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Snow accumulation on evergreen needle-leaved and deciduous broad-leaved trees

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We conducted laboratory experiments on the accumulation of snow on the canopies of small evergreen needle-leaved (*Picea glehnii*) and deciduous broad-leaved (*Betula ermanii*) trees using an artificial snowfall machine in a cold room. The maximum snow storage was 1.6 to 7.4 mm for *Picea glehnii* and 1.0 to 3.1 mm for leafless *Betula ermanii* under a constant snowfall rate of 1 mm h^{-1} (water equivalent). The maximum canopy snow storage and the fraction of direct through-fall were parameterized using the plant area index (PAI). We used these parameters in a canopy snow model and estimated the canopy snow storage of a coniferous evergreen needle-leafed forest using this model. The model reproduced the daily canopy snow storage within a relative error of 0.35. A sensitivity analysis using this model showed that the PAI was one of the most important parameters for the estimation of canopy snow storage. Further study is needed on mass release and melt of canopy snow.

Introduction

In northern Japan and northern Eurasia, most forested mountainous watersheds are covered by seasonal snow. Estimation of the amount of snow on the ground under the canopy is important for studies of the hydrologic cycle in the cryosphere.

During a thaw period, the amount of snow on the ground varies with snowmelt and sublimation. Snowmelt and sublimation beneath the forest canopy have been well understood and reported in the literature for North America and Europe, Siberia, and Japan (e.g., Hardy *et al*. 1997, Link and Marks 1997, Pomeroy and Granger 1997, Suzuki *et al*. 1999, Giesbrecht and Woo 2000, Woo and Giesbrecht 2000, Koivusalo and Kokkonen 2002, Suzuki and Ohta 2003, Suzuki *et al*. 2006). Most studies indicate that the timing of the thaw period is delayed when the density of the forest cover increases.

On the other hand, during the snow accumulation season, a portion of the snowfall is intercepted by the forest canopy and sublimates or melts. This demonstrates that snow interception is important when considering the effective amount of snow that falls onto the ground. Many studies of snow interception in forest canopies (e.g., Lundberg *et al*. 1998, Lundberg and Halldin 2001, Hedstrom and Pomeroy 1998, Nakai *et al*. 1999a, 1999b, Storck *et al*. 2002) report that snow interception is important for understanding the water and energy balance of snowy watersheds. The portion of snow interception by the forest canopy reported in previous studies has ranged from 5% of accumulated snowfall (Storck *et al*. 2002) to more than 30% (Lundberg *et al*. 1998). The snow held within the canopy sublimates or melts, which affects the water balance of the forested site by reducing the snow water equivalent beneath the forest canopy compared with that in an open field. The maximum snow load in the canopy is reported to be from 2.5 to 30 mm in Scotland (Lundberg *et al*. 1998), and 10 to 30 mm in Oregon, USA (Storck *et al*. 2002). Hedstrom and Pomeroy (1998) estimated that the maximum canopy snow loads for pine and spruce are 3.5 and 7 mm, respectively. However, the snow interception and maximum canopy snow load reported in previous studies as a function of tree species and structure are not well understood.

Lundberg and Halldin (2001) described the current problems facing the estimation of snow interception above the canopy. They reported that major problems exist in the estimation of the maximum snow water storage in the canopy and the aerodynamic roughness of snow-covered canopies with different leaf area indexes (LAI) and forest types. Previous studies of canopy snow were carried out under various field and canopy conditions. However, it is difficult to compare the amounts of canopy snow among different forest canopy and forest types. Koivusalo and Kokkonen (2002) developed a canopy snow model to evaluate the canopy snow storage and snowpack beneath the forest canopy. Their model requires the maximum canopy snow storage as a given parameter, and to apply the model to other forests it is necessary to parameterize the maximum canopy snow storage as a function of the canopy structure parameter.

Recently, Yamazaki *et al*. (2007) developed a sophisticated physically based land-surface model for the forest snowpack and simulated the state of canopy snow in a Siberian larch forest. In their model, the maximum canopy snow storage is parameterized as a function of leaf and plant area indexes. However, although their model reproduces the state of the snowpack in the forest well, the parameterization has not been yet verified by laboratory or field data.

Therefore, we used an artificial snowfall composed dendritic snowflakes in a large cold room to evaluate the parameters related to canopy snow storage. In the cold room, the amount of snowfall and the weight of the sample trees could be precisely measured under calm and stable conditions. Our experiment had two objectives: (1) to derive parameters for snow accumulation on evergreen-coniferous and deciduous broad-leaved canopies in relation to the plant area index; and (2) to estimate from laboratory experiments the seasonal canopy snow storage in natural coniferous forests by using these parameters.

Canopy snow model

Here, we introduce our data analysis method. For a forested site, the change in canopy snow storage is written as

$$\Delta I = W_{\mathrm{I}} - E_{\mathrm{I}} - D, \qquad (1)$$

where ΔI is the change in canopy snow storage (mm h^{-1}), W_{I} is the intercepted snow during a calculation time-step (mm h^{-1}), D is the mass release or melt drop of canopy snow from the canopy (mm h^{-1}), E_{I} is the snow interception evaporation (mm h^{-1}).

Aston (1979) examined the relationship between accumulated rainfall and canopy water storage by using eight small trees with artificial rainfall and developed a rainfall interception model. Later, Koivusalo and Kokkonen (2002) applied the Aston model to snowfall interception and expressed canopy snow storage as a function of accumulated snowfall as

$$I_{\mathrm{A}} = C_{\max}\left(1 - e^{-k_1 P_{\mathrm{cum}}/C_{\max}}\right), \qquad (2)$$

where I_A is the canopy snow storage (mm), C_{max} is the maximum canopy snow storage (mm), k_I is the model parameter (dimensioless), and P_{cum} the accumulated snowfall (mm). The Aston model was originally created for a single storm event. Aston (1979) noted that k_I is conceptually equivalent to $(1 - p)$, where p is the proportion of precipitation passing through the canopy projection area. Therefore, Eq. 2 can be rewritten as

$$I_A = C_{max}\left[1 - e^{-(1-p)P_{cum}/C_{max}}\right]. \quad (3)$$

Koivusalo and Kokkonen (2002) further applied the Aston model to multiple snowfall events under natural forest conditions as follows:

