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Seasonal variation in boreal pine forest albedo and effects of canopy snow on forest reflectance

Nea Kuusinen*, Pasi Kolari, Janne Levula, Albert Porcar-Castell, Pauline Stenberg, Frank Berninger

Department of Forest Sciences, P.O. Box 27, 00014 University of Helsinki, Finland

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ABSTRACT

The low shortwave albedo of evergreen coniferous forests increases net radiation and thus the local temperature as compared to open areas. The difference between albedos of evergreen forests and open areas is most pronounced in winter and spring, when the forest canopies mask the reflective ground snow. However, also the albedo of coniferous evergreen forests changes as a function of the amount and optical properties of snow in the ground and canopy. In this study, we examined the shortwave radiation balance of a boreal Scots pine dominated forest. Canopy snow cover was observed to substantially influence the albedo, increasing it by about 0.2 as compared to snow free conditions. However, albedo varied greatly between and within the canopy snow classes, probably due to differences in illumination conditions and snow amount and properties. During midwinter months, most of the incident solar radiation was reflected during days with a lot of snow in the canopy. The difference in reflected radiation between the winters with least and most snow was 54 MJ m^{-2}, which was also close to the difference (55 MJ m^{-2}) between the reflectance of an average winter and that of a simulated snow free winter, corresponding to less than 2% of the annual solar irradiance. The albedo of the forest was greatest in midwinter, when the cold weather and low solar radiation caused the falling snow to remain on the tree branches. As the incident solar radiation in these months is very low, we concluded that the positive feedback to climate warming in case of a potentially decreased snow cover in this boreal pine forest would remain small.

1. Introduction

Boreal coniferous forests cover a wide land area in the northern hemisphere, about 12 million km^2. Hence, energy exchange of these forests has an important effect on climate at local, regional and even at global scales. The boreal evergreen forests are characterized by a relatively low shortwave albedo all year round (e.g. Betts and Ball, 1997), which increases the net radiation compared to open land areas. Due to their northern location, energy fluxes of boreal forests have a high seasonal variability. Most of the solar radiation is received during summer, when the coniferous forest albedo is low as nearly 90% of the incident solar radiation is absorbed. In wintertime, the albedo is more variable due to changing snow cover (Moody et al., 2007), but the incoming solar radiation is low and therefore also the total amounts of absorbed and reflected radiation remain small.

There has recently been discussion about the influence of land use changes on climate through changes in carbon sequestration and albedo (e.g. Betts, 2000; Bounoua et al., 2002; Chapin et al., 2005; Bala et al., 2007). Deforestation reduces the carbon storage in vegetation and soil as well as the evaporative cooling. On the other hand it usually increases the albedo and thus decreases the net radiation. Because of these changes deforestation in high latitudes may have a net cooling effect, especially in areas with a long lasting winter snow cover that would otherwise be shaded by forest (Otterman et al., 1984; Thomas and Rowntree, 1992; Bonan et al., 1992, 1995; Betts, 2000; Bala et al., 2007). Bonan et al. (1992, 1995) simulated a 50–65 W m^{-2} decrease in net radiation in April at 50°N when forest was replaced by tundra or bare ground. A similar decrease of 50 W m^{-2} in net radiation was found by Betts and Ball (1997) when they compared albedos over grassland and forest sites in Canada (52–57°N) in March. Thomas and Rowntree (1992) simulated a net radiation decrease of 36 W m^{-2} in March and 41 W m^{-2} in April when forest was removed in the northern hemisphere. Both Bonan et al. (1995) and Thomas and Rowntree (1992) found a subsequent decrease in latent heat flux and atmospheric moisture as the forest was removed. The cooling effect of boreal deforestation is claimed to reach far south of the areas of deforestation (Bonan et al., 1995; Bala et al., 2007). Ni and Woodcock (2000) demonstrated that the absolute amount of reflected solar radiation from coniferous forests with snow on the ground can be equal or even greater to the amount

* Corresponding author. Tel.: +358 9 191 58144; fax: +358 9 191 58100.
E-mail address: nea.j.kuusinen@helsinki.fi (N. Kuusinen).

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reflected in summer. The increased albedo may thus be offsetting the higher levels of irradiance in summer.

As snow cover has a large impact on the wintertime radiation balance, it is important to understand the dynamics of its reflectance properties. Many factors are known to alter the reflectivity of snow. The albedo of snow is reduced by increasing water content and grain size (Wiscombe and Warren, 1980; Robock, 1980; Peltoniemi et al., 2005). New dry snow has thus on average higher reflectance than old or wet snow. Also, foliage litter and impurities such as black carbon on snow as well as a decreasing snow depth decrease the snow albedo (Wiscombe and Warren, 1980). The melting of snow decreases the snow albedo, as when snow melts, liquid water replaces air between the grains, and the effective grain size increases, and even if refrozen the snow albedo does not increase (Wiscombe and Warren, 1980). These snow albedo effects are important in climate models (e.g. Qu and Hall, 2007; Jin and Miller, 2011), but are often a source of bias and uncertainty (Munneke et al., 2011).

