

1 Dear Dr. Luyssaert,

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3 We have revised our manuscript. Please find below first our response to your concerns, followed by responses
4 to referees #1 and #2, and finally list of changes and the revised manuscript with tracked changes. Our
5 responses are indented and in blue font.

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7 On behalf of co-authors,

8 Aarne Hovi

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Associate Editor Decision: Reconsider after major revisions (24 Aug 2016) by dr. Sebastiaan Luyssaert

Comments to the Author:

Dear authors,

Thank you for your contribution to the on-line discussion in which you have addressed most of the reviewer's comments. Based on your discussion and my own reading of the paper, I would like to invite you to prepare a revised manuscript. While revising the manuscript, please, consider the following comments in addition to the concerns raised by the reviews:

- Reviewer 1 raised an important issue on the sensitivity of the model. Although I find the content of your response satisfactory, I would like to see this issue addressed by means of a comprehensive discussion. For example, a table showing for which parameters the sensitivity has already been tested (and the sensitivity itself) and for which parameters the sensitivity has not yet been tested.

We have expanded our response to reviewer #1's comment. As in our first response, we refer to the studies that have performed sensitivity analyses, but we now discuss more thoroughly how the model results were affected in those studies.

Regarding the parameters for which sensitivity analyses have not been published, we discuss the expected sensitivity from a theoretical point of view, and based on a small sensitivity analysis that we performed for three example stands (pine, spruce, and birch) in Finland (see Appendix 1 of this document).

- Please, discuss the validity of the model to simulate absorbed radiation (see above). Is the absorbed fraction calculated as the residual of the reflected and the transmitted fraction? Has absorbed light been validated against field measurements?

Absorbed fraction is calculated from the incoming and outgoing fluxes on-top-of and below canopy. We describe this in Section 2.2.1 of the manuscript. To our knowledge absorbed fraction has not been validated against field measurements, but transmitted and reflected fractions have been compared against other models in RAMI exercise (Widlowski et al. 2007), in which FRT has been among the best performing non-Monte Carlo models.

- Reviewer 2 raised the issue of understory and the possible role of lichens in the boreal zone. There is quite some literature on the effect of lichens on albedo. Please, discuss this issue in the light of forest management (see for example studies linking reindeer grazing - which is a non-wood forest use - to lichens, soil freezing and albedo).

We added a note about the role of forest management effects on forest floor composition in the Discussion Section where we discuss the role of understory in the forest albedo and FAPAR. We added a reference to Stoy et al. (2012) who reported the effect of reindeer grazing on lichens and albedo.

54 Anonymous Referee #1

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56 Received and published: 14 June 2016

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58 This paper presents an assessment of the impact of forest structure (type of tree &
59 broadleaf v deciduous proportion) on albedo and hence FAPAR as a proxy for productivity.

60 This is an important topic given the link between productivity and climate and the
61 use of remote sensing to estimate albedo across large areas. The paper is very well
62 written, clear and the results are well presented. I have a few queries regarding the
63 methods, particularly sensitivity and generality, but if the authors can address these
64 then the paper is suitable to publish and would be of wide interest.

65

66 One general query is the model sensitivity to choice of structural assumptions and parameters.
67 It's not clear to me that there is any real effort made to quantify the sensitivity
68 of the results to the assumptions of crown shape, and crown leaf area density. Tree
69 crowns vary a lot in shape, are heavily clumped, and leaf size, angle and woody material
70 have a big impact on the BRF. It would be good if the authors could quantify the impacts of some or all of these
71 assumptions on the results. They use tree classes but how big is within and between class variability? The issue
72 is the FRT parameters are driven by allometrics, but these are likely to be very specific aren't they?

73

74 We acknowledge that the choice of parameters has an influence on the exact values of the simulated
75 quantities in any modeling study. The main aim of our study is to describe the general relations
76 between forest structure, albedo, and FAPAR. Such studies have been limited by the low resolution of
77 remote sensing data and, on the other hand, by the lack of extensive in situ measurement data.
78 Therefore the modeling approach is a good (and often the only) option for studying albedo and FAPAR
79 in a large variety of forests, yet maintaining high spatial resolution. The advantage of FRT, when
80 compared to many other theoretical radiative transfer models, is that it can be parameterized with
81 standard forest inventory data and allometric models. These were used also in the current study,
82 because the forest field inventories did not directly measure the required parameters for radiative
83 transfer simulation (e.g. LAI, canopy cover).

84

85 FRT is one of the most well-known forest radiative transfer models and was originally published already
86 in 1991 (Nilson and Peterson, 1991) and later modified by Kuusk and Nilson (2000). There are already a
87 number of studies reporting the sensitivity of the FRT model to its input parameters. FRT has also
88 participated in the large international "Radiation transfer model intercomparison" (RAMI) effort
89 coordinated by JRC, and thus its performance in relation to other models has been documented in a
90 wide range of tests. The results from these tests are publicly available online ([http://rami-
91 benchmark.jrc.ec.europa.eu/HTML/](http://rami-benchmark.jrc.ec.europa.eu/HTML/)) and reported in peer-reviewed scientific papers by Widłowski et al.
92 Therefore, we have not reported sensitivity analyses in this manuscript.

93

94 The reviewer asked about the assumptions related to crown shape and their influence on the results.
95 The effect of crown shape on forest BRDF characteristics was quantified in Rautiainen et al. (2004). In
96 the studied forest stands, assuming conical crowns resulted the forest hemispherical-directional

reflectance to be 62%-98% (red), 77%-99% (near infrared), and 79%-98% (mid infrared) of the value obtained when assuming ellipsoid crown. The volume of conical crown was half of the volume of ellipsoid one. They also noted, that reducing the crown volume reduces scattering from crowns but increases scattering from the forest floor. The net effect is therefore either negative or positive, depending on whether scattering from crowns or scattering from forest floor dominates the total forest reflectance. In other words, the effect of crown shape depends on canopy closure. Based on Rautiainen et al. (2008) cone is least accurate for estimating crown volume of Scots pine and Norway spruce, whereas the differences between other crown shapes were minor.

The performance of a wide range of foliage mass and crown radius (i.e. canopy/crown closure) models in forming the input of FRT was reported by Lang et al. (2007), by comparing the simulated forest reflectance factors to actual satellite observations. Regarding foliage mass models, the conclusion was that simple foliage mass models that are based on tree stem diameter at breast height, predicted larger variability and resulted in slightly higher correlation between the simulated and measured reflectance factors than the multiple regression models that included tree height and crown depth. On the other hand, the authors noted that the estimates from the simple regression models can be biased. Regarding crown radius, models that account for stand density effects performed better compared to the regression equations based on the breast height diameter only. In reality one has to consider also the availability of the models for the study area. The simple linear models based on stem diameter, that we used for Finnish plots, were based on data that was geographically closest to our study area in Finland. For the Alaskan species, there were also versions that took into account the stand density, but their predictive power, measured as explained variability (R^2) in the crown radius, was only slightly better than the simpler models.

For tree size distribution no sensitivity analyses have been published. In theory, a forest with trees of very different sizes would have a higher canopy surface roughness, which would in turn lead to somewhat lower reflectance (albedo) values. The reason for not including several tree size classes was that there were no field measurements made on tree size distribution in the data from Finland. Stand basal area was measured in the field, but the stem diameter and tree height were measured only for a basal area median tree. For Alaskan data each tree was measured individually, and thus information on the size distribution was available. It was however not taken into account because we wanted to maintain the same calculation procedure for both study areas, in order not to introduce any differences due to data processing steps.

We added references to the publications mentioned above in Section 2.2.2.

Hence my comments about generality below.

Similarly, the authors show the importance of the understory, particularly with view and sun angle. Can they say more about this given that in many areas understory can be very significant and can be correlated in terms of cover with the overstory?

Yes, the density and species richness of forest floor vegetation may vary a lot, and may be correlated with the density of overstory layer. To be able to assess the contribution of forest floor vegetation to forest albedo in more detail, quantitative data on forest floor composition and spectral data on all of the components would be needed. Field data on forest floor species composition was available only for some of our study plots, but not for all of them. In our study sites where the data was available, the correlation between overstory and forest floor vegetation coverage was rather weak (Alaska $r = -0.27$; Hyytiälä (Finland) $r = -0.33$). More importantly, we did not have optical properties measurements for each of the forest floor components (litter, bare soil, various plant species) separately. Therefore, we decided not to model the forest floor in more detail than it was done in the current version.

Overall, the large contribution of understory implicates that, in addition to tree canopy structure, the species composition of understory has an important role in controlling boreal forest albedo and FAPAR. Therefore, future studies should aim at more accurate characterization of forest floor composition and optical properties. We added a note about this in the discussion where we discuss the importance of forest floor on albedo and FAPAR.

The authors are making a claim for generality based on the number of plots they have and the ranges of cover and density and deciduous v conifer mix they have. However I would question in particular how general the Finnish birch forests are likely to be - how representative of deciduous broadleaf forests? Can the authors justify this aspect better?

It is true that our study is limited by the available field data. One of the main ideas is to compare intensively managed (Finnish) with more naturally grown (Alaskan) forests. We have noted in our discussion that the data is not a probability sample, and we do not claim that the results would be applicable as such to entire boreal zone.

Regarding the broadleaved species; they existed in both Alaskan and Finnish forests, and the results were similar in both regions. Therefore we consider that the broadleaved species in the boreal zone are quite well represented.

We checked the wordings throughout the text and modified them when necessary to avoid making the impression that too broad generalizations were made.