$$W_I = \left(C_{max} - I_0\right) - \left(C_{max} - I_0\right)e^{-(1-p)(1-f_s)P/C_{max}}, \quad (4)$$

where W_I is the intercepted water during a calculation time-step (mm h^{-1}), I_0 is the initial canopy snow storage at the start of calculation step (mm), f_s is the sky view factor, and P is the precipitation (mm h^{-1}). In our opinion, theoretically f_s should be the portion of snowfall through open areas where canopy does not exist, not the sky view factor. Next, because some of the canopy snow storage will be sublimated, the change in canopy snow storage during a calculation time step is described as follows:

$$\Delta I = W_I - E_I, \quad (5)$$

where E_I is the interception sublimation above the canopy during a time step (mm water equivalent). Here, we neglect the effect of mass release or melt drop of snow from the canopy. Thus, after a given time the canopy snow storage will be

$$I_A = I_0 - \Delta I. \quad (6)$$

To estimate E_I, we used the interception evaporation method of Koivusalo and Kokkonen (2002) based on Penman-Monteith equation (Monteith and Unsworth 1990):

$$E_I = \frac{\delta R_{nc} + \rho_a c_P\left(e_S - e_a\right)/r_a}{\lambda_V\left(\delta + \gamma\right)}, \quad (7)$$

where δ is the gradient of the saturated vapor pressure–temperature curve (hPa K^{-1}), R_{nc} the net radiation in the canopy (W m^{-2}), ρ_a is the air density (kg m^{-3}), c_P is the specific heat of air (J kg^{-1} K^{-1}), e_S is the saturation vapor pressure (hPa), e_a is the surrounding air vapor pressure (hPa), r_S is the aerodynamic resistance to vapor transport (s m^{-1}), λ_V is the latent heat of vaporization (J kg^{-1}), and γ is the psychrometric constant (hPa K^{-1}). In addition:

$$r_a = \frac{1}{\kappa^2 u_r}\ln\left(\frac{z_r - d}{z_0}\right)\ln\left(\frac{z_r - d}{h - d}\right) + \frac{h}{nK_h}\left[e^{n-n(z_0+d)/h} - 1\right], \quad (8)$$

$$K_h = \frac{u_r\kappa^2\left(h - d\right)}{\ln\left(\frac{z_r - d}{z_0}\right)}, \quad (9)$$

where κ is the von Karman constant (= 0.4), u_r the wind speed at the reference height z_r (m s^{-1}), d (= 0.63h) is the zero-plane displacement height (m), z_0 (= 0.13h) is the roughness length of the canopy (m), h the vegetation height (m), n an extinction coefficient (dimensionless), and K_h the logarithmic diffusion coefficient at the top of the canopy (m^2 s^{-1}). Lundberg *et al*. (1998) and Lundberg and Halldin (2001) noted that the aerodynamic resistance increases by as much as one order of magnitude when snow exists within the forest canopy. This is because the smooth surface of the canopy covered by snow reduces the surface roughness and increases aerodynamic resistance. When the air temperature was below 0 °C, we multiplied r_a by 15 in accordance with the method of Koivusalo and Kokkonen (2002).

Methodology

Snowfall experiment

Canopy snow experiments with constant rates of artificial snowfall were carried out on six Sakhalin spruces (*Picea glehnii*) as representative evergreen needle-leaved trees, whereas three leafless birch trees (*Betula ermanii*) served as representative deciduous broad-leaved trees. The height of all sample trees was less than 1.5 m and cut at the ground level. The total leaf, branch, and stem areas of each tree was determined by direct surface measurement (removal of the green leaves, branch and stem from sample trees and measuring the area of all the leaves, branch and stem within a delimited area after cutting the branch and stem into small pieces of about 4 cm long) after the experiments were completed. The canopy projection area was estimated by using the distances in eight directions at an interval of 45° from the stem to the end of the branches around a tree. Thus, the canopy projection area is defined as the area of the canopy projected to the horizontal surface beneath the canopy. Leaf and plant area indexes were calculated by dividing the total leaf or plant surface area by the canopy projection area. Details regrding the sample trees for each experiment are presented in Table 1. Cermak (1989) showed that the plant area index (PAI) for trees with leaves is determined by the leaf area index (LAI) plus the wood biomass index (WBI). The LAI ranged from 3.6 to 7.4 for *Picea glehnii* and the PAI (equalling wood biomass index, WBI) ranged from 0.76 to 1.91 for *Betula ermanii*. We also determined the WBI for two *Picea glehnii*, but they were too small to compare with the LAI because the branches of *Picea glehnii* were very narrow. Therefore, we assumed that the PAI for evergreen needle-leaved trees was equivalent to the LAI.

We conducted the laboratory experiments on snow accumulation in the canopies of small *Picea glehnii* and *Betula ermanii* in the Cryospheric Environment Simulator (CES) at the Shinjo branch of the Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention in Japan. The CES has a snowfall machine that makes snow with dendritic (branching) crystal shapes similar to those of natural snow under steady meteorological conditions. The snowflakes had a diameter of about 1 mm. During the experiments, the snowfall rate was usually constant at around 1 mm h^{-1} (water equivalent). Air temperature and relative humidity were mostly constant at –10 °C and 65%, respectively, during the snowfall periods. There was some wind created by an air conditioner in the laboratory, but its speed was less than 0.8 m s^{-1}. The density of the accumulated snow was 30 kg m^{-3}. We assumed that the loss of intercepted snow by sublimation was negligible because there was no radiation and the gradient of specific humidity between the canopy snow surface and the surrounding air temperature in the laboratory was less than 1.4 g m^{-3}. We could not reproduce moist snowfall because the snowfall machine could operate only when the air temperature was below –10 °C. However, it was possible to perform experiments on snowfall with wind, but the wind speed could not be controlled. Thus, we carried out the experiments with dry snowfall under calm conditions.

To measure the canopy snow load directly, the weight of canopy snow on a single suspended sample tree was measured by weighing the tree with load cells (Model LU-50KSB34D, Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan) (Fig. 1). The load cell was placed at the center of a 2-m wire at a height of 2 m and the

Table 1. Descriptions of sample trees used in the experiment.

