IDENTIFYING SNOW INDICES FOR FOREST PLANNING IN SOUTHERN BRITISH COLUMBIA

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ABSTRACT

Snow accumulation and ablation rates vary significantly across the forested landscapes of British Columbia. Changes in snow accumulation and ablation through logging and forest re-growth are assumed to have a direct effect on the quantity and timing of streamflow. To minimise the risk of increased spring peak flows, tree height is used as an operational index to changes in snow accumulation and melt in planning forest development. However, detailed measurements at two research sites in the southern interior have shown that inventory variables such as crown closure account for a larger proportion of the variability among stands, and may be more suitable indices to potential changes in runoff, than tree height. In this study, data from a broad range of sites have been analysed to evaluate which inventory variable provides the best local snow-index. Crown closure explained 68% and 57% of the variability in average standardised peak snow water equivalent and melt rate, respectively. Though a large portion of the variability is not explained by this stand characteristic, it could provide an index to snow in second-growth stands relative to a mature forest. The analysis highlights the difficulties in identifying simple planning tools sought by regulators and industry.

INTRODUCTION

In B.C., most domestic, irrigation, and industrial water flows from snow-dominated, forested watersheds. In these watersheds, forest cover is removed for agriculture, grazing, mining, urbanisation, lumber production, and other land uses, and is also altered through natural processes such as fire, insects, and disease. Such changes may be permanent or temporary depending on forest establishment success and the rate of re-growth.

Forest cover, along with the weather, has a significant effect on snow accumulation and ablation (McKay and Gray 1981). The magnitude of this effect depends on forest cover characteristics such as species composition, stand age, density, and health. The removal of forest cover by logging increases snow accumulation expressed as snow water equivalent (SWE) by 10 to 70% depending on year, aspect, elevation, and stand characteristics (Golding and Swanson 1986; Toews and Gluns 1986). Ablation rate increases ranged from none to double. Research in south-central B.C. showed that peak SWE was reduced by up to 16% under mature lodgepole pine (*Pinus contorta* Dougl.) and up to 43% under mixed Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) (Winkler *et al.* 2004). In these stands, ablation rates are reduced to 0.7 to 0.4 times those in the open, respectively.

The effects of forest regrowth on snow accumulation and ablation have not been widely studied. Hardy and Hansen-Bristow (1990) found that in a 4-m tall lodgepole pine stand, SWE and ablation rates were reduced from those in the clearcut by 4 and 6%. In a 14-m tall pine stand SWE and ablation rates were 14 and 36% less than in the clearcut, respectively. In coastal B.C., Hudson (2000) predicted a 75% 'recovery' in, or return to pre-logging, SWE and ablation once a Douglas-fir stand was 8-m tall with 45% crown closure. In an interior juvenile lodgepole pine stand, peak SWE was 14% less than in the open and ablation rates were 20% less than those in the open. Thinning to remove 30% of the juvenile basal area did not significantly affect peak SWE but did advance the onset of ablation and the date the snowpack disappeared (Winkler et al. 2004).

Many studies have attempted to use stand attributes or forest inventory variables as an index to SWE or ablation. McKay and Gray (1981) summarised the literature suggesting that an inverse relationship exists between SWE and canopy density, making density a possible predictor of interception differences among forest types. Through its

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importance in energy transfer to the snow surface, they further suggested that canopy surface area may be a useful predictor of ablation. Lundberg *et al.* (2004) found that snowfall in the open, together with canopy closure could be used successfully to predict SWE in the forest. Lull and Rushmore (1960) found a 1 mm per degree-day decrease in ablation rate per 10% increase in crown closure. Packer (1971) reported a 7 mm decrease in daily ablation per 10% increase in canopy density on south facing slopes, and a 4 mm decrease on north aspects. Moore and McCaughey (1997) found a 6.4% decrease in peak SWE per 10% increase in canopy density. They also reported a better correlation between canopy density and peak SWE under spruce-fir forests than under pine, and further suggested that other forest-structure variables not measured in their study may also be influencing SWE. Pomeroy and Goodison (1997) reported a more or less linear decrease in the accumulation of SWE with increasing leaf area and noticeable differences in leaf area between stands of different species. SWEs were highest under aspen (*Populus tremuloides* Michx.), less under jack pine (*Pinus banksiana* Lamb.), and least under black spruce (*Picea mariana* (Mill.) B.S.P.). Since basal area and canopy density are often correlated, basal area may also provide a useful index to SWE and ablation as indicated by Talbot and Plamondon (2002). They found that the square root of basal area explained 73% of the variability in a coefficient of snow augmentation. Using basal area as the measure of stand structure, Hansen (1969) reported a 2% increase in SWE per approximately 2 m^2 ha^{-1} reduction in basal area. Hudson (2000) found that the height of the main canopy explained the largest proportion of the variability in a SWE and ablation recovery index.