177 The study by Hovi et al. is addressing the important topic of how forest management
178 and composition is influencing albedo and fapar. The understanding and quantification
179 of the relation of albedo and fapar are prerequisites for assessing the effectiveness
180 of forest management for climate mitigation, while including the radiative forcing effect
181 through the energy budget. The study complements observational studies through radiative
182 transfer modelling. Results reveal that radiative forcing can be reduced through
183 increased albedo by increasing the abundance of deciduous species. The study is an
184 important contribution towards a better understanding of forest structure on albedo and
185 FAPAR, thus linking two main components of the climate, i.e. the energy and carbon
186 cycle.

188 While the topic is interesting and important, the study has major shortcomings.

189 1. The study is based on bidirectional radiation quantities for albedo (black sky albedo),
190 no diffuse irradiance is taken into account. At the high latitudes of the test sites, the
191 fraction of diffuse radiation cannot be neglected. The effect of varying leaf angles might
192 significantly decrease under a scenario with diffuse irradiance. I expect that the results
193 (difference between broadleaf and needleleaf) might be much less significant when
194 introducing a realistic diffuse fraction. If the study is supposed to serve as a baseline for
195 future management, it needs to quantify differences under realistic irradiance scenarios
196 for the given latitudes.

198 In the first version of the manuscript, we chose to simulate direct illumination only i.e. black-sky
199 conditions, because this way the simulated albedo and FAPAR are independent of the parameterization
200 of the atmosphere. Introducing the effect of atmosphere would make the analysis more complicated,
201 and any differences in the modeled atmosphere, whether real or caused by uncertainty in the chosen
202 parameters values, would affect the comparisons between the study regions located on two continents.
203 We wanted to avoid this because the focus was on modeling the effects of forest structure.

205 However, we acknowledge that the effect of angular distribution of incoming solar radiation is
206 important, as seen already in the differences between sun zenith angles when assuming black-sky
207 conditions. In general, presence of atmosphere (and clouds) would reduce the relative share of short
208 (blue) wavelengths in the incoming solar spectrum due to scattering and ozone absorption. On the
209 other hand clouds would also increase the absorption by water vapor, which occurs in longer
210 wavelengths. Because reflectivity of vegetation is higher in the infrared than in the visible region, these
211 two phenomena have opposite effects on the simulated forest albedo and therefore would probably
212 cancel out each other.

214 Therefore, as suggested by the reviewer, we repeated the simulations in white-sky conditions i.e.
215 assuming totally isotropic incoming radiation. However, we retained the top-of-atmosphere solar

irradiance spectrum, because modeling the effect of clouds would be highly dependent on prevailing cloud conditions (e.g., thickness and altitude of clouds), about which we did not have measurement data.

Simulated white-sky albedo was similar to black-sky albedo at sun zenith angles of 50° – 70° , which is logical because in the case of isotropic illumination the albedo is weighted average of the black-sky albedos at all possible SZAs. The dominant tree species influenced which sun-zenith angle in the black-sky case best corresponded to the white-sky albedo. $FAPAR_{CAN}$ in white-sky conditions was similar to $FAPAR_{CAN}$ in black-sky conditions at SZAs of 40° – 50° . Similarly as for albedos, tree species influenced whether the black-sky $FAPAR_{CAN}$ at SZA of 40° or the one at 50° was closer to the white-sky case. In general, the differences between tree species in the white-sky case did not drastically change compared to black-sky cases. Rather than leaf angles, the species differences are mainly caused by the differences in leaf area index (visibility of forest floor) and in the spectral properties of the canopy elements. These factors have an influence at all angles of illumination, although some angular dependences may exist.

In the revised version, we report the simulated white-sky albedos (species-specific mean white-sky albedos and FAPARs were added in Tables 4 and 5). We also added to Section 2.2.1 explanations of how the white-sky albedos and FAPARs were calculated.

2. The study assumes that fapar is a proxy for productivity. This assumption (and related study title) is too simplistic as light is only one of several growth limiting factors, and light use efficiency needs to be accounted for at the species or plant functional type level. Also other limiting factors such as temperature, soil water, and vapor pressure deficit would need to be accounted for at the species or plant functional type level for the conversion of fapar to GPP. Further, productivity in sunlit and shaded leaves is not linearly scaling with APAR (see light saturation curve).

We agree that all these factors (and many others including e.g. diffuse to total irradiance ratio) affect gross primary productivity, which can be estimated from FAPAR and light use efficiency (LUE), using the well-known model by Monteith et al. (1972). Usually FAPAR can be estimated from remote sensing data since it is directly linked to the radiation reflected by the vegetation canopies. LUE, on the other hand, varies dynamically over different time scales, and depends on the physiological condition of the vegetation. It is true that LUE can be different for different plant functional types and e.g. for different tree species. However, to be able to take LUE into account in the analysis would require to model realistically its dependence on all the mentioned environmental factors, which was not possible and would have added a major uncertainty component into the analysis. Our study relies on the fact that although modified by the efficiency by which plants use the absorbed PAR radiation, ultimately the photosynthesis is driven by the absorbed PAR. Furthermore, rather than giving the exact numbers of GPP, we see that the main value of our study is that it adds basic understanding on how albedo and the solar energy used for photosynthesis are connected in differently structured forests. Linking GPP with albedo would require completely different approach, probably utilizing field measurements of CO_2 fluxes or tree growth directly. Alternatively, statistical growth and yield models could be used.

Nevertheless, we added to the introduction a note that in addition to FAPAR, productivity is affected also by LUE.

3. The definition and usage of fapar is unclear – when using fapar for GPP estimation, only fapar absorbed by leaves is relevant. Forest canopy fapar is not mainly determined by leaf area index and directionality of incoming solar radiation (as stated in line 64), but – depending on the fraction of leaf to plant area, very much by stems, branches, and the understory. It is mentioned that no correction was done for litter, but it is unclear if the same is true for stems, branches, and understory (which might contain open soils, lichen, etc.).

All quantities reported in the manuscript are total, including both green and woody/dead biomass components. We agree that green FAPAR would be more justified in terms of productivity, but it was not possible to separate here, because no measurements on fraction of branch area to leaf area were made in the study plots. The same 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. Concerning the forest floor, we would also like to note that open soils are very rarely seen in boreal forests where the floor is covered by (at least) green mosses.

We added to Section 2.2.1 a note that similarly as for $FAPAR_{TOT}$, also in the case of $FAPAR_{CAN}$ green biomass was not separated.

4. Equations section of albedo and fapar – both quantities are not fluxes (of radiation), but ratios! Review definitions and revise equations. Also, explain how spectral weighting based on TOA spectral distribution is influencing results compared to weighting by top of canopy irradiance spectral distribution.

In our study the fluxes are equal to ratios, because the incoming radiation in FRT simulation equals one. We changed the notation in the equations and in the text in Section 2.2.1. We now use terms “upward scattered fraction of incoming radiation” (f_i^-) and “downwelling (directly transmitted or downward scattered) fraction of incoming radiation” (f_i^+).

The explanation for using top-of-atmosphere spectrum is the same as in our response to Question #1 above, i.e. we wanted to avoid the uncertainty in modeling the atmosphere. However, to demonstrate the effect of using at-ground solar spectrum, as requested by the reviewer, we performed simulations also in blue-sky conditions, modeling the effect of atmosphere on the incoming solar irradiance (direct and diffuse components) using the SPCTRAL2 model by Bird & Riordan (1986). The model assumes clear skies (no clouds), and requires as parameters ozone and water vapor concentration, as well as aerosol optical depth (AOD). We used ozone and water vapor from the U.S. standard atmosphere, and AOD from measurement data. The values are the same as used for ASTM standard solar spectrum (ASTM standard G173-03). Because the data do not represent the study areas, the results are intended for demonstration purposes only. We repeated the blue-sky simulations at all SZAs (40° to 80°).

For all SZAs, the blue-sky albedo was very highly correlated ($r = 1.00$) with black-sky albedo, as expected. At small SZAs (40° to 60°), also the overall level of blue-sky albedo was almost equal to that of black-sky albedo (mean difference of up to 0.006 in absolute units). At SZAs of 70° and 80° the blue-sky albedos were somewhat higher than black-sky albedos (mean differences of 0.012 and 0.031 in absolute units). This was because at high SZAs the irradiance distribution of solar spectrum was shifted towards longer wavelengths in which the vegetation is more reflective. However, due to high correlation with black-sky albedo, the conclusions regarding species differences and the effect of forest structure on albedo would remain the same even if assuming blue-sky conditions. The conclusions regarding FAPAR were the same as those regarding albedo, i.e. assuming blue-sky would slightly affect the overall level of FAPAR at large SZAs while at low SZAs the level of FAPAR would remain almost the same.

We added a short summary of the results described above to end of Section 2.2.1, and denoted that because of the high correlation between black-sky and blue-sky results, the use of at-ground solar spectrum would not change our conclusions. All results reported in Section 3 are based on top-of-atmosphere solar spectrum.

Appendix 1. Theoretical discussion and sensitivity analysis on the effect of FRT parameters.

Below we discuss how the FRT parameters would affect simulation results. In addition, sensitivity of FRT on its input parameters was tested in three example stands in Finland. The stands were selected so that the forest variables are close to average species-specific forest variables in our data from Finland.

Tree distribution parameter would influence the visibility of the forest floor, more clumped distribution patterns rendering larger portion of the forest floor visible. On the other hand, the scattering from tree canopy would be larger when the trees are more regularly distributed. In our sensitivity analysis the albedo decreased by 4–18% when the tree distribution parameter increased from 0.9 to 1.4. The effect was largest in the spruce stand that had the largest LAI.

Leaf mass per area (LMA) would directly affect the leaf area index values. In our sensitivity analysis the albedo was reduced by 0–9% when the LMA increased from 70% to 130% of its default value.

