1 Comments to the Author:

2 Dear,

3

Since your submission of the revised manuscript a month ago, seven external reviewers (including the initial
reviewers) have been contacted for advice but all rejected or missed the deadlines. To avoid further delay, I
decided to base the decision solely on my own judgement.

- 7
- 8 Comments:

9 Readers should be able to read the manuscript and benefit from the discussion phase without having to go the 10 journal website and actually read the discussion. The assumptions, insights and caveats identified by the 11 reviewers should be used to improve the manuscript. This implies that the responses addressing the reviewers 12 concerns – which satisfied the reviewers and myself- should be integrated in the manuscript.

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When providing a revised manuscript, please, include a version of the manuscript where the changes are clearly marked ("Regarding author's changes, a marked-up manuscript version (track changes in Word, latexdiff in LaTeX) converted into a *.pdf and including the author's response must be provided" copied from http://www.biogeosciences.net/for_authors/submit_your_manuscript.html).

18

19 I'm looking forward to receive a revised manuscript at the earliest of your convenience,

- 20
- 21 Sebastiaan Luyssaert
- 22

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30

23 Dear Dr. Luyssaert,

We have prepared the second revision of our manuscript according to your comments. It is true that some of the issues discussed during the review process were not fully reflected in the manuscript. Particularly, we see now that explanations for some of our choices regarding model parameters or calculations were lacking in the manuscript, although they were included in our response to the reviewers. We hope that the revised version is more thorough in that sense.

In the following table we list the most important concerns raised by you and the reviewers, and explain
 how we modified the manuscript in order to better reflect the discussion related to these concerns.

Validation and sensitivity of the FRT model (Reviewer #1, Editor)	We added a reference to the original Nilson and Peterson (1991) paper, and a reference to the RAMI website where the reader can view the results of comparison to other models (Section 2.2.1). Now the literature list is more complete for those readers that are interested in the model validation and theoretical background. We also added an explanation for why we chose not to model different tree size classes and a short discussion explaining how including several size classes may affect the simulation results (Section 2.2.2). This completes the discussion about model sensitivity to the most important parameters (tree size classes, crown radius, crown shape) that the reviewer #1 was concerned about.
Importance of forest floor and the correlation between forest floor and overstory (Reviewer #1, Editor)	We think that the additions of text into Discussion Section in the first revision are enough to highlight the importance of forest floor. Regarding the correlation between overstory and forest floor cover, we now reported the results observed in our data, and added an explanation for why spatial variation in the forest floor reflectance was not modeled (end of Section 2.2.2). Now our reasoning behind the choices made in modeling forest floor reflectance should be evident for the reader without reading the online discussion forum.
Generality of results (Reviewer #1)	We think that the re-wordings that we implemented in the first revision round were enough to answer this concern.
Inclusion of a diffuse illumination scenario, the effect of atmosphere on the results (Reviewer #2)	We re-formulated the text in which we describe the black- and white-sky calculations and report the results of our test in which we compare the use of top-of-atmosphere vs. bottom-of-atmosphere solar spectra (last two paragraphs of Section 2.2.1). We also added a couple of sentences that justify to the reader why the atmosphere was ignored. We think that the revised text now well justifies our choices regarding the assumptions on atmosphere and angular properties of incoming solar radiation.
Separation of green vs. total FAPAR (Reviewer #2)	We added text which explains why green FAPAR was not calculated (Section 2.2.1).
Modeling light use efficiency (Reviewer #2)	We did not add discussion on this topic. We already state in the introduction that FAPAR is not exactly productivity, although it is commonly used as a proxy of it. Thus, this assumption will be clear to the reader right from the beginning.

Quantifying the missing link between forest albedo and productivity in the boreal zone

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48 Abstract. Albedo and fraction of absorbed photosynthetically active radiation (FAPAR) determine the shortwave radiation 49 balance and productivity of forests. Currently, the physical link between forest albedo and productivity is poorly understood, 50 yet it is crucial for designing optimal forest management strategies for mitigating climate change. We investigated the relationships between boreal forest structure, albedo and FAPAR using radiative transfer model FRT and extensive forest 51 52 inventory data sets ranging from southern boreal forests to the northern tree line in Finland and Alaska (N = 1086 plots). The 53 forests in the study areas vary widely in structure, species composition, and human interference, from intensively managed in 54 Finland to natural growth in Alaska. We show that FAPAR of tree canopies (FAPAR_{CAN}) and albedo are tightly linked in boreal coniferous forests, but the relationship is weaker if the forest has broadleaved admixture, or if canopies have low leaf 55 56 area and the composition of forest floor varies. Furthermore, the functional shape of the relationship between albedo and 57 FAPAR_{CAN} depends on the angular distribution of incoming solar irradiance. We also show that forest floor can contribute to 58 over 50% of albedo or total ecosystem FAPAR. Based on our simulations, forest albedos can vary notably across the biome. 59 Because of larger proportion of broadleaved trees, the studied plots in Alaska had higher albedo (0.141-0.184) than those in 60 Finland (0.136–0.171) even though the albedo of pure coniferous forests was lower in Alaska. Our results reveal that variation in solar angle will need to be accounted for when evaluating climate effects of forest management in different 61 62 latitudes. Furthermore, increasing the proportion of broadleaved trees in coniferous forests is the most important means of 63 maximizing albedo without compromising productivity: based on our findings the potential of controlling forest density (i.e., 64 basal area) to increase albedo may be limited compared to the effect of favoring broadleaved species.

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66 Keywords: FAPAR, conifer, broadleaved, radiative transfer, basal area, leaf area index, AGB, thinning

67 1 Introduction

Forest management practices, such as thinning and logging, alter the spatial, structural, and species composition of forests. 68 69 Through an altered albedo and productivity, these management practices may cause profound impacts on climate. Because 70 forest structure and species composition influence albedo, managing forests to increase albedo is a potential means of 71 maximizing the climate cooling effects of forests (Bright et al., 2014; Alkama & Cescatti, 2016; Naudts et al., 2016). 72 However, if forest management practices are altered in order to maximize albedo, productivity may be compromised, which 73 would result in reduced carbon uptake as well as reduced timber production and corresponding economic losses. There is an 74 urgent need to understand how forest management practices change forest albedo, and how forest albedo and productivity 75 are interconnected.

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Being the world's largest land-based biome, the boreal forest zone consists of vast forest areas under various human interference levels, from natural growth to intense silvicultural management. The biome plays an important role in controlling the global carbon and energy balances. It is estimated that the boreal forests comprise 32% of the total carbon in the world's forests, and account for a significant portion of the carbon uptake (Pan et al., 2011). In addition, the albedo of boreal forests varies considerably by forest structure, phenology, and snow cover (e.g., Ni & Woodcock, 2000; Kuusinen et al., 2012; Bright et al., 2013; Kuusinen et al., 2016).

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84 Previous studies based on local in situ measurements, or remote sensing data for local to regional study areas have shown 85 that boreal forest albedo is influenced by tree species, with broadleaved species rendering higher albedos than coniferous (Lukeš et al., 2013a, Kuusinen et al., 2014). Albedo of open areas or that of the forest floor is usually higher than in the 86 87 canopy areas (Bright et al., 2014, Kuusinen et al., 2014), except for burned sites (Amiro et al., 2006). A declining trend in 88 albedo with forest height or age has been observed for coniferous forests (Amiro et al., 2006; Kirschbaum et al., 2011; Bright 89 et al., 2013; Kuusinen et al., 2016) and may be at least partly explained by the increasing leaf area index (LAI) and thus 90 reduced contribution of the forest floor on albedo as the forests mature. Similarly, a declining trend in albedo with canopy 91 density has been observed (Lukeš et al., 2013a).

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Gross primary productivity of vegetation can be approximated by FAPAR, i.e. the fraction of PAR radiation (400–700 nm) absorbed by the vegetation canopy (Gobron & Verstraete, 2009), because photosynthesis is ultimately driven by the available solar energy. FAPAR is useful in monitoring and comparing productivity both spatially and temporally, especially in the absence of accurate growth and yield models, although it should be noted that productivity is affected also by light use efficiency (LUE) i.e. the efficiency by which plants convert the solar energy into photosynthesis products (Monteith, 1972). The main determinants of forest canopy FAPAR are leaf area index (LAI) and the directionality of incoming solar radiation (Majasalmi et al., 2014), because they determine the fraction of PAR radiation interceptable by the canopy. Similarly to 100 albedo, boreal forest FAPAR may differ by tree species (Roujean et al., 1999; Steinberg et al., 2006; Chasmer et al., 2008;

101 Serbin et al., 2013; Majasalmi et al., 2015) and stand age (Serbin et al., 2013), as both species and age are likely to influence

102 the LAI of the canopy.

103

104 Estimation methods set limits for the information that can be obtained on the spatial and temporal variation of albedo and 105 FAPAR. In situ measurements are accurate and can be directly linked with field measured forest structure. On the other 106 hand, they are extremely tedious and cannot cover large variations in forest structure. Satellite data provide ample coverage 107 of varying forest structures and wide spatial extent but may compromise spatial resolution and detail in the characterization 108 of forest structure. In addition, neither local albedo measurements nor satellite-based albedo products can explain the 109 causality between small-scale environmental management scenarios and changes in albedo or FAPAR. Radiative transfer 110 models offer a solution to these problems: forest radiative transfer models are a powerful tool for linking quantitative 111 changes in vegetation structure to albedo or FAPAR for large geographical regions. The models are parameterized using 112 mathematical descriptions of canopy structure (e.g., LAI, tree height, crown dimensions, stand density), optical properties of 113 foliage and forest floor, and spectral and angular properties of incoming radiation. Using these models, the albedo and 114 FAPAR of a forest can be calculated from readily measurable variables such as forest structure and leaf optical properties.

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116 To our knowledge only one study has examined the relation between forest albedo and FAPAR (Lukeš et al., 2016). In that 117 study, coarse resolution satellite products (MODIS) were used and one geographical area (Finland) was studied. 118 Furthermore, previous studies on forest structure and albedo have mainly focused on local geographical scales (e.g. Finland, 119 Norway, but see Kuusinen et al. (2013) for comparison between Finland and Canada). Comparison of the relationships 120 between forest structure, albedo and FAPAR has not been performed across the biome, i.e. including both European and 121 North American boreal forests which have very different natural structures and forest management scenarios. Due to the 122 large north-south gradient and consequent structural diversity of forests in the boreal zone, the impact of forest management 123 on albedo cannot be expected to be the same.