Streamflow, in particular peak flows, can be affected by forest removal (Troendle and Leaf, 1981). In B.C. for planning purposes, the relationships between forest cover, snowpack processes, and the risk of elevated peak flows are approximated by the single forest inventory variable - tree height (B.C. Min. Forests 1999). This variable is readily available for all stands through the provincial inventory database and is easily measured in the field. Though average tree height provides some indication of snow interception and shade, it does not necessarily reflect crown surface area, canopy density, or stem distribution, stand characteristics known to influence snowpack processes. At two forest – snow interaction research sites in south-central B.C., tree height accounted for only 9 to 13% of the variability in the ratio of forest to open SWE and 19 to 44% of the variability in forest to open ablation rates, depending on year. Other inventory variables, such as crown length, crown closure, and basal area, explained up to 79% of the variability in forest to open SWE and ablation at these sites (Winkler, 2001). In this study, surveys from several independent studies across the southern interior of B.C. are combined to determine whether any of the standard forest inventory variables can be used as an operational snow-index over a broad geographic area and range of forest cover types.

STUDY AREA

This study included snow courses throughout the southern interior of B.C. (Figure 1). The sites vary in elevation from approximately 1150 to 1950 m and include a wide range of aspects and slopes. Forest cover types at these sites included single species or mixed lodgepole pine, Engelmann spruce, subalpine fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn), as well as western larch (*Larix occidentalis* Nutt.). The study included clearcuts, second-growth, and mature stands. Heights of the dominant and codominant trees ranged from 1 to 33 m. Stand basal area varied from 0 to 128 m^2 ha^{-1} and canopy closure from 0 to 92% over the sites surveyed. Peak SWE ranged from 10 to 90 cm and seasonal average ablation rates from 0.1 to 2.9 cm d^{-1}.

METHODS

Field Measurements

Snow and forest inventory measurements were made at 11 study sites. Each study site consisted of at least a clearcut and mature stand, and most often an intermediate stand of natural and/or thinned juvenile trees. The sampling intensity varied from 10 to 64 survey points per stand depending on the study site, as summarised in Table 1.

