Available online at www.sciencedirect.com

ScienceDirect

International Soil and Water Conservation Research 3 (2015) 50–56

www.elsevier.com/locate/iswcr

Comparing the impacts of mature spruce forests and grasslands on snow melt, water resource recharge, and run-off in the northern boreal environment

Jiří Kremsa[a], Josef Křeček[b,*], Eero Kubin[c]

[a]Watershed Authority of the Elbe River, Víta Nejedlého 951/8, CZ-500 03 Hradec Králové, Czech Republic

[b]Department of Hydrology, Czech Technical University in Prague, Thákurova 7, CZ-166 29 Prague 6, Czech Republic

[c]Natural Resources Institute Finland, Natural Resources and Bioproduction, PO Box 413, FI-90014 University of Oulu, Finland

Received 10 February 2015; received in revised form 27 February 2015; accepted 28 February 2015

Available online 21 April 2015

Abstract

Snow-melt runoff is an important factor in control of flooding and soil erosion in higher and cold regions of the world. In 1992–2008–2008, processes of snow accumulation and melting were monitored at two adjacent sites of the Paljakka environmental research centre (Finland). The forest stand of mature spruce (*Picea abies*) has been compared with adjacent, local, and open grassland. In the forest, snowpack duration fluctuated for 180–245 days, with a maximum depth of 78–152 cm and snow–water content of 167–406 mm, while in the open grassland this occurred for some 20 days less, with maximum depth 65–122 cm, and snow–water content 143–288 mm. The snow–water captured in the canopy reached a maximum 27% of that registered on the ground; the loss of intercepted snow by sublimation was approximately 26% of the annual snowfall. During the high melt period (April–May), the degree-day factor in the forest stand achieved 60% of values observed in the grassland (2.3–3.5 against 3.8–6.0 mm $^{\circ}C^{-1}$ day^{-1}). The hydrological model BROOK 90 was employed to analyse potential water resources recharge, and flood risk at Paljakka. Considering the normal climate season, snow-melt runoff from the forest exceeded the grassland by 22% (225 against 185 mm). In extreme situations, the maximum daily runoff from snow-melt in the grasslands (57 mm day^{-1}) exceeded 2.6 times the values in spruce forest (22 mm day^{-1}).

Keywords: Spruce boreal forest; Snow-depth; Snow–water content; Canopy interception; Snowmelt; Degree-day factor; BROOK 90; Runoff distribution

1. Introduction

The biome of boreal forest is characterized by coniferous stands consisting mostly of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). The relationship between forest and snow cover has been extensively discussed (WMO, 1994). Brooks, Folliott, Gregersen, and DeBano (2003), Ishii and Fukushima (1993) emphasized differences

*Corresponding author.

E-mail addresses: kremsa@seznam.cz (J. Kremsa), josef.krecek@fsv.cvut.cz (J. Křeček), eero.kubin@metla.fi (E. Kubin).

Peer review under responsibility of IRTCES and CWPP.

http://dx.doi.org/10.1016/j.iswcr.2015.03.005

2095-6339/

in forest stand structures upon the snowmelt runoff; the most significant reduce in snowmelt intensity was found in the dense mature spruce plantation.

In Nordic countries of Europe, snow melt processes significantly affect the water resources recharge but also the occurrence of nature hazard (overland flow, flooding and soil erosion). In Finland, where forests cover now 74% of the land area, processes of snow accumulation and snow melting are controlled mainly by boreal forests. However, in the last years, the harvest of boreal forests in Finland has been rapidly increasing mainly because of the local energy demand (Parviainen & Västilä, 2011). In the future, with expected changes of the global climate IPCC, 2013, extensive changes in the vegetation cover should be still considered. In the north of Finland, forest growth may increase with the climate change but the special features of boreal forest may be diminished (Kellomäki, Peltola, Nuutinen, Korhonen, & Strandman, 2008).

The recent investigations in the boreal forest focused namely on the snow evidence; snow cover mapping was accomplished there by several methods including remote sensing (Metsämäki, Anttila, Huttunen, & Vepsäläinen, 2005). The general distribution of snow characteristics across the Taiga snow-zone of Finland is reported by the Finnish national overview (Rasmus, 2005). But, the detailed genesis of snowmelt, and, particularly, differences within forest stands and open fields are still not well understood, related to groundwater recharge (Kubin & Křeček, 2009), or water resources protection. The objective of this study is to evaluate the effects of mature spruce forests on the accumulation and melt of snow, in comparison with that in open grassland on moderate slopes and high altitudes in central Finland. The standard observation there was supported with continuous monitoring of snowpack in the forest canopy to identify the interception loss and the genesis of snow melt runoff.