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125 Here we report results from quantifying the links between boreal forest structure, albedo and FAPAR ranging from southern 126 boreal forests to the northern tree line using detailed, large forest inventory data sets from Finland and Alaska (N = 1086127 plots). The forests in the study areas vary widely in structure, species composition, and human interference, from intensively 128 managed (regularly thinned) forests in Finland to natural growth in Alaska. Using a radiative transfer modeling approach, we 129 quantify the effects of forest structure and species composition on albedo and FAPAR in order to answer how forest 130 management practices can be optimized for climate change mitigation. The significant benefit of the modeling approach is 131 that it enables to study structurally varying forests over large geographical areas, without compromising detail in the forest 132 structure representation or in the spatial resolution. Our study is therefore the first intercontinental study connecting albedo 133 and productivity of boreal forests, using accurate ground reference data.

134 2 Materials and methods

135 2.1 Study areas and field plots

This study is based on 1086 field plots located in Alaska, USA, and in Finland, between Northern latitudes of 60° and 68° . At these latitudes, solar zenith angle (SZA) at solar noon at midsummer ranges from 37° to 45° , and the annual average from 69° to 72° .

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140 The field plots in Alaska (N = 584) were permanent sample plots established as part of Co-operative Alaska Forest Inventory 141 that aims at long-term monitoring of forest conditions and dynamics (Malone et al., 2009). The plots were scattered in interior and southcentral Alaska across a region of about 300 000 km², from Fairbanks in the north to the Kenai Peninsula in 142 143 the south (Fig. 1, for more details see Liang et al. (2015)). Some of the plots were measured more than once. We used only 144 the most recent measurement of each plot. The plots in Finland (N = 502) were temporary or permanent sample plots. They 145 were located at four separate sites: Hyytiälä (Majasalmi et al., 2015), Koli, Sodankylä, and Suonenjoki (Korhonen, 2011) 146 ranging from southern to northern Finland (Fig. 1). Species-level attributes, including the number of stems per hectare, basal 147 area, mean diameter at breast height, tree height, and length of living crown, were available for the plots. Basal area, the total 148 cross-sectional area of stemwood (m^2 ha⁻¹) at breast height (i.e. at 1.3 m or 1.37 m), is a common measure of stand density in 149 forest inventories and, combined with information on tree height, used as an indicator of need for silvicultural thinning 150 operations.

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152 Tree species in the Alaskan data were coniferous black spruce (Picea mariana (Mill.) B. S. P.) and white spruce (Picea 153 glauca (Moench) Voss), and broadleaved quaking aspen (Populus tremuloides Michx.), black cottonwood or balsam poplar 154 (Populus trichocarpa Torr. & Gray, P. balsamifera L.), Alaskan birch (Betula neoalaskana Sarg.), and Kenai birch (Betula kenaica W.H. Evans). Tree species in the Finnish data were coniferous Scots pine (Pinus sylvestris L.) and Norway spruce 155 156 (Picea abies (L.) H. Karst), and broadleaved species comprising mainly of silver and downy birch (Betula pendula Roth, B. 157 pubescens Ehrh.). The birches accounted for 89% of the basal area of the broadleaved species in Finland. The forest 158 variables in the study plots are shown in Table 1, for all plots and separately for plots dominated by one species. The 159 Alaskan and Finnish forests differed in structure. The forests in Alaska were on average denser in terms of basal area (Fig. 2), and contained larger proportion of broadleaved species than the Finnish forests (Table 1). Managed forests in Finland, 160 161 which our plots mainly represent, are normally thinned 1–3 times during the rotation period so that coniferous species are 162 favored. In our plots from Alaska, on the other hand, no thinnings were applied.

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The plots in Finland were classified into six site fertility classes in the field, according to a local site type classification system (Cajander, 1949). We re-classified the original number of six fertility classes into three: "xeric", "mesic", and "herbrich". The cover of grasses is highest in the herb-rich, and decreases towards the xeric type. The cover of lichens, on the other hand, increases towards the xeric type (Hotanen et al., 2013). In the Alaskan plots no site fertility estimate was available but the cover of each species in the forest floor had been estimated. We labeled the plots as lichen- or grass dominated if either the cover of lichens or the total cover of herbs, grasses, rush, sedges, and fern was over 50%. The remaining plots were dominated by shrubs and mosses or were a mixture of all species groups. Hereafter we refer to these forest floor types as "grass", "shrub/moss", and "lichen". Forest floor types did not differ notably between forests dominated by different tree species, except for Scots pine forests in Finland, which were often found in the xeric type and were almost nonexistent in the herb-rich type (Table 2).

174 2.2 Albedo and FAPAR simulations

175 2.2.1 Simulation model

176 We simulated albedo and FAPAR using a radiative transfer model called Forest Reflectance and Transmittance model FRT. 177 It was originally published by Nilson and Peterson (1991) and later modified by Kuusk and Nilson (2000). (Kuusk & Nilson, 178 2000, version modified by Mõttus et al., 2007). FRT is a hybrid type model that combines geometric-optical and radiative 179 transfer based sub-models for modeling the first- and higher-order scattering components, respectively. The model has been 180intercompared and validated within RAdiative transfer Model Intercomparison exercise (RAMI) several times, including validation of both reflected and transmitted fractions of radiation (Widlowski et al., 2007). The results from these tests are 181 182 publicly available online (Joint Research Centre, 2016) and reported in peer-reviewed scientific papers (e.g., Widlowski et 183 al., 2007). In this study, we used a version of FRT modified by Mõttus et al. (2007). The advantage of FRT is that it can be 184 parameterized using standard forest inventory data, utilizing the allometric relations of forest variables to foliage biomass 185 and crown dimensions. This was important because field measurements of biophysical variables (e.g., LAI) are not 186 commonly available, as was the case also in our study plots.

187

188 FRT simulates stand-level bidirectional reflectance and transmittance factors (BRF, BTF) of a forest at specified 189 wavelengths. A 12×12 Gauss-Legendre cubature was used to integrate the simulated BRF and BTF values over the upper 190 and lower hemispheres, respectively. This resulted in upward scattered and downwelling (directly transmitted or downward 191 scattered) fractions of incoming radiation. The former is observed on top of, and the latter below the tree canopy. These 192 fractions were then used to calculate the shortwave broadband albedo and FAPAR. The simulations were carried out at 5 nm 193 resolution, and the albedo simulations covered a spectral region of 400-2100 nm which corresponds to the region from 194 which input data was available (see Section 2.2.2). The wavelengths below 400 nm account for 8%, and wavelengths over 195 2100 nm account for 2% of the solar irradiance on top of the atmosphere (Thuillier et al., 2003).

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197 The shortwave albedo was obtained as a weighted sum of the spectral albedos, i.e. upward scattered fractions of incoming 198 radiation (f_1 -):

200
$$albedo = \overset{2100}{\overset{2100}{a}} w_1 \times f_1 - ,$$
 (1)

201

The canopy and total FAPAR (FAPAR_{CAN}, FAPAR_{TOT}) were obtained as weighted sums of canopy absorption (a_l^C) and total absorption (a_l^T) over the PAR region:

204

205
$$FAPAR_{CAN} = \mathop{a}\limits^{700}_{I=400} w_I \times a_I^C$$
, (2)

206

207
$$FAPAR_{TOT} = \mathop{a}\limits^{700}_{I=400} w_I \times a_I^T$$
, (3)

208

209

The weights (w_{λ}) were obtained from the solar irradiance spectrum. Solar irradiance values (W m⁻²) were scaled by dividing them with the total solar irradiance within the spectral region used (i.e., 400–2100 or 400–700 nm). The weights were thus unitless and summed up to unity. <u>FAPAR_{TOT} and FAPAR_{CAN}</u> were separated because the former is a measure of total ecosystem productivity whereas the latter is more closely linked with timber production. Our FAPAR_{CAN} and FAPAR_{TOT} do not separate green biomass from woody or dead branches or from litter on the ground, and the values therefore represent upper limits of available solar energy for photosynthesis in tree canopy, and in the ecosystem as a whole.

The canopy and total absorptions needed for FAPAR determination were obtained using upward scattered (f_1 -) and downwelling (f_1 -) fractions of incoming radiation, and the reflectance factor of the forest floor (r_g) as follows:

216

220
$$a_{I}^{c} = 1 - f_{I} - f_{I}^{c} + f_{I}^{c} \times f_{I}^{c}$$
, (4)

222
$$a_i^T = 1 - f_i - ,$$
 (5)

223

FAPAR_{TOT} and FAPAR_{CAN} were calculated separatelyseparated, because the former is a measure of total ecosystem productivity whereas the latter is more closely linked with timber production. Our FAPAR_{CAN} and FAPAR_{TOT} do not separate green biomass from woody or dead branches or from litter on the ground, and the values therefore represent upper limits of available solar energy for photosynthesis in tree canopy, and in the ecosystem as a whole. Green biomass could not 228 <u>be separated, because no measurements on fraction of branch area to leaf area were made in the study plots. The same</u> 229 <u>applies to the cover of litter on the forest floor which was available for some of the field plots but not for all of them. It</u> 230 should also be noted that open soils are rarely seen in boreal forests where the floor is covered by (at least) green mosses.

231

232 The simulations were carried out assuming direct illumination only ("black-sky") and completely isotropic diffuse 233 illumination ("white-sky"). In both cases, we used a top of atmosphere irradiance spectrum (Thuillier et al., 2003) as 234 weights. The black-sky albedo and FAPAR were simulated for five SZAs typical for the study areas: 40°, 50°, 60°, 70°, and 235 80°. We use terms "small SZA" and "large SZA" to refer to SZAs of 40° 50° and 70° 80°, respectively. Black sky albedo 236 is, compared to actual (blue sky) albedo, less not dependent on assumptions of atmospheric scattering properties, and is 237 commonly used as input in climate modeling (Schaaf et al., 2009). The white-sky case was included in order to represent a 238 realistic diffuse illumination scenario, i.e. cloudy days. The black-sky albedo and FAPAR were simulated for five SZAs 239 typical for the study areas: 40°, 50°, 60°, 70°, and 80°. We use terms "small SZA" and "large SZA" to refer to SZAs of 40°– 240 50° and 70° - 80° , respectively.