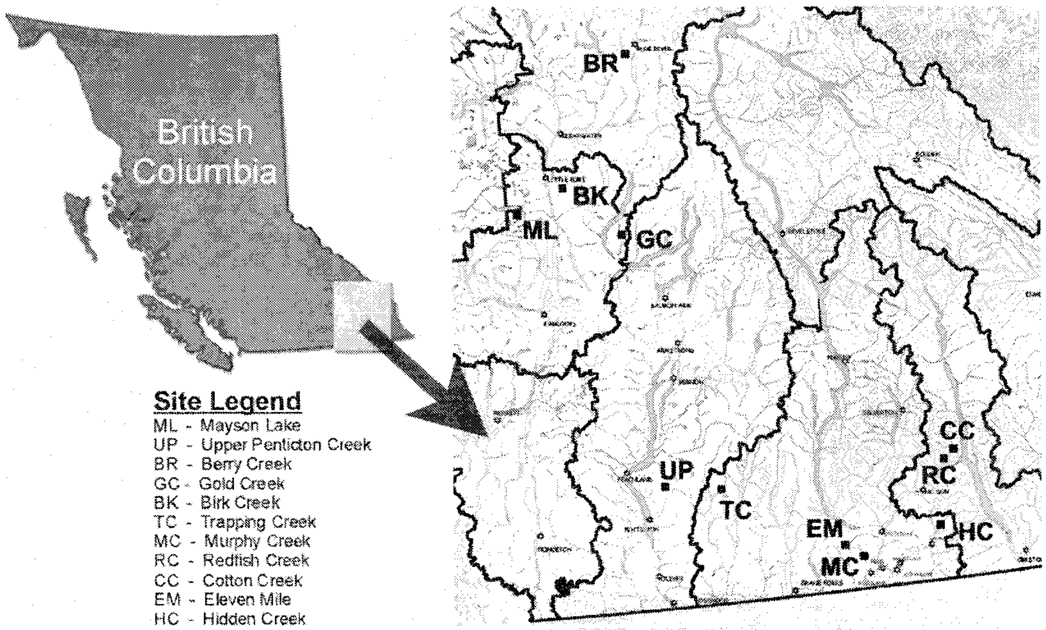

Figure 1. Locations of the forest – snow interaction survey sites in the southern interior of British Columbia.

Table 1. A summary of forest - snow interaction surveys in the southern interior of British Columbia.

Region	Location	# Stands	# Samples Per Stand	# Years	Years
Kamloops	Mayson Lake	4	64	3	1995-97
	U.Penticton Creek	5	64	3	1995-97
	U.Penticton Creek	4	32	4	1998-01
	U.Penticton Creek	2	32	2	2000-01
	Berry Creek	3	20	3	1995-97
	L.Penticton Creek	4	10	4	1989-91, 1993
	Birk Creek	12	10	5	1992-96
	Gold Creek	6	10	3	1993-95
Nelson	Trapping Creek	12	14	7	1991-96, 2000
	Murphy Creek	11	10	5	1984-86,1991-92
	Redfish Creek	4	10	3	1984-86
	Glenmerry	2	10	5	1984-86,1995-96
	Cotton Creek	4	10	1	1985
	Eleven Mile	7	10	3	1984-86
	Hidden Creek	2	10	2	1984-85
	Lamb Creek	2	10	3	1984-86
	Mephisto Creek	2	10	1	1986

Snow measurements were made within a 1-m radius of the station marker at each survey point using a standard Federal snow tube. Surveys were completed in early and mid March, April 1st and then more frequently through the snowmelt period. Peak SWE was taken as the SWE measured on the date at which the maximum was recorded in the clearcut. Ablation rates were calculated over the period beginning on April 1st until the date when snow covered less than half of the area within a 1 m radius of each snow survey point. If the field surveys ended prior to this, the ablation rate was calculated by estimating the date of snow disappearance using the ablation rate in the last survey period.

Each snow survey station marker indicated the centre of a 4 m radius plot (0.005 ha) within which all trees, 1 m in height or taller, were measured. Tree and stand characteristics were described by variables in three broad groups representing the species mix, stem, and canopy. The species mix was thought to reflect general tree form and distribution. The stem descriptors were intended to represent stand structure, density, and stage of development. The canopy variables represented the depth, volume, and extent of foliage in the stand. Species, condition (live or snag), diameter outside bark at breast height (dbh; 1.3 m above ground), height, height to live crown, and crown radius were noted for each tree. Basal area, crown length, and crown base area were then calculated for each tree.

Tree height (m) of the mature stands was measured using a clinometer and 30 m tape. Heights of the juvenile trees were measured using a height pole. Tree dbhs (cm) were measured with a diameter tape. Height of the main canopy was taken as the average of the dominant and co-dominant trees in a stand. Basal area per tree (m^2) was calculated from the dbh assuming trees were circular in cross-section. Crown length (m) was measured using a clinometer in the same way as tree height. Crown length (L_c) (m) was assumed to extend from the top of the tree to the base of the live crown, taken as the lowest whorl of branches with green foliage. Crown ratio (m/m) was calculated as crown length divided by total tree height. Crown radii (m) were measured from the stem to the projected outermost margin of the crown in the four cardinal directions. Crown base area (A_c) (m^2) was estimated using the average crown radius and calculating the area of a circle with this radius. Crown ratio was calculated as crown length divided by crown base area. Crown closure was measured using a moosehorn (Bunnell and Vale, 1990) or Lemmon densiometer (Lemmon, 1956), depending on location.