2. Material and methods

In 1992–2008, snow observations were carried out at the Paljakka research area (65°26′N, 26°26′E, elevation 350 m) in mature spruce (*Picea abies*) forests and in open grassland fields. The research area is in the middle-boreal coniferous zone (Hämet-Ahti, 1981). The climate is continental/micro-thermal (Dfc type, Köppen classification), the long-term mean annual temperature is 1 °C, and annual precipitation is 672 mm/year (with 50% snowfall). The even-aged (120 year) spruce stand was closed (basal area 25 m^2/ha, timber volume 160 m^3/ha), with a mean height of 15 m. The soils are sandy, developed on granite, and thr profiles normally less than one metre in depth. The saturated hydraulic conductivity, K, ranges from 1.8 to 2.0 m s^{-1} to the depth of 60–70 cm, at which depth a relatively impermeable podzolic layer normally occurs.

The field observation of snow characteristics were performed twice weekly between 9:00 and 10:00 am, except after the 25th April when they were performed three times a week because intensive changes in the snow cover begin to occur at this time. Ten sampling points at a distance of 10 m were used. The snow–water equivalent was measured by weighing vertical cores of the snow-pack (weighing cylinder with 100 cm^2 cross-section, Doesken & Judein, 1997). The standard daily meteorological data were provided by the climate station Suomussalmi Pesiö (25 km distance from the Paljakka research site).

In the last season, the canopy snowpack was monitored continuously by estimating snow weight on two full-size spruce trees by pressure sensors. The trees selected were typical of level, mature spruce stands, and approximated the surrounding canopy height of 15 m with crown projection of 3.5 and 3.0 m^2. Subtracting the tare from the force transducer measurement provided the mass of intercepted snow.

Snow–water characteristics are reviewed by Dewale and Rango (2008). The snow–water equivalent SWE [m] is expressed as

$$SWE = \frac{V_m}{A} \tag{1}$$

$$SWE = \frac{\rho_s}{\rho_w} \cdot h_s \tag{2}$$

where, V_m [m^3] is the volume of melted water from the snowpack of depth h_s [m], and the basal area A [m^2], ρ_s is the snow density (the mass per unit volume of snow) and ρ_w water density [kg m^{-3}].

A relatively simple, accepted empirical degree-day method was used for calculating the snowmelt in temperature dependent melting conditions (Martinec, Rango, & Roberts, 1998). The degree-day factor a [m $°C^{-1}$ day^{-1}]

converts the number of degree-days T [°C day] into the daily snowmelt depth M [mm]:

$$M = \alpha T \tag{3}$$

The modified degree-day method is used also in the deterministic hydrological model BROOK 90, developed by Federer (2002), to simulate hydrological processes in forested catchments of North America. This model was applied in this study to estimate the snow–water budget (accumulation, evaporation, and melting) in daily steps. The inputs to BROOK 90 are: daily sums of precipitation (mm); global solar radiation (MJ/m^2): mean daily values of air temperature (°C), vapour pressure (kPa); and wind speed (m/s). The parameters of the model address the geography and morphology of the site, the soil–vegetation complex, as well as internal flow processes (soil infiltration, percolation or evidence of macro-pores) and the groundwater storage and depletion. Federer (2002) recommends the values of parameters for several dominant forest ecosystems.

The BROOK 90 model was calibrated manually for the period of 2000–2005, by comparing observed and simulated values of the snow water equivalent (*SWE*), and tested during the period 2006–2008. Dewale and Rango (2008) recommend assessing the predictive power of simulating snow–water phenomena by the Nash–Sutcliffe efficiency coefficient E, defined as

$$E = 1 - \frac{\sum_{t=1}^{T} \left(Q_0^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q_0^t - \overline{Q_0}\right)^2} \tag{4}$$

where, Q_0 is the measured quantity, and Q_m modelled one at the time t. Generally, the simulation is supposed effective by $E > 0.5$.

3. Results and discussion

Seasonal changes in the snowpack (duration and depth) observed in the mature spruce stand and open grassland of Paljakka are shown in Figs. 1 and 2. During the 16 seasons (1992–2008), the snowpack in the forest ground occurred from October till the beginning of June; the annual duration of snow fluctuated during the 180–245 days, with maximum depth 78–152 cm and snow–water equivalent 167–406 mm. In the open grassland, however, the snowpack lasted for some 20 days less, with maximum annual depth 65–122 cm and snow–water equivalent 143–288 mm. The maximum snow-depth was registered between the 15th March and the 15th April.

