



Review Paper

Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results

Andrés Varhola^{a,*}, Nicholas C. Coops^a, Markus Weiler^b, R. Dan Moore^{a,c}^a Department of Forest Resources Management, University of British Columbia, 2424 Main Mall, Vancouver, BC, Canada V6T 1Z4^b Institut für Hydrologie, Universität Freiburg, Fahnbergplatz, 79098 Freiburg, Germany^c Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC, Canada V6T 1Z2

ARTICLE INFO

Article history:

Received 8 July 2009

Received in revised form 26 July 2010

Accepted 18 August 2010

This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Jiin-Shuh Jean, Associate Editor

Keywords:

Snow processes

Forest structure

Forest cover

Snow models

Empirical studies

Snow hydrology

SUMMARY

The past century has seen significant research comparing snow accumulation and ablation in forested and open sites. In this review we compile and standardize the results of previous empirical studies to generate statistical relations between changes in forest cover and the associated changes in snow accumulation and ablation rate. The analysis drew upon 33 articles documenting these relationships at 65 individual sites in North America and Europe from the 1930s to present. Changes in forest cover explained 57% and 72% of the variance of relative changes in snow accumulation and ablation, respectively. The incorporation of geographic and average historic climatic information did not significantly improve the ability to predict changes in snow processes, mainly because most of the studies did not provide enough information on site characteristics such as slope and aspect or meteorological conditions taking place during the experiments. Two simple linear models using forest cover as the sole predictor of changes in snow accumulation and ablation are provided, as well as a review of the main sources of variation that prevent the elaboration of more accurate multiple regression models. Further studies should provide detailed information regarding the main sources of variation influencing snow processes including the effect of year-to-year changes in weather variables during the monitoring period.

© 2010 Elsevier B.V. All rights reserved.

Contents

1. Introduction	220
2. Sources of variability affecting the interaction between forest cover and snow	221
2.1. Snowfall magnitude and inter-annual variations	221
2.2. Elevation	221
2.3. Aspect	222
2.4. Slope	222
2.5. Clearcut size	223
2.6. Wind	223
2.7. Specific weather conditions	224
2.8. Canopy geometry and tree spatial distribution	224
2.9. Measurement errors	224
2.9.1. Peak SWE	224
2.9.2. Snow melt rates	224
2.9.3. Forest cover	225
3. Meta-analysis	226
3.1. Empirical data review and compilation	226
3.2. Data standardizing	226
3.3. Statistical analysis	226
3.4. Results	227

* Corresponding author. Tel.: +1 778 987 5556; fax: +1 604 822 9106.

E-mail address: avarhola@interchange.ubc.ca (A. Varhola).

3.4.1.	Correlations	227
3.4.2.	Simple regression	229
3.4.3.	Multiple regression	230
3.5.	Discussion	230
4.	Conclusions	231
	Acknowledgements	231
	References	231

1. Introduction

The effects of forest cover on snow accumulation and ablation have been subject of substantial research over the last century. Snow accumulation is most often represented by the peak snow water equivalent (SWE) (mm) on the ground before the snow starts to melt, while snow ablation rate (mm/day) is usually computed as the peak SWE divided by the number of days of the ablation period (from date of peak SWE to date of snow disappearance).¹ Generally, as forest cover increases, snow accumulation on the ground is reduced because part of the snowfall intercepted in the canopies is returned to the atmosphere by sublimation (Essery et al., 2003). Although the magnitude of these combined phenomena varies according to specific conditions, it has been found that up to 60% and 40% of cumulative snowfall can be intercepted and sublimated, respectively (Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998). Many studies have shown that snow accumulated in forested areas is up to 40% lower than that in nearby open reference sites (e.g. D'Eon, 2004; Winkler et al., 2005; Jost et al., 2007).

The primary driver of snow ablation is the net available energy, which can be calculated with an energy balance model that includes incoming and reflected shortwave radiation, incoming and outgoing longwave radiation, sensible and latent heat fluxes and ground heat conduction as independent variables (Brooks et al., 2003; Boon, 2007). Forest cover is critical in this equation because even though it might increase longwave radiation, reductions in the incoming shortwave radiation from the sun generally lead to net losses in the total energy budget available for melting (Essery et al., 2008). Canopies also reduce wind speed and thus the magnitudes of the sensible and latent heat fluxes. A number of empirical studies have shown that snowmelt rates in forests can be up to 70% lower than in open areas (e.g. Hendrick et al., 1971; Boon, 2007; Teti, 2008).

Snow accumulation and melt play an important role in the hydrology of montane snow-dominated regions, where water supply is highly dependent on spring melting from forested areas (Uunila et al., 2006). The sensitive connection between forest structure and snow processes has, therefore, many significant implications (Musselman et al., 2008). Although the interest in this subject is not new (e.g. Connaughton, 1933a; Meagher, 1938), climate variability has recently increased concerns about the potential magnitude of the impacts. For example, evidence is showing that over the past decades decreasing snowpacks are melting at faster rates and earlier in the spring in western North America (e.g. Mote et al., 2005; Knowles et al., 2006) and other regions (e.g. Koenig and Abegg, 1997; Bavay et al., 2009), where up to 75% of the total water input comes from snow (Service, 2004). As a result, spring peak discharges are becoming larger while the summer/autumn flows are experiencing severe declines (Rood et al., 2008). These changes have generated concern about the current capacity of existing dams to handle higher peak flows, the need for more reservoirs

to regulate water release for summer irrigation and the loss of farmlands and wildlife habitat (D'Eon, 2001; Service, 2004).

Additional evidence also suggests that the changes in forest structure associated with alterations in wildfire, disease and insect infestation regimes could exacerbate the anomalies in the patterns of snow accumulation and melting (Musselman et al., 2008). Disturbed canopies over extensive areas might counteract the apparent snowpack decline observed in the past decades and result in larger snowpacks melting faster, with the potential to increase the magnitude–frequency of flooding events in rural as well as populated areas (Schnorbus, 2007). For example, the current mountain pine beetle (MPB) outbreak in British Columbia (BC) has infested 135,000 km² of lodgepole pine forests as of 2008 (BC Ministry of Forests, 2008), with uncertain impacts on water resources (Winkler, 2001; Uunila et al., 2006; Bewley et al., 2010). On the other hand, forest fire suppression policies could lead to changes in canopy cover and water resources in western North America (Matheussen et al., 2000) by creating large areas of overstocked stands with higher snow interception rates (Sampson, 1997).

The need to quantify the relationship between forest structure and snow accumulation and melting has motivated the development of several modelling approaches. Methods have ranged from local-scale empirical studies comparing forested and non-forested areas (e.g. Winkler et al., 2005; Woods et al., 2006; Boon, 2009) to the application of process-based simulation models (e.g. Hendrick et al., 1971; Hedstrom and Pomeroy, 1998; Essery et al., 2008). The latter are, in principle, applicable to a wide range of conditions but require input data that are not readily available in operational contexts. Empirical models such as the ones developed by Kuz'min (1960) or Woods et al. (2006) have been derived from a wide range of studies to provide first-order estimates of the effects of forest cover changes on snow processes. However, they do not explicitly account for the governing processes, which vary in both space and time, and therefore cannot be relied upon to generate precise predictions at different sites or different years.

To develop a better understanding of, and ability to, predict the interaction between forest structure and snow accumulation and melting, it is necessary to identify the additional factors that explain the spatial and temporal distribution patterns of snow. Forest cover is not the only variable influencing snow accumulation processes, nor the most important under certain conditions (Gary, 1975; Pomeroy et al., 1997). Other sources of variation that expose the complexity of the interaction between cover and snow process include snowfall magnitude (Anderson, 1956), year to year variations (Berndt, 1965), elevation (Daugharty and Dickinson, 1982), aspect and slope (Anderson et al., 1958a; Moore and Wondzell, 2005), size of the clearcut used as a reference (Golding and Swanson, 1986), wind speed (Woods et al., 2006), specific weather conditions (Lundquist et al., 2004; Lundquist and Flint, 2006), spatial distribution of trees (Dunford and Niederhof, 1944; Veatch et al., 2009), and canopy geometry (Essery et al., 2008).

This study has two objectives. The first is to review the results of empirical studies to identify the magnitudes of the effects that different factors have on snow accumulation and ablation. The sec-

¹ Although there are slight conceptual differences between snow ablation and melting, both terms are used in this review indistinctively.

ond is to use the compiled data in a meta-analysis to generate empirical models that could be used to predict the effects of forest cover change on snow processes, along with an estimate of the uncertainty associated with the prediction. Such a model could be a useful operational tool for generating first-order estimates of forest-snow interactions, particularly over large areas with sparse weather data, where the application of process-based models may involve significant uncertainty.

2. Sources of variability affecting the interaction between forest cover and snow

A variety of factors can influence the interactions between snow accumulation and melting and forest cover. In addition, errors in measuring snow accumulation, ablation and forest cover can add to the variability of observations around a statistical model. Each of these sources of variability, errors and bias is described in detail below.

2.1. Snowfall magnitude and inter-annual variations

Since tree branches cannot intercept an unlimited amount of snow, the influence of forest cover decreases in importance as total snowfall increases beyond a certain threshold (Boon, 2009). Similar to what occurs with rain (Brooks et al., 2003), a higher proportion of snow precipitation can be intercepted by tree canopies and sublimated to the atmosphere if the events are small. Snowfall magnitude varies significantly from year to year in many locations (Wilm and Dunford, 1948; Anderson, 1956), thus suggesting that relative and absolute snow accumulation under the same forested site will be different if measured consecutively during a long period of time.

Connaughton (1933b) studied snow accumulation and melting in five plots in Idaho in response to the recommendation of cutting forests in order to increase water supplies. The study revealed the strong influence of snowfall magnitude on forest-snow interactions: in a light snowfall year (1931), forested sites accumulated 27.5% less snow than open areas, while in the following average year that figure dropped to 4.3%. Winkler and Moore (2006) studied the relationship between forest stand properties and snow accumulation at two sites in the Interior Plateau region of British Columbia, for a three year period (1995–1997). They found that inter-annual variability in peak snow water equivalent was significant in both sites and explained 28–42% of the total variance. Additionally, the greatest inter-annual variations were found at the forested sites and not in the clearcuts, suggesting that the interaction between the effects of total snowfall and canopy cover is not linear. Boon (2009) found similar differences in snow accumulation in forests relative to clearcuts in a two-year study at Fraser Lake, BC. In the same province, Jost et al. (2007) showed that the influence of forest cover, relative to aspect and elevation, changes according to snowfall magnitude.

The influence of individual snowfall events on snow interception was studied by McNay et al. (1988) in Douglas-fir and western hemlock forests on Vancouver Island, BC. Regression analysis was used to relate forest cover and storm size to predict the amount of fresh snow under the canopy. The authors found a non-linear relationship between storm size and snow depth for events smaller than 15 cm and a linear trend for larger events. Fig. 1 summarizes the data of McNay et al. (1988) to show the overall relationship between storm size and the ratio of fresh snow accumulated under the forest and open areas for the storm events. We found a slight but significant [Pearson correlation coefficient (r) = 0.37; probability (p) = 0.008] positive correlation between storm size and the proportion of snow that accumulates under the forest as snowfall

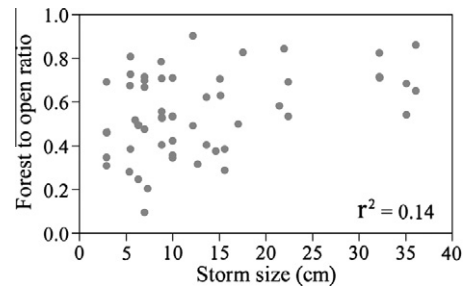


Fig. 1. Relationship between storm size and the ratio of fresh snow accumulated under the forest and a nearby open site [adapted from McNay et al. (1988)].

events become larger, although the lower frequency of large events is a limitation in the analysis.