Data Analysis

Peak SWE and ablation rate for each stand and all survey years were plotted against all forest inventory variables to identify any relationships. Correlations among independent variables were assessed with Pearson correlation matrices using SYSTAT 6.0 software (SPSS Inc., 1996). Single and multiple linear regression techniques were used to identify significant correlations among snow and forest inventory variables. The year of survey was included as a dummy variable in the analyses to provide an indication of whether relationships between the forest inventory and snowpack variables changed from year to year. Analyses were re-run using standardised peak SWE and standardised ablation rates, including each year of survey separately and again using the average for all years at each site. Standardised peak SWE and ablation rates were calculated as the SWE or ablation rate measured in the forest divided by that in the open (cm cm^{-1} and cm d^{-1}(cm $d^{-1})^{-1}$, respectively).

Regression analyses were completed using SAS software (SAS Institute Inc., 2001). Statistical significance for all tests was determined using $\alpha = 0.01$. Residuals were plotted to visually evaluate the assumptions of normality and homogeneity of variance. The 'best' models were chosen based on comparison of single or multiple coefficient of determination values, standard errors of the estimate, significance of the F values, and residual plots.

RESULTS AND DISCUSSION

The proportion of the variation in peak SWE and in average ablation rate explained by the forest inventory variables is shown by the coefficients of determination (r^2) in Table 2. The inventory variable crown closure was the single variable that explained the largest proportion of the variability in peak SWE and average ablation rate, 25 and 22%, respectively. Year, however, explained 46% of the variability in peak SWE and 24% of the variability in average ablation rates when included in the models as a dummy variable.

Table 2. The proportion of the variation (r^2) in peak snow water equivalent (SWE), average ablation rate (MR), standardised SWE (FOSWE), and ablation rate (FOMR) explained by forest inventory variables.

Stand Variable	**SWE** r^2	**MR** r^2	**FOSWE** r^2	**FOMR** r^2
Total stems	0.11	0.08	0.05	0.08
Dominant/codominant stems	0.07	0.09	0.26	0.20
Intermediate/suppressed stems	0.09	0.07	0.02	0.04
Average tree height	0.02	0.06	0.42	0.25
Dominant/codominant height	0.11	0.13	0.56	0.34
Intermediate/suppressed height	0.09	0.07	0.38	0.04
Basal area	0.07	0.10	0.52	0.29
Crown length	0.02	0.05	0.38	0.21
Crown diameter	0.05	0.08	0.40	0.25
Crown ratio	0.16	0.14	0.16	0.21
Crown closure	0.25	0.22	0.44	0.36

To account for the large effect of inter-annual variability, we standardised the snow measured in the forest to that in the open, assuming that the measurements in the open reflected both the weather and location. This approach worked well for peak SWE and was somewhat effective for ablation rate. Only 8% of the variability in standardised peak SWE and 19% of the variability in standardised ablation rate was explained by year.

When data for each year of survey were included in the analyses, crown closure explained 55% of the variability in standardised peak SWE with a standard error of the estimate (SE_e) of 0.09 (Table 3). Average height of the main canopy and basal area explained 45% and 42% of the variability in standardised peak SWE with a SE_e of 0.09 and 0.10, respectively. All single variable models were significant. Crown closure, main canopy height, and basal area explained less of the variability in standardised ablation rate, only 37%, 28%, and 19%, respectively with SE_e of 0.18, 0.20, and 0.22. In multi-variate models of standardised peak SWE, including interactions among variables, only main canopy height was significant. A multi-variate model including both crown closure and height of the main canopy explained 47% of the variability in standardised ablation rate with a SE_e of 0.16 (Table 3). Standardised peak SWE explained 21% of the variability in standardised ablation rate but was not significant in multi-variate models.

Averaging the data for all years at each site removed some of the variability as expected, though there was still considerable scatter around the lines describing the relationships. Crown closure explained 68% and 57% of the variability in average standardised peak SWE and ablation rate with a SE_e of 0.07 and 0.12, respectively (Table 3). Main canopy height and basal area explained 66% and 55% of the variability in average standardised peak SWE with a SE_e of 0.06 and 0.8 and 53% and 35% of the variability in ablation, with a SE_e of 0.12 and 0.15.