Qu and Hall (2007) state that the snow albedo feedback (i.e. the warming influence caused by decreased snow cover as the climate warms) varies in climate simulations with different treatment of the vegetation canopy. The models with a simple surface albedo parameterization (no explicit treatment of vegetation canopy) produced, on average, a too high albedo and therefore a strong snow albedo feedback whereas models with an explicit treatment of the vegetation canopy (i.e. canopy albedo either depends on the vegetation type in the model or the model employs a canopy radiative transfer model) tended to underestimate the reflected radiation. The authors discussed that the latter models might underestimate the canopy or snow albedo or overestimate the extent to which the vegetation masks the ground snow.

In this study, we focus on the factors determining the shortwave radiant energy balance of a boreal Scots pine dominated forest. We examine the factors affecting shortwave albedo, such as snow and surface wetness and suggest what effect the potential changes in snow cover might have on the energy balance. Because long term studies on the canopy snow cover and its influence on forest albedo are sparse, we give special attention to the winter albedo and radiation fluxes.

2. Materials and methods

2.1. Site description

The study was conducted using the measurements of the SMEAR II measuring station of the University of Helsinki, located in southern Finland, 61°51′N and 24°17′E. The forest site surrounding the measuring mast is dominated by Scots pine (*Pinus sylvestris* L.), sown in 1962. The understorey is mainly composed of dwarf shrubs lingonberry (*Vaccinium vitis-idaea* L.) and blueberry (*Vaccinium myrtillus* L.), and mosses (*Pleurozium* sp., *Dicranum* sp.). In 2010, the basal area of pine on a 200 m radius around the measuring mast was 17.85 m^2/ha, that of spruce (*Picea abies* (L.) Karsten) 3.7 m^2/ha and of deciduous trees 2.74 m^2/ha. The arithmetic mean diameter at breast height (dbh) and tree height were 17.6 cm and 16.5 m for pine, and those of spruce and deciduous trees were 5.6 cm and 5.4 m and 3.9 cm and 7.4 m, respectively. There was however both spruces and deciduous trees reaching the canopy top. The average effective leaf area index (LAI) was determined in July 2011 from hemispherical photographs taken systematically at permanent biomass sampling plots (see Ilvesniemi et al., 2009) within a radius of 200 m from the downward looking pyranometer. The effective LAI estimated from the hemispherical photographs was 2.2 using a GLA (Gap Light Analyzer) 2.0 software (SFU, New York). The downward looking pyranometer measuring the reflected global radiation was situated at 70 m height on a fixed mast standing on a small rocky outcrop, and was slightly more than 50 m above the forest canopy. In addition to forest, there are some wooden tracks, small sandy roads, three measurement towers (~6 m^2 basal area) just reaching the canopy top and small roofs in the view area of the pyranometer (~161 m radius covers 95% of the signal). Because of the large field of view of the pyranometer, this infrastructure only covers a minor part of the measured area.

2.2. Instrumentation

The incident shortwave solar radiation flux (0.3–4.8 μm) was measured in a tower just above the canopy with a Reemann TP-3 pyranometer (Astrodata, Tõravere, Tartumaa, Estonia) in the time period before June 2008 and thereafter with a Middleton Solar SK08 (Middleton Solar, Yarraville, Australia) pyranometer. Reflected solar radiation was measured with a Reemann TP-3 pyranometer situated at 70 m height on the measuring mast on a two meters long boom. Net radiation (incident shortwave and longwave radiation minus reflected shortwave and emitted longwave radiation, 3–40 μm) was measured with a Reemann MB-1 net radiometer and the incoming and outgoing longwave radiation with CNR1 net radiometer (Kipp & Zonen, Delft, the Netherlands) from the end of 2009, situated at 33 m height on the mast. There are fans next to all the radiation sensors preventing snow and ice accumulation. The upward facing TP-3 pyranometer was calibrated in summer 2006 and 2008 and the SK08 pyranometer replacing the TP-3 in summer 2008 was calibrated in 2011. The downward facing pyranometer was calibrated in 2002 and 2011. The calibrations were made in totally cloud free conditions against unused reference sensors kept in dark. The net radiometer has not been calibrated and the measurement should therefore be concerned with caution. The performance of the net radiometer was tested against that calculated from short- and longwave radiation measurements in 2010 and 2011 and some underestimation in net radiation measurement was noticed (r^2 0.93). The leveling of all the sensors has been adjusted with a spirit leveller. A more detailed description of the TP-3 and MB-1 sensors can be found in Sulev et al. (2000). Temperature measurements are conducted at different heights in the mast by PT-100 thermometers, ventilated by fans and shielded from solar radiation, whereas precipitation is measured with a FD12P Weather sensor (Vaisala Oyj, Helsinki, Finland) and an ARG-100 tipping bucket counter (Vector Instruments, Rhyl, Clwyd, UK). All measurements were averaged to yield half hour values. Daily photographs of the canopy taken by an automated digital camera since April 2008 were used to estimate canopy snow conditions.

As the reflected and incident solar radiation fluxes were measured with different sensors since June 2008, there might be a slight difference in the spectral response. We could, however, see no change in albedo or PAR/global radiation relation when comparing data before and after the upward facing pyranometer was changed.