The results showed approximately 26% higher snow-depth in the mature spruce stand (Table 1). This corresponds to results of Vajda, Venäläinen, Hänninen, and Sutinen (2005) in Finnish Lapland; it is explained particularly by the wind effect and higher snow erosion in the open grassland. The variation in maximum annual snow-depth corresponds to the regional characterization by Rasmus (2005). However, other snow characteristics (snow–water equivalent and snowpack duration) observed at Paljakka showed significant differences from that regional study (maximum snow–water equivalent 406 mm against 200 mm, and maximum snowpack duration of 245 days against 166).

During the snow season, the ratio between the observed snow–water equivalent and the snow-depth (SWE/h_s) increased from 0.12 to 0.25, corresponding to values reported by Storck, Kern, and Bolton (1999) and Pike, Redding, Moore, Winkler, and Bladon (2010) in similar geographic conditions. The final snowpack depletion in the forest occurred over 44 days, compared to 25 days – in grassland areas, with a mean melt intensity (7 versus 10 mm day^{-1}), Fig. 2. In the high melt period (April–May), the forest stand showed lower degree-day factors (2.3–3.5 mm °C^{-1} day^{-1}) compared to the more compact snowpack of the grasslands (3.8–6.0 mm °C^{-1} day^{-1}). This comparison roughly corresponded to the degree-day factor range given by WMO (1994) for catchments "moderately forested" and "non-forested". Observed maximum daily snow-melt intensities varied between 30 and 50 mm. The observed higher snow accumulation observed in the spruce stand, does not support the generalized outcomes of Brooks et al. (2003) or Storck et al. (1999), but it reflects the Nordic environment with relatively low vaporization.

Concerning the intercepted snow loads, t data (Fig. 3) indicate that increases in the intercepted snow load always accompany snowfall events, and that high loads persisted for a time after snowfall (January–February). The snow–water stored on the canopy reached a maximum of 27% of that registered at the forest ground. More rapid rates of decrease in snow load after a snowfall occurred when the air temperature was high (March–April). The snowpack