Tree species	No.	Leaf area index (LAI)	Canopy height (cm)	Projected canopy area (cm^2)	Wood biomass index (WBI)	Plant area index (PAI)
Picea glehnii	1	6.6	86	5.739	0.053	6.6
	2	5.1	96	4.654	0.047	5.1
	3	7.4	NA	4.234	NA	7.4
	4	6.9	NA	540	NA	6.9
	5	3.6	NA	2.162	NA	3.6
	6	3.6	NA	713	NA	3.6
Betula ermanii	1	0.0	125	538	0.76	0.76
	2	0.0	51	52	1.02	1.02
	3	0.0	43	132	1.91	1.91

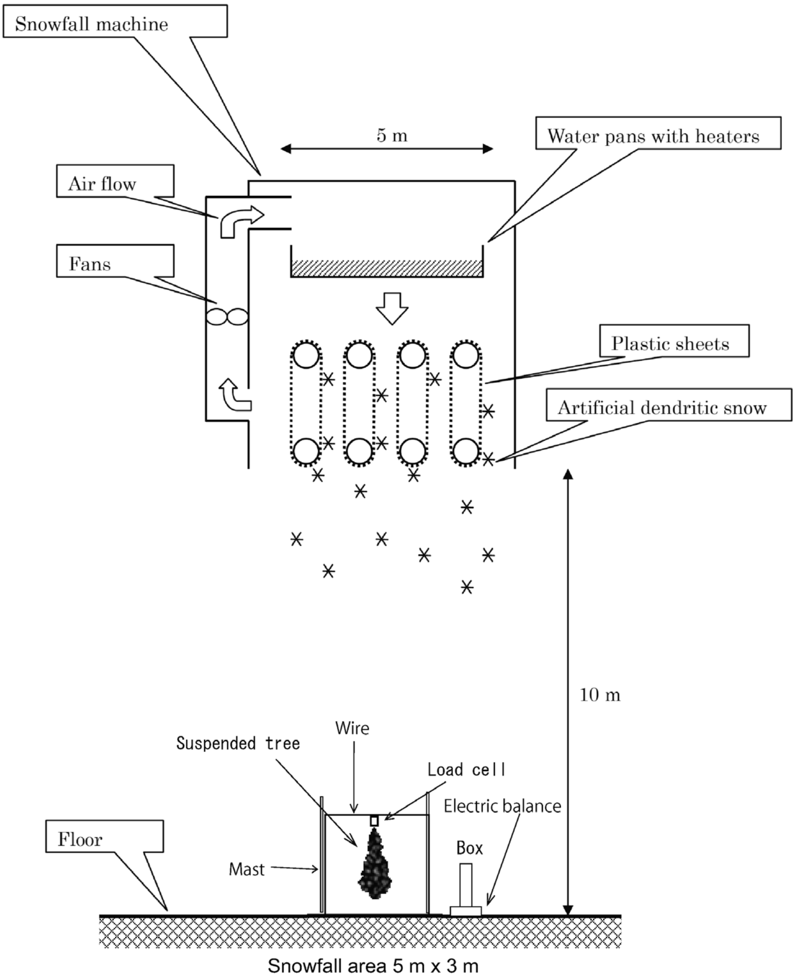

Fig. 1. Schematic diagram of the snowfall experiment. The entire apparatus is installed in a large cold room.

wire was strung horizontally between 2.5-m-tall masts. The diameter of the wire was about 1 mm, so we assumed that snow interception by the wire was negligible. The load cell was then connected to the tree by a 1-m steel wire. Each load cell was connected to a strain amplifier (Model DPM-613A, Kyowa Electronic Instruments Co. Ltd.) and the data were collected by a data logger (Model HP 34970A, Hewlett-Packard Company, USA) at 1-s intervals. The whole apparatus was installed in a large cold room. Each load cell was calibrated at nearly every 0.5-kg step by the suspension of known weights from 0 to 6 kg in the laboratory before the snowfall began. From these calibrations, we determined that all load cells had good linearity, with a high coefficient of determination ($r^2 > 0.95$) and the mean error of each load cell was about 6 g. Thus, the minimum resolution of the load cells was about 6 g. We also continuously measured the rate of snowfall using an electric balance (Model PG6002-S, Mettler Toledo, Ohio, USA; minimum resolution: 0.01 g) with a box (with an area of 0.2 × 0.2 m^2 and height of 1 m) to catch the snowfall at ground level. The electric balance data were collected on a personal computer. We confirmed that snowfall was for the most part constant at around 1 mm h^{-1} during all the experiments.

Field experiment

To validate the parameters of the canopy snow model in the field condition, we used the data obtained in the field experiment. The study site was located in a mixed evergreen coniferous plantation in the Hitsujigaoka Experimental Forest at the Hokkaido Research Center, Forestry and Forest Products Research Institute (42°59´N, 141°23´E; area 46 000 m^2; elevation 182 m a.s.l.). The forcing meteorological elements of air temperature, relative humidity, wind speed, and net all-wavelength radiation were observed at a height 9.5 to 12.0 m above the ground at the forest site, and precipitation was observed in the open field. The observation site was mostly flat, with a minimum fetch of about 100 m across a similarly forested landscape. The forest consisted of an almost pure stand of Sakhalin fir (*Abies sachalinensis*), with minor amounts of Jezo spruce (*Picea jezoensis*) and Sakhalin spruce (*P. glehnii*). At the time of the study the trees were 23 years old, with an average height of 6.4 m, a mean trunk diameter at breast height of 0.09 m, and a stand density of 2400 stems ha^{-1}. The winter PAI, including branches, was estimated to be about 6.0 m^2 m^{-2} from surface area measurements of three representative felled *A. sachalinensis*.