The results of this study are similar to the findings of others, in that stand inventory variables describing the amount and distribution of forest canopy provided the best index to SWE and ablation. Lull and Rushmore (1960) and Packer (1971) found that crown closure explained up to 76% of the variability in ablation and, more recently, Metcalfe and Buttle (1998) found that canopy gap fraction in a boreal forest explained up to 94% of the variability in ablation. The work of Talbot and Plamondon (2002) and Hudson (2000) showed that average dominant and co-dominant tree height is a good index to SWE and ablation in a second-growth stand relative to that in a mature forest.

Table 3. Forest inventory variables explained the greatest proportion of the variability (single r^2 or multiple R^2) in standardised SWE (FOSWE) and ablation rate (FOMR) for all years at each site and for the average of all years at each site, and the standard error of the estimate (SE_e). All variables in all models shown were significant at $p<0.01$. The results for other multi-variate models are not shown.

		All years included separately		Years averaged	
Snow Variable	**Inventory Variable**	**r^2 or R^2**	**SE_e**	**r^2 or R^2**	**SE_e**
FOSWE	Crown closure	0.55	0.09	0.68	0.07
	Main canopy height	0.45	0.09	0.66	0.06
	Basal area	0.42	0.10	0.55	0.08
FOMR	Crown closure	0.37	0.18	0.57	0.12
	Main canopy height	0.28	0.20	0.53	0.12
	Basal area	0.19	0.22	0.35	0.15
	Crown closure and Main canopy height	0.47	0.16	0.75	0.09
	FOSWE	0.21	0.21	0.53	0.13

For forest planners wanting to use a single inventory variable as an index to forest cover effects on peak SWE and average ablation rate, this study suggests that in the southern interior of B.C. crown closure would be the most appropriate. The relationships between crown closure and the standardised snow variables are shown in Figures 2 and 3. They indicate that in a second-growth stand with 20% crown closure and where a crown closure of 70% is expected at maturity, SWE recovery (1 - $FOSWE_{second\text{-}growth}$ / 1 - $FOSWE_{mature}$) is 25%. Snow ablation recovery would be 37%. In this study, stands with 20% crown closure included 3 m to 7 m tall (main canopy height) second-growth and a mature (18 m tall) stand from which 30% of the basal area had been removed.

If tree height continues to be used as an index in multi-layered stands, a clear definition of which canopy layers are to be included is necessary. For example, in those study stands where main canopy height was 15 m, the average tree heights calculated for each stand ranged from 3.5 m to 7 m. For stands with a main canopy height of 15 m, crown closures only varied from 57% to 63% whereas when an average tree height of 15 m was used to describe stands, crown closures varied from 40 to 80%, again illustrating a multi-layered structure. In the study stands, average tree height explained 42% and 25% of the variability in standardised peak SWE and standardised ablation rate whereas the height of the dominant and co-dominant trees, or main canopy height, explained 66% and 53%, respectively.

Though similar in the proportion of the variability in standardised SWE and ablation explained by crown closure and main canopy height, crown closure is assumed to better represent the amount and distribution of canopy, and indirectly snow interception and shading, than tree height. In this study, crown closure may have explained an even larger proportion of the variability in standardised SWE and ablation, if a single method of measuring it had been used at all sites. Both main canopy height and crown closure are readily available, easy to measure inventory variables.