Shoot shading coefficient would affect the results in exactly the same manner as the leaf mass per area, since it influences the effective LAI. It should be noted that the literature values of shoot shading coefficients for conifers varied between 0.50–0.65, and therefore the effect of shoot shading coefficient would be small.

Branch area to leaf area index (BAILAI) ratio would affect the plant area index (PAI) and the average scattering phase function of the canopy elements. In our sensitivity analysis the albedo was reduced by 5–16% when the BAILAI increased from 70% to 130% of its default value.

Shoot length would affect the calculation of bidirectional gap probabilities i.e. visibility of the lower canopy layers and understory. In our sensitivity analysis the effect was negligible: up to 3% increase in albedo when shoot length increased from 70% to 130% of its default value.

Spectra of leaves/needles, bark, and forest floor would have an effect that is dependent on the relative share of these scattering components. For some of the species the average contribution of forest floor on albedo was 50%, and therefore the forest floor would have on average as large an effect as the leaves/needles/bark have. For most of the species, however, the spectral properties of the tree canopy dominated.

Literature cited

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393 List of relevant changes in the manuscript

394

- 395 • Calculated and reported results on albedo and FAPAR in white-sky conditions. Methods described in
396 Section 2.2.1, results in Section 3.1 and in Tables 4 and 5.
- 397
- 398 • Calculated albedo and FAPAR in blue-sky conditions in order to test the effect of atmosphere on the
399 results. The findings are summarized in Section 2.2.1.
- 400
- 401 • Added a note about LUE concept and reference to Monteith 1972 (Section 1).
- 402
- 403 • Changed terminology used for incoming and outgoing fluxes (Section 2.2.1).
- 404
- 405 • Added a note that similarly as for $FAPAR_{TOT}$, also in the case of $FAPAR_{CAN}$ green biomass was not
406 separated (Section 2.2.1).
- 407
- 408 • Added discussion on the sensitivity of FRT to its input parameters (Section 2.2.2).
- 409
- 410 • Added discussion on the role of forest floor, particularly in light of reindeer grazing (Section 4)
- 411
- 412 • Changed the wordings throughout the text in order to avoid making the impression that too broad
413 generalizations were made (e.g. in the abstract: “forest in Alaska” changed to “studied plots in Alaska”)
- 414
- 415 • Added a reference to Lukeš et al. 2016, which was published since the submission of our manuscript,
416 and discussed our results in relation to those obtained in their study (Sections 1 and 4).
- 417

1 Quantifying the missing link between forest albedo and productivity

2 in the boreal zone

3

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

33
34 **Keywords:** FAPAR, conifer, broadleaved, radiative transfer, basal area, leaf area index, AGB, thinning

35 1 Introduction

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

44

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

51

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

60

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

68 albedo, boreal forest FAPAR may differ by tree species (Roujean et al., 1999; Steinberg et al., 2006; Chasmer et al., 2008;
69 Serbin et al., 2013; Majasalmi et al., 2015) and stand age (Serbin et al., 2013), as both species and age are likely to influence
70 the LAI of the canopy.

71
72 Estimation methods set limits for the information that can be obtained on the spatial and temporal variation of albedo and
73 FAPAR. In situ measurements are accurate and can be directly linked with field measured forest structure. On the other
74 hand, they are extremely tedious and cannot cover large variations in forest structure. Satellite data provide ample coverage
75 of varying forest structures and wide spatial extent but may compromise spatial resolution and detail in the characterization
76 of forest structure. In addition, neither local albedo measurements nor satellite-based albedo products can explain the
77 causality between small-scale environmental management scenarios and changes in albedo or FAPAR. Radiative transfer
78 models offer a solution to these problems: forest radiative transfer models are a powerful tool for linking quantitative
79 changes in vegetation structure to albedo or FAPAR for large geographical regions. The models are parameterized using
80 mathematical descriptions of canopy structure (e.g., LAI, tree height, crown dimensions, stand density), optical properties of
81 foliage and forest floor, and spectral and angular properties of incoming radiation. Using these models, the albedo and
82 FAPAR of a forest can be calculated from readily measurable variables such as forest structure and leaf optical properties.

83
84 To our knowledge only one study has examined the relation between forest albedo and FAPAR (Lukeš et al., 2016). In that
85 study, coarse resolution satellite products (MODIS) were used and one geographical area (Finland) was studied.
86 Furthermore, To date, previous studies on forest structure and albedo have mainly focused on ~~specific geographical~~
87 ~~areas~~ local geographical scales (e.g. Finland, Norway, but see Kuusinen et al. (2013) for comparison between Finland and
88 Canada). Comparison of the relationships between forest structure, albedo and FAPAR has not been performed across the
89 biome, i.e. including both European and North American boreal forests which have very different natural structures and
90 forest management scenarios. Due to the large north-south gradient and consequent structural diversity of forests in the
91 boreal zone, the impact of forest management on albedo cannot be expected to be the same. ~~In addition, while the relations~~
92 ~~of albedo and FAPAR to forest structure have been locally studied in boreal forests, the explicit link between FAPAR and~~
93 ~~albedo has not been shown.~~

94
95 Here we report results from quantifying the links between boreal forest structure, albedo and FAPAR ranging from southern
96 boreal forests to the northern tree line using detailed, large forest inventory data sets from Finland and Alaska (N = 1086
97 plots). The forests in the study areas vary widely in structure, species composition, and human interference, from intensively
98 managed (regularly thinned) forests in Finland to natural growth in Alaska. Using a radiative transfer modeling approach, we
99 quantify the effects of forest structure and species composition on albedo and FAPAR in order to answer how forest
100 management practices can be optimized for climate change mitigation. The significant benefit of the modeling approach is
101 that it enables to study structurally varying forests over large geographical areas, without compromising detail in the forest

102 structure representation or in the spatial resolution. Our study is therefore the first intercontinental study connecting albedo
103 and productivity of boreal forests, using accurate ground reference data.

104 **2 Materials and methods**

105 **2.1 Study areas and field plots**

106 This study is based on 1086 field plots located in Alaska, USA, and in Finland, between Northern latitudes of 60° and 68°.
107 At these latitudes, solar zenith angle (SZA) at solar noon at midsummer ranges from 37° to 45°, and the annual average from
108 69° to 72°.

109
110 The field plots in Alaska (N = 584) were permanent sample plots established as part of Co-operative Alaska Forest Inventory
111 that aims at long-term monitoring of forest conditions and dynamics (Malone et al., 2009). The plots were scattered in
112 interior and southcentral Alaska across a region of about 300 000 km², from Fairbanks in the north to the Kenai Peninsula in
113 the south (Fig. 1, for more details see Liang et al. (2015)). Some of the plots were measured more than once. We used only
114 the most recent measurement of each plot. The plots in Finland (N = 502) were temporary or permanent sample plots. They
115 were located at four separate sites: Hyttiälä (Majasalmi et al., 2015), Koli, Sodankylä, and Suonenjoki (Korhonen, 2011)
116 ranging from southern to northern Finland (Fig. 1). Species-level attributes, including the number of stems per hectare, basal
117 area, mean diameter at breast height, tree height, and length of living crown, were available for the plots. Basal area, the total
118 cross-sectional area of stemwood (m² ha⁻¹) at breast height (i.e. at 1.3 m or 1.37 m), is a common measure of stand density in
119 forest inventories and, combined with information on tree height, used as an indicator of need for silvicultural thinning
120 operations.

121
122 Tree species in the Alaskan data were coniferous black spruce (*Picea mariana* (Mill.) B. S. P.) and white spruce (*Picea*
123 *glauca* (Moench) Voss), and broadleaved quaking aspen (*Populus tremuloides* Michx.), black cottonwood or balsam poplar
124 (*Populus trichocarpa* Torr. & Gray, *P. balsamifera* L.), Alaskan birch (*Betula neoalaskana* Sarg.), and Kenai birch (*Betula*
125 *kenaica* W.H. Evans). Tree species in the Finnish data were coniferous Scots pine (*Pinus sylvestris* L.) and Norway spruce
126 (*Picea abies* (L.) H. Karst), and broadleaved species comprising mainly of silver and downy birch (*Betula pendula* Roth, *B.*
127 *pubescens* Ehrh.). The birches accounted for 89% of the basal area of the broadleaved species in Finland. The forest
128 variables in the study plots are shown in Table 1, for all plots and separately for plots dominated by one species. The
129 Alaskan and Finnish forests differed in structure. The forests in Alaska were on average denser in terms of basal area (Fig.
130 2), and contained larger proportion of broadleaved species than the Finnish forests (Table 1). Managed forests in Finland,
131 which our plots mainly represent, are normally thinned 1–3 times during the rotation period so that coniferous species are
132 favored. In our plots from Alaska, on the other hand, no thinnings were applied.

133

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

144 2.2 Albedo and FAPAR simulations

145 2.2.1 Simulation model

146 We simulated albedo and FAPAR using a radiative transfer model called Forest Reflectance and Transmittance model FRT
147 (Kuusk & Nilson, 2000, version modified by Möttus et al., 2007). FRT is a hybrid type model that combines geometric-
148 optical and radiative transfer based sub-models for modeling the first- and higher-order scattering components, respectively.
149 The model has been intercompared and validated within RAdiative transfer Model Intercomparison exercise (RAMI) several
150 times (Widlowski et al., 2007). The advantage of FRT is that it can be parameterized using standard forest inventory data,
151 utilizing the allometric relations of forest variables to foliage biomass and crown dimensions. This was important because
152 field measurements of biophysical variables (e.g., LAI) are not commonly available, as was the case also in our study plots.