From a 12-m-high meteorological tower installed in the middle of the study forest, meteorological data were collected above, within, and below the forest canopy. Eddy covariance flux was measured at 9.48 and 9.65 m above the ground, and the raw data were recorded by a TEAC DrM2a datalogger (Tokyo, Japan) 10 times per second. The sensible heat flux was measured using the eddy covariance technique, whereas the latent heat flux was evaluated by the bandpass eddy covariance method (Horst and Oncley 1995). Temporal fluctuations in air temperature and relative humidity were measured with a ventilated slow-response hygrothermometer because the open-path gas analyzer used for the eddy covariance method could not be used to measure fluctuations in specific humidity under the almost continuously snowfall that occurred during a winter from 1997 to1998.

To directly measure the canopy snow load, the weight of canopy snow on a single, suspended Sakhalin fir was measured by weighing the tree with a Kyowa LT-500KF load cell (resolution, 0.7 kg; Tokyo, Japan). The suspended tree was 5.07 m tall with the PAI of 12.7 m^2 m^{-2}, measured by the direct method, and had a crown projection area of 2.54 m^2. The mean branch angle of the cut tree was 17.2°. From the forest stem density of 0.24 m^{-2} in this stand, the PAI for the study area was calculated as 7.7 m^2 m^{-2} (12.7 m^2 m^{-2} $stem^{-1}$ × 0.24 stem m^{-2} × 2.54 m^2), using the information obtained from the suspended tree. This value is larger than the estimated value of 6.0 m^2 m^{-2} (this value was estimated by measuring 3 representative trees) for the PAI of the coniferous forest in the present study. Thus, the suspended tree was relatively large in relation to the surrounding trees.

We assumed that changes in the tree's weight were caused primarily by the addition or loss of snow. We obtained the weight of canopy snow W_S (kg) as follows:

$$W_S = W_{LC} - W_T, \tag{10}$$

where W_{LC} is the weight of the tree plus all intercepted snow (kg) and W_T is the weight of the tree without the snow (kg). The canopy snow water equivalent per unit of crown projection area I_{AT} (mm water equivalent) was evaluated as follows:

$$I_{AT} = \frac{1000 W_S}{\rho_W A_{CROWN}}, \tag{11}$$

where A_{CROWN} is the crown projection area (2.54 m^2) and ρ_W is the density of water (kg m^{-3}). Given the 0.7-kg resolution of the load cell, the resolution of I_{AT} was about 0.276 mm water equivalent.

To evaluate the representative snow storage by the forest canopy for the stand in our study area, we assumed that the canopy snow storage was correlated with the PAI. Thus, the mean canopy snow water equivalent for the forest stand I_A (mm water equivalent) was determined as follows:

$$I_A = \frac{I_{AT} \times PAI_{CF}}{PAI_C}, \tag{12}$$

where I_A is the canopy-snow water equivalent of the suspended tree (mm water equivalent), PAI_{CF} is the total PAI of this coniferous forest (m^2 m^{-2}), and PAI_C is the PAI of the cut tree (m^2 m^{-2}).

Here, we assumed that the proportion of snowfall through open area f_s was 0.53 (1 minus the aerial mean PAI of 6.0 divided by the single tree PAI of 12.7). The original work by Koivusalo and Kokkonen (2002) used the sky-view factor instead of the proportion of snowfall through open area, but it is our opinion that f_s is not directly equivalent to the sky-view factor and that there is uncertainty in both approaches. Russell *et al*. (1989) showed that spruce canopy has a highly grouped structure and that such structure can allow a larger transmission of radiation through canopy compared to a canopy structure with a uniform distribution of leaves. Here, we consider that the value of 0.53 obtained for the proportion of snowfall through open area was a result of the highly grouped canopy structure.

We define the sky-view factor (SVF, dimensionless) to be the ratio of the diffused shortwave radiation between the forest floor and the open site (I_F/I_O). Monsi and Saeki (2005) note that the radiation profile within a canopy can be approximated by an exponential relationship. Therefore the sky view factor can be written as

$$\mathrm{SVF} = I_F / I_O = e^{-K \times \mathrm{LAI}}, \quad (13)$$

where K is the extinction coefficient (dimensionless). Baldocchi *et al*. (1984) reported that K was 0.115 for fully-leafed oak–hickory forest. If we use Eq. 13 and $K = 0.115$, we obtain an SVF of 0.5 for the study site. This value is close to the estimated proportion of snowfall through open areas in the present study.

Precipitation was measured with a Japanese standard precipitation gauge (RT-4) at the National Agricultural Research Center for the Hokkaido Region, about 500 m from the Hitsujigaoka Experimental Forest. Recently, Yokoyama *et al*. (2003) evaluated the underestimation of winter precipitation measured with an RT-4 gauge caused by the effect of wind and derived the following equation for correcting the precipitation during winter:

$$P = \frac{P_{\mathrm{RT\text{-}4}}}{\left(\dfrac{1}{1+mU}\right)}, \quad (14)$$

where P is the corrected winter precipitation (mm water equivalent), $P_{\mathrm{RT\text{-}4}}$ the precipitation measured using the RT-4 precipitation gauge (mm water equivalent), m a gauge parameter (s m^{-1}) (0.128 for snow and 0.0192 for rain), and U the wind speed (m s^{-1}) at the height of the precipitation gauge. We used corrected precipitation data in our analysis. Precipitation was partitioned between snow and rain following the approach of Kondo (1994). The snowfall rate (P_{snow}) was estimated as follows:

$$\left.\begin{aligned} P_{\mathrm{snow}} &= P \quad \left(T_a \le 7.7 - 0.066\mathrm{rh}\right) \\ P_{\mathrm{rain}} &= P \quad \left(T_a > 7.7 - 0.066\mathrm{rh}\right) \end{aligned}\right\}, \quad (15)$$

where T_a is the air temperature (°C), rh is the relative humidity (ratio), and P_{rain} is the rate of rainfall (mm h^{-1}).

Verification

To evaluate the accuracy of canopy snow model, we used two indexes of accuracy: the Absolute and Relative Errors defined as:

$$\text{Absolute Error} = \frac{\sum |Q_E - Q_O|}{n}, \quad (16)$$

$$\text{Relative Error} = \frac{\sum |Q_E - Q_O|}{n\overline{Q_O}}, \quad (17)$$

where Q_F and Q_O are the estimated and observed values respectively, n is the total number of observed values, and $\overline{Q_O}$ is the mean observed value.