241

242 In both black- and white-sky simulations, we used a top-of-atmosphere irradiance spectrum (Thuillier et al., 2003) as weights, because the focus was on analysing the effects of forest structure, and we wanted to avoid introducing any 243 244 differences between the study areas due to imperfect parameterization of the atmosphere. However, in order to demonstrate 245 what would be the effect of atmosphere on our results, wWe tested the effect of atmosphere using applied a simple solar 246 spectral model (Bird and Riordan, 1986) for generating direct and diffuse components of at-ground solar irradiance 247 spectrum. The direct and diffuse components were then used to weight the spectral fluxes ($f_1 - f_1^{-1}$) simulated under 248 direct and diffuse illumination, respectively. The simulated blue-sky albedo and FAPAR - Albedo and FAPAR in these 249 actual blue-sky conditions were highly correlated ($r \ge 0.98$) with black-sky ones, but blue-sky albedo was higher than black-sky albedo when SZA was 70° or 80°. This is because scattering in the atmosphere increases as function of SZA. 250 251 Atmosphere scatters visible more effectively than infrared wavelengths, shifting the irradiance distribution of incoming solar 252 radiation towards longer wavelengths in which vegetation is more reflective. Because of high correlation with-between 253 black- and blue-sky results, we conclude that inclusion of atmosphere in the calculations would not significantly change the 254 interpretation of our results our conclusions, although would increase the simulated albedo values at large SZAs.

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256 2.2.2 Model parameters

Tree crowns are represented in the FRT model by geometric primitives (cylinders, cones, ellipsoids, or combinations of them). The foliage within a crown is assumed to be homogeneously distributed. The area volume density (area per unit crown volume) of the foliage depends on the crown dimensions and on the foliage area per tree. Several tree classes can be 260defined to represent different tree species or size classes. We used one class for each tree species but did not model size 261 variation within-species. In theory, a forest with trees of very different sizes would have a higher canopy surface roughness, 262 which could in turn lead to somewhat lower reflectance (albedo) values (Davidson and Wang, 2004). There were no field 263 measurements made on tree size distribution in our data from Finland, and we wanted to maintain the same calculation 264 procedure for both study areas, in order not to introduce any differences due to data processing steps. Because the maximum number of species was seven in the Alaskan data, there was a maximum of seven tree classes per plot. We assumed ellipsoid 265 crown shape. The effect of crown shape on simulated forest BRDF was quantified in Rautiainen et al. (2004) who showed 266 267 that increasing the crown volume may either increase or decrease the simulated reflectance values, depending on canopy 268 closure. Ellipsoid has been shown to estimate crown volume accurately (Rautiainen et al., 2008) and was therefore used in 269 our study. Crown length was obtained from field measurements, and the crown radius was modeled using species-specific 270 allometric equations that require stem diameter as independent variable (Jakobsons, 1970; Bragg, 2001). Leaf dry biomass 271 was estimated with species-specific biomass equations (Repola, 2008; Repola, 2009; Yarie et al., 2007) and converted into 272 hemisurface i.e. half of total leaf area, using leaf mass per area (LMA) values from literature (Table 3). The performance of 273 wide range of crown radius and foliage mass models in forming the input of FRT has been reported by Lang et al. (2007). 274 The models used in our study were chosen based on geographical proximity to our study areas, and also on model 275 availability, particularly for the Alaskan species for which there existed a limited number of models. A slightly regular 276 spatial distribution pattern of trees was assumed, i.e. a value of 1.2 for the tree distribution parameter (a value of 1 indicates 277 Poisson distribution, Nilson, 1999). Other structural parameters needed in FRT simulations are presented in Table 3.

278

279 Optical properties i.e. reflectance and transmittance of the leaves and needles were obtained from laboratory spectrometer 280 measurements. The data for Finnish species were from Hyytiälä, Finland (Lukeš et al., 2013b). Spectra of birch were used 281 for all broadleaved species. The data for Alaskan species were from Superior National Forest, Minnesota, USA (Hall et al., 282 1996). Data for all species could not be found separately, and therefore spectra of black spruce were used for both black and 283 white spruce, spectra of paper birch (Betula papyrifera Marsh.) were used for both birch species, and spectra of quaking 284 aspen were used for both quaking aspen and for the black cottonwood/balsam poplar group. Reflectance spectra of black and 285 white spruce needles have been found to be similar at least in the visible and near-infrared wavelengths (Richardson et al., 286 2003). In our data, the spectra of coniferous species did not differ notably from each other (Fig. 3a). The same applied to 287 broadleaved species. Bark spectra for spruces and *Populus* sp. in Alaska were obtained from Hall et al. (1996), and for Scots 288 pine and Norway spruce in Finland from Lang et al. (2002) (Fig. 3b). Spectra of birch from Lang et al. (2002) were used for 289 birches in Alaska and for broadleaved species in Finland.

290

We used the annual shoot as a basic scattering element for conifers, similarly as in Lukeš et al. (2013a). This accounts for the multiple scattering within shoot which results in the shoot albedo being lower than needle albedo. Shoot reflectance and transmittance spectra were obtained by upscaling the needle single scattering albedo to shoot albedo (Rautiainen et al., 2012), assuming that the reflectance to transmittance ratio of a shoot is equal to that of a needle. Bi-Lambertian scattering 295 properties of the scattering elements (leaves or shoots) were assumed.

296

297 Optical properties of the forest floor, i.e. reflectance factors at nadir view were obtained from field spectrometer 298 measurements. The data were collected from Poker Flat Research Range Black Spruce Forest, Alaska (measurements 299 described in Yang et al. (2014)), and from Hyytiälä, Finland (using similar methodology as in Rautiainen et al. (2011)). 300 Separate spectra for each forest floor type was used (Fig. 3c), because characteristics of the forest floor may influence the 301 forest reflectance and therefore also albedo (Rautiainen et al., 2007). Forest floor composition was assumed to be 302 independent of overstory density. Taking into account this dependence would have required quantitative data on forest floor 303 composition and spectral data on all of the forest floor components, which were not available. Analysis of a subset of plots 304 that had measurements of vegetation cover in the forest floor revealed that the cover of green vegetation in the forest floor 305 was only weakly correlated with the canopy closure of the overstory (Alaska r = -0.27; Hyvtiälä (Finland) r = -0.33).

306 2.3 Data analyses

307 2.3.1 Albedo, FAPAR, and forest structure

308 We analyzed albedo and FAPAR (FAPAR_{CAN}, FAPAR_{TOT}) against each other, and against the forest variables. The analyses 309 were performed separately for Alaskan and Finnish data, and repeated for all simulated solar illumination conditions. 310 Because of the strong emphasis on forest management, main focus of the analysis was on tree species and tree height which are usually measured as part of forest inventories. In addition, we analyzed albedo and FAPAR against effective leaf area 311 312 index (LAI_{eff}) and above ground biomass (AGB). LAI_{eff} is calculated by FRT, and corresponds to the LAI of a horizontally 313 homogeneous, optically turbid canopy that has exactly the same transmittance (gap probability) as the canopy under 314 examination. AGB was calculated with individual-tree allometric equations (Repola, 2008; Repola, 2009; Yarie et al., 2007), 315 similarly as the foliage biomass.

316

317 In the next phase, all simulations were repeated assuming black soil (i.e., a totally absorbing background), in order to better 318 explain the dependencies of albedo on tree height and illumination conditions as well as to explain the differences of albedo 319 between Alaskan and Finnish forests. The albedo obtained in black soil simulation represents the plain canopy albedo 320 without the contribution of forest floor vegetation. We refer to this as "canopy contribution". Correspondingly, the 321 contribution of forest floor can be calculated by subtracting the canopy contribution from the albedo obtained when 322 assuming a vegetated forest floor. We refer to this as "forest floor contribution". Canopy and forest floor contributions can 323 be expressed as absolute values or relative values which sum up to 100%. For comparison with the results regarding albedo, 324 the forest floor contribution to total ecosystem FAPAR was also calculated, by subtracting FAPAR_{CAN} from FAPAR_{TOT}.

326 We report the relationships of albedo and FAPAR against forest structure in Sect. 3.1. Results of these experiments are

327 needed for understanding the relations between albedo and FAPAR, which we report in Sect. 3.2.

328 2.3.2 Relative importance of density and tree species

329 To examine the relative importance of density and species composition, we analyzed albedo and FAPAR_{CAN} against basal 330 area and the proportion of broadleaved trees. The analyses were performed separately for Alaska and Finland, and repeated 331 for all simulated solar illumination conditions. We excluded all plots with tree height less than 10 m from the analyses in order to evaluate the effect of basal area independent of tree height. This was done based on the following reasoning. Basal 332 area was correlated with tree height when studying all plots (r = 0.61 (Alaska), r = 0.64 (Finland)). Preliminary analysis was 333 334 performed by successively removing plots with smallest trees and each time checking the correlation between height and 335 basal area. The correlation was reduced until a height threshold of 10 m (r = 0.40 (Alaska), r = 0.34 (Finland)) (cf. Fig. 2). 336 Therefore, the 10 m threshold was used to exclude the smallest trees from our analyses. Analysis of albedo and FAPAR against basal area in this restricted set of plots gives an approximation of how thinnings would affect albedo and FAPAR_{CAN} 337 338 although in reality thinning a stand affects not only the basal area but also the spatial pattern and size distribution of trees.

339

340 Mean and standard deviation (SD) of albedo and FAPAR_{CAN} in conifer-dominated forests were calculated for ten equally 341 spaced classes with respect to basal area. The center of the lowest class corresponded to the 5th and that of the highest class 342 to the 95th percentile of basal area in the data. To examine the effect of broadleaved proportion, mean and SD of albedo and 343 FAPAR_{CAN} were calculated for ten equally spaced classes with respect to proportion of broadleaved trees, i.e. the 344 broadleaved proportions ranging from 0-10% to 90-100%. The analysis was repeated for sparse (basal area percentiles from 345 0th to 30th) and dense forest (basal area percentiles from 70th to 100th). We hypothesized that the proportion of broadleaved 346 trees would have smaller effect on albedo in sparse than in dense forest, because the forest floor has more significant role in 347 the sparse canopies. Results regarding the analysis of basal area and proportion broadleaved trees are reported in Sect 3.3.