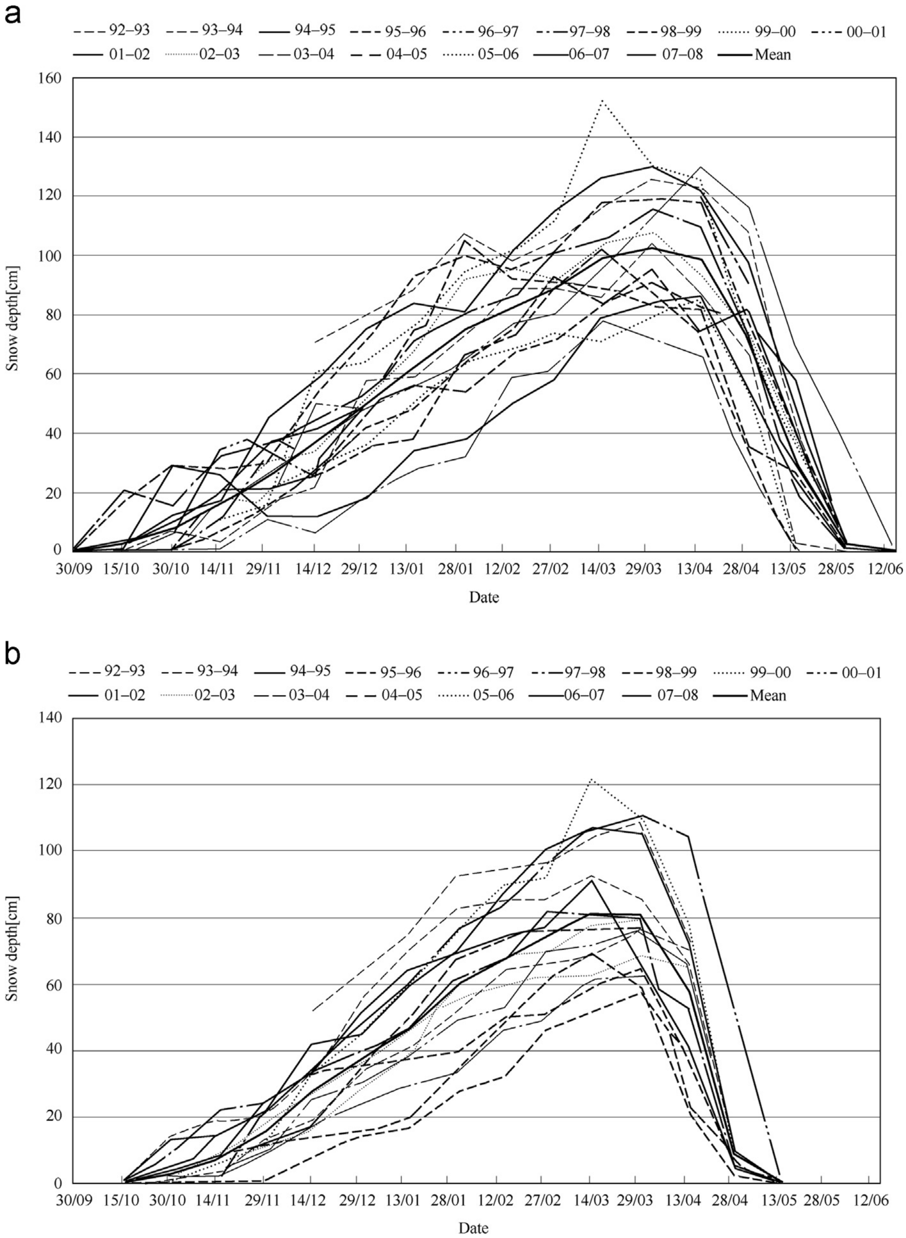

Fig. 1. (a) Seasonal variability of the snowpack observed at Paljakka – mature spruce stand (1992–2008). (b) Seasonal variability of the snowpack observed at Paljakka – grassland (1992–2008).

intercepted by the spruce canopy depleted rapidly (7.5 mm per day) during the 12 days beginning in March (45 days before the snow depletion from the forest ground starts). The loss of intercepted snow by sublimation (approximately 90 mm, from the calculation of daily water balance by neglecting the vaporization from the forest ground) was 26% of the annual snowfall (i.e. 13% of the annual precipitation).

In cold boreal forests, intercepted snow may be retained in the canopy much longer (Fig. 2), compared with more temperate forests where the intercepted snow load is presumed to decline to zero between snowfall events. Generally, low wind speed and low snow density are associated with cold temperatures and increased interception efficiency; conversely, warming temperatures after a snowfall increase snow unloading (Hedstrom & Pomeroy, 1998).

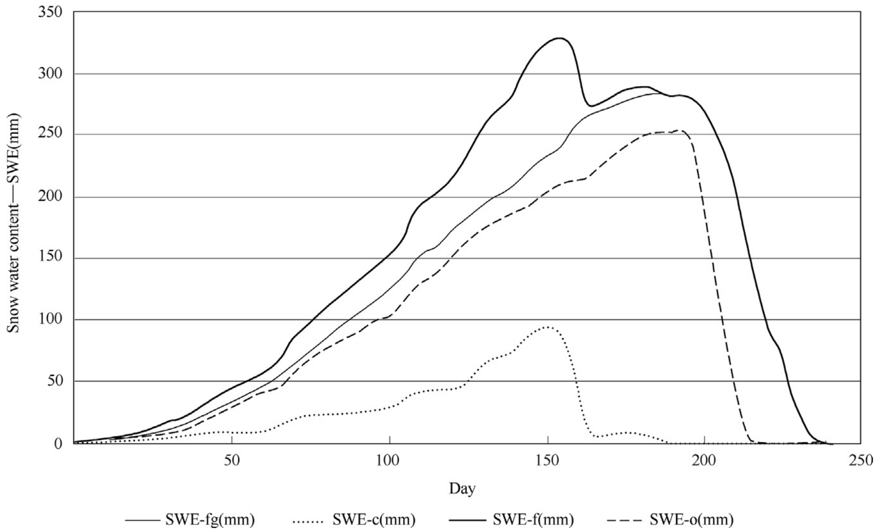

Fig. 2. Mean annual snow–water content stored at Paljakka (1992–2008): spruce forest total (SWE-f), forest canopy (SWE-c), forest ground (SWE-fg) and open grassland (SWE-o).

Table 1
The statistics of maximum annual snow-depth (cm) at Paljakka (1992–2008).

