and reduced interception respectively.

Simulated wind redistribution varied from a maximum 65 percent to a minimum 23 percent on the northwest facing aspects of Block D in Fool Creek during a 17-year period between 1959 and 1975.

This research suggests that on average, after treatment, approximately 49 percent of the gross differential snow accumulation in Block D on Fool Creek was from wind redistribution and 51 percent was from reduced snow interception. At the Wilm and Dunford study site where the commercially clearcut blocks were on northwest facing aspects, at a lower elevation in Lodgepole pine, wind redistribution was less significant, accounting for approximately 27 percent of the differential snow accumulation (Table 7).

The gain from reduced interception (I) in Table 7 was calculated from Table 1 and equation [2] for an average n of 64 storm events during 1941-1943 (Haeffner, 1977). The gain from wind redistribution was calculated from equation [5].

Wind redistribution was somewhat less significant than on Fool Creek, due to a smaller wind exposure index and less wind energy available for transport (Leaf, 2009).

Table 7. Relative Significance of Seasonal Gains From Reduced Interception and Wind Redistribution in Lodgepole Pine Harvest Plots (Wilm and Dunford, 1948) For Average Year

Season	Δwe	I	ΔE_s	R	Ratio $\frac{I}{\Delta we + \Delta E_s}$	Ratio $\frac{R}{\Delta we + \Delta E_s}$
	(mm)	(mm)	(mm)	(mm)		
1941-1943	81.28	81.28	30.40	30.40	0.727	0.272

Troendle and King (1985) reported that on average, mean area water equivalents had increased on Fool Creek from an analysis of a longer period of record than was available to Hoover and Leaf (1967). Troendle and King (1985) showed that some portion of the increased water yield from Fool Creek was from reduced canopy interception losses. However, they did not show the relative significance of wind redistribution in causing observed differential snow accumulation.

Tables 6 and 7 show that the relative significance of interception and redistribution depends on available wind energy and seasonal snowfall. From Table 3 it is seen that mean wind speed exceeded 2 ms^{-1} in 1964-1965 and 1965-1966, hence wind redistribution is proportional to the amount of seasonal snowfall. On Fool Creek during the 1964-1965 snow accumulation season, R>I, implying that some of the differential snow accumulation in the strip cut occurred at the expense of snow accumulation in the adjacent uncut strip.

During 1965-1966 on Fool Creek and during 1941-1943 on the Lodgepole pine harvest plots R<I. In this case, wind redistributed snow derived from the surrounding canopy would have otherwise been lost to the atmosphere, with little change in pre-treatment snow accumulation in the uncut forest.

During the average year on Fool Creek, R is very nearly equal to I, implying essentially no change in pre-treatment snow accumulation in the uncut forest, with an increase in watershed snow storage as reported by Troendle and King (1985). The above inferences are supported by an analysis of long-term snow accumulation on Fool Creek summarized in Table 8.

Table 8. Deviations of Observed Peak Water Equivalent Beneath Forest Canopy in Blocks A-D Width 6 from Predicted Peak Water Equivalent Beneath Forest Canopy

Snow Accumulation Season	Predicted Peak w.e. From Pre-Treatment Regression [4] (mm)	Observed Peak w.e. From Blocks A-D Width 6 Stripcuts (mm)	Difference: Obs. - Pred. (mm)
1964-1965	485.85	349.25	-136.6
		384.05 (all widths)	-101.8
1965-1966	144.78	165.18	20.38

[4] FC = 0.6245 + 1,000 ESL $R^2 = 0.9565$
Where ESL is the control watershed snowcourse peak water equivalent, and FC is the Fool Creek peak water equivalent beneath the forest canopy from 50 points measured along the “Figure Eight” snowcourse.

APPLICATIONS

Following are procedures for quantitatively estimating increased snow accumulation for reduced interception loss and wind redistribution based on equations [1] through [5] and recent work by Leaf (2009).

Wind Redistribution

Geiger (1957) presented research that showed the significance of wind on seed distribution at the margin of a pine stand. Seed distribution was analyzed using eddy diffusion theory (Brunt, 1952). As previously discussed, wind is also significant in affecting (a) the transport of snow from the surrounding canopy, and (b) its subsequent redistribution across adjacent clearings.