348 3 Results

349 3.1 Albedo, FAPAR, and forest structure

Mean albedo of study plots in Alaska (0.141–0.184) was higher than in Finland (0.136–0.171). In general, the albedo of broadleaved species was 42–130% higher than that of coniferous (Table 4). However, albedo varied greatly even among coniferous species: in Alaska, the albedo of black spruce was 19–33% higher than that of white spruce, and in Finland, the albedo of Scots pine forests was 20–31% higher than that of Norway spruce. Overall, the mean albedo of coniferous species was 28–32% higher in Finland (0.131–0.161) than in Alaska (0.102–0.122). The mean albedos of broadleaved species in Alaska did not differ significantly from each other (p > 0.05 in ANOVA), except in the white-sky case. Therefore the 356 broadleaved species were treated as one group hereafter. Increasing the SZA increased the black-sky albedos of all species

357 (Table 4).

358

359 The forest canopies in Alaska absorbed more PAR radiation than in Finland: mean FAPAR_{CAN} in Alaska was 0.71–0.92 and in Finland 0.63–0.89. At the smallest SZA (40°) in black-sky simulations, FAPAR_{CAN} was highest for broadleaved species in 360 361 Alaska, followed by Norway spruce in Finland, white spruce in Alaska, and broadleaved in Finland (Table 4). Scots pine in 362 Finland and black spruce in Alaska had lowest FAPAR_{CAN} among the species. The mean FAPAR_{CAN} of broadleaved species in Alaska did not differ significantly from each other in any of the simulated illumination conditions (p > 0.05 in ANOVA). 363 364 Increasing the SZA increased FAPAR_{CAN} of all species and also reduced the differences between species. The relative increase was smaller for broadleaved than for coniferous species. Therefore, the order of species in FAPAR_{CAN} was different 365 366 at small and large SZAs (Table 4). FAPAR_{TOT}, an approximation of total ecosystem productivity, ranged from 0.93 to 0.98 367 and did not depend strongly on direction of illumination. FAPAR_{TOT} of coniferous forests was higher than that of 368 broadleaved but the differences were not large in relative terms because FAPAR_{TOT} was consistently high.

369

370 White-sky albedo corresponded best with black-sky albedo observed at SZA of 60° (r = 0.97, RMSE = 0.011, mean 371 difference = -0.001). It correlated strongly also with black-sky albedos observed at other SZAs ($r \ge 0.93$). White-sky 372 FAPAR_{CAN} corresponded best with black-sky FAPAR_{CAN} observed at SZA of 40° (r = 1.00, RMSE = 0.04, mean difference = 0.03) and very closely also with those observed at SZAs of 50° and 60°. On the other hand, it deviated notably from the 373 374 black-sky FAPAR_{CAN} observed at SZAs of 70° and 80°. Because white-sky albedo and FAPAR were highly correlated with 375 their black-sky counterparts observed at small to moderate SZAs, we report the results hereafter for black-sky conditions 376 only, except for contribution of forest floor (Table 5) that is presented also for white-sky case, in order to maintain 377 comparability with results presented in Table 4.

378

Albedo decreased with increasing tree height in coniferous forests (Fig. 4). The decrease was most rapid at small tree heights and saturated after the height reached approximately 10 m. When SZA increased, the difference in albedo between short and tall forests became smaller (compare Fig. 4a,b to Fig. 4c,d). The albedo of broadleaved forests was similar for all tree heights at the smallest SZA (40°). At large SZAs, however, there was an initial rapid increase in albedo for broadleaved forests with small trees (Fig. 4d), after which the albedo remained stable. AGB was correlated with tree height (r = 0.72-0.78) and the albedo responded to AGB with a similar saturating trend as in the case of tree height (Fig. 4e,f).

385

FAPAR_{CAN} initially increased with increasing tree height, but saturated at large tree heights (Fig. 5). The saturation was reached earlier and the maximum level of FAPAR_{CAN} was higher at large SZAs. Similar saturating trends and SZA dependencies were observed also against AGB although there was less variation in the y direction (Fig. 5e,f). FAPAR_{TOT} increased as function of tree height in coniferous forests, and was stable in broadleaved forests (Fig. 6). However, the variation in FAPAR_{TOT} with tree height was small (values ranging from 0.93 to 0.98).

391

392 The average contribution of forest floor to total forest albedo depended on tree species and ranged from 4% to 53% (Table 393 5). It was largest at small SZAs and for tree species that had low LAI_{eff} (see LAI_{eff} values in Table 1). Forest floor 394 contribution decreased as a function of tree height (Fig. 7). The relation was even tighter when the forest floor contribution 395 was analyzed against LAI_{eff} (not shown). This is logical because LAI_{eff} is more directly linked with canopy transmittance 396 than is tree height. Increasing the SZA increased the canopy contribution in all plots. This caused the albedo to increase In 397 general, the net effect was an increase of albedo as a function of SZA. Only a few sparse canopies (low LAI_{eff}) were an 398 exception. In these plots, an increase in SZA reduced the forest floor contribution more than it increased the canopy 399 contribution. Results regarding contribution of forest floor to total ecosystem FAPAR were similar as those observed for 400 albedo, i.e. there were differences between tree species and decreasing trends with increasing SZA (Table 5).

401

The differences in albedos between coniferous species, i.e. black spruce vs. white spruce, and Scots pine vs. Norway spruce, were almost non-existent when comparing albedos obtained in black soil simulations (Table 5). This indicates that at least some of the differences in albedos between coniferous species are explained by the varying forest floor contribution between species. However, the differences in albedos between coniferous forests of Finland and Alaska remained, indicating that other factors than forest floor influenced the species differences between the study areas.

407

408 FAPAR_{CAN} varied notably more than albedo when comparing forests of same height, particularly at small SZAs (Fig. 4, Fig. 409 5). This can be explained by the link of $FAPAR_{CAN}$ with canopy interception. Interception was tightly related with LAI_{eff} (not 410 shown), and it determined FAPAR_{CAN} almost directly, because the foliage absorbed strongly at PAR wavelengths (Fig. 3a) 411 and therefore the multiple scattering was negligible. LAI_{eff} , in turn, varied considerably between forests of same height. The 412 outliers (tall trees, low FAPAR_{CAN}) in Fig. 5d were plots that had only few trees and therefore very low LAI_{eff}. Similarly, 413 Scots pine had lower FAPAR_{CAN} compared to other species with same height (Fig. 5d). Further examination revealed that Scots pine had short crowns and therefore low LAI_{eff}, although the leaf area per unit crown volume did not differ from the 414 other coniferous species. The strong link between $FAPAR_{CAN}$ and LAI_{eff} explained also the observed species- and SZA 415 416 dependencies of FAPAR_{CAN}. At the lowest SZA (40°) the species-specific FAPAR_{CAN} (Table 4) was strongly correlated with species-specific LAI_{eff} (Table 1) (r = 0.93). At large SZAs the canopy interception approached 100% at almost all LAI_{eff} 417 values (cf. Fig. 5c,d) and FAPAR_{CAN} was therefore mainly determined by the absorption of the foliage at PAR wavelengths. 418 419 Leaves of broadleaved trees absorbed less than conifer needles, which explains why FAPAR_{CAN} of broadleaved species did 420 not increase as rapidly as a function of SZA as did FAPAR_{CAN} of coniferous species (Table 4).

421 3.2 Relation of albedo to FAPAR

422 FAPAR_{CAN} was negatively correlated with albedo in conifer dominated forests (Fig. 8). The correlation was strongest at the 423 smallest SZA (r = -0.91, r = -0.90) and weakest at the largest SZA (r = -0.63, r = -0.59). When including mixed plots and the 424 plots dominated by broadleaved trees, correlation of FAPAR_{CAN} to albedo varied from almost non-existent in Alaska (r 425 ranging from -0.17 to 0.07) to moderate in Finland (r ranging from -0.62 to -0.30). The higher correlation in Finland can be 426 explained by the small number of broadleaved dominated forests in our data from Finland. In addition to the proportion of 427 broadleaved trees, variation in forest floor characteristics influenced the albedo-FAPAR_{CAN} relations by altering the albedo values (Fig. 8). The effect of forest floor was seen in relatively sparse canopies only. For example, at SZA of 40° the effect 428 429 of forest floor on albedo started to show at FAPAR_{CAN} values below 0.5 (Fig. 8). Remembering that FAPAR_{CAN} was tightly 430 related to LAI_{eff}, this value corresponds LAI_{eff} of approx. 1. FAPAR_{TOT} was strongly and negatively correlated with albedo (r ranging from -0.97 to -0.88). The only plots that deviated from this otherwise strong relation were those Scots pine plots that 431 432 had low FAPAR_{TOT} and xeric forest floor.

433 **3.3** Relative importance of density and tree species

The variation in density of forests was larger in Alaska than in Finland; the 5th and 95th percentiles of basal area were 8 and 434 43 m² ha⁻¹ in Alaska, and 10 and 34 m² ha⁻¹ in Finland. In both study areas, decrease in basal area resulted in higher albedo 435 but lower FAPAR_{CAN}. At the smallest SZA (40°) the decrease in basal area from its 95th to 5th percentile resulted in increase 436 of albedo by 36% in Alaska and by 21% in Finland (Fig. 9). Correspondingly, FAPAR_{CAN} decreased by 48% in Alaska and 437 by 44% in Finland. When SZA increased, the response of FAPAR_{CAN} to basal area became weaker. For example, at SZA of 438 70° the basal area could be reduced to approx. $20 \text{ m}^2 \text{ ha}^{-1}$ with equal relative changes in albedo and FAPAR_{CAN} (Fig. 9b). At 439 the largest SZA (80°) both albedo and FAPAR_{CAN} varied very little (max. 6%) between the 5th and 95th basal area 440 441 percentiles. In other words, the effect of basal area depended strongly on SZA. However, the relative decrease of FAPAR_{CAN} 442 with decreasing basal area was always larger than or equal to the relative increase in albedo.