2.3. Calculation

Typical values of clear sky radiation were used to estimate the cloud cover. The clear sky radiation (St) was estimated as a sum of direct and diffuse clear sky radiation as: $\mathrm{St} = \mathrm{So} \times \tau^m \times \cos(\mathrm{SZA}) + \mathrm{So} \times \tau_d \times \cos(\mathrm{SZA})$ (Gates, 1980), where So is the solar irradiance at top of the atmosphere (1366 W m^{-2}) corrected for the varying distance of the sun from the earth, SZA is the solar zenith angle, τ is the atmospheric transmittance for direct beam at nadir, m is the air mass and the portion of diffuse radiation τ_d was calculated as $0.271–0.294\tau^m$ (Liu and Jordan, 1960). Air mass was calculated according to Young (1994, Eq. (6)). The local value of the clear sky atmospheric transmittance (τ) was found by comparing the calculated clear sky radiation to the measured one, where all completely clear days (determined from the solar irradiance curve) during the study years taken into account. The best fit for the model was found when the transmittance was set to 0.74. The relation of measured global to estimated clear sky radiation is hereafter referred as Rg/St.

Shortwave albedo over a certain period (day, month) is always calculated as a ratio of the sum of reflected solar radiation to the sum of incident solar radiation during that period. Daytime used in the sum is defined as the time when solar zenith angle is at or lower than 90°, global radiation > 0 and albedo 0–1. For simplicity, the same criteria except for the albedo restriction were used when calculating the sums of global radiation.

The study years were 2008, 2009, 2010 and January–July 2011. As daily photographs of the canopy were not available before April 2008, the January–March 2008 is lacking when examining the effects of canopy snow cover on albedo. Only pine trees were in the view field of the automatic camera, so we have no information about the extent to which the deciduous branches might have been covered with snow. Data on the ground snow depth at weekly interval was available for each year, as well as measurements of the ground snow water content every month or fortnight in spring time.

We used the daily canopy images to classify canopy snow cover into six classes. Snow covered canopies were divided into four classes based on the digital canopy images; in addition one class (0) was assigned to snow free and one to frosted canopies (frost). The criteria for the snow classes in decreasing order of canopy snow amount were: 4 = no snow free branches or needles are visible, 3 = most of the branches and needles are covered with snow but some are bare, 2 = about equal amounts of snow covered and other surfaces are visible in the canopy, 1 = most of the canopy is snow free. Images of the canopy in each of the snow classes on a typical day are shown in supplementary data. Dividing the canopy snow load into four classes is of course somewhat arbitrary and subjective. We acknowledge that there is a lot of variation in the amount and quality of snow inside the classes, especially inside the lowest canopy snow class 1. The classification was however done twice by the main author, and its reproducibility was checked by a test person. Using the written criteria for the classification and two example images of each class, 82% of 50 randomly selected canopy snow images were classified similarly by the two persons. The "misclassified" images were always assigned to a class that was adjacent to the "correct" one. The aim here was not to accurately quantify the snow amount in the canopy, but to gain information about the relative effects of canopy snow load on forest albedo. Moreover, no attempt was undertaken to assess the quality of the snow in the canopy (wet, dry, old, new, etc.).

We, also, estimated a hypothetical, average albedo of a snow free winter. This was done by simply calculating separately the mean of the daily albedos of snow free (both canopy and ground) days in November, December and May, and taking a mean of these. A hypothetical albedo was also calculated for conditions, where the ground snow situation was normal but there was no snow on the trees. Here, the albedo was calculated for each month by taking the mean of the daily albedos of days with no canopy snow.

The influence of surface wetness on albedo was tested by stratifying the days in May–September into dry or wet days. Vegetation was assumed wet at noon, if a canopy photograph taken at noon showed droplets in the canopy, or when a precipitation event of at least five mm had occurred during the morning or night (that is, within 12 h). However, each case without a midday canopy photograph (photograph taken later in the day) was considered carefully paying attention also to temperature, i.e. on a cold day the canopy was assumed to stay wet longer than on a warm day. All the days when it had not rained for at least one and a half days were classified as dry days. All the days which qualified for either of these classes were selected. It should be noted that there were many intermediate days that were neither "wet" nor "dry".

2.4. Gap filling of data

The solar irradiance data was gap filled to fill short measurement breaks. Gap filling of global radiation was performed using the clear sky shortwave radiation flux and cloudiness as follows: the fraction of the measured global radiation to that of the typical clear sky radiation (Rg/St, see Section 2.3) was calculated for the hours just before and after the measurement gap to represent the cloudiness. These fractions were then linearly averaged to the measurement gaps and multiplied by the typical clear sky radiation. The gap filled data of global radiation was used only for the calculation of annual/monthly sums and not for any other calculations. The monthly sums of total reflected radiation are estimated by using the gap filled global radiation data and the albedo calculated for that period using only measured data. 1.8% of global radiation data was missing in 2008, in 2009 the value was 0.6%, in 2010 2.3% and in 2011 1.4%.

3. Results

3.1. Weather conditions and radiation balance

Fig. 1 shows the course of incident solar radiation, reflected solar radiation, daily albedo and net radiation as seven day moving averages each year. The annual sum of solar irradiance and weather conditions are summarized in Table 1. Year 2011 is not included as only data from January to end of July was available.

Permanent ground snow cover took place earliest in winter 2010–2011, when the forest floor was continuously snow covered from mid November. In 2008–2009 and 2009–2010, the permanent snow fell around mid December. The snow pack was always thickest (30–60 cm) in mid March, after which it gradually decreased and melted by the end of April.