2.2. Elevation

Elevation also has an influence on the magnitude of snowfall events and snow processes (Anderson and West, 1965). In the Nelson Forest Region (BC), snow accumulation in paired forested and clearcut sites along an elevation gradient was found to increase at a rate of 11–15 mm of SWE per 100 m increase in elevation for forested sites, and 21–27 mm for open sites (Toews and Gluns, 1986). D'Eon (2004) measured snow accumulation in 27 transects (455 plots) in open and forested areas ranging in elevation from 500 to 1500 m. The absolute values of snow depth showed a significant correlation with elevation ($r^2 = 0.40$; $p < 0.001$) (Fig. 2). However, the relation between canopy cover and snow depth proved to be significant only in low elevation sites, which the author attributed to greater snow accumulation in the higher sites and a corresponding decrease in the importance of canopy influence. Elevation also provided the best correlation and regression coefficients with snow depth in a study of snow distribution in forested and deforested landscapes in New Brunswick (Daugharty and Dickinson, 1982).

Lower temperatures at higher elevations are also expected to have an influence on snow melting rates. Hendrick et al. (1971) studied the influences of elevation, slope-aspect and forest cover types on snowmelt in the Sleepers River Watershed (Vermont). The 111 km² watershed (200 to 800 m in elevation) was stratified into 96 environments that represented the combinations of the three variables of study. The significant influence of elevation on snowmelt led to conclude that mountainous watersheds with high variability in elevation are at a lower risk of spring snowmelt flooding due to differentiated onset and rates of melting along the gradient. Similar conclusions are reported by Alila et al. (2007), while rare exceptions to this generalization are explained by Lundquist et al. (2004).

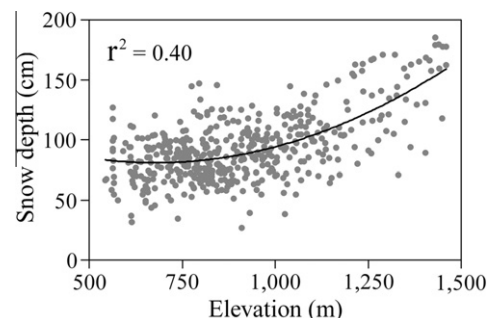


Fig. 2. Snow depth as a function of elevation in Little Slovan Valley, British Columbia [adapted from D'Eon (2004)].

2.3. Aspect

The effect of aspect on snow accumulation and melting is principally a function of exposure to solar radiation, with more snow expected to accumulate on northerly aspects (in the northern hemisphere) due to reduced melting and sublimation rates during the accumulation phase (Golding and Swanson, 1986). Predominant local wind directions may also influence the effect of aspect on accumulation and melting.

Berndt (1965) conducted an experiment in lodgepole pine stands and clearcuts in Wyoming to determine changes on peak snow accumulation due to aspect and clearcut size. The results indicated that the combination of both variables had a significant influence on snow accumulation, with east aspects showing greater responses to clearcutting and south aspects subject to a larger influence of clearcut sizes than the others. Murray and Buttle (2003) analyzed the effect of north and south facing slopes on snow accumulation and melt in the Turkey Lakes Watershed (Ontario) by comparing a hardwood maple stand and a nearby open site in 2000 and 2001. As expected, melt rates were significantly higher in south-facing sites with the forested south-facing stands showing an even higher rate than the north-facing clearcut. It was concluded that aspect had a stronger influence on melting than forest cover. Comparable results were reported by Haupt

(1951), Anderson and West (1965), Hendrick et al. (1971), Rowland and Moore (1992), D'Eon (2004) and Jost et al. (2007).

In California, a network of snow sampling points ranging in elevation from 1800–2400 m was established to compare coniferous forests and clearcuts in different slopes and aspects (Anderson et al., 1958a). The effect of aspect on April 22 SWE and June 1 melting rates is shown on Fig. 3. Forests with 35% cover showed larger peak SWE in north aspect sites, a tendency that is weaker in 65% cover forests and unclear in 90% cover forests. Snow melting appears to occur faster in south and west aspect sites with the three different forest cover values. In all cases, forests with 90% cover tend to show less snow accumulation and lower melting rates. In British Columbia, D'Eon (2004) showed that southern aspects (180°) generally presented decreased amounts of snow accumulation relative to northern aspects in different elevation ranges (Fig. 4).

2.4. Slope

The overall impact of increasing slope is to reduce snow accumulation due to snow moving downhill, exposure to wind and higher temperatures in sunnier aspects during the accumulation period (Golding and Swanson, 1986). Slope is expected to influence snow melting in combination with aspect (e.g. a south facing steep-

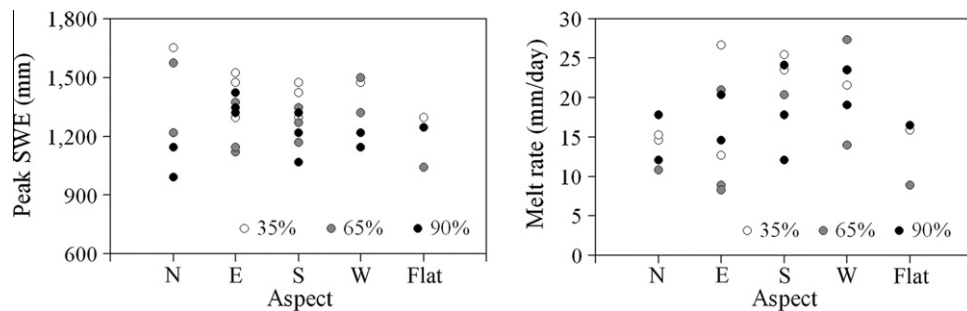


Fig. 3. Effect of aspect on peak SWE and melting in coniferous forests with 35%, 65% and 90% of forest cover in Central Sierra Snow laboratory, California [adapted from Anderson et al. (1958a)].

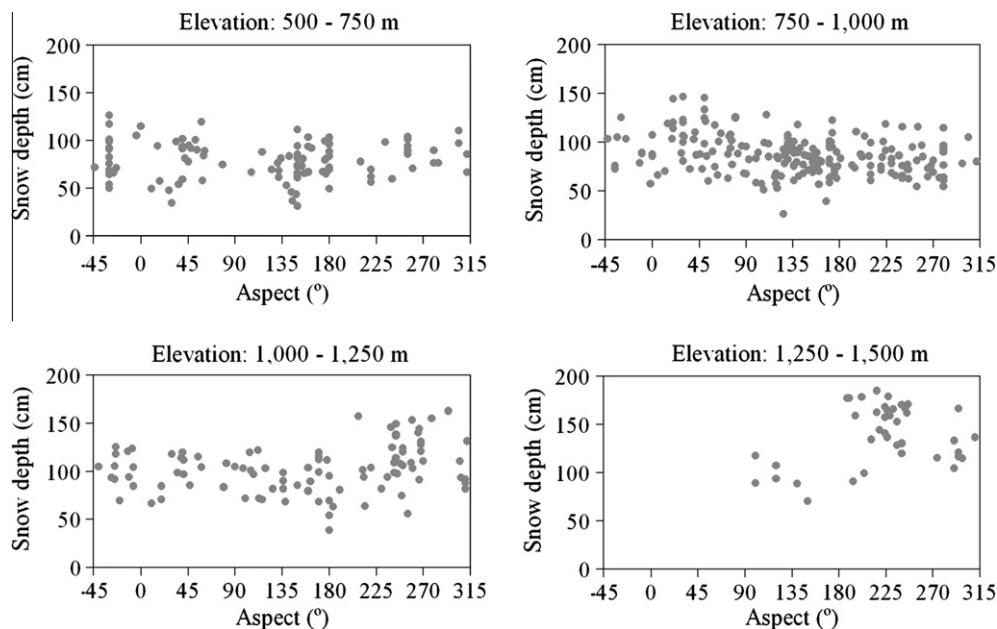


Fig. 4. Effect of aspect on snow depth according to elevation ranges in Little Slokan Valley, British Columbia [adapted from D'Eon (2004)].

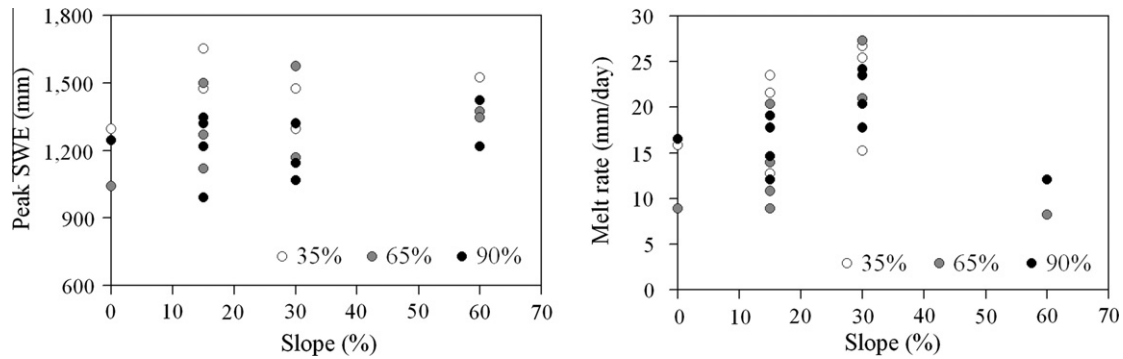


Fig. 5. Effect of slope (%) on peak SWE and melting in coniferous forests with 35%, 65% and 90% of forest cover [adapted from Anderson et al. (1958a)].

per slope exposes the snow to solar radiation at lower incidence angles in the northern hemisphere).

In Wyoming, Berndt (1965) compared snow accumulation in three clearcuts on south facing aspects covering a range of slopes. Results indicated that a plot with 18% slope accumulated 20–30% less snow than those sites with gentler slope (5% and 6%). Fig. 5 summarizes a similar comparison undertaken in California (Anderson et al., 1958a), where a clear trend in the impact of slope on snow accumulation was not evident; however, 30% slopes had a higher melt rate than 15% slopes and more variability existed at gentler than steeper slopes.

2.5. Clearcut size

When comparing snow accumulation and melting between forested sites and nearby clearcuts, the area of the clearcut plays an important role. Small clearcut openings are often still sheltered by surrounding forests, while larger clearcuts are exposed to wind erosion that reduces overall snow accumulation (Pomeroy et al., 2002). Intermediate-sized clearcuts are therefore expected to accumulate the largest amounts of snow. With respect to snow melting, shade from adjacent trees in smaller clearcuts has been shown to retard melting by decreasing the daily incoming shortwave radiation and reducing the differences with melting rates in the adjacent forest.