153

154 FRT simulates stand-level bidirectional reflectance and transmittance factors (BRF, BTF) of a forest at specified
155 wavelengths. A 12×12 Gauss-Legendre cubature was used to integrate the simulated BRF and BTF values over the upper
156 and lower hemispheres, respectively. This resulted in upward scattered (directly transmitted or downward scattered) fractions of incoming radiation. The former is observed on
157 top of, and the latter below the tree canopy (below canopy). These fractions ~~fluxes~~ were then used to calculate the shortwave
158 broadband albedo and FAPAR. The simulations were carried out at 5 nm resolution, and the albedo simulations covered a
159 spectral region of 400–2100 nm which corresponds to the region from which input data was available (see Section 2.2.2).
160 The wavelengths below 400 nm account for 8%, and wavelengths over 2100 nm account for 2% of the solar irradiance on
161 top of the atmosphere (Thuillier et al., 2003). ~~The simulations were performed assuming direct illumination only, i.e. in~~
162 ~~black sky conditions. Black sky albedo is, compared to actual (blue sky) albedo, less dependent on assumptions of~~
163 ~~atmospheric scattering properties. It is commonly used as input in climate modeling (Schaaf et al., 2009). We repeated the~~
164 ~~simulations at five SZAs typical for the study areas. These were 40°, 50°, 60°, 70°, and 80°. We use terms “small SZA” and~~

~~“large SZA” in the text hereafter, to refer to SZAs of 40°–50° and 70°–80°, respectively. It should be noted that small SZA refers to the situation where the sun is at its highest position.~~

The shortwave ~~black-sky~~ albedo, ~~hereafter referred to as “albedo”~~, was obtained as a weighted sum of the spectral albedos, i.e. upward scattered fractions of incoming radiation fluxes (f_I^-), ~~on top of canopy~~:

$$albedo = \sum_{I=400}^{2100} w_I \times f_I^- , \quad (1)$$

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

$$FAPAR_{CAN} = \sum_{I=400}^{700} w_I \times a_I^C , \quad (2)$$

$$FAPAR_{TOT} = \sum_{I=400}^{700} w_I \times a_I^T , \quad (3)$$

The weights (w_I) were obtained from the ~~standard-reference~~ solar irradiance spectrum ~~on top of the atmosphere~~ (Thuillier et al., 2003). ~~To obtain the weights, the s~~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. $FAPAR_{TOT}$ and $FAPAR_{CAN}$ 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 $FAPAR_{TOT}$ ~~does~~ not separate green biomass from woody or dead branches or from litter on the ground, and the values therefore represent ~~an~~ upper limits of productivity 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 flux ~~on top of canopy~~ (f_I^-) ~~and~~ downwelling flux ~~below canopy~~ (f_I^+), and the reflectance factor of the forest floor (r_G) as follows:

$$a_l^C = 1 - f_l - f_l^- + r_l^G \times f_l^- , \quad (4)$$

$$a_l^T = 1 - f_l - , \quad (5)$$

The simulations were carried out assuming direct illumination only (“black-sky”) and completely isotropic diffuse illumination (“white-sky”). In both cases, we used a top-of-atmosphere irradiance spectrum (Thuillier et al., 2003) as weights. The black-sky albedo and FAPAR were simulated for five SZAs 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°–50° and 70°–80°, respectively. Black sky albedo is, compared to actual (blue sky) albedo, less dependent on assumptions of atmospheric scattering properties, and is commonly used as input in climate modeling (Schaaf et al., 2009). We tested the effect of atmosphere using a simple solar spectral model (Bird and Riordan, 1986) for generating at-ground solar irradiance spectrum. Albedo and FAPAR in these actual blue-sky conditions were highly correlated ($r \geq 0.98$) 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. Atmosphere scatters visible more effectively than infrared wavelengths, shifting the irradiance distribution of incoming solar radiation towards longer wavelengths in which vegetation is more reflective. Because of high correlation with black- and blue-sky results, we conclude that inclusion of atmosphere in the calculations would not significantly change the interpretation of our results, although would increase the simulated albedo values at large SZAs.

2.2.2 Model parameters

Tree crowns are represented in the FRT model by geometric primitives (cylinders, ~~cones,~~ ~~or~~ 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 defined to represent different tree species or size classes. We used one class for each tree species. 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 crown shape. ~~The effect of crown shape on simulated forest BRDF was quantified in Rautiainen et al. (2004) who showed that increasing the crown volume may either increase or decrease the simulated reflectance values, depending on canopy closure. Ellipsoid has been shown to estimate~~ ~~which estimates the~~ crown volume accurately. ~~(Rautiainen et al., 2008) and was therefore used in our study.~~ Crown length was obtained from field measurements, and the crown radius was modeled using species-specific allometric equations that require stem diameter as independent variable (Jakobsons, 1970; Bragg, 2001). Leaf dry biomass was estimated with species-specific biomass equations (Repola, 2008; Repola, 2009; Yarie et al., 2007) and converted into hemisurface i.e. half of total leaf area, using leaf mass per area (LMA) values from literature (Table 3). ~~The performance of wide range of crown radius and foliage mass models in forming the input of FRT has been reported by~~

226 Lang et al. (2007). The models used in our study were chosen based on geographical proximity to our study areas, and also
 227 on model availability, particularly for the Alaskan species for which there existed a limited number of models. A slightly
 228 regular spatial distribution pattern of trees was assumed, i.e. a value of 1.2 for the tree distribution parameter (a value of 1
 229 indicates Poisson distribution, Nilson, 1999). Other structural parameters needed in FRT simulations are presented in Table
 230 3.
 231
 232 Optical properties i.e. reflectance and transmittance of the leaves and needles were obtained from laboratory spectrometer
 233 measurements. The data for Finnish species were from Hyytiälä, Finland (Lukeš et al., 2013b). Spectra of birch were used
 234 for all broadleaved species. The data for Alaskan species were from Superior National Forest, Minnesota, USA (Hall et al.,
 235 1996). Data for all species could not be found separately, and therefore spectra of black spruce were used for both black and
 236 white spruce, spectra of paper birch (*Betula papyrifera* Marsh.) were used for both birch species, and spectra of quaking
 237 aspen were used for both quaking aspen and for the black cottonwood/balsam poplar group. Reflectance spectra of black and
 238 white spruce needles have been found to be similar at least in the visible and near-infrared wavelengths (Richardson et al.,
 239 2003). In our data, the spectra of coniferous species did not differ notably from each other (Fig. 3a). The same applied to
 240 broadleaved species. Bark spectra for spruces and *Populus* sp. in Alaska were obtained from Hall et al. (1996), and for Scots
 241 pine and Norway spruce in Finland from Lang et al. (2002) (Fig. 3b). Spectra of birch from Lang et al. (2002) were used for
 242 birches in Alaska and for broadleaved species in Finland.
 243
 244 We used the annual shoot as a basic scattering element for conifers, similarly as in Lukeš et al. (2013a). This accounts for the
 245 multiple scattering within shoot which results in the shoot albedo being lower than needle albedo. Shoot reflectance and
 246 transmittance spectra were obtained by upscaling the needle single scattering albedo to shoot albedo (Rautiainen et al.,
 247 2012), assuming that the reflectance to transmittance ratio of a shoot is equal to that of a needle. Bi-Lambertian scattering
 248 properties of the scattering elements (leaves or shoots) were assumed.
 249
 250 Optical properties of the forest floor, i.e. reflectance factors at nadir view were obtained from field spectrometer
 251 measurements. The data were collected from Poker Flat Research Range Black Spruce Forest, Alaska (measurements
 252 described in Yang et al. (2014)), and from Hyytiälä, Finland (using similar methodology as in Rautiainen et al. (2011)).
 253 Separate spectra for each forest floor type was used (Fig. 3c), because characteristics of the forest floor may influence the
 254 forest reflectance and therefore also albedo (Rautiainen et al., 2007).

255 **2.3 Data analyses**

256 **2.3.1 Albedo, FAPAR, and forest structure**

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

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

275 We report the relationships of albedo and FAPAR against forest structure in Sect. 3.1. Results of these experiments are
276 needed for understanding the relations between albedo and FAPAR, which we report in Sect. 3.2.

277 **2.3.2 Relative importance of density and tree species**

278 To examine the relative importance of density and species composition, we analyzed albedo and $FAPAR_{CAN}$ against basal
279 area and the proportion of broadleaved trees. The analyses were performed separately for Alaska and Finland, and repeated
280 for all simulated solar illumination conditionsSZAs. We excluded all plots with tree height less than 10 m from the analyses
281 in order to evaluate the effect of basal area independent of tree height. This was done based on the following reasoning.
282 Basal area was correlated with tree height when studying all plots ($r = 0.61$ (Alaska), $r = 0.64$ (Finland)). Preliminary
283 analysis was performed by successively removing plots with smallest trees and each time checking the correlation between
284 height and basal area. The correlation was reduced until a height threshold of 10 m ($r = 0.40$ (Alaska), $r = 0.34$ (Finland)) (cf.
285 Fig. 2). Therefore, the 10 m threshold was used to exclude the smallest trees from our analyses. Analysis of albedo and
286 FAPAR against basal area in this restricted set of plots gives an approximation of how thinnings would affect albedo and

287 FAPAR_{CAN} although in reality thinning a stand affects not only the basal area but also the spatial pattern and size distribution
288 of trees.