3.2. Growing season albedo

The albedo varied somewhat during the growing season (May–September), slightly increasing throughout the summer. The mean monthly albedos from May to September were: 0.117, 0.121, 0.125, 0.128, and 0.138, when all years except 2011 were taken into account. (Notice that the summer albedos in Fig. 2 differ from these as they are means of daily albedos. The monthly albedos are higher than the monthly means of daily albedos as the monthly mean weights the amount of radiation reflected and therefore the clear days when albedo was noticed to be higher in summer (see below).) This increase was entirely attributable to clear sky conditions (Rg/St > 0.75), and was present also when only certain solar angels were selected. For example, if only moments with solar zenith angles between 55 and 65° were chosen, 65° corresponding approximately to the end of September noon SZA the mean clear sky albedos were: 0.119, 0.127, 0.129, 0.132 and 0.136 from May to September. However, when this was still divided into morning and afternoon, the increase was stronger in the morning, possibly attributable to illumination conditions in the pyranometer view area. In summer (June–August), the albedo was on average higher on clear (0.128) than on cloudy (0.116) days (p-value with a classical t-test <0.0001).

3.3. Effects of snow on albedo

The mean daily albedo when the canopy was snow free in January–March was 0.188 with a standard deviation of 0.058. When

Table 1
Weather conditions and solar irradiance in the study years.

	Solar irradiance, MJ m^{-2}	Mean temperature, °C, 16 m height	Precipitation, mm	Snowfall, mm
2008	2786	5.09	883	1639
2009	2990	4.03	566	1385
2010	2967	2.76	706	2163

the canopy had snow cover (all canopy snow classes included), the mean daily albedo for the same months was 0.314 and SD 0.14. The mean daily albedos of days representing each snow class in each month, as well as their standard deviations, can be seen from Fig. 2. The average albedo of a frosted canopy is not presented in the Fig. 2 for clarity reasons (overlapping points), but in January–March it was 0.222 with a SD of 0.092. In January–March, the ground was continuously snow covered in all years.

As seen from Figs. 2 and 3, albedo increased with increasing amount of snow in the canopy, although the variation in albedo inside the snow classes was high. In addition to the amount of snow, the following factors were found to affect the albedo of a snow covered canopy. Snow aging generally decreased albedo. After an initial increase in albedo after a snowfall greater than 2 mm in January–March, the albedo usually substantially decreased about two days later, after which it remained rather stable. In some cases, however, the albedo increased a few days after snowfall without any new snow. This increase was usually accompanied by clear weather, which was generally correlated with high albedo when the canopy was snow covered (Fig. 3). The effect of cloudiness on half hourly albedo in January–March was tested by defining the sky clear when the Rg/St ratio was over 0.75 and cloudy when the ratio was lower than 0.5. When SZA was lower than 80° and canopy snow class more than one, the albedo was on average higher on clear sky conditions with a mean albedo of 0.401 and SD of 0.113 than when it was overcast (0.267 and 0.089, respectively). This difference was statistically significant with a p-value < 0.0001 (classical t-test). In January–February 2010, when the canopy was fully snow covered (snow class 4) for a one and a half month period, the daily albedo varied from 0.204 to 0.855 with a mean of 0.43 and SD of 0.155. During this time (only SZAs below 80° included) the half hourly albedo seemed to be mostly correlated with clear sky conditions, as the albedo was explained by decreasing temperature (r^2 0.403 and RSE 0.095), increasing global radiation (r^2 0.477, RSE 0.089) and decreasing incoming longwave radiation (r^2 0.702 and RSE 0.069). SZA, which varied from 74 to 80°, did not affect albedo during this period.

Fig. 4 shows the percentage of days in each month when the canopy is in a certain snow class and the total amount of reflected radiation each month and snow class. The figures indicate high canopy snow coverage in midwinter, December–February. During this time, most of the incident solar radiation is reflected when the canopy snow class is the highest or second highest (4 or 3). Fig. 4b reminds that the irradiance and therefore the reflected radiation are low during midwinter months, regardless of the snow conditions. However, already in mid to end February in 2010 and 2011, the absolute reflected shortwave radiation around the solar noon exceeded in some days the maximum amount reflected in summer (ca. 100 W m^{-2}), reaching at maximum 168 W m^{-2}.

If the whole winter is hypothesized to be snow free with a fixed daily albedo of 0.106 (calculated as explained in Section 2.3), the