In James River and the Marmot Creek Experimental Watershed (Alberta), Golding and Swanson (1986) expressed the clearcut diameter in terms of number of tree heights of surrounding forests (H). The results of average peak SWE measured from 1973 to 1976 in James River indicated that at most of the locations, snow accumulation was higher in 2 and 3H clearcuts (Fig. 6). Peak SWE increased significantly from forests (0H) to clearcuts of 0.25, 0.5, 0.75 and 1H, suggesting that snow interception of the adjacent forest maintains an important role below that threshold. In Colorado,

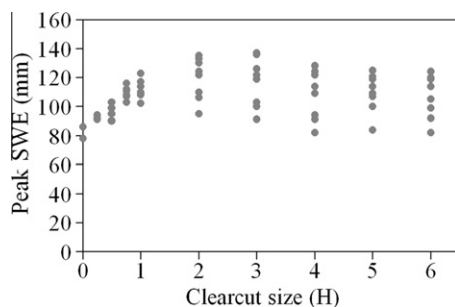


Fig. 6. Influence of clearcut size (in number of tree heights of adjacent forests, H) on snow accumulation in James River, Alberta [adapted from Golding and Swanson (1986)].

Troendle and Leaf (1980) found maximum snow accumulation in 5H clearcuts, while in Saskatchewan Pomeroy et al. (1997) found no differences in snow accumulation between a large (km scale) and small (100 m) clearcut, which was attributed to lower local wind speeds than in other areas. Berndt (1965) also found minor differences in snow accumulation and melting in 2, 4 and 8 ha clearcut blocks in Wyoming. However, all three clearcut sizes showed up to 40% more snow accumulation and snow disappearance 10 days earlier than the surrounding lodgepole pine stands, indicating that the combination of clearcut size and aspect was more influential on snowpacks than their individual impacts.

In the Central Sierra Nevada (California), Anderson and West (1965) sampled 163 snow courses to determine the effect of terrain and year-to-year snowfall variation on snow accumulation and melting. The effect of snowfall magnitudes interacted closely with clearcut size, as accumulation was higher on a 4H than in a 1H clearcut on the year of heaviest snowfall and differences were reduced by more than 60% in the following two dry years. They also observed that larger clearcuts accumulated more snow in higher than in lower elevations.

2.6. Wind

Just as aspect and slope interact to produce combined effects on snow accumulation and melting, so do clearcut size and wind speed (Woods et al., 2006). As suggested by Pomeroy et al. (1997), wind is the main factor affecting snow redistribution since it can reduce snow accumulation in clearcuts by erosion and enhanced sublimation, and increase snow ablation rates during the melting period. This effect was examined in detail by Gary (1975), who hypothesized that the greater amount of snow in openings is explained by the lack of interception and also by movement of snow from the forest to the clearing's leeward. This implies that total quantities of snow in the system as a whole may not always be affected by changing proportions of forests and openings. This hypothesis is supported by the results of Troendle and King (1987), which showed that the overall average peak snow accumulation in a catchment in Colorado did not change after harvesting. Wind is one of the drivers of these important redistribution processes. Measurements of snow accumulation and wind speed before and after a clearcutting treatment in a lodgepole pine stand in Wyoming indicated that accumulation was consistently larger in the geometrical center of a 1H $\times$ 5H clearing, where the wind speed declines and releases the snow transported from upwind canopy flow (Gary, 1975).

Woods et al. (2006) studied the effect of thinning on snow accumulation in lodgepole pine stands at the Tenderfoot Creek Experimental Forest (Montana). Thinning increased wind speed and solar radiation, producing sublimation that offset the effect of the inter-

ception reduction. As a result, the treatment had no net effect on peak SWE. In coastal British Columbia, McNay et al. (1988) performed linear regression analysis to study the relationship between snow interception and several descriptors of forest structure and snowfall event size. Explicitly acknowledging the confounding effects of wind as a snow redistributor, the authors measured interception immediately after each storm. In central Ontario, accumulation differences on a ridge crest and a south facing slope in a clearcut were the result of the redistributing effects of northerly winter winds (Murray and Buttle, 2003).

2.7. Specific weather conditions

As energy is the primary driver of snow melting, this process is particularly susceptible to local and short-term variations of weather systems. Murray and Buttle (2003) measured snow melting duration in forested sites during two consecutive years and found that the ablation period took 27 days longer than a clearcut in 2000 and only 4 days longer in 2001. Lundquist et al. (2004) observed that while generally snow melting started at lower elevations in two catchments at Sierra Nevada, California, streams showed a synchronous rise on March 29, 2002. This was a result of simultaneous snow melting in 70% of the sites due to an unusual 12 °C temperature increase in 5 days, providing enough energy to overwhelm the effects of elevation (1500–3400 m), aspect and forest cover. A follow-up study (Lundquist and Flint, 2006) explained how weather and atmospheric conditions hypothetically ideal to initiate synchronous melting in mountainous environments can be offset by shading if they take place too early in spring, when solar angles are lower.

2.8. Canopy geometry and tree spatial distribution

In the Fraser Experimental Forest (Colorado), an aspen stand with 65% forest cover showed greater snow accumulation than an open area and a lodgepole pine stand with 75% cover and (Dunford and Niederhof, 1944). Pomeroy et al. (2002) compared snow accumulation in several forest types and found that a mature jack pine with 82% forest cover and a black spruce stand with 95% forest cover consistently showed the same percentage of reduction in peak SWE in comparison with the clearcut control during several years of measurement. These studies led to conclude that forest cover per se is not a physical attribute that can explain all of the differences in snow accumulation. In the case of the aspen stand studied by Dunford and Niederhof (1944), the higher accumulation was attributed to a leafless canopy that reduced snow interception, yet providing enough shelter and shade to prevent sublimation and erosion by wind. The nearby lodgepole pine with similar canopy cover was a more efficient snow interceptor due to the differences in canopy structure and geometry. Correspondingly in the study by Pomeroy et al. (2002), the amount of accumulated snow was similar despite the 13% difference in forest cover between the black spruce and jack pine stands. Several properties in the forest canopies can explain these factors. Branch flexure was proposed by Schmidt et al. (1988) and Lundberg and Halldin (2001) as influential on snow interception. In an experiment to better understand interception processes in trees, Pfister and Schneebeli (1999) utilised boards of different sizes, shapes and inclination. Snow accumulation varied systematically with both inclination and shape, which are variables also relevant to tree branches. Despite their importance, metrics describing these attributes in real trees are difficult to measure (Parveaud et al., 2008) and therefore are seldom used in models of snow interception.

Tree distribution has an influence on snow accumulation. Even-spaced stands are expected to show less variability in snow accumulation, which will normally decrease as the forest becomes den-

ser. A less predictable trend might exist on stands with clustered trees that resemble a combination of dense homogeneous stands and adjacent small openings. In both cases, there is evidence showing that spatial variability in snow processes will be higher when forest cover approaches zero. Regarding snow melting, stands with reduced forest cover (either due to a small number of trees or small tree size) can increase melting rates because the canopies are unable to provide significant shading to the surface and will additionally increase the longwave radiation component of the energy balance (Swanson and Stevenson, 1971). Studies conducted in New Mexico by Veatch et al. (2009) showed a strong control of forest edges on snow depth, where the absence of interception and the shading of nearby trees favoured more snow accumulation than the interior of the forest. This process is also influenced by the orientation of the edge interacting with local distribution patterns, as Golding and Swanson (1986) and Veatch et al. (2009) found larger snow accumulation in northern edges.

2.9. Measurement errors

Measurements and calculation of peak SWE, snow melt rates and forest cover are subject to errors that can be significant and bias results. They are explained below.

2.9.1. Peak SWE

This variable is defined as the maximum snow water equivalent accumulated in a specific site prior to melting. Since snowfall varies from year to year, it is impractical for field crews to determine exactly the date in which peak SWE occurs. This has led to the standardization of April 1 as the date for comparisons in North America. If SWE is captured in paired sites, often the peak occurs in different dates at each site (e.g. Skidmore et al., 1994), raising questions about how the comparison should be done (using real peaks from different dates or comparing two SWE measurements taken at one specific moment). Additionally, manual snow surveys are usually performed with aluminum snow tubes that extract samples from the ground to be weighed. This procedure could lead to a bias of up to 12% (Peterson and Brown, 1975; Goodison et al., 1981) due to snow compression when taking the sample, scale calibration, scale reading, retention of the snow core in the sampler (Winkler et al., 2005) and subjective measurement of debris and soil depth in the bottom of the pit. Possibly the most important source of error when measuring SWE is landscape heterogeneity, as large sample sizes are often needed to account for the effects of terrain variation. The optimal sampling schemes for the estimation of SWE under these variable conditions were studied by Watson et al. (2006), who concluded that up to 54 cores are needed to obtain a representative mean at small scales (<100 m) by narrowing the effects of vegetation and radiation on snowpack. Additional considerations about snow survey sampling are given by Peterson and Brown (1975), Spittlehouse and Winkler (1996) and Watson et al. (2006).

2.9.2. Snow melt rates

Since snowmelt is estimated from peak SWE, it is subject to the same errors plus additional biases derived by dividing peak SWE by the ablation period to obtain snowmelt rates. First, the precision with which the date of snow disappearance is determined is limited by the frequency of site visits (Jost et al., 2007). Some studies record this date while others calculate melting rates between two consecutive snow surveys that do not necessarily account for the entire melting period. Snow disappearance is also subject to variability within a plot, as it does not occur in all the area simultaneously. Second, additional snowfall occurring during the melting period and mid-winter melting (Russel Smith, pers. comm.) are often ignored in the calculations. Third, SWE samples taken in melt-

ing, denser snow are subject to larger measurement errors, especially when the snowpack layer is thin and liquid water is present in the surface. Boon (2009) measured melting rates both by dividing peak SWE by the melting period and with the use of an energy balance model. The latter provided melt rates up to three times larger than the former, thus revealing the errors and uncertainty inherent to the estimations with both methods.

2.9.3. Forest cover

Although the term “forest cover” has been used in this review without formal definition, there are differences in the specific concepts and measurement methods employed in previous studies. Forest cover is usually understood as a percentage in which 0% corresponds to an open field and 100% to a dense forest where there are no gaps between the touching canopies. However, the lack of consistency in precisely defining forest cover is evident when listing all the terminology used in the literature: *canopy cover* (Moore and McCaughey, 1998; Pomeroy et al., 2002), *forest density* (Anderson et al., 1958a), *forest shade* (Anderson, 1956; Anderson et al., 1958b), *percent canopy density* (Hardy and Hansen-Bristow,

1990), *canopy closure* (Patch, 1981), *crown closure* (Winkler and Roach, 2005), *crown completeness* (Bunnell and Vales, 1990), and *crown coverage* (Kittredge, 1953). Other variables such as leaf area index (LAI) have been used by some studies as an indicator of forest cover and can be transformed to percentage by simple equations (Pomeroy et al., 2002). Only a few authors have defined what they consider a measure of forest cover [e.g. “the proportion of the sky obstructed by tree foliage from a point on the ground” (D'Eon, 2004)] and provide details about how they measured this variable (e.g. Ingebo, 1955; Moore and McCaughey, 1998; Pomeroy et al., 2002). Further evidence showing that the procedure by which forest cover is measured can have critical effects on statistical analyses is provided by Moore and McCaughey (1998), who used two different instruments (spherical densitometer and a 30° photocanopyometer) for this purpose and discarded the first one due to low accuracy and poor regression with SWE. Bunnell and Vales (1990) reviewed the use and measurement of forest cover in studies of snow-canopy interactions. Novel remote sensing-based forest structure metrics potentially applicable to snow process modelling were explored by Varhola et al. (2010).

Table 1

List of studies used for empirical data relating forest cover to snow accumulation and melting.