Characteristic	**Forest ground**	**Open grassland**
Arithmetic mean	102	81
Standard deviation	21	18
Standard error of mean	5	5
Coefficient of variation	0.21	0.22
Coefficient of skewness	0.87	0.89
Coefficient of kurtosis	3.42	3.52
Autocorrelation coefficient	0.07	0.03
Trend ($n=16$, $p=0.05$)	Not significant	Not significant

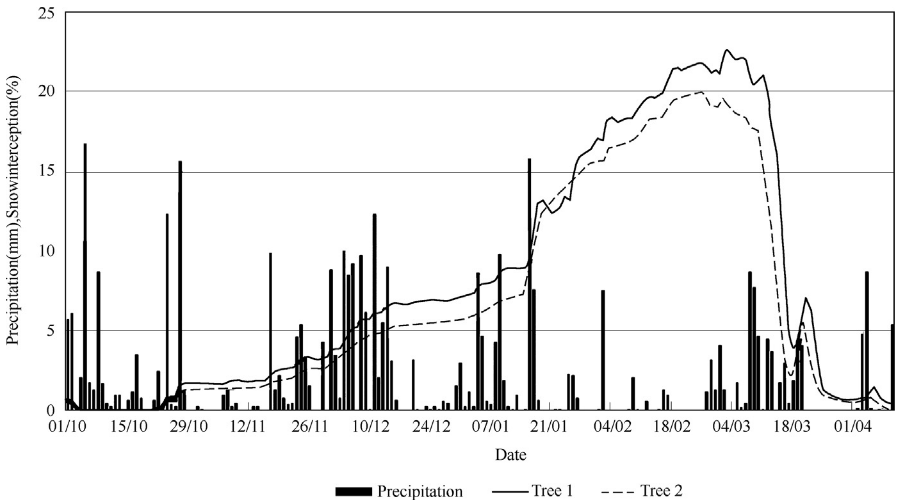

Fig. 3. Snow interception in the spruce forest (2007–2008).

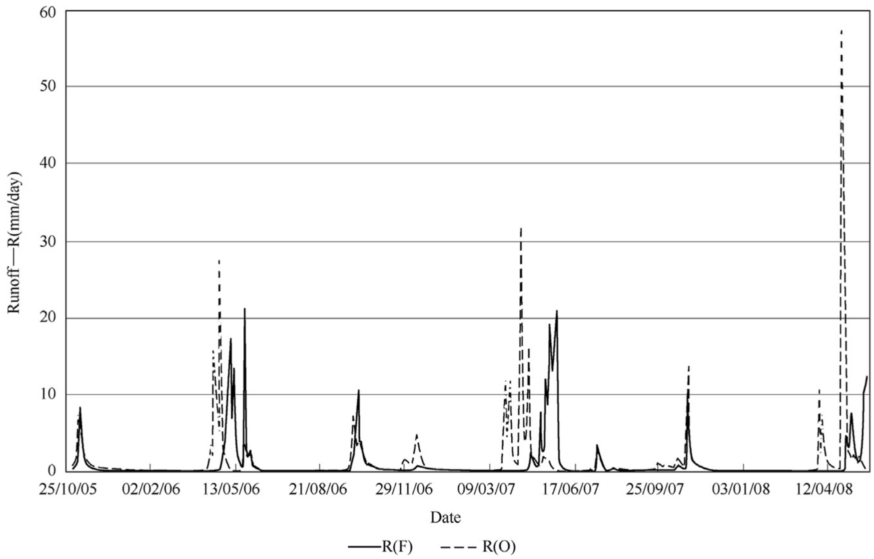

Fig. 4. Runoff at Paljakka simulated by BROOK 90: mature spruce forest (F) and open field (O).

Considering the snowmelt depletion at Paljakka (April–May), linear dependence between the mean daily air temperature T_d (°C) and the daily snow-melt M (mm) were found for the spruce forest (5) and the open grassland (6):

$$M = 2.75\,Td + 2.96 \tag{5}$$

$$M = 3.81\ Td + 6.21 \tag{6}$$

High correlations ($R^2=0.91$ and 0.92) thus confirm the air temperature as the dominant snowmelt factor in the boreal environment.

The snow–water equivalent, simulated for 2006–2008 (Fig. 4) by the hydrological model BROOK 90 (calibrated for the period 2000–2005) provided relatively good agreement with the observed data (correlation coefficient R^2 ranged from 0.91 to 0.99 and the Nash–Sutcliffe efficiency E from 0.82 to 0.88). For an average season, snow-melt runoff from the forest exceeded the grassland by 22% (225 against 185 mm). Considering extremes during the period of 16 years, maximum daily snow-melt runoff in the open (57 mm day^{-1}) was higher than in the spruce stand (57 mm).