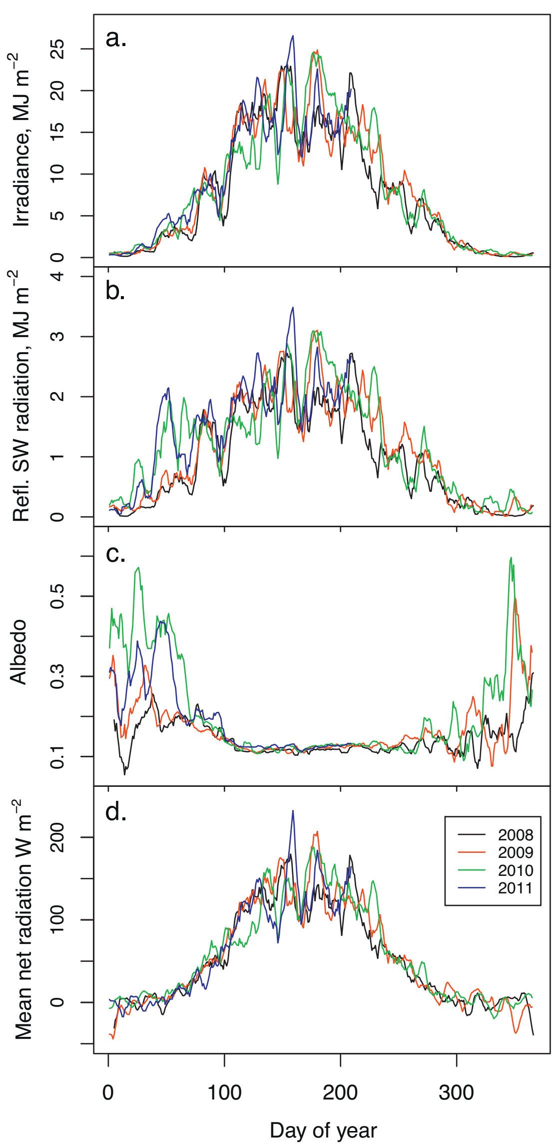

Fig. 1. (a.) Summed daily solar irradiance, MJ m^{-2}. (b) Summed daily reflected solar radiation, MJ m^{-2}. (c) Daily albedo. (d) Mean net radiation, W m^{-2}. All figures represent seven day moving averages.

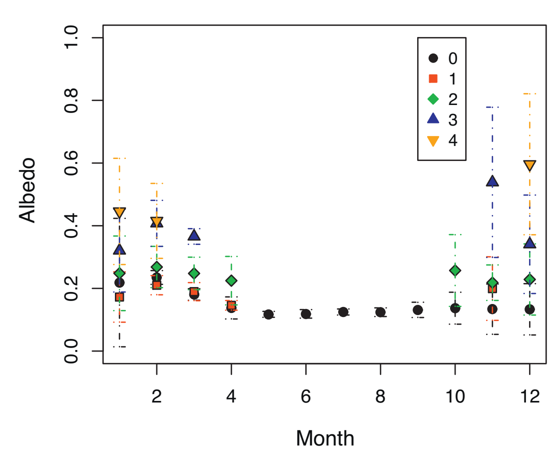

Fig. 2. Average daily albedo of days in a certain canopy snow class in each month and standard deviation (0 = no canopy snow, 4 = maximum amount of snow in the canopy).

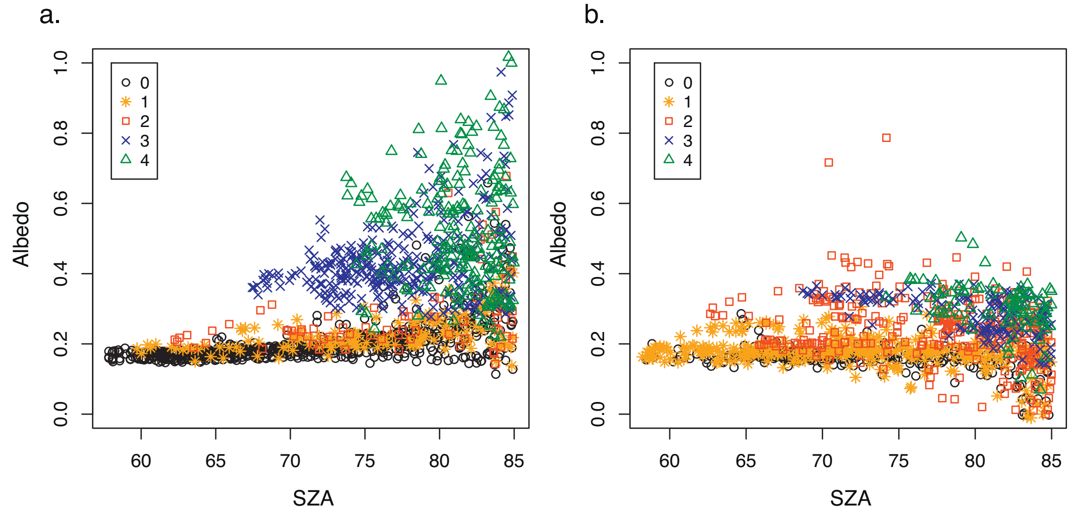

Fig. 3. Variation in albedo with solar zenith angle (in degrees) and snow class in January–March on clear (a) and cloudy weather (b).

total amount of reflected solar radiation in November–April was 55 MJ m^{-2} less than the real average value. The difference was greatest in February and March, with 18.4 and 18.3 MJ m^{-2}, respectively. If the canopy would have been snow free all winter, but the ground snow conditions the same as measured, the reflected radiation during November–April would have been 18 MJ m^{-2} lower than in the averaged real situation.

There was a large variation in the total amount of reflected radiation between the winters (November–April). During the warmest winter with least snow, 2007–2008 (other information about 2007 not reported), altogether 94.3 MJ m^{-2} of incident solar radiation was reflected. Second least was reflected in 2008–2009, 103.3 MJ m^{-2}. Much more radiation was reflected in the cold and snowy winters 2009–2010 and 2010–2011, 138.9 MJ m^{-2} and 148 MJ m^{-2}, respectively.

3.4. Canopy snow interception

The weather conditions resulted in high canopy snow retention in winter 2010, when the canopy was covered with snow all winter from mid December 2009 until second week of March 2010. The snow was able to retain long on the branches in midwinter: the longest period without a new snowfall was 16 days in January 2010, during which time the canopy snow class remained the same. During this time, temperatures were constantly below freezing, wind speeds moderate and sky cloudy. As spring proceeded, canopy snow cover decreased always very fast after a snow event if no new snowfall occurred. The maximum length of persisting canopy snow cover without a new snowfall after February in any year was 4 days in beginning of March 2009. In April, snow covered branches only occasionally, right after snowfall, and was always disappeared until the next day.