The quantity of snow available for wind transport into an open area can result from two sources: (1) from snow intercepted by the adjacent forest canopy that otherwise would have been lost to evapo-sublimation, and (2) from intercepted snow that otherwise would have contributed to the snowpack beneath the upwind forest.

Leaf (2009) presented the following equation for quantifying wind redistribution across a forest clearing as follows:

$$u_{cr} = \frac{2\omega}{\tan\propto(1+m)} \qquad [6]$$

where

u_{cr} = the critical velocity at which snow will begin to blow into a clearing from the surrounding canopy, in ms^{-1},

ω = snow particle terminal fall velocity in ms^{-1},

$\propto$ = the angle at a distance X from the Leeward margin and approximately 2 meters above the snow surface to the top of the canopy, and

m = a dimensionless vegetation parameter that describes wind exposure.

The wind exposure index is key to quantifying the significance of wind redistribution. This index is defined by the equation:

$$m = \frac{\overline{U}}{\overline{U}_o} \qquad [7]$$

where

m = the wind exposure index,

$\overline{U}$ = the average local or ambient windspeed above the forest canopy, and

$\overline{U}_o$ = the average regional reference windspeed at canopy level for large open areas.

From the work by Leaf (2009), a relationship was developed which defines snowpack accumulation that is attributable to wind as a function of wind exposure index (Figure 3).

Table 6 above has shown that the relative significance of wind redistribution also varies according to the amount of snow precipitation (supply). Thus, the wind-induced component of increased snow accumulation each year is calculated directly by the equation:

$$R = \frac{\eta'}{0.5} I \qquad [8]$$

where

R = the area water equivalent of wind redistributed snow in mm,

I = seasonal intercepted snow evapo-sublimation loss given by equation [2] in mm, and

η' = wind redistributed snowpack accumulation factor given by the equation:

$$\eta' = \mu \frac{we_r}{\overline{we}_r} \overline{\eta}$$

where

μ = a modifier coefficient which defines the extent of forest cover density (Cd) modification from Cdx, where Cdx is the maximum (baseline) forest cover density,

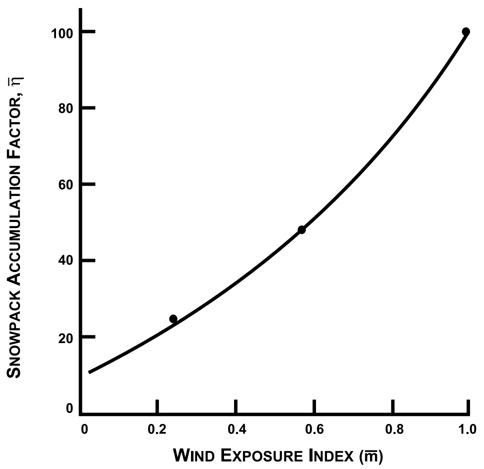
$\frac{we_r}{\overline{we}_r}$ = the ratio of the peak water equivalent in a reference area for a given year to the average reference area peak water equivalent, and

$\overline{\eta}$ = the average wind-caused snowpack accumulation factor from Figure 3.

Interception

Increased snow accumulation caused by reduced evapo-sublimation loss from intercepted snow in a small opening (less than or equal to approximately 10 tree heights in width) is given by equation [2] above. Reduced interception losses from partial removal of the forest cover density is given by the equation:

Figure 3. Average Year Snowpack Accumulation in Subalpine Forest Opening that is Attributable to Wind as a Function of Wind Exposure Index ($\overline{m}$)



$$I = n\phi\gamma Sm \qquad [9]$$

where

γ = a modifier coefficient for maximum snow storage which defines the reduction of forest cover density removal (Cd) from Cdx.

Snow Surface Evaporation

Increased snow surface evaporation can be similarly calculated for partial removal of the forest cover density by the equation:

$$\Delta E_s = t\beta(e_s - v_s) \qquad [10]$$

where

t = the duration of the winter snow accumulation season (approximately 152 days,

β = a modifier coefficient which defines the reduction due to forest cover density removal from Cdx,

e_s = surface evapo-sublimation loss rate in open in mmd^{-1}, and

v_s = surface evapo-sublimation loss rate beneath the forest canopy in mmd^{-1}.