443

444 Increasing the proportion of broadleaved trees increased the albedos considerably more than did reduction in basal area (Fig. 445 9c,d). The effect of broadleaved trees was slightly smaller in sparse than in dense forests. For example, at SZA of 40°, increasing the broadleaved proportion from 0-10% to 90-100% resulted in relative increase of albedo by 130% (in Alaska) 446 447 and 80% (in Finland) in forests with high basal area (i.e., basal area percentiles from 70th to 100th). In forests with low basal 448 area (i.e., basal area percentiles from 0th to 30th) the corresponding figures were 112% (Alaska) and 71% (Finland). The 449 smaller relative increase in Finland is explained by the higher albedo of Finnish coniferous forests, because the albedos of 450 broadleaved species did not differ between Alaska and Finland. FAPAR_{CAN} was almost independent on the proportion of broadleaved trees, except for large SZAs where FAPAR_{CAN} tended to decrease slightly when broadleaved proportion 451

452 increased (Fig. 9d). This is explained by the fact that at large SZAs FAPAR_{CAN} was mainly determined by the absorption of

453 canopy elements, and the absorption was lower for broadleaved than for coniferous trees.

454 4 Discussion

Despite recent studies published on the relationships between albedo and boreal forest structure, and despite the widespread use of FAPAR to monitor vegetation productivity, the physical link between forest albedo and productivity has been poorly understood. To our knowledge, the relationship between these two quantities has not been quantified earlier for an extensive geographical area. Another gap in the discussion has been the role of latitude: solar paths vary across the biome, and therefore, need to be taken into account before making any generalizations on how altering forest structure through silvicultural operations can be used to influence albedo (and furthermore, climate).

461

462 Our results show that albedo and FAPAR_{CAN} are tightly linked in boreal coniferous forests. The prerequisites for this are that 463 there is only a limited proportion of broadleaved trees present in the forest and that the tree canopy is not very sparse (i.e. 464 LAI is not very low). The explanation for the tight connection between albedo and FAPAR_{CAN} is that they respond with 465 opposite trends to forest structural variables. However, the shapes of these trends depended on directional characteristics of 466 the incoming solar radiation which was also reflected in the albedo vs. FAPAR_{CAN} relations. This underlines the importance 467 of taking into account latitude and season (i.e. solar angle) when evaluating climate impacts of forests even within one 468 biome. FAPAR_{TOT} was also tightly linked with albedo. Because FAPAR_{TOT} equals one minus PAR albedo, this finding 469 indicates that PAR albedo and shortwave albedo of vegetation are correlated. However, the overall variation in FAPAR_{TOT} 470 was small in magnitude. Our results differ slightly from those observed by Lukeš et al. (2016) who compared satellite-based 471 (MODIS) albedo and FAPAR in Finland and observed much weaker (but still negative) correlation between these quantities. 472 The spatial resolution in their study (1×1 km) was coarser than in our study, and the FAPAR definition differed: MODIS 473 FAPAR is defined as PAR absorbed by green elements of vegetation canopy, both trees and understory included. In addition, 474 Lukeš et al. (2016) did not separate coniferous and broadleaved trees, although this effect is likely minor since the proportion 475 of broadleaved trees is on average low in Finland. Finally, simulation model used here, although parameterized by field 476 observations, cannot capture all the variability in real forests, and on the other hand, satellite products are likely to include 477 observation and modelling errors that increase the noise in the data.

478

The responses of albedo to tree species and forest structure were similar across the biome in Alaska and Finland. This corroborates findings in previous, local studies (Amiro et al., 2006; Bright et al., 2013; Lukeš et al., 2014; Kuusinen et al. 2014; Kuusinen et al., 2016). Also the results regarding overall level of FAPAR_{CAN}, and the dependence of FAPAR_{CAN} on tree species were similar to earlier studies (Roujean, 1999; Steinberg et al., 2006). However, as our study was based on extensive field data from two continents, drawing more general conclusions on how forest structure, albedo and productivity 484 are interconnected is now possible. In addition, to our knowledge only one study has previously evaluated the forest floor 485 contribution to albedo (Kuusinen et al., 2015). We showed that forest floor vegetation (which is often in practical forestry 486 e.g. a proxy for site fertility type) can significantly contribute to forest albedo; its average contribution can be up to 50%, 487 varving between forests dominated by different tree species. Similarly, the average contribution of forest floor to total ecosystem FAPAR can be up to or even over 50%, as reported previously also by Ikawa et al. (2015) for an eddy-covariance 488 489 study site in Alaska. In other words, even though forest floor vegetation often contributes only little to, for example, total 490 forest biomass, it can have a significant role as a key driving factor of forest albedo and ecosystem productivity. Quantifying 491 the variation in forest floor composition and optical properties across the boreal biome constitutes therefore an important 492 research topic in the future. The important role of forest floor means also that any forest management that influences forest 493 floor composition can significantly alter the biophysical climate effects of forests. For example, reindeer grazing has been 494 suggested to reduce land surface albedo, because it reduces the cover of reindeer lichens that have higher albedo compared to 495 mosses (Stoy et al., 2012).

496

497 The black soil simulations that we conducted in order to quantify the contribution of forest floor explained also why the 498 albedo increased as a function of solar zenith angle. From previous simulation studies it is known that when the sun 499 approaches the horizon, the path length of radiation and therefore scattering from the canopy layer increase while the 500 contribution of forest floor decreases (Kimes et al., 1987; Ni & Woodcock, 2000). The net effect is dependent on the density 501 (gap fractions) of the canopy layer, and on the reflectance of the forest floor: if the canopy is sparse or clumped, or if the 502 reflectance of the forest floor is high, it is likely that increasing the solar zenith angle reduces the forest floor contribution more than it increases the scattering from canopy. Our results generalize the findings of these previous studies that examined 503 504 only few stands locally. It should be noted that our results apply only to summertime conditions. If the forest floor has high 505 reflectance due to e.g. snow cover, a decrease of albedo as a function of solar zenith angle is expected to be observed more 506 often (Ni & Woodcock, 2000).

507

508 We observed some interesting differences between Alaskan and Finnish datasets which deserve to be highlighted. Even 509 though our field data do not represent a probability sample they are still well representative of the forests in the study areas. 510 The mean albedo was higher in Alaska than in Finland, because of the higher proportion of broadleaved species in Alaska. 511 However, the coniferous forests in Alaska had lower albedos than those in Finland. There is some previous evidence to support this, because the lowest values reported by Amiro et al. (2006) for spruce forests in Alaska are lower than those 512 reported by Kuusinen et al. (2014) for spruce in Finland. Because the difference remained also when assuming black soil, the 513 514 reason is in the properties of the canopy layer. Particularly, the low reflectance of bark in the Alaskan species (Fig. 3b) 515 explains part of the difference.

517 Radiative transfer models offer a useful tool for assessing the radiation regime of forests, especially when the modeling 518 approach can utilize readily available common forest inventory databases. Validating the simulated albedo and FAPAR 519 values, however, is challenging. Even though international model intercomparison efforts such as RAMI (Widlowski et al., 520 2007) provide a rigorous set of reports on performance of radiative transfer models, the quality of available input data in 521 each study where a radiative transfer model is applied is crucial. For example, the forest floor albedos that we calculated 522 from the available reflectance spectra (Fig. 3) were clearly higher (0.18–0.23) than forest floor albedos measured in the field 523 at other boreal sites (approx. 0.15 in Manninen & Riihelä, 2008; Manninen & Riihelä, 2009; Kuusinen et al., 2014). If we 524 had scaled our reflectance factors in order to obtain forest floor albedos of 0.15, the simulated forest albedos would have 525 decreased by 7–10%. Furthermore, including also the UV region in the simulations would have reduced the simulated 526 albedos by up to 7%, assuming that the optical properties of the canopy and forest floor are similar at UV than at 400 nm. 527 However, particularly the lack of field measured spectra for some of the Alaskan species is a limitation of our study and 528 shows that there is an urgent need for comprehensive spectral database of boreal tree species.

529

530 Our results regarding basal area give an idea of the magnitude of the effects that varying thinning regimes could have on 531 forest albedo and productivity. The effect of thinnings on albedo have previously been estimated mainly by in situ 532 measurements at few selected sites (Kirschbaum et al., 2011; Kuusinen et al., 2014). In our study, reduction in the basal area 533 reduced FAPAR_{CAN} equally or more compared to how albedo changed. In contrast to basal area, the proportion of 534 broadleaved trees had a notably larger effect on forest albedo while having only a negligible influence on forest productivity 535 (FAPAR_{CAN}). The relative importance of basal area and tree species nevertheless depends on the spectral properties of the 536 tree species and forest floor. Based on our results, the effect of thinning (removal of basal area) on albedo and FAPAR 537 depends on solar angle. Therefore, the influence of thinning on forest productivity differs between latitudes. Furthermore, 538 because the basal area influenced albedo and FAPAR_{CAN} less at large sun zenith angles, the effects of thinning integrated 539 over entire rotation period may not be as large as they seem when studying them only at solar noon.

540

541 Global satellite products have provided us insight on coarse-scale trends of albedo in different biomes. However, their 542 weakness is that even though we can establish correlations between changes in albedo and changes in land cover, we are still 543 not able to identify and quantify the biophysical factors which cause the albedo of a forest area to change. In addition, a 544 specific challenge in coupling forest management operations with changes in satellite-based albedo products is that the scale 545 of these operations significantly differs in North America and Northern Europe, and often does not directly correspond to the 546 spatial resolution of current albedo products. With an understanding of the consequences of, for example, forest management 547 practices on the albedo, best-practice recommendations for forest management in future climate mitigation policies will 548 become more justified. By coupling extensive field inventory data sets and radiative transfer modeling, we showed that 549 albedo and FAPAR_{CAN} are tightly linked in boreal coniferous forests at stand level. However, the relation is weaker if the forest has deciduous admixture, or if the canopies are sparse and at the same time the species composition (i.e. optical 550

properties) of the forest floor vary. Because the shape of the relationship between albedo and FAPAR_{CAN} was shown to depend on solar angle, studies evaluating the climate effects of forest management strategies need to consider latitudinal effects due to varying solar paths. The comparisons between Alaska and Finland revealed that albedo and FAPAR_{CAN} differ between geographical regions because of the differences in forest structure. However, regardless of geographical region in the boreal zone, the potential of using thinning to increase forest albedo may be limited compared to the effect of favoring broadleaved species.