3.5. Effects of surface wetness on albedo

The effect of canopy and surface wetness on albedo was tested in the snow free period from beginning of May until end of September each year. The total number of days marked as dry was 289 and as wet 45. Table 2 shows the results of different comparisons. The albedo values are averages of albedos from 3 h around the local solar noon. Because the summer albedo was higher on clear than on overcast weather (see Section 3.2), and wet days tend to be cloudier,

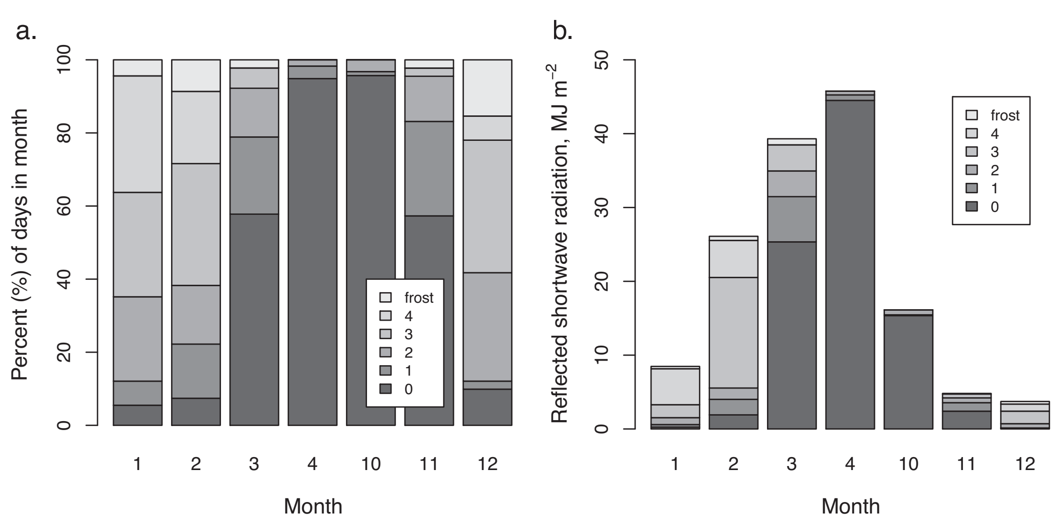

Fig. 4. (a) Average share of days in each canopy snow class in each winter month. (b) Total amount of solar irradiance (MJ m^{-2}) reflected during each winter month and snow class.

Table 2
Comparisons of average albedos in wet and dry middays in the growing season.

	Dry	Wet	Dry, clear	Wet, clear	Dry, cloudy	Wet, cloudy
Albedo	0.117	0.101	0.119	0.114	0.112	0.098
SD	0.012	0.015	0.011	0.008	0.015	0.015
p-Value	<0.0001		0.0269		<0.0001	

a comparison of the noon albedos in clear (Rg/St > 0.75) and overcast (Rg/St < 0.5) conditions was made. This comparison showed that although the albedo decreased in cloudy conditions when it was wet, no considerable difference existed between the albedos of wet and dry forest in clear sky conditions. However, the number of wet but clear middays was small, only four. All the comparisons showed a significant difference between wet and dry conditions with a classical *t*-test, *p*-value < 0.0001, except for the clear midday comparison, with a *p*-value of 0.0269. The morning dew should not have influence on this comparison, as the temperature was always clearly above dew point by midday.

4. Discussion

The albedo varied strongly as a function of ground and canopy snow cover. Our results suggest that canopy snow cover on this boreal Scots pine forest increases the forest albedo on average by more than 0.2. If only the ground was covered with snow, the increase in albedo was less, on average 0.1. If less than half of the visible branch or needle area was covered by snow (snow class 1), the albedo did not increase (Figs. 2 and 3). In midwinter, when canopy snow pack is heaviest and SZA high, the forest albedo is highest. As noticed also by Ni and Woodcock (2000), the maximum total amount of reflected global radiation at midday can be higher in winter when a canopy is snow covered than in summer: the reflected shortwave radiation at midday reached 168 W m^{-2} in February 2010 whereas the maximum in summer was about 100 W m^{-2}. However, the high reflectance in winter is naturally restricted to hours close to solar noon.

The results indicate, however, a complex interaction between snow cover and albedo. Albedo varied depending on the extent to which the canopy was snow covered, and also the variation within the snow classes was quite large. The snow cover of the canopy varied strongly temporally, the highest snow cover concentrating on January and February. The higher albedo values during these months were, however, associated with low solar irradiance.