Source	Area	Site(s)	Species	Control description
Anderson and Gleason (1960)	California	Swain Mountain Experimental Forest, Onion Creek	Red fir, white fir	Fully stocked stand
Anderson et al. (1958a)	California	Central Sierra Snow Laboratory	Various conifers	Fully stocked stand
Anderson et al. (1976)	California	Central Sierra Snow Laboratory	Red fir	Fully stocked stand
Berndt (1965)	Wyoming	Big Horn Mountains	Lodgepole pine	Fully stocked stand
Berris and Harr (1987)	Oregon	Andrews Experimental Forest	Douglas-fir, western hemlock	Open area
Bewley et al. (2010)	British Columbia	Baker Creek	Lodgepole pine	Open area
Boon (2007)	British Columbia	Nechako Plateau, Vanderhoof	Lodgepole pine	Open area
Boon (2009)	British Columbia	Fraser Lake	Lodgepole pine	Open area
Davis et al. (1997)	Saskatchewan	BOREAS Southern Study Area	Black spruce	Open area
D'Eon (2004)	British Columbia	Little Slokan Valley	Lodgepole pine	Open area
Dunford and Niederhof (1944)	Colorado	Fraser Experimental Forest	Aspen	Open area
Goodell (1952)	Colorado	Fraser Experimental Forest	Lodgepole pine	Fully stocked stand
Hardy and Hansen-Bristow (1990)	Montana	Hyalite Creek Watershed	Subalpine fir	Open area
Hendrick et al. (1971)	Vermont	Sleepers River Watershed	Various species	Open area
Kittredge (1953)	California	Stanislaus National Forest	Red fir	Open area
Kuusisto (1980)	Finland	Various	Pine	Open area
Mayer et al. (1997)	Germany	Forstbezirk Schluchsee	Spruce	Open area
McCaughey and Farnes (2001)	Montana	Tenderfoot Creek Experimental Forest	Lodgepole pine	Open area
McCaughey et al. (1995)	Montana	Tenderfoot Creek Experimental Forest	Lodgepole pine	Open area
Moore and McCaughey (1998)	Montana	Tenderfoot Creek Experimental Forest	Various conifers	Fully stocked stand
Murray and Buttle (2003)	Ontario	Turkey Lakes Watershed	Hardwood species	Open area
Pomeroy et al. (1998)	Saskatchewan	Waskeiu Lake, Prince Albert National Park	Black spruce	Assumed clearcut
Pomeroy et al. (2002)	Saskatchewan, Yukon	Prince Albert Model Forest, Wolf Creek Research Basin	Jack pine	Open area
Skidmore et al. (1994)	Montana	Gallatin National Forest	Lodgepole pine	Open area
Stähli et al. (2000)	Switzerland	Erlenhöhe, Bruch	Norway spruce, silver fir	Open area
Teti (2008)	British Columbia	Baker Creek, Fraser Lake, Mayson Lake, Rosita, Taseko, Moffat	Lodgepole pine	Open area
Troendle and King (1987)	Colorado	Deadhorse Creek	Subalpine forest	Fully stocked stand
Weitzman and Bay (1959)	Minnesota	Northern Minnesota	Aspen	Fully stocked stand
Wilm and Dunford (1948)	Colorado	Fraser Experimental Forest	Englemann spruce	Fully stocked stand
Winkler and Moore (2006), Winkler (2001)	British Columbia	Upper Penticton Creek	Lodgepole pine	Open area
Winkler and Roach (2005)	British Columbia	Upper Penticton Creek	Lodgepole pine	Open area
Winkler et al. (2005)	British Columbia	Mayson lake	Lodgepole pine	Open area
Woods et al. (2006)	Montana	Tenderfoot Creek Experimental Forest	Lodgepole pine	Fully stocked stand

3. Meta-analysis

3.1. Empirical data review and compilation

Empirical studies have traditionally evaluated the effects of canopy cover on snow accumulation and melting using a paired-plot approach. Open areas adjacent to the studied forest stands are the most common reference controls (e.g. Hendrick et al., 1971; Winkler and Roach, 2005), while fully stocked stands are usually the baseline for the evaluation of the effects of thinning or harvesting (e.g. Wilm and Dunford, 1948; Woods et al., 2006). Some studies include measurements of forest cover or describe forest structure in some way (basal area, volume, number of trees, etc.), while others only provide snow measurements for forests and controls without quantifying forest cover (e.g. Connaughton, 1933a; Meagher, 1938; Haupt, 1951; Brechtel, 1970, 1979; Swanson and Stevenson, 1971; Brechtel and Balazas, 1976; Brechtel and Scheele, 1981; Schwarz, 1982; Felix et al., 1988; Troendle et al., 1988). Many of these experiments have been designed to isolate the effects of one or several of the sources of variation mentioned above; however, their results have not been integrated and standardized to explore the possibilities of developing a global model suitable not only for making usefully accurate predictions but also quantifying the uncertainties in the predictions.

As a first step, previously published results were reviewed to select studies appropriate for inclusion in the meta-analysis. Only studies sharing reasonably compatible methodological procedures and experimental designs were considered prior to building a central database, although it is certain that such an integration involving several decades of research inevitably introduces an unknown additional magnitude of error to any analysis. To ensure supplementary consistency for the statistical modelling, only datasets explicitly presenting numerical indicators of forest cover, snow accumulation and/or ablation in nearby locations were considered. Thus, a total of 33 publications complied with these requirements and were summarized for this analysis (Table 1, Fig. 7). They included 65 different individual locations in Canada (26), the United States (24), Finland (12), Switzerland (2) and Germany (2). All the studies except 3 were fully based on conifer species, 13 of which were related to lodgepole pine (*Pinus contorta*).

For each study, the following additional parameters were compiled: year(s) of experiment, forest species, elevation above sea level (m), latitude and longitude, forest structure variable used in the analysis and type of reference control (either open sites of fully stocked stands). Information on the average climate was based on the following variables: historic mean temperature (°C), historic winter mean temperature (°C) (average of December–March mean temperatures), historic March–April mean temperature (average of March and April mean temperatures) (°C), historic total annual

precipitation (mm), historic winter precipitation (mm) and historic March–April precipitation (mm). This data, as well as elevation for each site, were extracted from the WorldClim database (<http://www.worldclim.org/>), a global 1 km-resolution geographic raster dataset providing climatic data representative of 1950–2000 (Hijmans et al., 2005).

3.2. Data standardizing

In order to ensure consistent comparisons of the snow accumulation and melting, observations were normalised to a percentage relative to a reference site. This normalisation isolates the influence of inter-annual and inter-location variability in snowfall magnitude. The following equation was applied for this purpose:

$$\Delta y = \left(\frac{x - R}{R} \right) \times 100 \quad (1)$$

where Δy is the change in the variable of interest (%), x is the value of the variable in a specific site, and R is the value of the same variable in a nearby reference site. Since this reference (R) represents either an open area of a fully stocked stand, Δy can be negative or positive as snow accumulation and ablation are usually higher in open areas than in forests.

Each value for Δy was paired with the corresponding value of change in forest cover. These changes were assigned negative values of forest cover in studies using fully stocked stands as references, and positive values in studies using open areas.

Overall, the 33 studies provided 234 observations relating snow accumulation and forest cover, and 110 observations for snow ablation.

3.3. Statistical analysis

First, simple correlation matrices were examined to assess the relationship between the relative snow accumulation and ablation with forest cover and the other site variables. Pearson correlation coefficients (r) and significance levels (p) were used to determine the strength of the correlations.

Second, simple linear regression was used to relate the forest cover variable to the snow accumulation and ablation observations. The purpose of fitting simple linear models from the data is to provide an empirically-based tool to estimate relative changes in snow accumulation and ablation derived from changes in forest cover. These empirical models are useful for establishing a general relationship between the variables, and are readily applicable given that only a gross average change in snow accumulation or ablation is required (e.g. for multi-site and/or multi-temporal studies in which it can be assumed that sources of variation other than forest cover compensate each other when modelling snow pro-

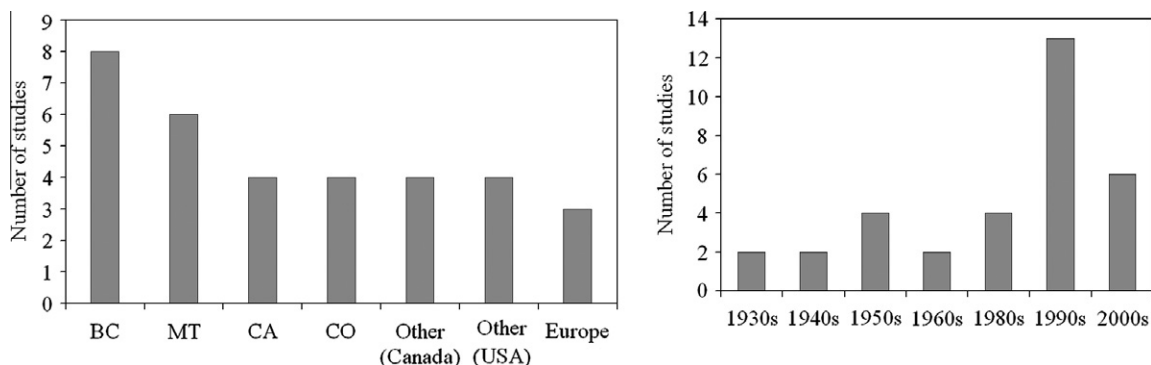


Fig. 7. Distribution of relevant studies according to location (left) and decade (right). BC = British Columbia (Canada); MT = Montana (USA); CA = California (USA); CO = Colorado (USA); other Canadian provinces include Saskatchewan, Ontario and Yukon, while other USA states include Wyoming, Oregon, Minnesota and Vermont.

cesses). The models are not applicable to make accurate predictions under specific conditions.

Two assumptions were made prior to fitting the models: that the relationship between forest cover and snow accumulation and ablation is linear (i.e. a reduction of forest cover from 70% to 50% has the same effect as a reduction from 50% to 30%), and that the use of fully stocked stands as a reference (i.e. reduction in forest cover) provides the same—but mirror-imaged—results as using open areas as references (i.e. increase in forest cover). The null hypothesis of linear regression, stating that there is no relationship between the variables, was tested with *F* tests and rejected when $p < \alpha$ ($\alpha = 0.05$). Since a 0% change in forest cover should result in a 0% change in either snow accumulation or melting, the regression models did not include an intercept.

Multiple linear regression was then applied to include the geographic and climatic variables described in Table 2. Variables were added in a stepwise procedure, where the software automatically generated all possible combinations for each step. Models that showed the best improvements in coefficient of determination (R^2) compared to the simple linear model were subject to further analysis: *t*-tests were performed in order to reject or accept the null hypothesis stating that each variable is not significant given the other variables (with $\alpha = 0.05$). Non-significant variables and those showing variance inflation factors larger than 30 were dropped, one at a time, and the analysis was redone with the remaining variables until all complied with these requirements.