Results

Parameters for the canopy snow storage model

The canopy snow storage generally increased as accumulated snowfall increased (Fig. 2). Initially canopy snow depth increased linearly as accumulated snowfall increased (red line in Fig. 2). Mass release of canopy snow then occurred and the storage depth decreased to its minimum value. After this point, canopy snow storage increased again at the same initial rate. The maximum canopy snow storage increased as accumulated snowfall increased. One cause of the systematic drop in canopy snow storage was the air-conditioner fan in the laboratory. The *P. gleh-*

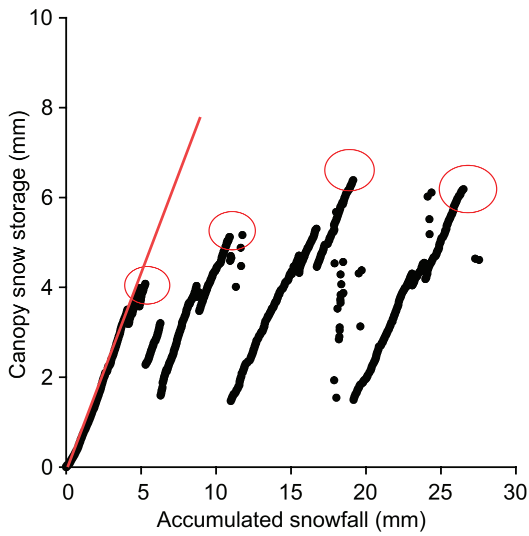

Fig. 2. Example of experimental data relating canopy snow storage and accumulated snowfall for *Picea glehnii* no. 1. Red line indicates the initial rate of increase in canopy snow storage. Red circles identify the data we used for analysis.

nii tree was shaped like a triangular pyramid and the canopy snow dropped when the light wind from the fan caused the suspended tree to swing. Therefore, we used the continuous set of canopy snow data before the first large mass release occurred and also the maximum canopy snow values before the large mass releases occurred again (red circles in Fig. 2).

Relations between canopy snow storage and accumulated snowfall for *P. glehnii* are presented in Fig. 3 (for the model parameters *see* Table 2). The regression coefficients (r^2 calculated with the least-square method) were greater than 0.9, indicating that the data fit the model well. Hedstrom and Pomeroy (1998) estimated the maximum canopy snow load for pine as 3.5 mm and for spruce as 7 mm. Our results (Table 2) for *Picea glehnii* are similar to their values.

The relationship between canopy snow storage and accumulated snowfall for *B. ermanii* nos. 1–3 is presented in Fig. 4. The results for *B. ermanii* no. 2 (Fig. 4b) exhibit a low coefficient of determination (0.36), thus some discrepancy may have existed. One reason was the resolution of the load cell, the minimum of which, as previously noted, was about 6 g. The canopy projection area of *B. ermanii* no. 2 was about 52 cm^2; thus the canopy snow storage resolution for this tree was about 1 mm. Most of the canopy snow storage results for *B. ermanii* no. 2 were less than the resolution of the load cell. The data for *B. ermanii* nos. 1 and 3, however, were well fitted by Eq. 3, with high coefficients of determination (more than 0.8). The model parameters obtained for *B. ermanii* are listed in Table 2.

Lundberg and Halldin (2001) showed that canopy snow parameters are related to forest canopy factors such as the sky view factor and the LAI. We tested the relationship between the model parameters derived from the experiments and the PAI. Using the values for maximum canopy snow storage (C_{max}) and the model parameter k_I from Table 2, we determined the relationships between C_{max} (Fig. 5a) and k_I (Fig. 5b) for both *P. glehnii* and *B. ermanii* and the PAI, because the difference between these relationships for the two species was not large. When k_I was greater than 1, k_I was set to 1. k_I did not reach 0 as the PAI decreased because, we assume, the PAI of the tree increased as snow-covered branches caught additional snow flakes.

Table 2. Estimated parameters for the canopy snow model for *Picea glehnii* and *Betula ermanii*.

Tree species	No.	Leaf area index	Plant area index	C_{max} (mm)	k_I
Picea glehnii	1	6.6	6.6	7.4	0.99
	2	5.1	5.1	4.9	0.44
	3	7.4	7.4	4.5	0.49
	4	6.9	6.9	7.4	1.10
	5	3.6	3.6	1.6	0.28
	6	3.6	3.6	4.2	0.45
Betula ermanii	1	0.0	0.76	1.0	0.41
	2	0.0	1.02	1.2	0.51
	3	0.0	1.91	3.1	0.38