289

290 Mean and standard deviation (SD) of albedo and FAPAR_{CAN} in conifer-dominated forests were calculated for ten equally
291 spaced classes with respect to basal area. The center of the lowest class corresponded to the 5th and that of the highest class
292 to the 95th percentile of basal area in the data. To examine the effect of broadleaved proportion, mean and SD of albedo and
293 FAPAR_{CAN} were calculated for ten equally spaced classes with respect to proportion of broadleaved trees, i.e. the
294 broadleaved proportions ranging from 0–10% to 90–100%. The analysis was repeated for sparse (basal area percentiles from
295 0th to 30th) and dense forest (basal area percentiles from 70th to 100th). We hypothesized that the proportion of broadleaved
296 trees would have smaller effect on albedo in sparse than in dense forest, because the forest floor has more significant role in
297 the sparse canopies. Results regarding the analysis of basal area and proportion broadleaved trees are reported in Sect 3.3.

298 3 Results

299 3.1 Albedo, FAPAR, and forest structure

300 Mean albedo of ~~study plots~~forests in Alaska (0.141–0.184) was higher than in Finland (0.136–0.171). In general, the albedo
301 of broadleaved species was 42–130% higher than that of coniferous (Table 4). However, albedo varied greatly even among
302 coniferous species: in Alaska, the albedo of ~~black-white~~ spruce forests was ~~1920~~–33% higher than that of ~~black-white~~ spruce,
303 and in Finland, the albedo of Scots pine forests was ~~202~~–31% higher than that of Norway spruce. Overall, the mean albedo
304 of coniferous species was 28–32% higher in Finland (0.131–0.161) than in Alaska (0.102–0.122). The mean albedos of
305 broadleaved species in Alaska did not differ significantly from each other ~~at any SZA~~ ($p > 0.05$ in ANOVA), ~~except in the~~
306 ~~white-sky case. T~~and therefore the broadleaved species were treated as one group hereafter. Increasing the SZA increased the
307 ~~black-sky~~ albedos of all species (Table 4).

308

309 The forest canopies in Alaska absorbed more PAR radiation than in Finland: mean FAPAR_{CAN} in Alaska was 0.71–0.92 and
310 in Finland 0.63–0.89. ~~FAPAR_{CAN} increased with increasing SZA (Table 4).~~At the smallest SZA (40°) ~~in black-sky~~
311 ~~simulations,~~ FAPAR_{CAN} was highest for broadleaved species in Alaska, followed by Norway spruce in Finland, white spruce
312 in Alaska, and broadleaved in Finland (Table 4). Scots pine in Finland and black spruce in Alaska had lowest FAPAR_{CAN}
313 among the species. ~~Similarly as for albedo, t~~The mean FAPAR_{CAN} of broadleaved species in Alaska did not differ
314 significantly from each other ~~in any of the simulated illumination conditions at any SZA~~ ($p > 0.05$ in ANOVA). Increasing
315 the SZA increased FAPAR_{CAN} of all species and also reduced the differences between species. The relative increase was
316 smaller for broadleaved than for coniferous species. Therefore, the order of species in FAPAR_{CAN} was different at small and
317 large SZAs (Table 4). ~~FAPAR_{TOT}~~, an approximation of total ecosystem productivity, ranged from 0.93 to 0.98 ~~and did not~~

depend strongly on direction of illumination. FAPAR_{TOT} of coniferous forests was higher than that of broadleaved but the differences were not large in relative terms because FAPAR_{TOT} was consistently high.

White-sky albedo corresponded best with black-sky albedo observed at SZA of 60° ($r = 0.97$, RMSE = 0.011, mean difference = -0.001). It correlated strongly also with black-sky albedos observed at other SZAs ($r \geq 0.93$). White-sky 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 black-sky FAPAR_{CAN} observed at SZAs of 70° and 80°. Because white-sky albedo and FAPAR were highly correlated with their black-sky counterparts observed at small to moderate SZAs, we report the results hereafter for black-sky conditions only, except for contribution of forest floor (Table 5) that is presented also for white-sky case, in order to maintain comparability with results presented in Table 4.

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 ($r = 0.72\text{--}0.78$) and the albedo responded to AGB with a similar saturating trend as in the case of tree height (Fig. 4e,f).

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).

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

352

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

358

359 $FAPAR_{CAN}$ varied notably more than albedo when comparing forests of same height, particularly at small SZAs (Fig. 4, Fig.
360 5). This can be explained by the link of $FAPAR_{CAN}$ with canopy interception. Interception was tightly related with LAI_{eff} (not
361 shown), and it determined $FAPAR_{CAN}$ almost directly, because the foliage absorbed strongly at PAR wavelengths (Fig. 3a)
362 and therefore the multiple scattering was negligible. LAI_{eff} , in turn, varied considerably between forests of same height. The
363 outliers (tall trees, low $FAPAR_{CAN}$) in Fig. 5d were plots that had only few trees and therefore very low LAI_{eff} . Similarly,
364 Scots pine had lower $FAPAR_{CAN}$ compared to other species with same height (Fig. 5d). Further examination revealed that
365 Scots pine had short crowns and therefore low LAI_{eff} , although the leaf area per unit crown volume did not differ from the
366 other coniferous species. The strong link between $FAPAR_{CAN}$ and LAI_{eff} explained also the observed species- and SZA
367 dependencies of $FAPAR_{CAN}$. At the lowest SZA (40°) the species-specific $FAPAR_{CAN}$ (Table 4) was strongly correlated with
368 species-specific LAI_{eff} (Table 1) ($r = 0.93$). At large SZAs the canopy interception approached 100% at almost all LAI_{eff}
369 values (cf. Fig. 5c,d) and $FAPAR_{CAN}$ was therefore mainly determined by the absorption of the foliage at PAR wavelengths.
370 Leaves of broadleaved trees absorbed less than conifer needles, which explains why $FAPAR_{CAN}$ of broadleaved species did
371 not increase as rapidly as a function of SZA as did $FAPAR_{CAN}$ of coniferous species (Table 4).

372 3.2 Relation of albedo to $FAPAR$

373 $FAPAR_{CAN}$ was negatively correlated with albedo in conifer dominated forests (Fig. 8). The correlation was strongest at the
374 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
375 plots dominated by broadleaved trees, correlation of $FAPAR_{CAN}$ to albedo varied from almost nonexistent in Alaska (r
376 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
377 explained by the small number of broadleaved dominated forests in our data from Finland. In addition to the proportion of
378 broadleaved trees, variation in forest floor characteristics influenced the albedo- $FAPAR_{CAN}$ relations by altering the albedo
379 values (Fig. 8). The effect of forest floor was seen in relatively sparse canopies only. For example, at SZA of 40° the effect
380 of forest floor on albedo started to show at $FAPAR_{CAN}$ values below 0.5 (Fig. 8). Remembering that $FAPAR_{CAN}$ was tightly
381 related to LAI_{eff} , this value corresponds LAI_{eff} of approx. 1. $FAPAR_{TOT}$ was strongly and negatively correlated with albedo (r
382 ranging from -0.97 to -0.88). The only plots that deviated from this otherwise strong relation were those Scots pine plots that
383 had low $FAPAR_{TOT}$ and xeric forest floor.

384 3.3 Relative importance of density and tree species

385 The variation in density of forests was larger in Alaska than in Finland; the 5th and 95th percentiles of basal area were 8 and
386 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
387 but lower FAPAR_{CAN}. At the smallest SZA (40°) the decrease in basal area from its 95th to 5th percentile resulted in increase
388 of albedo by 36% in Alaska and by 21% in Finland (Fig. 9). Correspondingly, FAPAR_{CAN} decreased by 48% in Alaska and
389 by 44% in Finland. When SZA increased, the response of FAPAR_{CAN} to basal area became weaker. For example, at SZA of
390 70° the basal area could be reduced to approx. 20 m² ha⁻¹ with equal relative changes in albedo and FAPAR_{CAN} (Fig. 9b). At
391 the largest SZA (80°) both albedo and FAPAR_{CAN} varied very little (max. 6%) between the 5th and 95th basal area
392 percentiles. In other words, the effect of basal area depended strongly on SZA. However, the relative decrease of FAPAR_{CAN}
393 with decreasing basal area was always larger than or equal to the relative increase in albedo.

394

395 Increasing the proportion of broadleaved trees increased the albedos considerably more than did reduction in basal area (Fig.
396 9c,d). The effect of broadleaved trees was slightly smaller in sparse than in dense forests. For example, at SZA of 40°,
397 increasing the broadleaved proportion from 0–10% to 90–100% resulted in relative increase of albedo by 130% (in Alaska)
398 and 80% (in Finland) in forests with high basal area (i.e., basal area percentiles from 70th to 100th). In forests with low basal
399 area (i.e., basal area percentiles from 0th to 30th) the corresponding figures were 112% (Alaska) and 71% (Finland). The
400 smaller relative increase in Finland is explained by the higher albedo of Finnish coniferous forests, because the albedos of
401 broadleaved species did not differ between Alaska and Finland. FAPAR_{CAN} was almost independent on the proportion of
402 broadleaved trees, except for large SZAs where FAPAR_{CAN} tended to decrease slightly when broadleaved proportion
403 increased (Fig. 9d). This is explained by the fact that at large SZAs FAPAR_{CAN} was mainly determined by the absorption of
404 canopy elements, and the absorption was lower for broadleaved than for coniferous trees.