The canopy interception of snow by evergreen trees can be substantial; in a boreal pine forest in Canada, Pomeroy et al. (1998) reported it to vary between 30 and 44% of cumulative snowfall. Snow depletion from the branches is caused by temperature, radiation and wind and enhanced by increasing VPD. Snow is bound to the tree branches with ice or liquid bonds between the snow crystals and the branches (Hedtröm and Pomeroy, 1998). As the temperature gets closer to the melting point, these bonds are weakened and snow may drop. This might also happen in freezing conditions, when solar radiation warms the needles. Melting or sublimation of snow due to above zero temperatures or radiation driven snow sublimation at below freezing temperatures are both enhanced by increasing VPD and wind, which decreases the surface resistance. Wind can also drop the snow. Sublimation of intercepted snow on boreal forests is a rather widely studied subject, many authors suggesting the sublimation losses to be remarkable (Harding and Pomeroy, 1996; Pomeroy et al., 1998; Lundberg et al., 1998). Pomeroy et al. (1998) report that 31% of the annual intercepted snow might be lost by sublimation. Thus, it is most probable that the snow stays longest in the canopy in the cold and dark midwinter months when it is still, causing the high albedo of a snow covered forest to have a negligible influence on a larger scale energy balance.

As spring proceeds, the influence of forest albedo on climatic processes increases as the solar irradiance incident on the forest increases. However, the duration of snow remaining on the branches after a snowfall event rapidly shortens in March and April. Thus, the amount of days with snow cover in the canopy was clearly lower in spring than in midwinter, leading to a lower albedo in spring. Also, the ground snow water content increases in spring, litter accumulates on the snow surface, snow grain size increases and snow depth decreases, all of which factors tend to lower snow and thus forest albedo. These factors and the increased direct beam transmission caused by the decreasing SZA probably caused the forest albedo to fall from 0.22 and 0.23 in January and February to 0.18 in March, when the canopy was free of snow.

The snowy forest albedos presented here differ from most measurements reported in the literature. For example, Pomeroy and Dion (1996) stated that the snow intercepted by the canopy had no effect on the clear sky albedo in a mature jack pine stand (LAI 2.2) in Canada (53.87°N). On the same site, Harding and Pomeroy (1996) found that the pine forest albedo increased from 0.12 when there was snow only in the ground to 0.135 when also the canopy had snow cover in March. Regarding only the forest floor snow, Betts and Ball (1997) reported an average albedo of 0.15 for three jack pine stands in Canada with snow background and 0.086 without snow. Riihelä and Manninen (2008) measured albedo profiles during two clear winter days in a Scots pine forest in northern Finland (67.34°N), where both the ground and canopy had snow cover, and mentioned a value of 0.2 for the above forest albedo. Stähli et al. (2009) found an increase in a Swiss sub-alpine spruce forest albedo when there was snow in the canopy from 0.074–0.094 to 0.118–0.242. We suppose that our high snow covered forest albedos might be partly due to the low sun elevation in winter, which would have increased the clear sky albedos as compared to studies conducted at more southern latitudes. Also, the large view area of the pyranometer in the Smear II tower might have contributed to high winter albedos: the pyranometer is positioned approximately 50 m above the canopy and sees in addition to the forest also some tracks, small roads and some small roofs. All of these are covered with snow in winter and have a less dense canopy trapping the radiation above them. However, the area of these non forest areas in the view of the pyranometer is small and it is unlikely that this would explain our results. In addition to these, the Smear site is not a pure coniferous forest but has a considerable deciduous mixture, most probably increasing the reflectance of a snowy forest.

We found a relationship between winter albedo and cloudiness, which, in contrast to some earlier reports on the matter (e.g. Betts and Ball, 1997), indicated that the snow covered forest albedo was higher when the sky was clear than when it was overcast. Snow albedo alone should be greater in cloudy conditions, because the reflectance of snow, unlike vegetation, is greater in visible wavelengths due to the water absorption bands at longer wavelengths. Diffuse radiation is richer in shorter wavelengths compared to direct radiation and should therefore be better reflected from snow (Wiscombe and Warren, 1980). At the our study site (61°51′N and 24°17′E), sun SZA is very high in winter and the effect of high zenith angle increasing the direct beam albedo might be stronger than the snow albedo increase caused by the spectral shift toward shorter wavelengths in cloudy conditions. A thick canopy snow cover may also partly cause the reduced transmittance of direct radiation. This could be seen from the lower albedo of a frosted canopy than a snow covered one, as the frost does not fill the gaps between needles and shoots and therefore does not reduce the amount of solar radiation transmitted through gaps. On the other hand, the better penetration of diffuse light into the forest due to smaller effective SZA in cloudy conditions should enhance reflection when the radiation reaches the snow covered forest floor (Betts and Ball, 1997). During a long period of maximum canopy snow cover in January–February 2010, the midday albedo followed the clear sky conditions, i.e. was explained by decreasing temperature, increasing global radiation and decreasing longwave radiation. However, because temperature often negatively correlates with cloudiness in winter, the higher albedo of snow covered surfaces on clear and cold weather could be to some extent caused by temperature driven changes in snow reflectance properties. Snow metamorphism is faster in warmer temperatures even in constantly below freezing conditions, leading to smaller specific surface area and larger grain size of snow (Taillandier et al., 2007) and thus lower albedo.

Some studies (e.g. Petzold, 1981; Sicart et al., 2004) note the effect of longwave radiation on the forest floor radiative balance in times when the solar irradiance is low and/or ground albedo high due to snow cover. In these conditions, and when the atmospheric emissivity is low, the longwave radiation emitted from a dense canopy can offset the attenuation of shortwave radiation by the canopy and thus increase net radiation at the forest floor. This effect is important for example when studying the snow melt in forests. However, the longwave radiation emitted from the forest to the atmosphere is largely a function of surface temperature, which again depends on air temperature and solar irradiance (e.g. Pomeroy et al., 2009). It is therefore unlikely that the longwave emittance from the forest would much depend on canopy snow conditions or markedly differ from longwave radiation emitted from other land cover types. Nevertheless, it can be expected that the snow covered open areas with higher albedo and colder surface temperature, especially in spring time, would emit less longwave radiation than the forested areas.