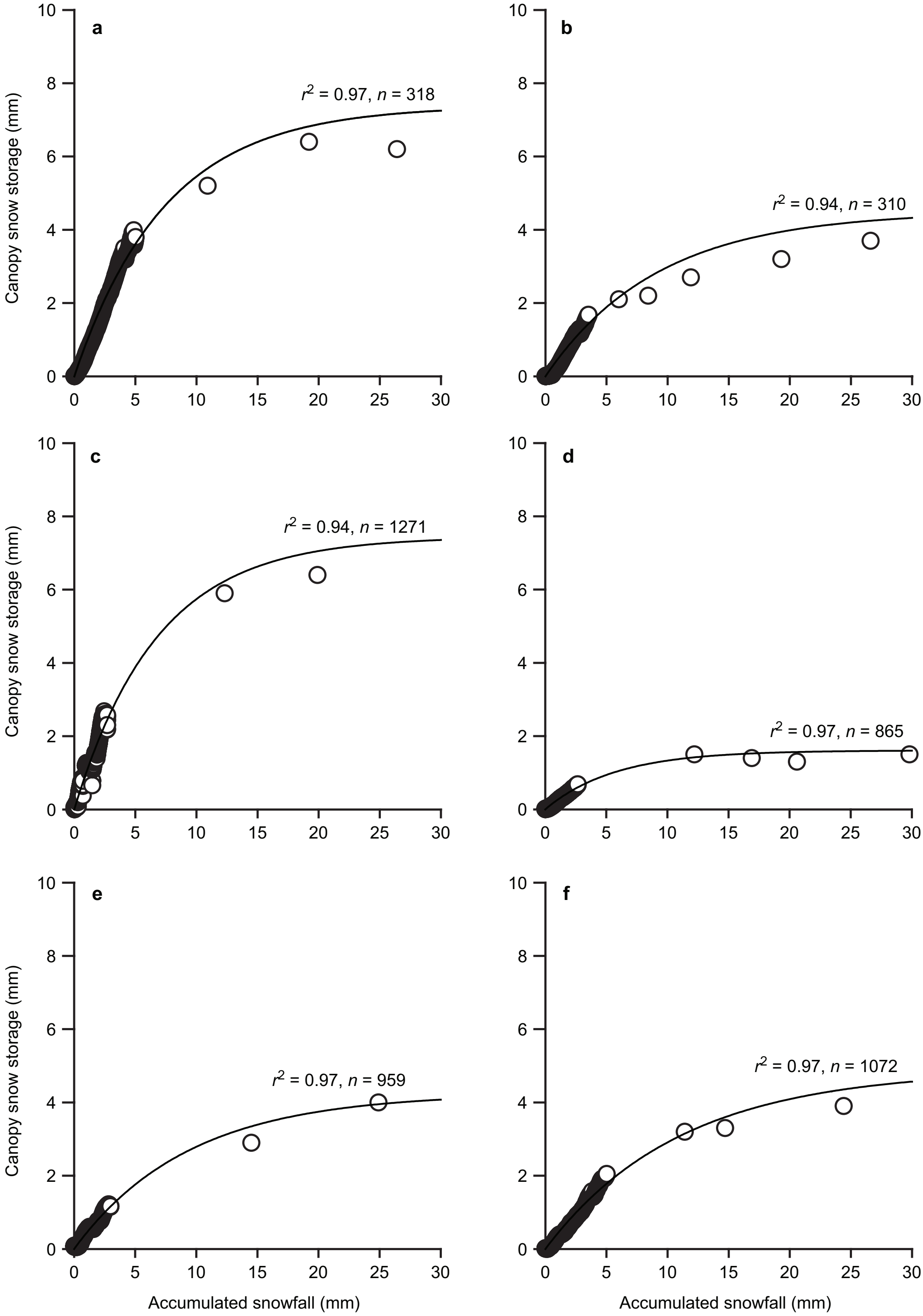

Fig. 3. Relatiion between canopy snow storage and accumulated snowfall for *Picea glehnii*: (**a**) no. 1, (**b**) no. 2, (**c**) no. 3, (**d**) no. 4, (**e**) no. 5, and (**f**) no. 6. Solid lines indicate the fit with Eq. 3, r^2 is the determination coefficient of the fitted curves.

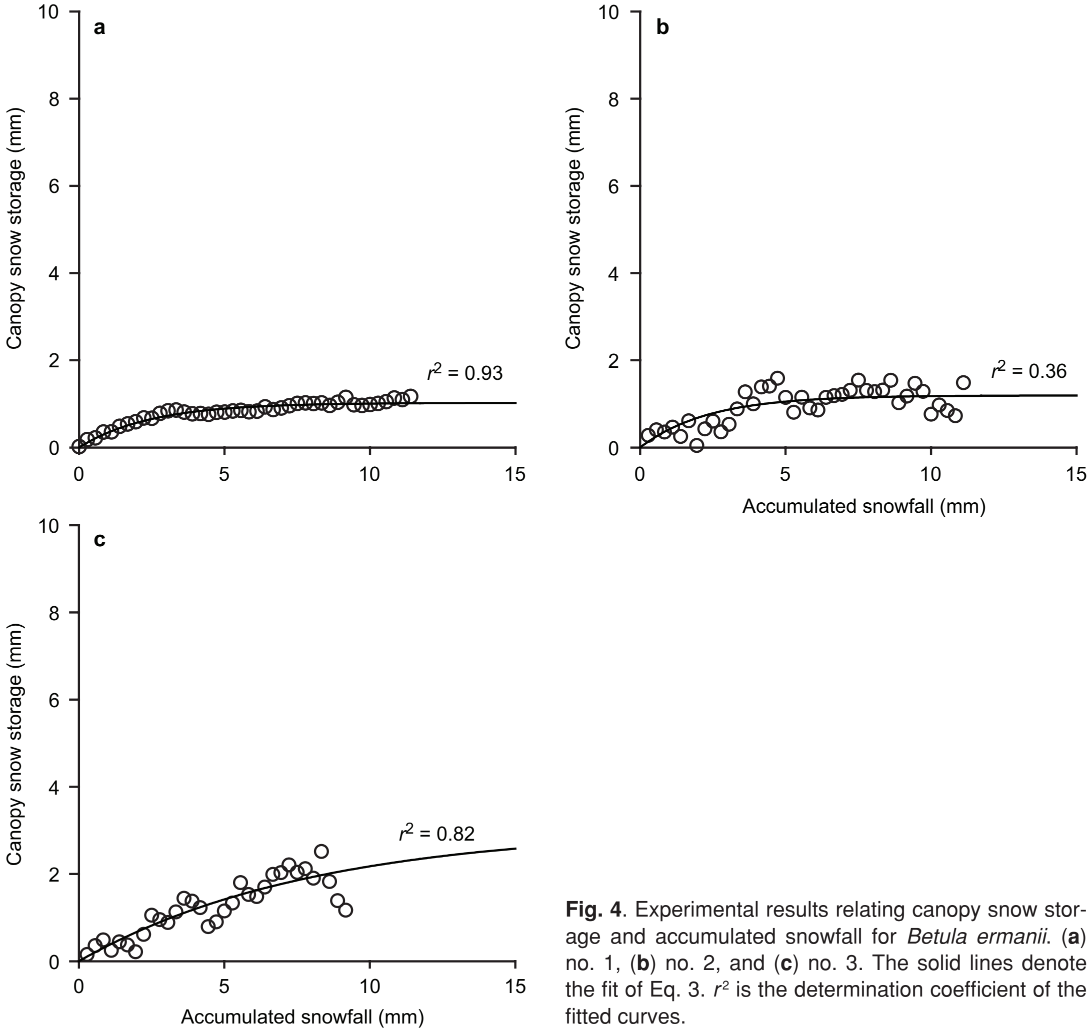

Fig. 4. Experimental results relating canopy snow storage and accumulated snowfall for *Betula ermanii*. (**a**) no. 1, (**b**) no. 2, and (**c**) no. 3. The solid lines denote the fit of Eq. 3. r^2 is the determination coefficient of the fitted curves.