405 4 Discussion

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

412

413 Our results show that albedo and FAPAR_{CAN} are tightly linked in boreal coniferous forests. The prerequisites for this are that
414 there is only a limited proportion of broadleaved trees present in the forest and that the tree canopy is not very sparse (i.e.
415 LAI is not very low). The explanation for the tight connection between albedo and FAPAR_{CAN} is that they respond with

416 opposite trends to forest structural variables. However, the shapes of these trends depended on directional characteristics of
417 the incoming solar radiation~~solar angle~~ which was also reflected in the albedo vs. FAPAR_{CAN} relations. This underlines the
418 importance of taking into account latitude and season (i.e. solar angle) when evaluating climate impacts of forests even
419 within one biome. FAPAR_{TOT} was also tightly linked with albedo. Because FAPAR_{TOT} equals one minus PAR albedo, this
420 finding indicates that PAR albedo and shortwave albedo of vegetation are correlated. However, the overall variation in
421 FAPAR_{TOT} was small in magnitude, ~~and therefore the total ecosystem productivity is highly independent on forest~~
422 ~~structure, at least when comparing forests with similar site fertilities.~~ Our results differ slightly from those observed by
423 Lukeš et al. (2016) who compared satellite-based (MODIS) albedo and FAPAR in Finland and observed much weaker (but
424 still negative) correlation between these quantities. The spatial resolution in their study (1×1 km) was coarser than in our
425 study, and the FAPAR definition differed: MODIS FAPAR is defined as PAR absorbed by green elements of vegetation
426 canopy, both trees and understory included. In addition, Lukeš et al. (2016) did not separate coniferous and broadleaved
427 trees, although this effect is likely minor since the proportion of broadleaved trees is low in Finland. Finally, simulation
428 model used here, although parameterized by field observations, cannot capture all the variability in real forests, and on the
429 other hand, satellite products are likely to include observation and modelling errors that increase the noise in the data.

430
431 The responses of albedo to tree species and forest structure were similar across the biome in Alaska and Finland. This
432 corroborates findings in previous, local studies (Amiro et al., 2006; Bright et al., 2013; Lukeš et al., 2014; Kuusinen et al.
433 2014; Kuusinen et al., 2016). Also the results regarding overall level of FAPAR_{CAN}, and the dependence of FAPAR_{CAN} on
434 tree species were similar to earlier studies (Roujean, 1999; Steinberg et al., 2006). However, as our study was based on
435 extensive field data from two continents, drawing more general conclusions on how forest structure, albedo and productivity
436 are interconnected is now possible. In addition, to our knowledge only one study has previously evaluated the forest floor
437 contribution to albedo (Kuusinen et al., 2015). We showed that forest floor vegetation (which is often in practical forestry
438 e.g. a proxy for site fertility type) can significantly contribute to forest albedo; its average contribution can be up to 50%,
439 varying between forests dominated by different tree species. Similarly, the average contribution of forest floor to total
440 ecosystem FAPAR can be up to or even over 50%, as reported previously also by Ikawa et al. (2015) for an eddy-covariance
441 study site in Alaska. In other words, even though forest floor vegetation often contributes only little to, for example, total
442 forest biomass, it can have a significant role as a key driving factor of forest albedo and ecosystem productivity. Quantifying
443 the variation in forest floor composition and optical properties across the boreal biome constitutes therefore an important
444 research topic in the future. The important role of forest floor means also that any forest management that influences forest
445 floor composition can significantly alter the biophysical climate effects of forests. For example, reindeer grazing has been
446 suggested to reduce land surface albedo, because it reduces the cover of reindeer lichens that have higher albedo compared to
447 mosses (Stoy et al., 2012).

448

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

459

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

468

469 Radiative transfer models offer a useful tool for assessing the radiation regime of forests, especially when the modeling
470 approach can utilize readily available common forest inventory databases. Validating the simulated albedo and FAPAR
471 values, however, is challenging. Even though international model intercomparison efforts such as RAMI (Widlowski et al.,
472 2007) provide a rigorous set of reports on performance of radiative transfer models, the quality of available input data in
473 each study where a radiative transfer model is applied is crucial. For example, the forest floor albedos that we calculated
474 from the available reflectance spectra (Fig. 3) were clearly higher (0.18–0.23) than forest floor albedos measured in the field
475 at other boreal sites (approx. 0.15 in Manninen & Riihelä, 2008; Manninen & Riihelä, 2009; Kuusinen et al., 2014). If we
476 had scaled our reflectance factors in order to obtain forest floor albedos of 0.15, the simulated forest albedos would have
477 decreased by 7–10%. Furthermore, including also the UV region in the simulations would have reduced the simulated
478 albedos by up to 7%, assuming that the optical properties of the canopy and forest floor are similar at UV than at 400 nm.
479 However, particularly the lack of field measured spectra for some of the Alaskan species is a limitation of our study and
480 shows that there is an urgent need for comprehensive spectral database of boreal tree species.

481

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

492

493 Global satellite products have provided us insight on coarse-scale trends of albedo in different biomes. However, their
494 weakness is that even though we can establish correlations between changes in albedo and changes in land cover, we are still
495 not able to identify and quantify the biophysical factors which cause the albedo of a forest area to change. In addition, a
496 specific challenge in coupling forest management operations with changes in satellite-based albedo products is that the scale
497 of these operations significantly differs in North America and Northern Europe, and often does not directly correspond to the
498 spatial resolution of current albedo products. With an understanding of the consequences of, for example, forest management
499 practices on the albedo, best-practice recommendations for forest management in future climate mitigation policies will
500 become more justified. By coupling extensive field inventory data sets and radiative transfer modeling, we showed that
501 albedo and FAPAR_{CAN} are tightly linked in boreal coniferous forests at stand level. However, the relation is weaker if the
502 forest has deciduous admixture, or if the canopies are sparse and at the same time the species composition (i.e. optical
503 properties) of the forest floor vary. Because the shape of the relationship between albedo and FAPAR_{CAN} was shown to
504 depend on solar angle, studies evaluating the climate effects of forest management strategies need to consider latitudinal
505 effects due to varying solar paths. The comparisons between Alaska and Finland revealed that albedo and FAPAR_{CAN} differ
506 between geographical regions because of the differences in forest structure. However, regardless of geographical region in
507 the boreal zone, the potential of using thinning to increase forest albedo may be limited compared to the effect of favoring
508 broadleaved species.

509 **Data availability**

510 Data from Co-operative Alaska Forest Inventory prior to 2009 are available at LTER Network Data Portal
511 (<http://dx.doi.org/10.6073/pasta/d442e829a1adf7da169b6076826de563>). Forest inventory data from Finland are described in
512 Korhonen (2011) and Majasalmi et al. (2015). Leaf and needle optical properties measured in Hyytiälä are repositied at
513 SPECCHIO database (<http://www.specchio.ch/>), and those measured in Superior National Forest are repositied at ORNL

514 DAAC by NASA (<http://dx.doi.org/10.3334/ORNLDAAAC/183>). Forest floor spectra were presented in Fig. 3 of this
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669 Yarie, B. J., Kane, E., Hall, B.: Aboveground Biomass Equations for the Trees of Interior Alaska. *AFES Bulletin*, 115, 1–16,
670 2007.

671 Table 1. Mean (standard deviation) of forest variables by dominant tree species in Alaska and Finland. The species
672 dominance was determined by basal area proportion: If the basal area of one of the species exceeded 80% of the total basal
673 area, the plot was considered to be dominated by that species. The remaining plots were labeled as mixed.

Tree species	Number of plots	Stems per hectare	Diameter at breast height (cm) ¹⁾	Height (m)	Crown ratio (%) ₂₎	Basal area (m ² ha ⁻¹)	Effective LAI (m ² m ⁻²) ₃₎
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/ balsam poplar	8	672 (658)	35.1 (14.7)	20.5 (5.8)	62 (11)	34.8 (14.5)	2.7 (1.1)
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)

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

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

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

677 Table 2. Number of study plots by dominant tree species and ~~by~~ forest floor type. The species dominance was determined by
678 basal area proportion: If the basal area of one of the species exceeded 80% of the total basal area, the plot was considered to
679 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

680

681 Table 3. Structural input parameters used in the FRT model simulations.

	Leaf mass per area (g m ⁻²) ¹⁾	Shoot shading coefficient ²⁾	Shoot length (m) ³⁾	Branch area to 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

682 1) Black spruce and white spruce (Reich et al., 1999), quaking aspen and birches in Alaska (Bond-Lamberty et al., 2002),
683 balsam poplar (Sigurdsson et al., 2001), Scots pine (Palmroth & Hari, 2001), Norway spruce (Stenberg et al., 1999),
684 broadleaved species in Finland (values of birch from Kull & Niinemets, 1993)
685 2) Projected to total needle area in a shoot. Measures the effective leaf area, taking into account the self-shading of needles in
686 a shoot. Black spruce and white spruce (Thérézien et al., 2007), Scots pine (Smolander et al., 1994), Norway spruce
687 (Stenberg et al., 1995)
688 3, 4) Same values as used by Lukeš et al. (2013a)

689 Table 4. Albedo, FAPAR_{CAN}, and FAPAR_{TOT} by dominant tree species and SZA. The reported value for given species is the
690 mean of plots in which the basal area proportion of that species exceeded 80%. The number of plots and mean forest
691 variables for each species are reported in Table 1.