Validation of the models was performed by the method described by Kutner et al. (2005), which involves running the regression with all but one record for *n* times (where *n* is the number of observations). The similarity between the sum of squares of the error (SSE) from this procedure and the SSE for the model using all data reveals a good performance of the model with independent observations. Both simple and multiple linear models were subject to analysis of residuals. Shapiro–Wilk, Kolmogorov–Smirnov, Cramer–von Mises and Anderson–Darling tests were applied to test for deviations from normality of the residuals. In these tests, the null hypothesis assumes that the residuals are normally distributed and is rejected when $p < \alpha$. White's test (White, 1980) was applied to test for deviations from homogeneity of error variances (null hypothesis states homogeneity and is rejected when $p < \alpha$, where α was set to 0.05 for all tests). Finally, these multivariate models were examined to confirm that the fitted coefficients were consistent with physical processes (e.g. checking if an increase in temperature would result in a higher change in melting).

3.4. Results

3.4.1. Correlations

The correlation matrix between site variables and snow accumulation and ablation is presented in Table 3. For both changes in snow accumulation and melting, forest cover is the most highly correlated variable, providing the strongest and most significant

Table 3

Correlation between snow accumulation and melting (*r*).

Variable (<i>n</i> = 110)	Snow accumulation (<i>n</i> = 234)	Snow ablation
Forest cover	−0.76***	−0.85***
Elevation	0.42***	0.53***
Latitude	−0.37***	−0.65***
Mean temperature	0.10	0.10
Winter mean temperature	0.22**	0.24*
March–April mean temperature	0.01	−0.18
Total annual precipitation	0.05	0.19*
Winter precipitation	0.11	0.34***
March–April precipitation	0.20**	0.44***

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

correlations. Elevation was the second best potential predictor of snow accumulation, with a positive correlation supporting the assumption that the differences become smaller in forested and non-forested sites at higher sites. Elevation also had a significant positive correlation with changes in snow ablation, showing that at higher altitudes the differences between melting in the forests and clearcuts become larger. The correlation between latitude and snow accumulation suggests that at higher latitudes the absolute differences in snow accumulation in forests and open sites increase, possibly due to higher incidence of sublimation. These differences also become larger for snow ablation as latitude increases, suggesting that ablation is more synchronous in lower latitudes. Of all the extracted temperature indicators, only winter mean temperature was significantly correlated to snow accumulation: absolute differences between forests and open sites are reduced in warmer locations. The same occurs with snow ablation rates. March–April precipitation was significantly correlated to both snow accumulation and melting.

Fig. 8 presents the relation between change in forest cover and change in snow accumulation and ablation. Despite the scatter, there is a clear trend for both snow accumulation and ablation to

Table 2

Description of variables used in modelling.

Code	Unit	Description
AC	%	Change in snow accumulation
AB	%	Change in snow ablation
FC	%	Change in forest cover
ELEV	m	Elevation above sea level
LAT	°	Latitude
MTEMP	°C	Mean temperature
WTEMP	°C	Winter temperature (December, January, February, March)
ATEMP	°C	Ablation temperature (March, April)
PP	mm	Total annual precipitation
WPP	mm	Winter precipitation (December, January, February, March)
APP	mm	Ablation precipitation (March, April)

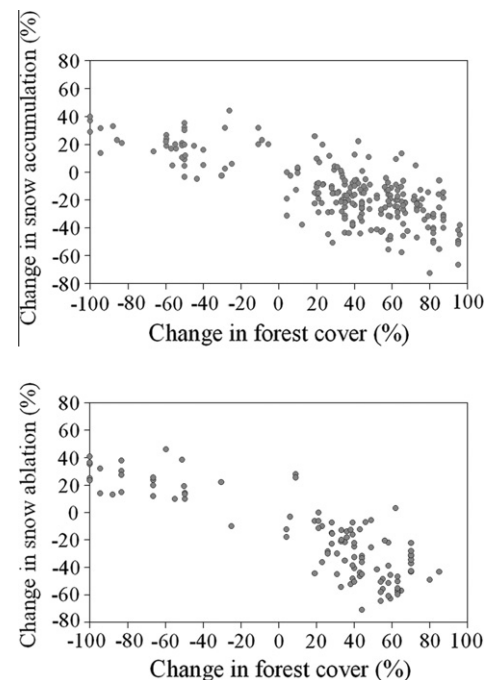


Fig. 8. Compilation of results showing change in snow accumulation (top) and ablation (bottom) according to change in forest cover.

decrease as forest cover increases. The studies show maximum absolute changes in snow accumulation and ablation of up to 75% and 110% respectively. Fig. 8 also highlights that the majority of studies used clearcuts as a reference (positive change in forest cover).

Fig. 9 shows the correlation trends between snow accumulation and elevation, latitude and representative variables of temperature and precipitation. The same information is presented for snow ablation on Fig. 10.

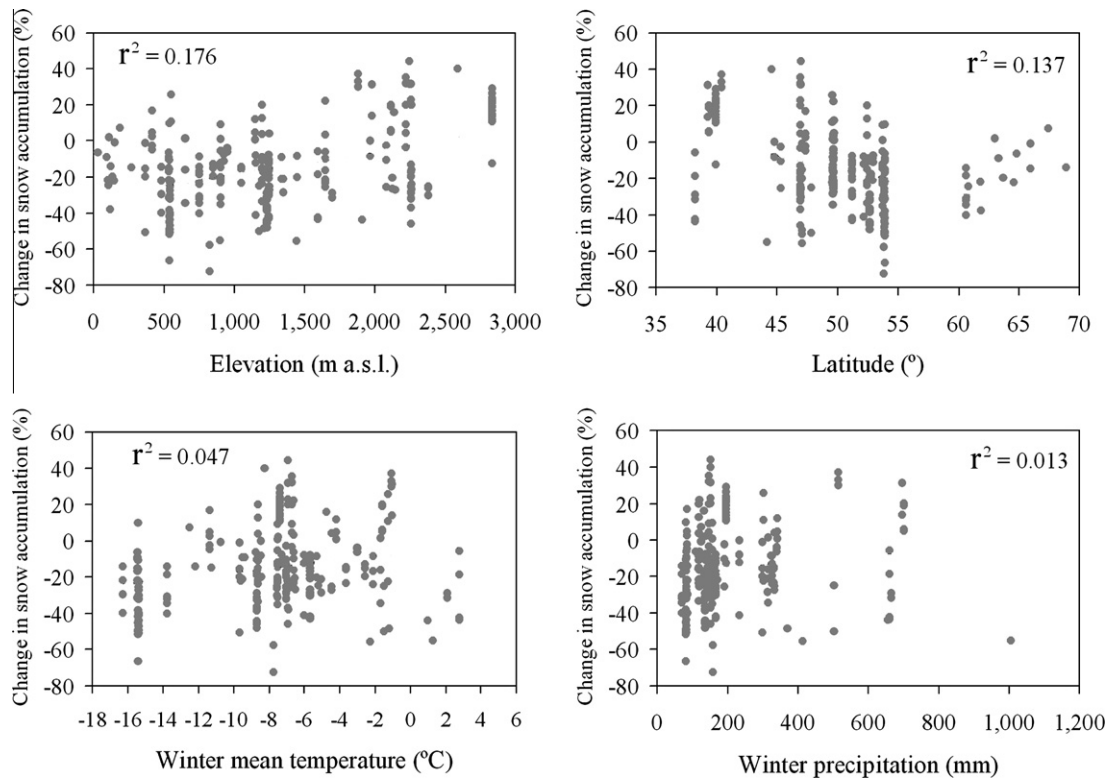


Fig. 9. Correlations between snow accumulation and representative geographic and climatic variables.

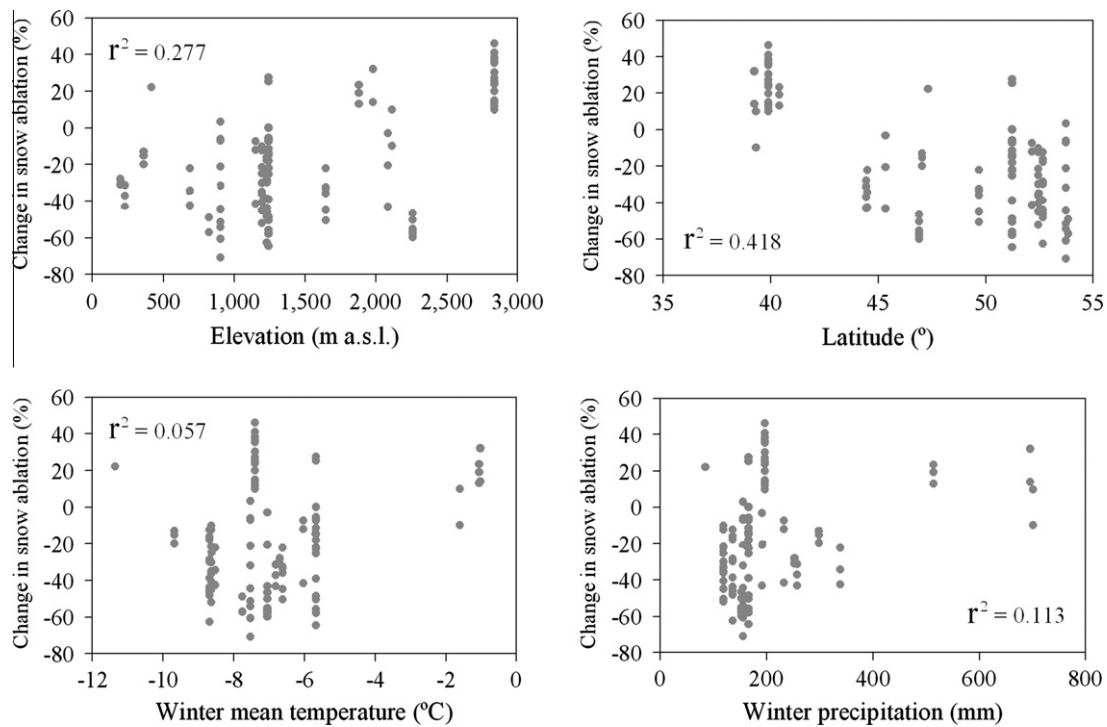


Fig. 10. Correlations between snow ablation and representative geographic and climatic variables.

Table 4

Results of simple linear regression.