Therefore, the canopy model parameters C_{max} and k_I introduced earlier are related to the PAI as follows:

$$C_{max} = 0.92\text{PAI}, \quad (18)$$

and

$$k_I \cong 1 - p = 0.30 + 0.06e^{0.30\text{PAI}}. \quad (19)$$

The relationships have good coefficients of determination (0.72 for Eq. 18 and 0.41 for Eq. 19); thus, we believe that the above parameterizations are useful for estimating canopy snow storage and that they can be applied to other tree species because the difference between the relationships for the above two tree species was not large. Following the above relationship, we obtained a maximum snow load per unit PAI of 0.92 mm. Jansson and Karlberg (2004) reported that the maximum snow load in the Swedish forest canopy was 1 mm per unit LAI. On the other hand, Mellander *et al*. (2005) reported that the maximum snow load in the Scots pine canopy was 3 mm per unit LAI. Our obtained value of 0.92 mm per unit PAI is smaller than the values by the previous studies.

Application of the parameters to canopy snow storage by evergreen needle-leaved trees in northern Japan

Next, we determined the usefulness of the param-

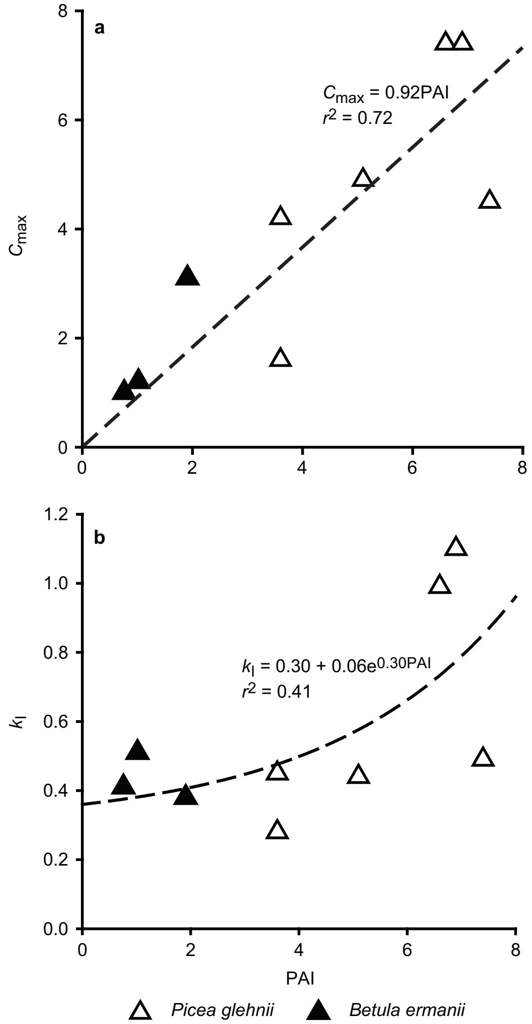

Fig. 5. Relationships between the parameters (**a**) C_{max} and (**b**) k_l and the PAI. Open and closed triangles denote *Picea glehnii* and *Betula ermani*, respectively. Dashed lines are regression lines.

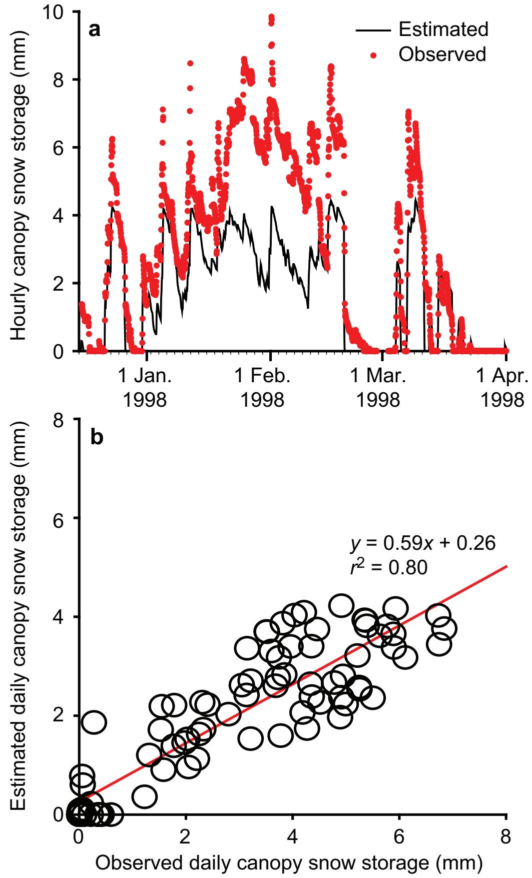

Fig. 6. (**a**) Temporal variations in observed and estimated hourly canopy snow storage. Red dots and solid lines indicate observed and estimated amounts, respectively, of snow loaded onto the canopy. (**b**) Comparison of estimated and observed daily canopy snow storage. Red solid line indicate linear regression.

eters for estimating canopy snow storage under natural conditions in a temperate forest in Japan. The canopy snow model was applied to a field experiment using the forcing parameters.

The simulated canopy snow storage reproduced the timing of maximum canopy snow storage and the duration of canopy snow storage well (Fig. 6a). However, the maximum canopy snow storage was significantly underestimated by the simulation as compared with the observed values. We consider that the parameterization of canopy snow storage was not accurate for multiple snowfall events. We assumed that the maximum canopy snow storage increased as the multiple snowfall events occurred. Thus, we need to do more research on the effect of multiple snowfall events on canopy snow storage. The observed canopy snow storage decreased rapidly when the maximum canopy snow storage was reached, whereas the simulated canopy snow storage decreased gradually due to sublimation loss. This difference could have been caused by mass releases or melt drop of snow from the canopy because we did not take this into account in the canopy snow model. The estimated snow interception evaporation by the canopy was about 16% of the snowfall when continuous canopy snow was present from 1 January to 19 February 1998. Sublimation given by the model was 28 mm for the same period, but sublimation from the flux measurement was 20 mm, i.e. smaller than the present model estimate. We assume that this difference was caused by the aerodynamic roughness parameter because the aerodynamic resistance was set to be constant when the canopy was covered by snow, but the roughness parameter should vary as a function of the amount of canopy snow. Future study should focus on the relationship between the roughness parameter of the canopy and the amount of canopy snow.