557 Data availability

558 Data from Co-operative Alaska Forest Inventory prior to 2009 are available at LTER Network Data Portal 559 (<u>http://dx.doi.org/10.6073/pasta/d442e829a1adf7da169b6076826de563</u>). Forest inventory data from Finland are described in 560 Korhonen (2011) and Majasalmi et al. (2015). Leaf and needle optical properties measured in Hyytiälä are reposited at 561 SPECCHIO database (<u>http://www.specchio.ch/</u>), and those measured in Superior National Forest are reposited at ORNL 562 DAAC by NASA (<u>http://dx.doi.org/10.3334/ORNLDAAC/183</u>). Forest floor spectra were presented in Fig. 3 of this 563 manuscript.

564 Acknowledgments

This study was funded in parts by the Academy of Finland projects BOREALITY and SATLASER, and by the Davis College of Agriculture, Natural Resources & Design, West Virginia University, under the US Department of Agriculture (USDA) McIntire–Stennis Funds WVA00106. We thank Petr Lukeš and Matti Mõttus for advice on radiative transfer modeling, and Titta Majasalmi, Pekka Voipio, Jussi Peuhkurinen and Maria Villikka for organizing the measurements of field plots in Finland. We also thank the School of Natural Resources and Agricultural Sciences, University of Alaska for the establishment and maintenance of the Co-operative Alaska Forest Inventory. The forest floor reflectances at Poker Flag Research Range were obtained under the JAMSTEC and IARC/UAF collaborative study (PI: Rikie Suzuki).

572 **References**

Alkama, R. and Cescatti, A.: Biophysical climate impacts of recent changes in global forest cover, Science, 351, 600–604,
2016.

575 Amiro, B. D., Orchansky, A. L., Barr, A. G., Black, T. A., Chambers, S. D., Chapin, F. S., Goulden, M. L., Litvak, M., Liu,

576 H. P., McCaughey, J. H., McMillan, A. and Randerson, J. T.: The effect of post-fire stand age on the boreal forest energy

577 balance, Agric. For. Meteorol., 140, 41–50, 2006.

- 578 Bird, R. E. and Riordan, C.: Simple Solar Spectral Model for Direct and Diffuse Irradiance on Horizontal and Tilted Planes
- 579 at the Earth's Surface for Cloudless Atmospheres, J. Clim. Appl. Meteorol., 25, 87–97, 1986.Bond-Lamberty, B., Wang, C.,
- 580 Gower, S. T. and Norman, J.: Leaf area dynamics of a boreal black spruce fire chronosequence., Tree Physiol., 22, 993-
- 581 1001, 2002.
- 582 Bragg, D. C.: A local basal area adjustment for crown width prediction, North. J. Appl. For., 18, 22–28, 2001.
- 583 Bright, R. M., Antón-Fernández, C., Astrup, R., Cherubini, F., Kvalevåg, M. and Strømman, A. H.: Climate change
- implications of shifting forest management strategy in a boreal forest ecosystem of Norway, Glob. Chang. Biol., 20, 607–
 621, 2014.
- Bright, R. M., Astrup, R. and Strømman, A. H.: Empirical models of monthly and annual albedo in managed boreal forests
 of interior Norway, Clim. Change, 120, 183–196, 2013.
- 588 Cajander, A. K.: Forest types and their significance. Acta Forestalia Fennica, 56, 1–71, 1949.
- 589 Chasmer, L., Hopkinson, C., Treitz, P., McCaughey, H., Barr, A. and Black, A.: A lidar-based hierarchical approach for
- 590 assessing MODIS fPAR, Remote Sens. Environ., 112, 4344–4357, 2008.
- 591 Davidson, A. and Wang, S.: The effects of sampling resolution on the surface albedos of dominant land cover types in the
 592 North American boreal region, Remote Sens. Environ., 93, 211–224, 2004.
- 593 Gobron, N., Verstraete, M.M.: Assessment of the status of the development of the standards for the terrestrial essential
- climate variables. T10 Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). V8, GTOS65, pp. 1–24. NRC,
 FAO, Rome, Italy, 2009.
- 596 Hall, F. G., Huemmrich, K. F., Strebel, D. E., Goetz, S. J., Nickeson, J. E., and Woods, K. D.: SNF Leaf Optical Properties:
- 597 Cary-14. [Superior National Forest Leaf Optical Properties: Cary-14]. Data set. Available on-line [http://www.daac.ornl.gov]
- 598 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A, 1996. Based on
- 599 Hall, F. G., Huemmrich, K. F., Strebel, D. E., Goetz, S. J., Nickeson, J. E., and Woods, K. D.: Biophysical, Morphological,
- 600 Canopy Optical Property, and Productivity Data from the Superior National Forest, NASA Technical Memorandum 104568,
- 601 National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, U.S.A., 1992.
- 602 doi:10.3334/ORNLDAAC/183
- Hotanen, J-P., Nousiainen, H., Mäkipää, R., Reinikainen, A., Tonteri, T.: Metsätyypit opas kasvupaikkojen luokitteluun (In
 Finnish), pp. 1–192. Metsäkustannus Oy, Porvoo, Finland, 2013.
- 605 Ikawa, H., Nakai, T., Busey, R. C., Kim, Y., Kobayashi, H., Nagai, S., Ueyama, M., Saito, K., Nagano, H., Suzuki, R. and
- 606 Hinzman, L.: Understory CO2, sensible heat, and latent heat fluxes in a black spruce forest in interior Alaska, Agric. For.
- 607 Meteorol., 214-215, 80–90, 2015.

- 608 Jakobsons, A.: Sambandet mellan trädkronans diameter och andra trädfaktorer, främst brösthöjdsdiametern: analyser
- 609 grundade på riksskogstaxeringens provträdsmaterial (the relationship between crown diameter and other tree factors,
- 610 diameter at breast height in particular: analysis based on the sample tree material of the National Forest Inventory).
- 611 Stockholms skoghögsskolan, institutionen för skogstaxering (Rapporter och uppsatser 14), pp.1–75, 1970.
- <u>Joint Research Centre, RAdiation transfer Model Intercomparison (RAMI): http://rami-benchmark.jrc.ec.europa.eu/HTML/,</u>
 last access: 12 October 2016.
- Kimes, D. S., Sellers, P. J. and Newcomb, W. W.: Hemispherical reflectance variations of vegetation canopies and
 implications for global and regional energy budget studies, J. Clim. Appl. Meteorol., 26, 959–972, 1987.
- 616 Kirschbaum, M. U. F., Whitehead, D., Dean, S. M., Beets, P. N., Shepherd, J. D. and Ausseil, A. G. E.: Implications of
- 617 albedo changes following afforestation on the benefits of forests as carbon sinks, Biogeosciences, 8, 3687–3696, 2011.
- 618 Korhonen, L.: Estimation of boreal forest canopy cover with ground measurements, statistical models and remote sensing.
- 619 Dissertationes Forestales, 115, 1–56, 2011.
- Kull, O. and Niinemets, U.: Variations in Leaf Morphometry and Nitrogen Concentration in Betula-Pendula Roth, CorylusAvellana L and Lonicera-Xylosteum L, Tree Physiol., 12, 311–318, 1993.
- 622 Kuusinen, N., Kolari, P., Levula, J., Porcar-Castell, A., Stenberg, P. and Berninger, F.: Seasonal variation in boreal pine
- 623 forest albedo and effects of canopy snow on forest reflectance, Agric. For. Meteorol., 164, 53–60, 2012.
- Kuusinen, N., Tomppo, E. and Berninger, F.: Linear unmixing of MODIS albedo composites to infer subpixel land cover
 type albedos, Int. J. Appl. Earth Obs. Geoinf., 23, 324–333, 2013.
- Kuusinen, N., Lukeš, P., Stenberg, P., Levula, J., Nikinmaa, E. and Berninger, F.: Measured and modelled albedos in Finnish
 boreal forest stands of different species, structure and understory, Ecol. Modell., 284, 10–18, 2014.
- Kuusinen, N., Stenberg, P., Tomppo, E., Bernier, P., Berninger, F., Kuusinen, N., Stenberg, P., Berninger, F., Tomppo, E.
- and Bernier, P.: Variation in understory and canopy reflectance during stand development in Finnish coniferous forests, Can.
- 630 J. For. Res, 45, 1077–1085, 2015.
- Kuusinen, N., Stenberg, P., Korhonen, L., Rautiainen, M. and Tomppo, E.: Structural factors driving boreal forest albedo in
 Finland, Remote Sens. Environ., 175, 43–51, 2016.
- 633 Kuusk, A. and Nilson, T.: A directional multispectral forest reflectance model, Remote Sens. Environ., 72, 244–252, 2000.
- 634 Lang, M., Kuusk, A., Nilson, T., Lükk, T., Pehk, M., Alm, G.: Reflectance spectra of ground vegetation in sub-boreal
- 635 forests. Web page. Available online. http://www.aai.ee/bgf/ger2600/ (from Tartu Observatory, Estonia. Accessed 6 Feb,
- 636 2013), 2002.