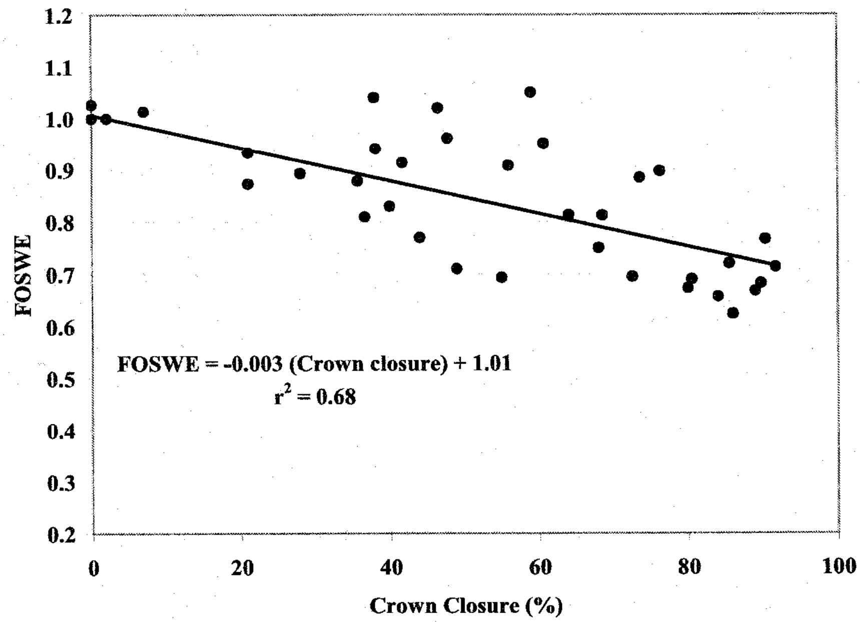

Figure 2. The relationship between standardised peak snow water equivalent (FOSWE), averaged over the years of survey, and crown closure at eleven locations in the southern interior of B.C.

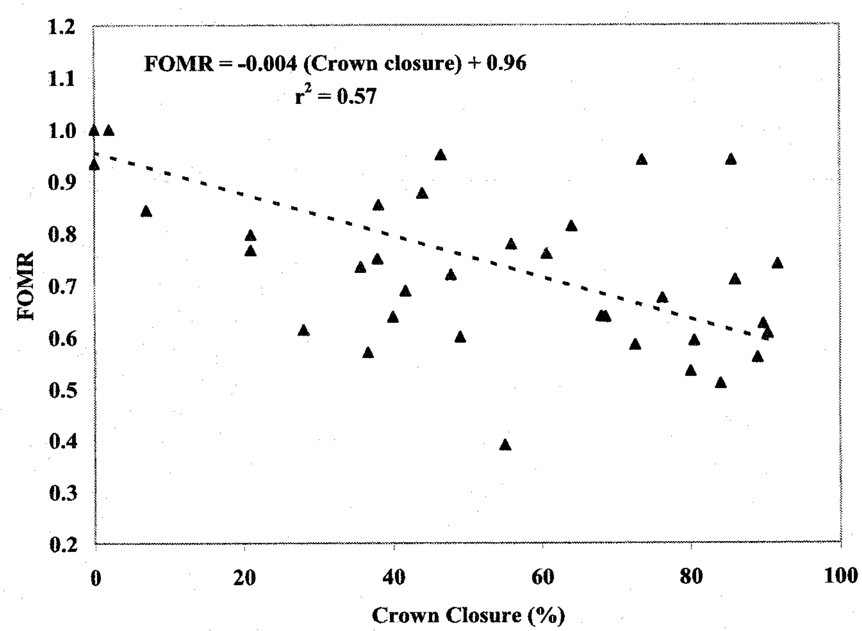

Figure 3. The relationship between standardised ablation rate (FOMR), averaged over the years of survey, and crown closure at eleven locations in the southern interior of B.C.

CONCLUSIONS

This study highlights the large inter-annual variability in snow accumulation and ablation in the southern interior of B.C. This variability, along with the diversity of forest cover types, makes it difficult to identify a single forest inventory variable that provides an index to relative changes in snow accumulation ablation under different cover types.

The results indicate that some of the inter-annual variability, and influence of location, can be accounted for by standardising snow in the forest to that in the open. Among the study stands, the inventory variable crown closure explained the largest proportion of the variability in standardised peak SWE and standardised ablation rate (68 and 57%, respectively). This single variable, or crown closure and height of the main canopy (together explaining 75% of the variability in standardised ablation), may provide a useful index for forest development planning purposes.

Additional studies are investigating snow accumulation and ablation in juvenile stands, as they have grown from 5 to 10-m tall, and the use of hemispherical photography as an operational tool to determine canopy density. Along with the work described in this paper, the new work should provide a better understanding of forest – snow interactions in the southern interior of B.C. and the applicability of an operational snow index such as crown closure.

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