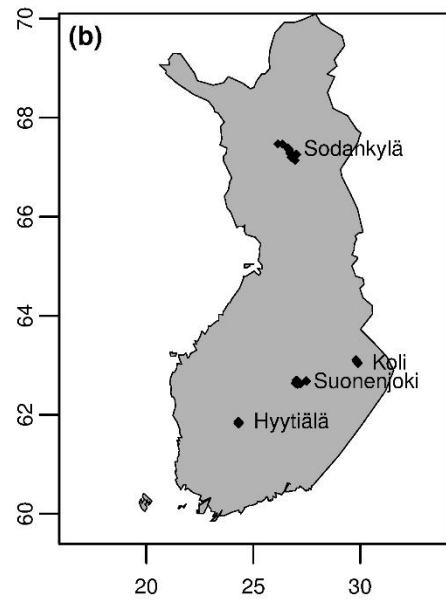
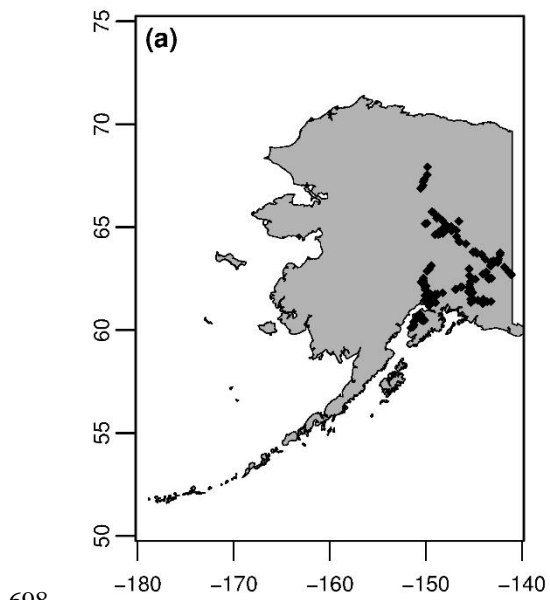
Tree species	Black-sky (SZA)					White-sky
	40°	50°	60°	70°	80°	
Albedo						
Black spruce	0.121	0.122	0.124	0.128	0.137	<u>0.124</u>
White spruce	0.091	0.094	0.097	0.103	0.114	<u>0.104</u>
Broadleaved (Alaska)	0.194	0.204	0.218	0.236	0.262	<u>0.205</u>
Scots pine	0.144	0.147	0.152	0.159	0.172	<u>0.151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

692

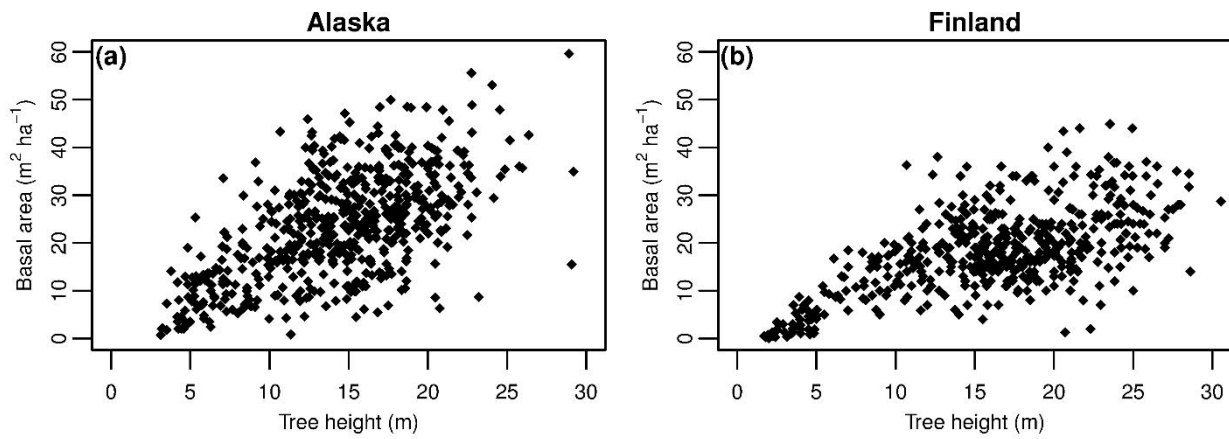
693 Table 5. Canopy and forest floor contributions to albedo, and forest floor contribution to FAPAR_{TOT} by dominant tree
694 species and SZA. The reported value for given species is the mean of plots in which the basal area proportion of that species
695 exceeded 80%. Note that the values are directly comparable to the species specific forest albedos and FAPAR values
696 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	<u>0.066</u>
White spruce	0.062	0.068	0.076	0.087	0.104	<u>0.081</u>
Broadleaved (Alaska)	0.169	0.182	0.199	0.221	0.251	<u>0.186</u>
Scots pine	0.075	0.084	0.096	0.114	0.140	<u>0.094</u>
Norway spruce	0.079	0.087	0.097	0.109	0.128	<u>0.102</u>
Broadleaved (Finland)	0.140	0.155	0.173	0.197	0.231	<u>0.165</u>
Contribution of forest floor to total forest albedo, %						
Black spruce	52.9	48.0	41.4	32.4	20.2	<u>46.8</u>
White spruce	27.9	23.7	19.0	13.7	8.0	<u>22.1</u>
Broadleaved (Alaska)	12.9	10.9	8.7	6.5	4.3	<u>9.3</u>
Scots pine	45.6	40.6	34.5	26.8	17.9	<u>37.7</u>
Norway spruce	23.5	19.7	15.8	11.9	8.0	<u>19.0</u>
Broadleaved (Finland)	32.7	29.5	25.9	21.9	17.1	<u>26.3</u>
Contribution of forest floor to FAPAR _{TOT} , %						
Black spruce	50.1	44.1	36.0	25.1	11.1	<u>45.7</u>
White spruce	26.4	20.6	14.5	8.3	2.6	<u>24.3</u>
Broadleaved (Alaska)	16.9	12.5	8.3	4.6	2.0	<u>15.9</u>
Scots pine	46.3	39.8	31.7	21.5	10.5	<u>42.8</u>
Norway spruce	24.4	18.7	13.2	8.3	4.4	<u>23.3</u>
Broadleaved (Finland)	34.7	29.3	23.5	17.7	12.4	<u>34.3</u>

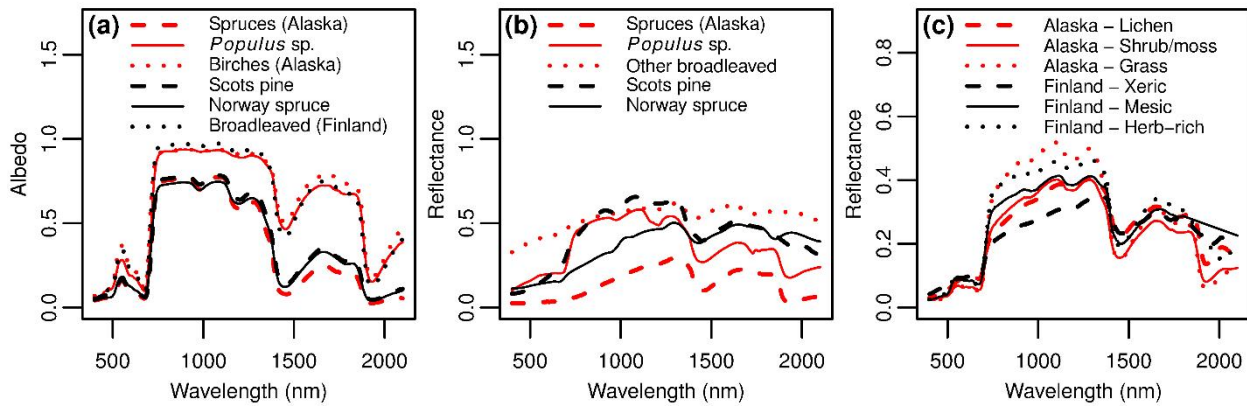
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699 Figure 1. Location of the field plots.

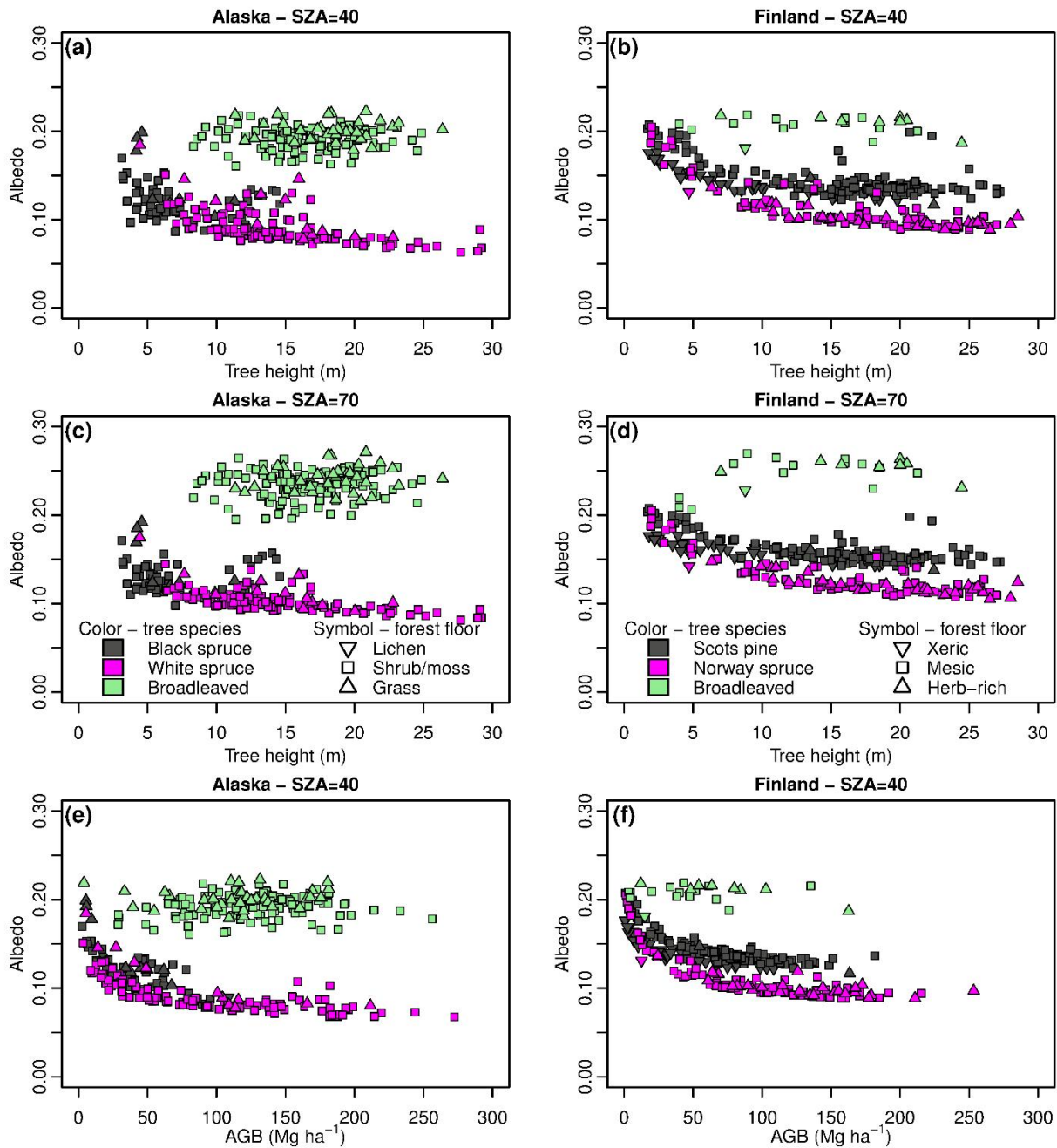


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701 Figure 2. Basal area against tree height in the study plots in Alaska (a) and Finland (b).