Equation	Analysis of variance					Parameter estimates					
	<i>n</i>	<i>F</i>	<i>p</i> > <i>F</i>	<i>R</i> ²	Adj. <i>R</i> ²	<i>b</i>	<i>b</i> 95% upper limit	<i>b</i> 95% lower limit	SE	<i>t</i>	<i>p</i> > <i>t</i>
(2)	234	539.4	<0.0001	0.6984	0.6971	−0.39642	−0.36146	−0.43139	0.01707	−23.23	<0.0001
(3)	110	352.5	<0.0001	0.7166	0.7140	−0.53574	−0.47199	−0.59949	0.03227	−16.60	<0.0001

3.4.2. Simple regression

The two simple linear models fitted from the data described on Sections 3.1 and 3.2 are:

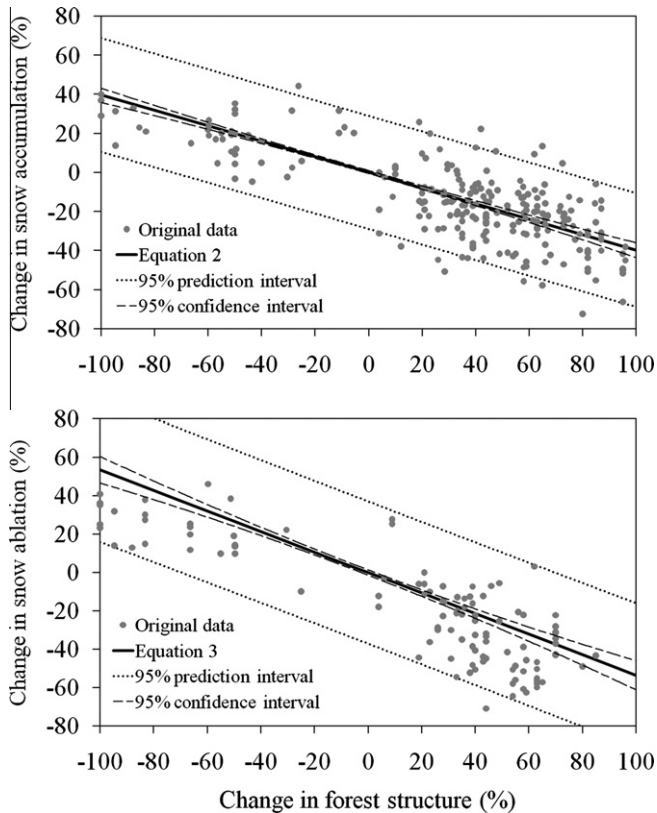


Fig. 11. Simple linear models relating changes in forest structure to changes in snow accumulation (left) and ablation (right) (Eqs. (2) and (3)) were fitted using the data in the figures).

$$AC = b \times FC \quad (2)$$

$$AB = b \times FC \quad (3)$$

where *AC* = predicted change in snow accumulation (%), *AB* = predicted change in snow ablation (%), *b* = fitted regression slope and *FC* = change in forest cover (%). The results of the simple linear regression, including the value for parameter *b*, are shown in Table 4, while the fitted equations are illustrated with the data on Fig. 11.

For both models, normality tests for residuals did not indicate significant deviations from normality, with *p* ranging from 0.15 to 0.28 for all four tests in the case of Eq. (2), and from 0.07 to 0.15 for Eq. (3) (*p* < 0.05 was required to discard normal distribution of the residuals). Homogeneity of variance was also confirmed for the residuals of Eqs. (2) and (3), with *p* = 0.26 and 0.24, respectively. Predicted vs. observed values are shown on Fig. 12. Validation of the models was successful, with SSE from the leave-one-out procedure (Kutner et al., 2005) differing from the SSE including all data by only 0.7% for Eq. (2) and 2% for Eq. (3).

Other studies have also fitted simple models relating snow accumulation with forest cover. Two models presented by Pomeroy et al. (2002) and the model by Kuz'min (1960) were adapted to be expressed in the same form as models 2 and 3. The models by Pomeroy et al. (2002), originally using LAI as independent variable, were transformed to use forest cover with the equation provided by the same author:

$$C_c = 0.29 \times \ln(LAI) + 0.55 \quad (4)$$

where *C_c* = forest cover (%) and *LAI* = leaf area index. The resulting equations were (Pomeroy et al., 2002; Kuz'min, 1960):

$$AC = 1 - 0.144 \times \frac{FC - 0.55}{0.29} + 0.223 \quad (5)$$

$$AC = 1 - 0.125 \times \frac{FC - 0.55}{0.29} + 0.237 \quad (6)$$

$$AC = 1 - 0.37 \times FC \quad (7)$$

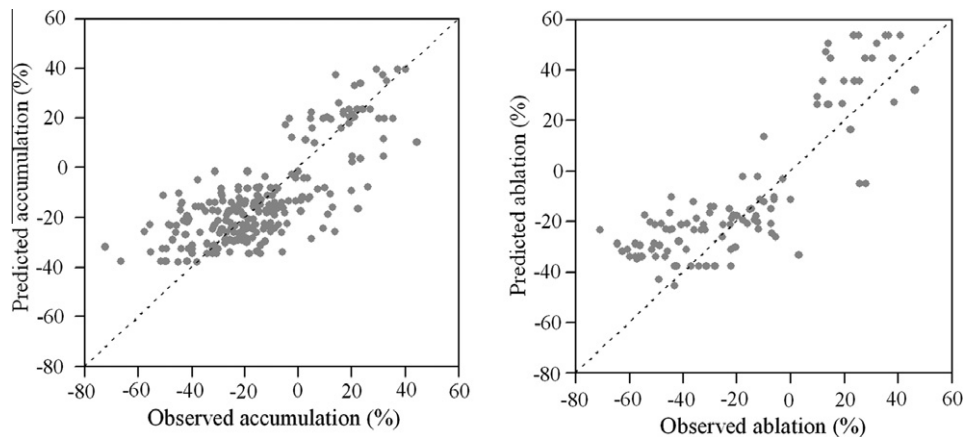


Fig. 12. Observed vs. predicted snow accumulation (left) and ablation (right) for simple linear models.

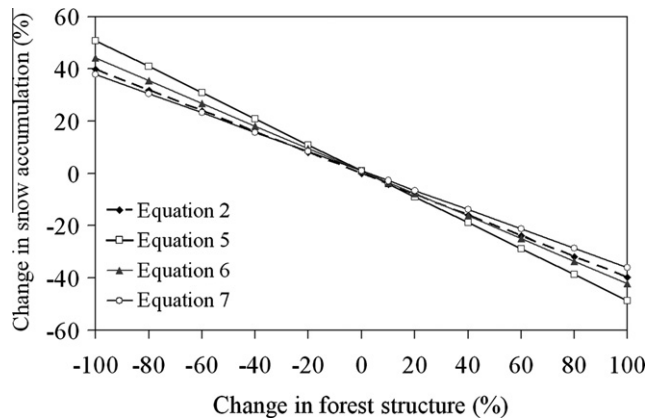


Fig. 13. Comparison of simple linear models (Pomeroy et al., 2002; Kuz'min, 1960) predicting effects of forest structure on snow accumulation.

In order to assess the similarity of the developed model (Eq. (2)) with those by Kuz'min (1960) and Pomeroy et al. (2002), equations were plotted against the original data (Fig. 13). The four linear models linking forest cover to snow accumulation are similar, showing a maximum difference of 10% in snow accumulation prediction when change in forest cover equals 100% or –100%. Eq. (5), in particular, shows higher differences than the other snow accumulation equations as forest cover approaches these values. The differences between the models are mainly due to the use of different datasets to derive their parameters, especially in the case of the Kuz'min equation, developed in Russia (Pomeroy et al., 2002).

3.4.3. Multiple regression

The poor correlations between snow accumulation and melting with variables other than change in forest cover (Table 3) prevented the development of multi-variable models. In general, the inclusion of geographic and historic climatic variables did not significantly improve the regression coefficients. R^2 values only increased marginally (by up to 0.03) when more variables were included to the simple linear model based on forest cover changes. The resulting multivariate models that complied with the assumptions of regression did not show logical physical meaning and were difficult to interpret, suggesting that neither the data, nor the model structure, were appropriate for the purpose of obtaining valid snow accumulation and melting models of intermediate complexity from the variables analyzed. Testing empirical models with different structures is not in the scope of this study because it would also require an improvement in the original dataset.

3.5. Discussion

The results of this review confirm that the relationship between snow accumulation and melting with forest cover is strong and significant but complex and highly variable. The confidence limits shown on Fig. 11 indicate that despite the dispersion of the data, the sample size was large enough to locate the regression lines with certainty, and therefore the general inferences made with regard to the relationship between forest cover and snow accumulation and ablation have a solid basis. However, the prediction limits indicate that observed percentage changes can differ from predicted values by up to 30–40% at a 95% confidence level. Therefore, caution is required when analyzing individual records. Of particular concern is that several show behaviour opposite to the general trend. For example, stands with up to a 70% increase in forest cover

still led to an increase in snow accumulation. A similar case is observed for snow ablation, thus demonstrating that snow interception, sublimation and energy balance could often be governed by variables other than forest cover, or possibly that measurement errors can obscure the effect. Since the majority of the studies of the dataset took place in the cold, dry areas of the interior of North America, where interception and sublimation dominate, data dispersion is not attributable to significantly different geoclimatic conditions. A combination of the many factors discussed in Section 2 is a better explanation for the variability observed in Fig. 8. Given that most of the studies do not provide specific information about those factors, it is not possible to isolate their influence in a statistical model.

The development of the two simple regression models for the estimation of changes in snow accumulation and melting with changes in forest cover over such a wide range of sites confirms the strong universal relationship between these factors. To apply these models at new sites requires the absolute value of snow accumulation in a reference site (either a fully stocked stand or an open area) to be known as well as an expression of forest cover. The simple linear snow accumulation model (Eq. (2)) was consistent with similar models found in the literature, suggesting that no significant improvements can be achieved by this approach. Eq. (2) has a conceptual advantage when compared to the simple models presented by other Kuz'min (1960) and Pomeroy et al. (2002) because it intercepts the origin (i.e. 0% change in forest cover = 0% change in snow accumulation). However, all these simple models are not capable of accurately predicting snow accumulation and ablation under specific conditions, and are only useful to obtain general average estimations.

The inclusion of general geographic and historic climatic parameters failed to provide greater predictive power. One of the reasons for the relatively poor relation between snow processes and these variables is the repetition of values within the same location. Several studies provided multi-temporal results of snow accumulation and/or melting that had to be linked with unique values of elevation, latitude, temperature and precipitation. If studies had provided detailed climatic information for the actual years of the experiments, it may have been possible to generate a more accurate model, given the known dependence of forest-snow interactions on the characteristics of snow storms and weather conditions during the melt period. Future empirical studies should therefore provide detailed information such as accurate coordinates, elevation, aspect, slope and reference clearcut size. Ideally, detailed measurements of temperature and precipitation during the monitoring periods should also be recorded. This review shows again how important metadata are in order to use collected information for later analysis. Furthermore, inclusion of such information would allow the data to be used in modelling studies.

Evidence shows that the interaction of the many factors adding variability to the snow processes—snowfall, interception, sublimation, accumulation, redistribution and melting—is too complex to be modelled accurately, even by physically-based equations. In fact, Rutter et al. (2009) evaluated 33 snowpack models of a wide range of complexity and purpose in forests and open sites of five locations of the Northern Hemisphere during two winter seasons. They concluded that there is no universal best model that fits all the locations, and no consistency was found regarding general models' behaviour in open and forested sites. Despite intensive measurements, many other studies have failed to fully explain the origin of the energy that leads to rates of snow evaporation that are significantly larger than expected. This lack of closure of the energy balance shows how complex snow processes are (Lundberg and Halldin, 2001). It is not a surprise, then, that the simple historic empirical information compiled in this review was only useful for fitting simple general linear models.

4. Conclusions

An extensive literature review was conducted to explore the relationship between forest cover and snow accumulation and melting. Generally, studies confirm that as forest cover increases, the interception of snow in the canopies reduces the amount of snow that accumulates the ground. Forest cover also provides shelter and shading to the snow and thus reduces snow ablation rates when compared to an open area. However, the interaction of forest cover and snow accumulation and melting is subject to a number of sources of variability that make their prediction under specific conditions highly difficult. The major sources of variability in snow-forest studies include the inter-annual variability in magnitude of snowfall, elevation, aspect, slope, clearcut size of the reference to which forests are compared, wind speed, specific meteorological conditions, canopy geometry and spatial distribution, and several types of measurement and sampling errors.

The main contribution of this review is the compilation of data from studies extending back to the 1930s and standardizing the results so that they could be subjected to meta-analysis. This exercise provided two simple models able to predict changes in snow accumulation and melting associated with changes in forest cover. While the fitted relations were significant and the sample size was large enough to define the average trend with reasonable precision, there was substantial scatter, so that the models would not provide accurate predictions for particular cases. Unfortunately, most studies did not provide enough information so that other variables could be incorporated in the models. Geographic and historic climatic variables were compiled from available data sources for all the sites, but their inclusion did not improve the fit of the models.