Effect of Forest Cover Density Modification on Differential Snow Accumulation

The effect of forest cutting on differential snow accumulation can be determined by solving the equation:

$$we_f = we' - I - R + \Delta E_s \qquad [11]$$

where

we_f = peak seasonal water equivalent in the undisturbed forest in mm, and

we' = peak seasonal water equivalent in the modified forest in mm.

I, R, and ΔE_s are as previously defined.

The WRENSS model developed by Troendle and Leaf (1980), uses a system of "modifier coefficients" to adjust a water balance according to forest cover density ratios: Cd/Cdx, where Cdx is the maximum (baseline) forest cover density. Similarly, Table 9 summarizes modifier coefficients necessary to solve equations [8] through [10] for various aspects, two forest cover types, and several levels of Cd/Cdx in central Colorado.

Table 9. Summary of Estimated Modifier Coefficients for Increased Differential Snow Accumulation According to Aspect, Two Forest Cover Types, and Several Levels of Cd/Cdx in Central Colorado

a. Interception

Cd/Cdx			North						East/West						South					
Lodge-pole pine	Spruce/fir	Ba/Bax	Lodgepole pine			Spruce/fir			Lodgepole pine			Spruce/fir			Lodgepole pine			Spruce/fir		
			ϕ	Sm	γ	ϕ	Sm	γ	ϕ	Sm	γ	ϕ	Sm	γ	ϕ	Sm	γ	ϕ	Sm	γ
0.00	0.00	0.00	0.27	4.36	1.00	0.27	5.22	1.00	0.30	4.36	1.00	0.30	5.22	1.00	0.32	4.36	1.00	0.32	5.22	1.00
0.43	0.44	0.25			0.57			0.56			0.57			0.56			0.57			0.56
0.61	0.65	0.50			0.39			0.35			0.39			0.35			0.39			0.35
0.82	0.81	0.75			0.18			0.19			0.18			0.19			0.18			0.19
1.00	1.00	1.00			0.00			0.00			0.00			0.00			0.00			0.00

b. Wind Distribution

Cd/Cdx		Ba/Bax	North		East/West		South	
Lodgepole pine	Spruce/fir		Lodgepole pine	Spruce/fir	Lodgepole pine	Spruce/fir	Lodgepole pine	Spruce/fir
			μ	μ	μ	μ	μ	μ
0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
0.43	0.44	0.25	0.80	0.80	0.80	0.80	0.80	0.80
0.61	0.65	0.50	0.53	0.53	0.53	0.53	0.53	0.53
0.82	0.81	0.75	0.32	0.32	0.32	0.32	0.32	0.32
1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00

c. Increased Snow Surface Evaporation

Cd/Cdx		Ba/Bax	North						East/West						South					
Lodge-pole pine	Spruce/fir		Lodgepole pine			Spruce/fir			Lodgepole pine			Spruce/fir			Lodgepole pine			Spruce/fir		
			e_s	v_s	β	e_s	v_s	β	e_s	v_s	β	e_s	v_s	β	e_s	v_s	β	e_s	v_s	β
0.00	0.00	0.00	0.33	0.15	1.00	0.33	0.13	1.00	0.37	0.15	1.00	0.37	0.15	1.00	0.41	0.16	1.00	0.41	0.16	1.00
0.43	0.44	0.25			0.59			0.59			0.59			0.59			0.59			0.59
0.61	0.65	0.50			0.39			0.39			0.39			0.39			0.39			0.39
0.82	0.81	0.75			0.17			0.17			0.17			0.17			0.17			0.17
1.00	1.00	1.00			0.00			0.00			0.00			0.00			0.00			0.00

Simulated Differential Snow Accumulation

Table 10 summarizes simulated peak seasonal water equivalent increases and the relative role of wind redistribution in affecting these increases at a high elevation (3,231 m) NNE aspect site in a mixed stand of Spruce/fir and Lodgepole pine for four levels of forest cover density reduction.