- 637 Lang, M., Nilson, T., Kuusk, A., Kiviste, A. and Hordo, M.: The performance of foliage mass and crown radius models in
- forming the input of a forest reflectance model: A test on forest growth sample plots and Landsat 7 ETM+ images, Remote
 Sens. Environ., 110, 445–457, 2007.
- Liang, J., Zhou, M., Tobin, P. C., McGuire, A. D. and Reich, P. B.: Biodiversity influences plant productivity through nicheefficiency., Proc. Natl. Acad. Sci. U. S. A., 112, 5738-5743, 2015.
- Lukeš, P., Stenberg, P. and Rautiainen, M.: Relationship between forest density and albedo in the boreal zone, Ecol. Modell.,
 261-262, 74–79, 2013a.
- Lukeš, P., Stenberg, P., Rautiainen, M., Mõttus, M. and Vanhatalo, K. M.: Optical properties of leaves and needles for boreal
- tree species in Europe, Remote Sens. Lett., 4, 667–676, 2013b.
- 646 Lukeš, P., Rautiainen, M., Manninen, T., Stenberg, P. and Mõttus, M.: Geographical gradients in boreal forest albedo and
- 647 structure in Finland, Remote Sens. Environ., 152, 526–535, 2014.
- 648 Lukeš, P., Stenberg, P., Mõttus, M. and Manninen, T.: Multidecadal analysis of forest growth and albedo in boreal Finland,
- 649 Int. J. Appl. Earth Obs. Geoinf., 52, 296–305, 2016.
- 650 Majasalmi, T., Rautiainen, M. and Stenberg, P.: Modeled and measured fPAR in a boreal forest: Validation and application
- 651 of a new model, Agric. For. Meteorol., 189-190, 118–124, 2014.
- 652 Majasalmi, T., Rautiainen, M., Stenberg, P. and Manninen, T.: Validation of MODIS and GEOV1 fPAR Products in a
- Boreal Forest Site in Finland, Remote Sens., 7, 1359–1379, 2015.
- 654 Malone, T., Liang, J., Packee, E.C.: Cooperative Alaska Forest Inventory. General Technical Report PNW-GTR-785, USDA
- 655 Forest Service, Pacific Northwest Research Station, 32 Portland, OR, pp. 1–58, 2009.
- 656 Manninen, T., Riihelä, A.: Subarctic boreal forest albedo estimation using ENVISAT ASAR for BRDF determination.
- 657 Proceedings of IGARSS'08, July 6 11, 2008, CD, p. 1–4, 2008.
- 658 Manninen, T., Riihelä, A.: ENVISAT/ASAR VV/HH backscattering and the radiation characteristics of Subarctic boreal
- forest. Proceedings of PolInSAR 2009, 26–30 January 2009, Frascati, Italy, Special publication of ESA SP-668, pp. 1–8,
 2009.
- 661 Monteith, J. L.: Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology, 9, 744–766, 1972.
- 662 Mõttus, M., Stenberg, P. and Rautiainen, M.: Photon recollision probability in heterogeneous forest canopies: Compatibility
- with a hybrid GO model, J. Geophys. Res. Atmos., 112, 1–10, 2007.
- 664 Naudts, K., Chen, Y., McGrath, M. J., Ryder, J., Valade, A., Otto, J., Luyssaert, S.: Europe's forest management did not
- 665 mitigate climate warming. Science, 351, 597–601, 2016.

- Ni, W. and Woodcock, C. E.: Effect of canopy structure and the presence of snow on the albedo of boreal conifer forests, J.
 Geophys. Res., 105, 11879, 2000.
- 668 Nilson, T.: Inversion of gap frequency data in forest stands, Agric. For. Meteorol., 98-9, 437–448, 1999.
- 669 Nilson T. and Peterson U.: A forest canopy reflectance model and a test case. Remote Sens. Environ. 37, 131–142, 1991.
- 670 Palmroth, S. and Hari, P.: Evaluation of the importance of acclimation of needle structure, photosynthesis, and respiration to
- 671 available photosynthetically active radiation in a Scots pine canopy, Can. J. For. Res., 31, 1235–1243, 2001.
- 672 Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L.,
- 673 Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S. and Hayes, D.: A
- 674 Large and Persistent Carbon Sink in the World's Forests, Science, 333, 988–993, 2011.
- 675 Rautiainen, M., Suomalainen, J., Mõttus, M., Stenberg, P., Voipio, P., Peltoniemi, J. and Manninen, T.: Coupling forest
- 676 canopy and understory reflectance in the Arctic latitudes of Finland, Remote Sens. Environ., 110, 332–343, 2007.
- Rautiainen, M., Mottus, M., Stenberg, P. and Ervasti, S.: Crown envelope shape measurements and models, Silva Fenn., 42,
 19–33, 2008.
- 679 Rautiainen, M., Mõttus, M., Heiskanen, J., Akujärvi, A., Majasalmi, T. and Stenberg, P.: Seasonal reflectance dynamics of
- 680 common understory types in a northern European boreal forest, Remote Sens. Environ., 115, 3020–3028, 2011.
- Rautiainen, M., Mõttus, M., Yáñez-Rausell, L., Homolová, L., Malenovský, Z. and Schaepman, M. E.: A note on upscaling
 coniferous needle spectra to shoot spectral albedo, Remote Sens. Environ., 117, 469–474, 2012.
- Rautiainen, M., Stenberg, P., Nilson, T. and Kuusk, A.: The effect of crown shape on the reflectance of coniferous stands,
 Remote Sens. Environ., 89, 41–52, 2004.
- 685 Reich, P. B., Ellsworth, D. S., Walters, M. B., Vose, J. M., Gresham, C., Volin, J. C. and Bowman, W. D.: Generality of leaf
- trait relationships: A test across six biomes, Ecology, 80, 1955–1969, 1999.
- 687 Repola, J.: Biomass equations for birch in Finland, Silva Fenn., 42, 605–624, 2008.
- 688 Repola, J.: Biomass equations for Scots pine and Norway spruce in Finland, Silva Fenn., 43, 625–647, 2009.
- Richardson, A. D., Berlyn, G. P. and Duigan, S. P.: Reflectance of Alaskan black spruce and white spruce foliage in relation
 to elevation and latitude, Tree Physiol., 23, 537–544, 2003.
- Roujean, J. L.: Measurements of PAR transmittance within boreal forest stands during BOREAS, Agric. For. Meteorol., 93,
 1–6, 1999.
- Schaaf, C. B.: Assessment of the status of the development of the standards for the terrestrial essential climate variables. T8
 albedo and reflectance anisotropy. V12, GTOS63, pp. 1–20 NRC, FAO, Rome, 2009.

- Serbin, S. P., Ahl, D. E. and Gower, S. T.: Spatial and temporal validation of the MODIS LAI and FPAR products across a
 boreal forest wildfire chronosequence, Remote Sens. Environ., 133, 71–84, 2013.
- Sigurdsson, B. D., Thorgeirsson, H. and Linder, S.: Growth and dry-matter partitioning of young Populus trichocarpa in
 response to carbon dioxide concentration and mineral nutrient availability., Tree Physiol., 21, 941–50, 2001.
- Smolander, H., Stenberg, P. and Linder, S.: Dependence of light interception efficiency on structural parameters, TreePhysiol., 14, 971–980, 1994.
- Steinberg, D., Goetz, S. and Hyer, E.: Validation of MODIS FPAR products in boreal forests of Alaska, IEEE Trans. Geosci.
 Remote Sens., 44, 1818–1828, 2006.
- Stenberg, P., Kangas, T., Smolander, H. and Linder, S.: Shoot structure, canopy openness, and light interception in Norway
 spruce, Plant, Cell Environ., 22, 1133–1142, 1999.
- Stenberg, P., Linder, S. and Smolander, H.: Variation in the ratio of shoot silhouette area to needle area in fertilized and
 unfertilized Norway spruce trees., Tree Physiol., 15, 705–12, 1995.
- 707 Stoy, P. C., Street, L. E., Johnson, A. V, Prieto-Blanco, A. and Ewing, S. A.: Temperature, heat flux, and reflectance of
- 708 common subarctic mosses and lichens under field conditions: might changes to community composition impact climate-
- relevent surface fluxes?, Arct. Antarct. Alp. Res., 44, 500–508, 2012.
- 710 Thérézien, M., Palmroth, S., Brady, R. and Oren, R.: Estimation of light interception properties of conifer shoots by an
- 711 improved photographic method and a 3D model of shoot structure., Tree Physiol., 27, 1375–87, 2007.
- 712 Thuillier, G., Hers, M., Simon, P. C., Labs, D., Mandel, H. and Gillotay, D.: Observation of the solar spectral irradiance
- from 200 nm to 870 nm during the ATLAS 1 and ATLAS 2 missions by the SOLSPEC spectrometer, Metrologia, 35, 689–
 695, 2003.
- 715 Widlowski, J. L., Taberner, M., Pinty, B., Bruniquel-Pinel, V., Disney, M., Fernandes, R., Gastellu-Etchegorry, J. P.,
- 716 Gobron, N., Kuusk, A., Lavergne, T., Leblanc, S., Lewis, P. E., Martin, E., Mõttus, M., North, P. R. J., Qin, W., Robustelli,
- 717 M., Rochdi, N., Ruiloba, R., Soler, C., Thompson, R., Verhoef, W., Verstraete, M. M. and Xie, D.: Third Radiation Transfer
- 718 Model Intercomparison (RAMI) exercise: Documenting progress in canopy reflectance models, J. Geophys. Res. Atmos.,
- 719 112, 1–28, 2007.
- 720 Yang, W., Kobayashi, H., Suzuki, R. and Nasahara, K.: A Simple Method for Retrieving Understory NDVI in Sparse
- 721 Needleleaf Forests in Alaska Using MODIS BRDF Data, Remote Sens., 6, 11936–11955, 2014.
- Yarie, B. J., Kane, E., Hall, B.: Aboveground Biomass Equations for the Trees of Interior Alaska. AFES Bulletin, 115, 1–16,
 2007.

724 Table 1. Mean (standard deviation) of forest variables by dominant tree species in Alaska and Finland. The species

725 dominance was determined by basal area proportion: If the basal area of one of the species exceeded 80% of the total basal

Tree species	Number of plots	Stems per hectare	Diameter at breast	Height (m)	Crown ratio (%)	Basal area (m ² ha ⁻¹)	Effective LAI (m ² m ⁻²)
	1		height		2)		3)
			(cm) ¹⁾				
			Alaska				
Black spruce	70	2361 (1542)	9.3 (3.8)	7.3 (3.2)	69 (11)	14.6 (9.3)	1.0 (0.6)
White spruce	124	806 (653)	21.3 (7.9)	14.7 (5.2)	74 (9)	22.8 (13.1)	2.4 (1.3)
Quaking aspen	22	1572 (916)	15.8 (5.1)	13.9 (3.5)	37 (7)	26.0 (8.8)	2.8 (0.9)
Black cottonwood/	8	672 (658)	35.1 (14.7)	20.5 (5.8)	62 (11)	34.8 (14.5)	2.7 (1.1)
balsam poplar							
Birches	84	873 (662)	22.6 (8.4)	17.5 (2.9)	58 (11)	25.1 (8.1)	3.2 (1.4)
Mixed	276	1082 (1131)	22.0 (8.3)	15.1 (3.9)	62 (12)	25.2 (10.1)	2.7 (1.2)
All	584	1160 (1139)	20.3 (9.0)	14.4 (4.9)	64 (13)	23.6 (11.0)	2.5 (1.3)
Finland							
Scots pine	184	1165 (1301)	18.0 (8.5)	14.7 (6.4)	51 (16)	15.9 (7.7)	1.1 (0.5)
Norway spruce	115	980 (1014)	19.7 (8.9)	16.6 (6.9)	68 (15)	19.8 (9.4)	2.4 (1.1)
Broadleaved	23	1409 (1419)	13.6 (7.1)	13.9 (6.0)	62 (16)	12.6 (7.1)	1.9 (1.2)
Mixed	180	1094 (1782)	20.5 (8.0)	17.2 (5.8)	58 (14)	20.3 (9.1)	2.2 (1.1)
All	502	1109 (1444)	19.1 (8.5)	16.0 (6.4)	58 (16)	18.2 (8.9)	1.8 (1.1)

area, the plot was considered to be dominated by that species. The remaining plots were labeled as mixed.