Further research exploring the relationship between forest cover and snow processes should aim to the development of new experimental designs that measure as many sources of variability as possible. There is still a need for models of intermediate complexity that can be easily applicable to other areas by using simple additional variables such as elevation, latitude, aspect, slope, clearcut size and temperature. These variables do not require special techniques or equipment to be measured, and yet no model was found in the literature that incorporates them to predict snow accumulation and melting. We believe that an ideal situation for a multivariate approach to be successful would require: (a) that the locations of all the studies be accurate enough so that microclimate factors could be retrieved; (b) that current meteorological conditions (temperature, precipitation, radiation, etc.) at the moments during which the experiments took place were available rather than historic averages; (c) that the authors of the studies described in more detail the experimental sites and specific methodologies, especially to obtain topographic conditions such as aspect and slope which, despite being easy to measure, are rarely provided. If this information would have been collected by all the studies, resulting empirical models of intermediate complexity might be in a better position to compete with physically-based models.

Given that stream discharge is of ultimate interest to water resources management because it affects water availability, properties of drought and flooding events, stability of wildlife habitats, hydropower production, fisheries, and others, it is important for snow accumulation and ablation to be properly linked to the magnitude–frequency of low or peak flows at the watershed level. For this purpose, long-term time series of snow accumulation and ablation must be recorded so that their temporal (and not only spatial) variability can be assessed and comprehensive frequency analyses be conducted.

Empirical studies might continue to be important in the future for new research at larger scales and basins, where detailed param-

eterization of processes is unlikely to be successful given our current knowledge. We encourage authors in Hydrology and other disciplines to provide as much information as possible in their experimental designs and publications to ensure better integration and meta-analysis in the future.

Acknowledgements

We thank Dr. Valerie LeMay and Christopher Bater for their support in the statistical analysis, Dr. Georg Jost for his valuable comments on this review, Dr. Mark Johnson for providing relevant references, and Sally Taylor for helping to find old publications. The following authors of some of the studies cited in this review kindly provided additional information that allowed a better understanding of their data: Craig Murray, Esko Kuusisto, Rita Winkler, Dan Bewley and William Veatch. Special thanks to Robert D'Eon for providing a complete database of his studies. This research is partly supported by the British Columbia Forest Science Program (Y09-2171) and Discovery Grants from the Natural Sciences and Engineering Research Council to N.C. Coops. We thank the co-Editor-in-Chief of the Journal of Hydrology, Laurent Charlet, and two anonymous reviewers for their relevant and valuable inputs to this manuscript.

References

- Alila, Y., Kuras, P., Bewley, D., Teti, P., Blair, T., 2007. Effects of pine beetle infestations and treatments on hydrology: integrating stand-level data into mesoscale watershed functions. In: Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado. FORREX, Kelowna, British Columbia, July 10, 2007.
- Anderson, H.W., 1956. Forest-cover effects on snowpack accumulation and melt. Central Sierra Snow Laboratory. Trans. Amer. Geophys. Union 37 (3), 307–312.
- Anderson, H.W., Rice, R.M., West, A.J., 1958a. Snow in forest openings and forest stands. In: Proc. Soc. Am. For., pp. 46–50.
- Anderson, H.W., Rice, R.M., West, A.J., 1958b. Forest shade related to snow accumulation. In: Proceedings of the 26th Western Snow Conference, Bozeman, MT, April 16–18, 1958, pp. 21–31.
- Anderson, H.W., Gleason, C.H., 1960. Effects of logging and brush removal on snow water runoff. Int. Assoc. Sci. Hydrol. 51, 478–489.
- Anderson, H.W., West, A.J., 1965. Snow accumulation and melt in relation to terrain in wet and dry years. In: Proceedings of the 33rd Western Snow Conference, Colorado Springs, CO, April 20–22, 1965, pp. 73–82.
- Anderson, H.W., Hoover, M., Reinhart, K., 1976. Forests and Water: Effects of Forest Management on Floods, Sedimentation, and Water Supply. USDA Forest Service General Technical Report PSW-18, 96 p.
- Bavay, M., Lehning, M., Jonas, T., Löwe, H., 2009. Simulations of future snow cover and discharge in Alpine headwater catchments. Hydrol. Proc. 23, 95–108.
- Berndt, H., 1965. Snow accumulation and disappearance in lodgepole pine clearcut blocks in Wyoming. J. Forest. 63 (2), 88–91.
- Berris, S., Harr, D., 1987. Comparative snow accumulation and melt during rainfall in forested and clearcut plots in the Western Cascades of Oregon. Water Resour. Res. 23 (1), 135–142.
- Bewley, D., Alila, Y., Varhola, A., 2010. Variability of snow water equivalent and snow energetics across a large catchment subject to mountain pine beetle infestation and rapid salvage logging. J. Hydrol. 388, 464–479.
- Boon, S., 2007. Snow accumulation and ablation in a beetle-killed pine stand in northern interior British Columbia. BC J. Ecosyst. Manage. 8 (3), 1–13.
- Boon, S., 2009. Snow ablation energy balance in a dead forest stand. Hydrol. Proc., doi:10.1002/hyp.7246.
- Brechtel, H.M., 1970. Wald und Retention-Einfache Methoden zur Bestimmung der lokalen Bedeutung des Waldes für die Hochwasserdämpfung. Deutsche Gewässerkundliche Mitteilungen 14, 91–103.
- Brechtel, H.M., 1979. Wald und Schnee – Ergebnisse forsthydrologischer Schneemessungen in der Bundesrepublik Deutschland und der Schweiz. Schriftenreihe des DVWK 41.
- Brechtel, H.M., Balazas, H., 1976. Auf – und Abbau der Schneedecke im westlichen Vogelsberg in Abhängigkeit von Höhenlage, Exposition und Vegetation. Beiträge zur Hydrologie Heft 3, 35–107.
- Brechtel, H.M., Scheele, G., 1981. Einfluss des Waldes auf Schneean Sammlung und –schmelze in der Hessischen Rhön und Möglichkeiten zur Erhöhung des nutzbaren Wasserdargebotes durch forstliche Maßnahmen. AFZ 48, 1286–1289.
- British Columbia Ministry of Forests, 2008. Beetle Facts. <http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/facts.htm#infestation> (accessed March, 2009).
- Brooks, K.N., Ffolliott, P.F., Gregersen, H.M., DeBano, L.F., 2003. Hydrology and the Management of Watersheds, third ed. Iowa State Press, Ames, IA.
- Bunnell, F., Vales, D., 1990. Comparison of methods for estimating forest overstory cover: differences among techniques. Can. J. Forest Res. 20, 101–107.