Table 10. Simulated Effect of Partial and Total Forest Cover Density Reduction on Differential Snow Accumulation. NNE Aspect, 3,231 m, $\overline{U} = 4.4 ms^{-1}$ in a Mixed Stand of Lodgepole pine and Spruce/fir

we_f (mm)		Increased Peak Water Equivalent (mm)					Wind Redistribution Component $\frac{R}{\Delta we + \Delta E_s}$				
	Forest Cover Density Reduction (1 - Cd/Cdx)	0.00	0.44	0.63	0.81	1.00	0.00	0.44	0.63	0.81	1.00
	Basal Area Reduction (Ba/Bax) [5)]	0.00	0.25	0.50	0.75	1.00	0.00	0.25	0.50	0.75	1.00
383.16	1965	0.00	17.96	47.20	93.45	177.42	0.00	0.28	0.40	0.50	0.55
244.04	1966	0.00	13.00	32.57	82.34	115.37	0.00	0.20	0.30	0.39	0.44
355.77	1967	0.00	14.37	37.43	73.82	139.78	0.00	0.26	0.37	0.47	0.52
331.17	1968	0.00	16.47	42.59	83.31	157.27	0.00	0.25	0.36	0.46	0.52
302.82	1969	0.00	15.73	44.25	78.23	146.81	0.00	0.24	0.35	0.44	0.50
483.25	1970	0.00	12.24	49.24	99.42	191.12	0.00	0.32	0.44	0.54	0.60
540.07	1971	0.00	22.29	60.97	124.08	239.96	0.00	0.35	0.48	0.58	0.63
377.18	**Mean**	0.00	16.01	44.89	90.66	166.82	0.00	0.27	0.39	0.48	0.54
103.00	**Std. Dev**	0.00	3.40	9.09	17.14	40.67	0.00	0.05	0.06	0.06	0.06

5) from Ba vs. Cd relationships (Troendle and Leaf, 1980)

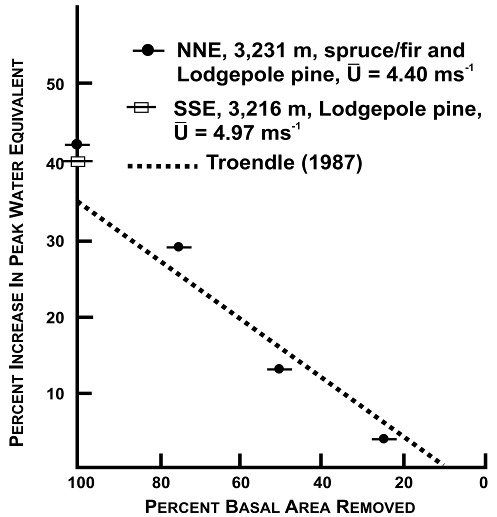
Comparison of Simulated Results with Observed Data

Simulated results from this study are superimposed on a relationship developed by Troendle (1987) which shows the increase in peak snowpack water equivalent as a function of basal area removed (Figure 4). This graph was developed from a number of studies at the Fraser Experimental Forest.

The simulated data points plot well within the scatter in Troendle's average relationship.

It should be noted that simulated results from this study show wide variation in patch cuts (100 percent forest cover density reduction) as the result of diversity in aspect, forest cover type, elevation, and wind exposure.

Figure 4. Percent Increase in Seasonal Peak Water Equivalent as a Function of Basal Area Removed



CONCLUSIONS

This research has shown that both snowfall interception and wind redistribution are important in subalpine forest differential snow accumulation.

As discussed in this paper, the relative significance of each process depends on the complex relationships that exist between forest vegetation, topography, wind, opening size, and the amount of snow precipitation. Equations are presented for quantifying the effects of each process at the watershed level. It is hoped that holistic quantification of these processes as has been done in this paper and by Leaf (2009) will provide a new benchmark for future research.

For 100 percent forest cover density reduction, the principles are valid where sufficient wind protection is afforded to trap snow. Larger openings (larger than say, 8 tree-heights), require additional analyses of blowing snow evapo-sublimation, and transport (Leaf, 2009 and DeWalle and Rango, 2008).

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