The influence of phenology on forest reflectance is more commonly examined on deciduous species where the seasonality is clear and discernible from remote sensing images. For example, Hollinger et al. (2010) did not report any clear changes caused by phenology in evergreen conifer forest albedos. Our data showed a small but consistent summer increase in clear sky albedo, similar in shape every year and not caused by solar angle. The lowest albedo in May might be explained by darker background, as some of the understory vegetation drop their leaves for winter, and also the deciduous trees in the pyranometer view area are not yet fully leaf bearing. The senescence and falling of leaves and the oldest needles in autumn could increase the visible reflectance, but on the other hand it may decrease the reflectance the in the near-infrared spectrum. For example, Nilson et al. (2008) used satellite images to estimate seasonal reflectance trends in Estonian forests and reported a decrease in NIR reflectance in the end of the growing season both in coniferous and deciduous dominated forests, but only a slight increase in visible reflectance in a birch forest. However, as the increase in albedo was only present in clear sky conditions and as the increase was greater in the morning than in the afternoon, we are inclined to believe that at least part of the reason should be accounted for the topography and illumination conditions.

Surface wetness is said to decrease vegetation albedo (Lafleur et al., 1997), as water has a very low albedo at low solar zenith angles. However, in our case there were no ponds of water on the ground, but only the vegetation surfaces were wet. In this case, it is difficult to say what the effect of SZA on albedo of a wet forest should be. In all sky conditions we noticed a decrease in albedo in May–September from wet to dry vegetation by on average 0.016. However, in the growing season the albedo was lower on overcast than on clear days due to the higher absorbance of vegetation of shorter wavelengths and greater transmittance of diffuse radiation to the canopy. Thus, when diffuse and sunny conditions were considered separately, the decrease in albedo was only 0.005 in clear sky conditions and 0.014 in overcast conditions at midday.

Snow cover and wetness are factors affected by climate, which is again influenced by the changes in these factors through surface albedo. The most obvious climate feedback would follow an increase in temperatures in winter and spring, when the precipitation would fall as rain rather than snow. However, when simulating a completely snowless and moist winter, the amount of reflected solar radiation during November–April was 55 MJ m^{-2} (1.79 W m^{-2} throughout a year) less than the real average value, which corresponds to less than 2% of the annual solar irradiance and is clearly smaller than its inter-annual variation. If the ground snow conditions were those as in the real situation but the canopy assumed to be snow free, the total reflected radiation was simulated to be 18 MJ m^{-2} less than the average measured one. The variation in total reflected solar radiation between winters with different weather conditions was however of the same magnitude as the simulation between average and snow free winter, the difference between the winters with least and most reflected solar radiation being 54 MJ m^{-2}. Due to the relatively small amount of incoming and therefore reflected solar radiation in winter time, small changes in canopy or ground snow conditions in coniferous forests at high latitudes in midwinter hardly seem important to a larger scale climate. In spring, when the radiation is more intense, the canopy snow load is already low and short-lived and therefore a further reduction in the canopy snow would also most likely not cause any significant warming effect. The ground snow albedo in spring time tends to be rather low due to old snow and litter, making the forest albedo in the snow free canopy conditions approaching the summer values. However, 1.79 W m^{-2} difference in the annual averaged reflectance corresponds approximately to the increased radiative forcing caused by the increased atmospheric CO_2 thus far (1.66 W m^{-2} in 2005, IPCC, 2007).

When simulating the climate cooling effect of boreal deforestation, Bonan et al. (1995) and Betts (2000) used albedo values for winter evergreen needleleaf forest (0.32 and a maximum of 0.26, respectively) that were close to the albedos measured here, or even higher if extended to March–April when the canopy is mostly snow free. Although this stresses the possibly warming effect of boreal conifer forests on climate trough albedo, this study also suggested that the change in feedback of coniferous forests on climate in case of shortened winter snow cover is much smaller than that of open areas with a high snow albedo feedback. Therefore, in case of hypothetical snowless winters and low albedos across landscapes, the carbon sequestration capabilities of boreal forests might again turn them beneficial to climate cooling.

5. Conclusions

The influence of canopy snow on forest albedo has not been well known. Our study suggested that boreal pine forest albedo can substantially increase when the canopy is fully covered with snow. On the other hand, it is often possible for snow to remain on the branches and needles only in the cold and dark midwinter months, when the solar irradiance is low at the northern latitudes and therefore the albedo climate feedback negligible. The difference between the total amount of solar radiation reflected in winter with the least and most snow was 54 MJ m^{-2}, which was close to the difference in reflected radiation estimated for an average winter and for a completely snow free winter (55 MJ m^{-2}). These values are less than the inter-annual variation in solar irradiance at the site, and indicate a rather small change in the climatic feedback of these forests in case of possible snowless winters. This study emphasized the importance of correctly assessing the quantity, properties and first of all the timing of canopy snow cover when estimating the albedo of snow covered forests. It is clear that the influence of snow properties on canopy reflectance should be studied further, and forests with variable species compositions at different climatic conditions should be taken into consideration.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2012.05.009.

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