The estimated amount of daily snow loaded onto the canopy was underestimated by about 40% as a result of the variations in the observed canopy snow (Fig. 6b). The coefficient of determination (r^2) and absolute error were about 0.8 and 1 mm, respectively, and the relative error was 0.35. Therefore, our study parameters are useful for evaluating the existence of canopy snow under field conditions, and we conclude that the canopy model was useful for the evaluation of the state of canopy snow storage during the observation period. The parameters derived from this study can be further improved to evaluate the amount of snow in the canopy at natural forested sites.

We also examined the sensitivity of the mean canopy snow storage to perturbations in the parameter values of the model (Table 3). The percentage change in the model output (mean canopy snow storage) was evaluated after a ±10% change in each model parameter. The estimated canopy snow storage was most sensitive to changes in the PAI, and the change in maximum canopy snow storage directly corresponded to the change in mean canopy snow storage. Most of the parameters were similarly affected by changes in canopy snow storage.

Table 3. Sensitivity of the mean canopy snow storage to perturbations in the parameter values of the model. The computation period is from 1 January to 28 February 1998, when the reference value of the mean snow storage (no perturbations) was 2.41 mm.

Parameter	Change in parameter (%)	Change of mean canopy snow storage (%)
PAI	+10	+18.7
	–10	–17.0
f_s		
	+10	–9.9
	–10	+8.3
r_a		
	+10	+7.5
	–10	–8.7
p		
	+10	–4.1
	–10	+4.1
C_{max}		
	+10	+10
	–10	–10

Discussion

Effect of tree structure on canopy snow

Canopy snow stored on *B. ermanii* did not drop to the ground as frequently as it did in the case of *P. glehnii* because the *B. ermanii* canopy held snow more strongly around the stems and branches. Therefore, when considering mass releases of canopy snow, we must take into account the stability of the canopy snow and the tree structure. Pomeroy and Gray (1995) explained that as the interception approaches its maximum for a specific set of conditions of snow cohesiveness and the horizontal area of branches and intercepted snow, the sharp vertical angles of the snow surface promote crystal rebound and erosion rather than continued accumulation. Mass releases of canopy snow by *P. glehnii* could be caused by the bending of branches, which are not as stiff as those of *B. ermanii*. We presume that the stiffer branches of *B. ermanii* produce a stronger snow structure than those of *P. glehnii*.

The initial rate of increase in canopy snow storage on *B. ermanii* (Fig. 4) was smaller than that on *P. glehnii* (Fig. 3). This implies that the k_I parameter and the proportion of precipitation passing through the canopy of *B. ermanii* were larger than for *P. glehnii*, because *P. glehnii* had a large number of leaves whereas *B. ermanii* was free of leaves. The leaves of *P. glehnii* reduced the portion of through-fall precipitation.

Limitations of the canopy snow model

The model parameters may have certain limitations when applied to other forests. First, we used directly measured values of the PAI whereas most previous studies of snow interception by canopy have used the effective LAI (LAI´) (e.g., Pomeroy *et al*. 2002) measured using devices such as the Li-Cor LAI-2000 leaf-area meter. The relation between the real LAI and the effective LAI (LAI´) can be written as

$$LAI' = \Omega \times LAI, \quad (20)$$

where Ω is the stand clumping index. Smith *et al*. (1993) noted that neglect of clumping can cause underestimation of the LAI for coniferous trees. Therefore, a user of the present canopy snow model must use the real PAI instead of the effective PAI (PAI´).

Second, we did not include mass releases from the canopy due to factors such as bending branches, strong winds, or canopy snow melt. Our experimental results indicate that the role of snow release from the canopy is important (*see* Fig. 2). Thus, it is necessary to include this process in future research.

In addition, we measured canopy snow storage for only two typical boreal forest types: evergreen needle-leaved and deciduous broad-leaved trees. It is essential to confirm the relationships between canopy snow storage and accumulated snowfall for other tree types, for example, deciduous conifers. Further study should confirm the applicability of the model parameters to canopy snow storage as a function of the PAI in other tree species or natural mixed forests.

In this study, we assumed that the aerodynamic resistance was constant during a period when the canopy was covered by snow, but the interception by the model was overestimated. Thus, future studies should focus on parameterization of the aerodynamic resistance with canopy snow conditions.

Conclusions

Laboratory experiments to determine parameterizations of snow accumulation on the canopy were carried out by using artificial snowfall in the Cryospheric Environment Simulator. We used the experimental results to determine model parameters by the method of Koivusalo and Kokkonen (2002) as functions of the PAI for evergreen needle-leaved and deciduous broad-leaved trees. We then developed a canopy snow model and obtained the following results:

1. The maximum canopy snow storage in *P. glehnii* was 1.6 to 7.4 mm, and that in leafless *B. ermanii* was 1.0 to 3.1 mm. The maximum canopy snow storage in evergreen needle-leaved trees was larger than in deciduous broad-leaved trees.
2. The maximum snow storage above a canopy C_{max} and the portion of snowfall (p) passing through the canopy projection area were correlated with the PAI. We parameterized C_{max} and p as functions of the PAI.
3. The canopy snow model reproduced the seasonal variation in canopy snow storage and daily canopy snow storage with a relative error of 0.35 in accordance with the parameterizations of C_{max} and p.
4. The sensitivity analysis of the mean canopy snow storage as a function of perturbations in the parameter values of the model identified PAI as one of the most important parameters in the canopy snow model. Changes in the maximum canopy snow storage directly corresponded to changes in the mean canopy snow storage during the study period.
5. Finally, it was important to evaluate the release of snow from the canopy when we evaluated the time series of canopy snow storage. Our future studies will focus on the effects of snow unloading from the canopy and the bending of branches on the canopy snow model.

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