1) Definition of breast height differed between Alaska (1.37 m) and Finland (1.3 m).

728 2) Ratio of the length of living crown to tree height.

3) Not measured in the field. The values are calculated by the FRT model.

- 730 Table 2. Number of study plots by dominant tree species and forest floor type. The species dominance was determined by
- basal area proportion: If the basal area of one of the species exceeded 80% of the total basal area, the plot was considered to
- 732 be dominated by that species.

Tree species	Forest floor					
	Grass	Shrub/moss	Lichen			
Black spruce	8	60	2			
White spruce	13	111	0			
Quaking aspen	4	18	0			
Black cottonwood/balsam poplar	2	6	0			
Birches	23	61	0			
Mixed	40	236	0			
All	90	492	2			
	Herb-rich	Mesic	Xeric			
Scots pine	2	145	37			
Norway spruce	28	86	1			
Broadleaved	8	14	1			
Mixed	26	152	2			
All	64	397	41			

Table 3. Structural input parameters used in the FRT model simula	ations.
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	Leaf mass per	Shoot shading	Shoot length	Branch area to
	area (g m ⁻²) $^{1)}$	coefficient ²⁾	$(m)^{3)}$	leaf area ratio 4)
		Alaska		
Black spruce	187	0.50	0.05	0.18
White spruce	182	0.50	0.05	0.18
Quaking aspen	57	1	0.40	0.15
Balsam poplar	86	1	0.40	0.15
Birches	54	1	0.40	0.15
		Finland		
Scots pine	158	0.59	0.10	0.18
Norway spruce	200	0.64	0.05	0.18
Broadleaved	57	1	0.40	0.15

1) Black spruce and white spruce (Reich et al., 1999), quaking aspen and birches in Alaska (Bond-Lamberty et al., 2002),

736 balsam poplar (Sigurdsson et al., 2001), Scots pine (Palmroth & Hari, 2001), Norway spruce (Stenberg et al., 1999),

737 broadleaved species in Finland (values of birch from Kull & Niinemets, 1993)

2) Projected to total needle area in a shoot. Measures the effective leaf area, taking into account the self-shading of needles in

a shoot. Black spruce and white spruce (Thérézien et al., 2007), Scots pine (Smolander et al., 1994), Norway spruce

740 (Stenberg et al., 1995)

741 3, 4) Same values as used by Lukeš et al. (2013a)

742 Table 4. Albedo, FAPAR_{CAN}, and FAPAR_{TOT} by dominant tree species and SZA. The reported value for given species is the

743 mean of plots in which the basal area proportion of that species exceeded 80%. The number of plots and mean forest

variables for each species are reported in Table 1.

Tree species	Black-sky (SZA)					White-sky		
	40°	50°	60°	70°	80°			
Albedo								
Black spruce	0.121	0.122	0.124	0.128	0.137	0.124		
White spruce	0.091	0.094	0.097	0.103	0.114	0.104		
Broadleaved (Alaska)	0.194	0.204	0.218	0.236	0.262	0.205		
Scots pine	0.144	0.147	0.152	0.159	0.172	0.151		
Norway spruce	0.110	0.114	0.120	0.128	0.141	0.126		
Broadleaved (Finland)	0.207	0.218	0.231	0.248	0.273	0.224		
FAPAR _{CAN}								
Black spruce	0.47	0.53	0.61	0.72	0.86	0.53		
White spruce	0.72	0.77	0.84	0.90	0.95	0.74		
Broadleaved (Alaska)	0.78	0.82	0.86	0.89	0.91	0.80		
Scots pine	0.50	0.57	0.65	0.75	0.86	0.55		
Norway spruce	0.73	0.79	0.84	0.89	0.92	0.74		
Broadleaved (Finland)	0.60	0.65	0.71	0.76	0.81	0.62		
FAPAR _{TOT}								
Black spruce	0.97	0.97	0.97	0.97	0.97	0.97		
White spruce	0.98	0.98	0.98	0.98	0.98	0.98		
Broadleaved (Alaska)	0.95	0.95	0.94	0.94	0.93	0.95		
Scots pine	0.97	0.97	0.97	0.97	0.96	0.96		
Norway spruce	0.97	0.97	0.97	0.97	0.97	0.97		
Broadleaved (Finland)	0.95	0.95	0.94	0.94	0.93	0.94		

746 Table 5. Canopy and forest floor contributions to albedo, and forest floor contribution to FAPAR_{TOT} by dominant tree

species and SZA. The reported value for given species is the mean of plots in which the basal area proportion of that species

748 exceeded 80%. Note that the values are directly comparable to the species specific forest albedos and FAPAR values

reported in Table 4, i.e. exactly the same plots were used to calculate the average values in both tables.

Tree species	Black-sky (SZA)				White-sky		
	40°	50°	60°	70°	80°	-	
Forest albedo when assuming black soil							
Black spruce	0.053	0.059	0.069	0.084	0.108	0.066	
White spruce	0.062	0.068	0.076	0.087	0.104	0.081	
Broadleaved (Alaska)	0.169	0.182	0.199	0.221	0.251	0.186	
Scots pine	0.075	0.084	0.096	0.114	0.140	0.094	
Norway spruce	0.079	0.087	0.097	0.109	0.128	0.102	
Broadleaved (Finland)	0.140	0.155	0.173	0.197	0.231	0.165	
Contribution of forest floor to total forest albedo, %							
Black spruce	52.9	48.0	41.4	32.4	20.2	46.8	
White spruce	27.9	23.7	19.0	13.7	8.0	22.1	
Broadleaved (Alaska)	12.9	10.9	8.7	6.5	4.3	9.3	
Scots pine	45.6	40.6	34.5	26.8	17.9	37.7	
Norway spruce	23.5	19.7	15.8	11.9	8.0	19.0	
Broadleaved (Finland)	32.7	29.5	25.9	21.9	17.1	26.3	
Contribution of forest floor to FAPAR _{TOT} , %							
Black spruce	50.1	44.1	36.0	25.1	11.1	45.7	
White spruce	26.4	20.6	14.5	8.3	2.6	24.3	
Broadleaved (Alaska)	16.9	12.5	8.3	4.6	2.0	15.9	
Scots pine	46.3	39.8	31.7	21.5	10.5	42.8	
Norway spruce	24.4	18.7	13.2	8.3	4.4	23.3	
Broadleaved (Finland)	34.7	29.3	23.5	17.7	12.4	34.3	



752 Figure 1. Location of the field plots.



754 Figure 2. Basal area against tree height in the study plots in Alaska (a) and Finland (b).



Figure 3. Spectra of vegetation elements used in the simulations: (a) leaves/shoots, (b) bark, (c) forest floor. The values for leaf and shoot are single scattering albedos (reflectance + transmittance), and the values for bark and forest floor are

758 reflectance factors.



Figure 4. Forest black-sky albedo as a function of tree height (a–d) and AGB (e–f). Relations to tree height are shown for two SZAs, 40° (a–b) and 70° (c–d), representing solar noon at midsummer and the annual average in the study regions. Left hand column shows the results for the Alaskan data, and right hand column for the Finnish data. The figures show only monospecific plots, i.e. plots in which the basal area proportion of one of the species exceeded 80%.



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Figure 5. Black-sky FAPAR_{CAN} as a function of tree height (a–d) and AGB (e–f). Relations to tree height are shown for two SZAs, 40° (a–b) and 70° (c–d), representing solar noon at midsummer and the annual average in the study regions. Left hand column shows the results for the Alaskan data, and right hand column for the Finnish data. The figures show only monospecific plots i.e. plots in which the basal area proportion of one of the species exceeded 80%. For explanation of the symbols, see legend in Fig. 4.



Figure 6. FAPAR_{TOT} as a function of tree height at SZA of 40° . The figures show only monospecific plots i.e. plots in which the basal area proportion of one of the species exceeded 80%. For explanation of the symbols, see legend in Fig. 4.



Figure 7. Canopy and forest floor contributions to forest black-sky albedo as function of tree height. Canopy contribution was obtained by assuming black soil in the simulation. Forest floor contribution was obtained by subtracting the canopy contribution from the total forest albedo. The data shown are from Norway spruce dominated forests in Finland.



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Figure 8. Relation of FAPAR to forest black-sky albedo by dominant tree species. The figures show only plots that were dominated by one species i.e. in which the basal area proportion of one of the species exceeded 80%. a–d: FAPAR_{CAN} against albedo at two SZAs, 40° and 70°, representing solar noon at midsummer and the annual average in the study regions; $e_{\rm f}$: FAPAR_{TOT} against albedo at SZA of 40°.



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Figure 9. Effect of basal area (a–b) and proportion of broadleaved trees (c–d) on black-sky albedo and FAPAR_{CAN} at sun zenith angles of 40° and 70° in Alaska. Points represent mean and whiskers the standard deviation in ten equally spaced classes. Effect of broadleaved proportion on albedo is presented separately for dense (basal area > 31 m² ha⁻¹) and sparse (basal area < 21 m² ha⁻¹) forest. These limits correspond to 30th and 70th percentiles of basal area in Alaskan data. The points representing dense and sparse forest are shifted along the x axis in order to make them visible.