4. Conclusions

The boreal spruce forest maintained a higher snowpack (in average by 21 cm, 26%) compared to the grassland. This can be explained mainly by higher aerodynamic roughness in the forest and the wind redistribution of snow in the open field. The maximum snow–water content observed in the forest exceeded that in the open by 32%. The snow–water intercepted in the canopy reached a maximum of 27% of the snow stored in the forest ground, and the loss of intercepted snow by sublimation was approximately 26% of the annual snowfall.

The role of the boreal spruce forest in the local water cycle is particularly important for supporting the seasonal water resources recharge (22%), and reducing the risk of spring floods ((22 mm day^{-1}). However, to control the flood risk by watershed planning, the design with a certain percentage of open areas (or forest openings) might still help to prolong the snowmelt period.

Snow characteristics observed in this study do not fully correspond with values reported by the Finnish national overview (Rasmus, 2005). These conclusions support the need for a more dense snow observation network in the Taiga snow-zone of Finland.

Acknowledgements

This research was supported by the Muhos Research Unit of the Finnish Forest Research Institute (Reijo Seppänen organized the field snow survey), the Oulu University (Pertti Vuolteenaho and Leo Koutaniemi developed the tree-weighting equipment), and by the Czech Technical University in Prague (SGS 14/128/OHK1/2T/11).

References

Brooks, K. H., Folliott, P. F., Gregersen, H. M., & DeBano, L. F. (2003). *Hydrology and the management of watersheds*. Ames, (Iowa, U.S.): Iowa State University Press.

Dewale, D. R., & Rango, A. (2008). *Principles of snow hydrology*. Cambridge (U.K.): Cambridge University Press.

Doesken, N. J., & Judein, A. (1997). *The snow booklet: A guide to the science,climatology, and measurement of snow in the United States*. Fort Collins (Colorado, U.S.): Colorado State University.

Federer, A. C. (2002). *BROOK 90: A simulation model for evapotranspiration, soil water and streamflow. Documentation to the version 4*. Durham (NH, U.S.): USDA Forest Service.

Hämet-Ahti, L. (1981). The boreal zone and its biotic subdivision. *Fennia*, *159*, 69–75.

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, *12*, 1611–1625.

IPCC (2013). Climate change 2013: The ohysical science basis. *The fifth assessment report of the Intergovernmental Panel on Climate Change*. World Meteorological Organization, Geneva.

Ishii, T., & Fukushima, Y. (1993). Effects of forest coverage on snowmelt runoff. *IAHS Publication*, *223*, 237–245.

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T., & Strandman, H. (2008). Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philosophical Transactions of the Royal Society B*, *363*, 2341–2351.

Kubin, E., & Křeček, J. (2009). Impact of fortestry practices on groundwater quality in the boreal environment. In: M. Taniguchi, & M. (Eds.), *From headwaters to the ocean* (pp. 91–96). London, UK: Tailor & Francis Group.

Martinec, J., Rango, A., & Roberts, R. (1998). *Snowmelt runoff model (SRM) user's manual*. Bern, (Switzerland): Geographica Bernensia, P-35, University of Bern.

Metsämäki, S., Anttila, S., Huttunen, M., & Vepsäläinen, J. (2005). A feasible method for fractional snow cover mapping in boreal zone based on a reflectance model. *Remote Sensing of Environment*, *95*, 77–95.

Parviainen, J., & Västilä, S. (2011). State of Finland's Forests 2011 – based on the criteria and indicators of sustainable forest management. *Publication of Ministry of Agriculture and Forestry*, *5A*, 95.

Pike, R., Redding, T. E., Moore, R. D., Winkler, R. D., & Bladon, K. T. (2010). *Compendium on forest hydrology and geomorphology in British Columbia*. *Land management handbook, 66*. BC, Canada: FORREX. 2 volumes.

Rasmus, S. (2005). Snow pack structure characteristics in Finland – measurements and modelling. *Report Series in Geophysics, 48*. University of Helsinki.

Storck, P., Kern, T., & Bolton, S. (1999). Measurement of differences in snow accumulation, melt, and micrometeorology due to forest harvesting. *Northwest Science*, *73*, 119–130.

Vajda, A., Venäläinen, A., Hänninen, P., & Sutinen, R. (2005). Effect of vegetation on snow cover at the northern timberline: a case study in Finnish Lapland. *Silva Fennica*, *40*, 195–207.

WMO (1994). *Guide to hydrological practices. Report 168*. Geneva: World Meteorological Organization.