- Connaughton, C.A., 1933a. The accumulation and rate of melting of snow as influenced by vegetation. *J. Forest.* 33 (6), 564–569.
- Connaughton, C.A., 1933b. Effect of forest cover on snow melt. *For. Work.* 9 (2), 9–10.
- Davis, R., Hardy, J., Ni, W., Woodcock, C., McKenzie, J., Jordan, R., Li, X., 1997. Variation of snow cover ablation in the boreal forest: a sensitivity study on the effects of conifer canopy. *J. Geophys. Res.* 102, 29389–29395.
- D'Eon, R., 2001. Using snow-track surveys to determine deer winter distribution and habitat. *Wildlife Soc. Bull.* 29 (3), 879–887.
- D'Eon, R., 2004. Snow depth as a function of canopy cover and other site attributes in a forested ungulate winter range in southeast British Columbia. *BC J. Ecosyst. Manage.* 3, 1–9.
- Daugherty, D., Dickinson, B., 1982. Snow cover distribution in forested and deforested landscapes in New Brunswick, Canada. In: *Proceedings of the 39th Eastern Snow Conference*, Reno, NV, April 19–23, 1982, pp. 10–19.
- Dunford, E.G., Niederhof, C.H., 1944. Influence of aspen, young lodgepole pine, and open grassland types upon factors affecting water yield. *J. Forest.* 42 (9), 673–677.
- Essery, R.L., Pomeroy, J.W., Parviainen, J., Storck, P., 2003. Sublimation of snow from coniferous forests in a climate model. *J. Climate* 16, 1855–1864.
- Essery, R.L., Bunting, P., Hardy, J., Link, T., Marks, D., Melloh, R., Pomeroy, J., Rowlands, A., Rutter, N., 2008. Radiative transfer modeling of a coniferous canopy characterized by airborne remote sensing. *J. Hydrometeorol.* 9, 228–241.
- Felix, R., Priesmeier, K., Wagner, V.H., Wilhelm, F., 1988. Abfluß in Wildbächen. *Münchner Geograph. Abh.*, Band 6.
- Gary, H.L., 1975. Airflow patterns and snow accumulation in a forest clearing. In: *Proceedings of the 43rd Western Snow Conference*, Coronado, CA, April 23–25, 1975, pp. 106–113.
- Golding, D., Swanson, R., 1986. Snow distribution patterns in clearings and adjacent forest. *Water Resour. Res.* 22 (13), 1931–1940.
- Goodell, B.C., 1952. Watershed management aspects of thinned young lodgepole pine stands. *J. Forest.* 50 (5), 374–378.
- Goodison, B.E., Ferguson, H.L., McKay, G.A., 1981. Measurement and data analysis. In: Gray, D.M., Male, D.H. (Eds.), *Handbook of Snow*. Pergamon Press Canada Ltd., Willowdale, pp. 191–274.
- Hardy, J.P., Hansen-Bristow, K.J., 1990. Temporal accumulation and ablation patterns of the seasonal snowpack in forests in varying stages of growth. In: *Proceedings of the 58th Western Snow Conference*, Sacramento, CA, April 17–19, 1990, pp. 32–34.
- Haupt, H.E., 1951. Snow accumulation and retention on ponderosa pine lands in Idaho. *J. Forest.* 49 (12), 869–871.
- Hedstrom, N., Pomeroy, J., 1998. Measurements and modelling of snow interception in the boreal forest. *Hydrol. Proc.* 12, 1611–1625.
- Hendrick, R.L., Filgate, B.D., Adams, W.M., 1971. Application of environment analysis to watershed snowmelt. *J. Appl. Meteorol.* 10, 418–429.
- Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climat.* 25, 1965–1978.
- Ingebo, P.A., 1955. An instrument for measurement of the density of plant cover over snow course points. In: *Proceedings of the 23rd Western Snow Conference*, Portland, OR, April 13–15, 1955, pp. 26–29.
- Jost, G., Weiler, M., Gluns, D., Alia, Y., 2007. The influence of forest and topography on snow accumulation and melt at the watershed-scale. *J. Hydrol.* 347, 101–115.
- Kittredge, J., 1953. Influence of forests on snow in the ponderosa-sugar pine-fir zone of the central Sierra Nevada. *Hilgardia* 22, 1–95.
- Knowles, N., Dettinger, M.D., Cayan, D.R., 2006. Trends in snowfall versus rainfall in the western United States. *J. Climate* 19, 4545–4559.
- Koenig, U., Abegg, B., 1997. Impacts of climate change on winter tourism in the Swiss Alps. *J. Sustain. Tourism* 5 (1), 46–58.
- Kutner, M.H., Nachtsheim, C.J., Neter, J., Li, W., 2005. *Applied Linear Statistical Models*, fifth ed. McGraw-Hill, New York, NY.
- Kuusisto, E., 1980. On the values and variability of degree-day melting factor in Finland. *Nord. Hydrol.* 11, 235–242.
- Kuz'min, P.P., 1960. Formirovanie Snezhnogo Pokrova i Metody Opredeleniya Snegozapasov. *Gidrometeoizdat: Leningrad*. (Published 1963 as *Snow Cover and Snow Reserves*. [English Translation by Israel Program for Scientific Translation, Jerusalem]. National Science Foundation: Washington, DC).
- Lundberg, A., Halldin, S., 2001. Snow interception evaporation. Review of measurement techniques, processes, and models. *Theor. Appl. Climatol.* 70, 117–133.
- Lundquist, J.D., Cayan, D.R., Dettinger, M.D., 2004. Spring onset in the Sierra Nevada: when is snowmelt independent of elevation? *J. Hydrometeorol.* 5, 327–334.
- Lundquist, J.D., Flint, A.L., 2006. Onset of snowmelt and streamflow in 2004 in the western United States: how shading may affect spring streamflow timing in a warmer world. *J. Hydrometeorol.* 7, 1199–1271.
- Matheussen, B., Kirschbaum, R.L., Goodman, I.A., O'Donnell, G.M., Lettenmaier, D.P., 2000. Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). *Hydrol. Proc.* 14, 867–885.
- Mayer, H., Feger, K.H., Ackertvann, B., Armbruster, M., 1997. Schneedeckenentwicklung in Fichtenwäldern im südlichen Hochschwarzwald. *Forstw. Cbl.* 116, 370–380.
- McCaughy, W., Hansen, K., Farnes, P., 1995. Preliminary information on snow interception, accumulation, and melt in northern Rocky Mountain lodgepole pine forests. In: *Proceedings of the 63rd Western Snow Conference*, Sparks, NV, April 18–20, 1995, pp. 49–55.
- McCaughy, W., Farnes, P.E., 2001. Snowpack comparison between an opening and a lodgepole pine stand. In: *Proceedings of the 69th Western Snow Conference*, Sun Valley, ID, 17–19 April, 2001, pp. 59–64.
- McNay, R., Peterson, L., Nyberg, B., 1988. The influence of forest stand characteristics on snow interception in the coastal forests of British Columbia. *Can. J. Forest Res.* 18, 566–573.
- Meagher, G., 1938. Forest cover retards snow melting. *J. Forest.* 36 (12), 1209–1210.
- Moore, C., McCaughy, W., 1998. Snow accumulation under various forest stand densities at Tenderfoot Creek Experimental Forest, Montana, USA. In: *Proceedings of the 54th Eastern Snow Conference*, Banff, Alberta, May 4–8, 1998, pp. 42–51.
- Moore, R.D., Wondzell, S.M., 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. *J. Am. Water. Res. Assoc.* 41, 753–784.
- Mote, P., Hamlet, A., Clark, M., Lettenmaier, D., 2005. Declining mountain snowpack in western North America. *Bull. Am. Met. Soc.* 86, 39–49.
- Musselman, K., Molotch, N.P., Brooks, P.D., 2008. Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrol. Proc.* 22, 2767–2776.
- Murray, C., Buttle, J., 2003. Impacts of clearcut harvesting on snow accumulation and melt in a northern hardwood forest. *J. Hydrol.* 3, 197–212.
- Parveaud, C.-E., Chopard, J., Dauzat, J., Courbaud, G., Shephard, A., 2008. Modelling foliage characteristics in 3D tree crowns: influence on light interception and leaf irradiance. *Trees* 22, 87–104.
- Patch, J., 1981. Effects of forest cover on snow cover distribution in the Nashwaak Experimental Watershed Project. In: *Proceedings of the 38th Eastern Snow Conference*, Syracuse, NY, June 4–5, 1981, pp. 76–87.
- Peterson, N.R., Brown, A.J., 1975. Accuracy of snow measurements. In: *Proceedings of the 43rd Western Snow Conference*, Coronado, CA, April 23–25, 1975, pp. 1–5.
- Pfister, R., Schneebeli, M., 1999. Snow accumulation on boards of different sizes and shapes. *Hydrol. Proc.* 13, 2345–2355.
- Pomeroy, J.W., Granger, R.J., Pietroniro, A., Elliot, J., Toth, B., Hedstrom, N.R., 1997. Hydrological Pathways in the Prince Albert Model Forest. *NHRI Contribution Series CS-97004*. Saskatoon, Saskatchewan. 154 p.
- Pomeroy, J.W., Parviainen, J., Hedstrom, N., Gray, D.M., 1998. Coupled modelling of forest snow interception and sublimation. *Hydrol. Proc.* 12, 2317–2337.
- Pomeroy, J., Gray, D., Hedstrom, N., Janowicz, J., 2002. Prediction of seasonal snow accumulation in cold climate forests. *Hydrol. Proc.* 16, 3543–3558.
- Rood, S., Pan, J., Gill, K., Franks, C., Samuelson, G., Shephard, A., 2008. Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests. *J. Hydrol.* 349, 397–410.
- Rowland, J.D., Moore, R.D., 1992. Modelling solar irradiance on sloping surfaces under leafless deciduous forests. *Agric. Forest Meteorol.* 60, 111–132.
- Rutter, N., Essery, R., Pomeroy, J., Altirir, N., Andreadis, K., Baker, I., Barr, A., Bartlett, P., Boone, A., Deng, H., Douville, H., Dutra, E., Elder, K., Ellis, C., Feng, X., Gelfan, A., Goodbody, A., Gusev, Y., Gustafsson, D., Hellström, R., Hirabayashi, Y., Hirota, T., Jonas, T., Koren, V., Kuragina, A., Lettenmaier, D., Li, W., Luce, C., Martin, E., Nasonova, O., Purnanen, J., Pyles, R., Samuelsson, P., Sandells, M., Schädler, G., Shmakin, A., Smirnova, T., Stähli, M., Stöckli, R., Strasser, U., Su, H., Suzuki, K., Takata, K., Tanaka, K., Thompson, E., Vesala, T., Viterbo, P., Wiltshire, A., Xia, K., Xue, Y., Yamazaki, T., 2009. Evaluation of forest snow processes models (SnowMIP2). *J. Geophys. Res.* 114, 1–18.
- Sampson, R.N., 1997. Forest Management, Wildfire and Climate Change Policy Issues in 11 Western States. Report Prepared under the EPA/American Forests Cooperative Research Agreement CR-820-797-01-0. American Forests, Washington, DC. 44 p.
- Schnorbus, M., 2007. Mountain pine beetle from a flood and public safety perspective. In: *Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado*. FORREX, Kelowna, British Columbia, July 10, 2007.
- Schmidt, R.A., Jairell, R.L., Pomeroy, J.W., 1988. Measuring snow interception and loss from an artificial conifer. In: *Proceedings of the 56th Western Snow Conference*, Kalispell, MT, April 19–21, 1988, pp. 166–169.
- Schwarz, O., 1982. Forsthydrologische Schneemessungen im deutschsprachigen Raum. Beiträge zur Hydrologie, Sonderheft 4, Kirchzarten, 145–163.
- Service, R., 2004. As the west goes dry. *Science* 303, 1124–1127.
- Skidmore, P., Hansen, K., Quimby, W., 1994. Snow accumulation and ablation under fire-altered lodgepole pine forest canopies. In: *Proceedings of the 62nd Western Snow Conference*, Santa Fe, NM, April 18–21, 1994, pp. 43–52.
- Spittlehouse, D.L., Winkler, R.D., 1996. Forest canopy effects on sample size requirements in snow accumulation and melt comparisons. In: *Proceedings of the 64th Western Snow Conference*, Bend, OR, April 16–18, 1996, pp. 39–46.
- Stähli, M., Papritz, A., Waldner, P., Forster, F., 2000. Die Schneedeckenverteilung in einem voralpinen Einzugsgebiet und ihre Bedeutung für den Schneeschmelzabfluss. *Schweiz. Z. Forstwes* 151 (6), 192–197.
- Swanson, R.H., Stevenson, D.R., 1971. Managing snow accumulation under leafless aspen to enhance watershed value. In: *Proceedings of the 39th Western Snow Conference*, Billings, MT, April 20–22, 1971, pp. 63–69.
- Teti, P., 2008. Effects of Overstory Mortality on Snow Accumulation and Ablation. Ministry of Forests and Range, Williams Lake, British Columbia. 41 p.

- Toews, D.A.A., Gluns, D.R., 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in southeastern British Columbia. In: *Proceedings of the 54th Western Snow Conference*, Phoenix, AZ, April 15–17, 1986, pp. 101–111.
- Troendle, C.A., Leaf, C.F., 1980. *Hydrology. An approach to water resources evaluation of non-point silviculture sources*. US Environmental Protection Agency, Athens, GA. 173 p.
- Troendle, C.A., King, R.M., 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *J. Hydrol.* 90, 145–157.
- Troendle, C.A., Schmidt, R.A., Martinez, M.H., 1988. Snow deposition processes in a forest stand with a clearing. In: *Proceedings of the 56th Western Snow Conference*, Kalispell, MT, April 19–21, 1988, pp. 78–86.
- Uunila, L., Guy, B., Pike, R., 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: key questions and current knowledge. *Stream. Water. Manage. Bull.* 9 (2), 1–6.
- Varhola, A., Coops, N.C., Bater, C.W., Teti, P., Boon, S., Weiler, M., 2010. The influence of ground- and lidar-derived forest structure metrics on snow accumulation and ablation in disturbed forests. *Can. J. Forest Res.* 40, 812–821.
- Veatch, W., Brooks, P.D., Gustafson, J.R., Molotch, N.P., 2009. Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. *Ecohydrology*, 1–14. doi:10.1002/eco.45.
- Watson, F., Anderson, T., Newman, W., Alexander, S., Garrott, R., 2006. Optimal sampling schemes for estimating mean snow water equivalents in stratified heterogeneous landscapes. *J. Hydrol.* 328, 432–452.
- Weitzman, S., Bay, R., 1959. Snow behavior in forests of northern Minnesota and its management implications. *US Dep. Agric. Forest Serv.* 69, 1–19.
- White, H., 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica* 48, 817–838.
- Wilm, H.G., Dunford, E.G., 1948. Effect of timber cutting on water available for stream flow from a lodgepole pine forest. *US Dep. Agric. Tech. Bull.*, vol. 968, 43 p.
- Winkler, R., 2001. *The Effects of Forest Structure on Snow Accumulation and Melt in South-Central British Columbia*. PhD Thesis, Faculty of Forestry, University of British Columbia, Vancouver, BC, 178 p.
- Winkler, R., Roach, J., 2005. Snow accumulation in BC's southern interior forests. *Stream. Water. Manage. Bull.* 9 (1), 1–5.
- Winkler, R.D., Spittlehouse, D.L., Golding, D.L., 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. *Hydrol. Proc.* 19, 51–62.
- Winkler, R.D., Moore, R.D., 2006. Variability in snow accumulation patterns within forest stands on the interior plateau of British Columbia, Canada. *Hydrol. Proc.* 20, 3683–3695.
- Woods, S., Ahl, R., Sappington, J., McCaughey, W., 2006. Snow accumulation in thinned lodgepole pine stands, Montana, USA. *Forest Ecol. Manag.* 235, 202–211.