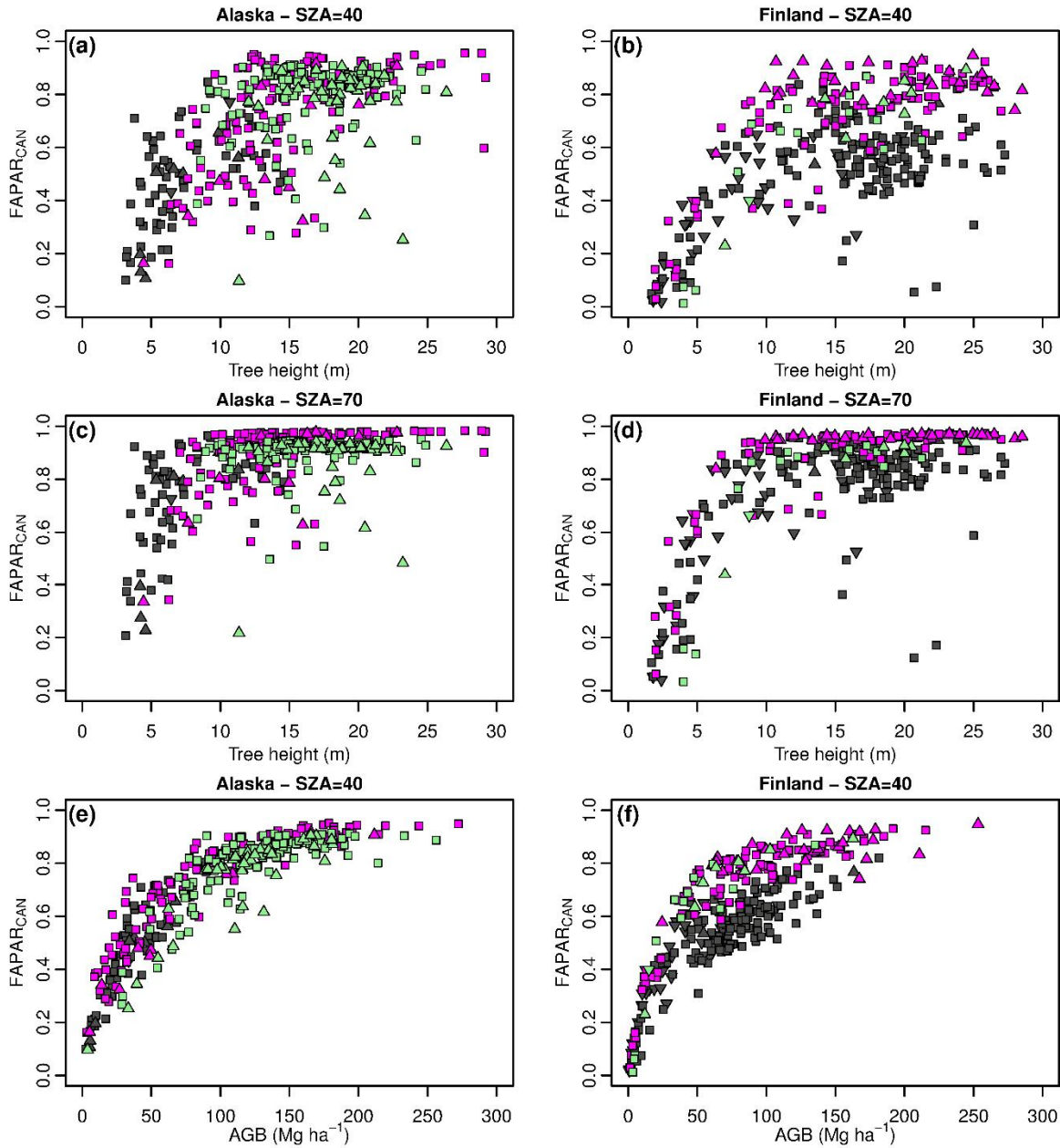
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703 Figure 3. Spectra of vegetation elements used in the simulations: (a) leaves/shoots, (b) bark, (c) forest floor. The values for
 704 leaf and shoot are single scattering albedos (reflectance + transmittance), and the values for bark and forest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



706

707 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
 708 two SZAs, 40° (a–b) and 70° (c–d), representing solar noon at midsummer and the annual average in the study regions. Left
 709 hand column shows the results for the Alaskan data, and right hand column for the Finnish data. The figures show only
 710 monospecific plots, i.e. plots in which the basal area proportion of one of the species exceeded 80%.



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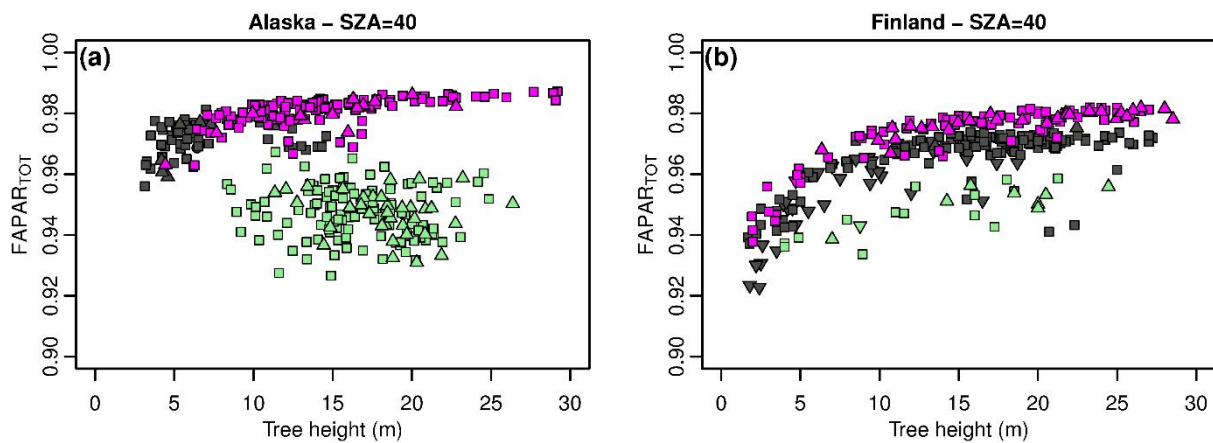
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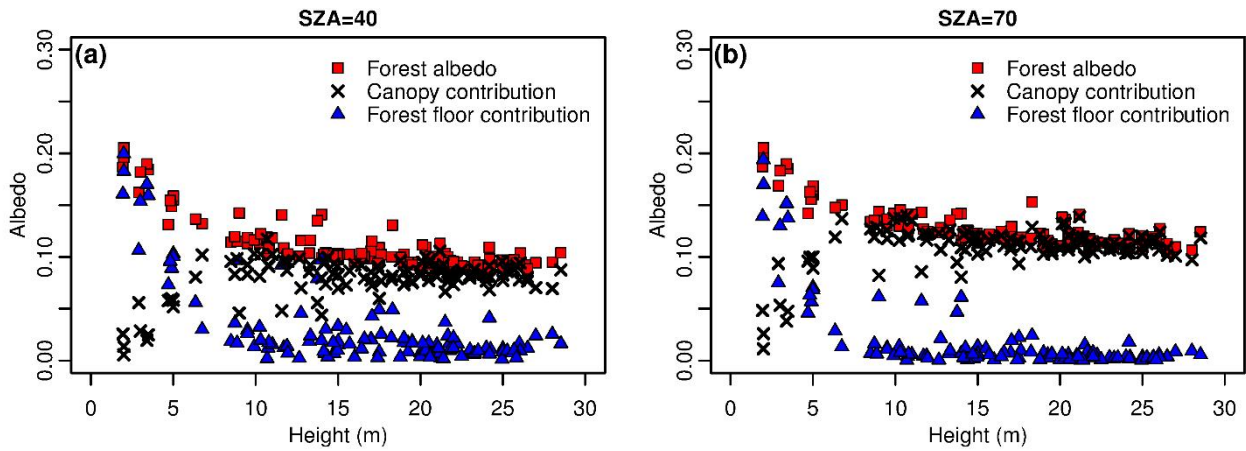
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Figure 5. Black-sky FAPAR_{CAN} as a function of tree height (a–d) and AGB (e–f). Relations to tree height are shown for two SZAs, 40° (a–b) and 70° (c–d), representing solar noon at midsummer and the annual average in the study regions. Left hand 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.



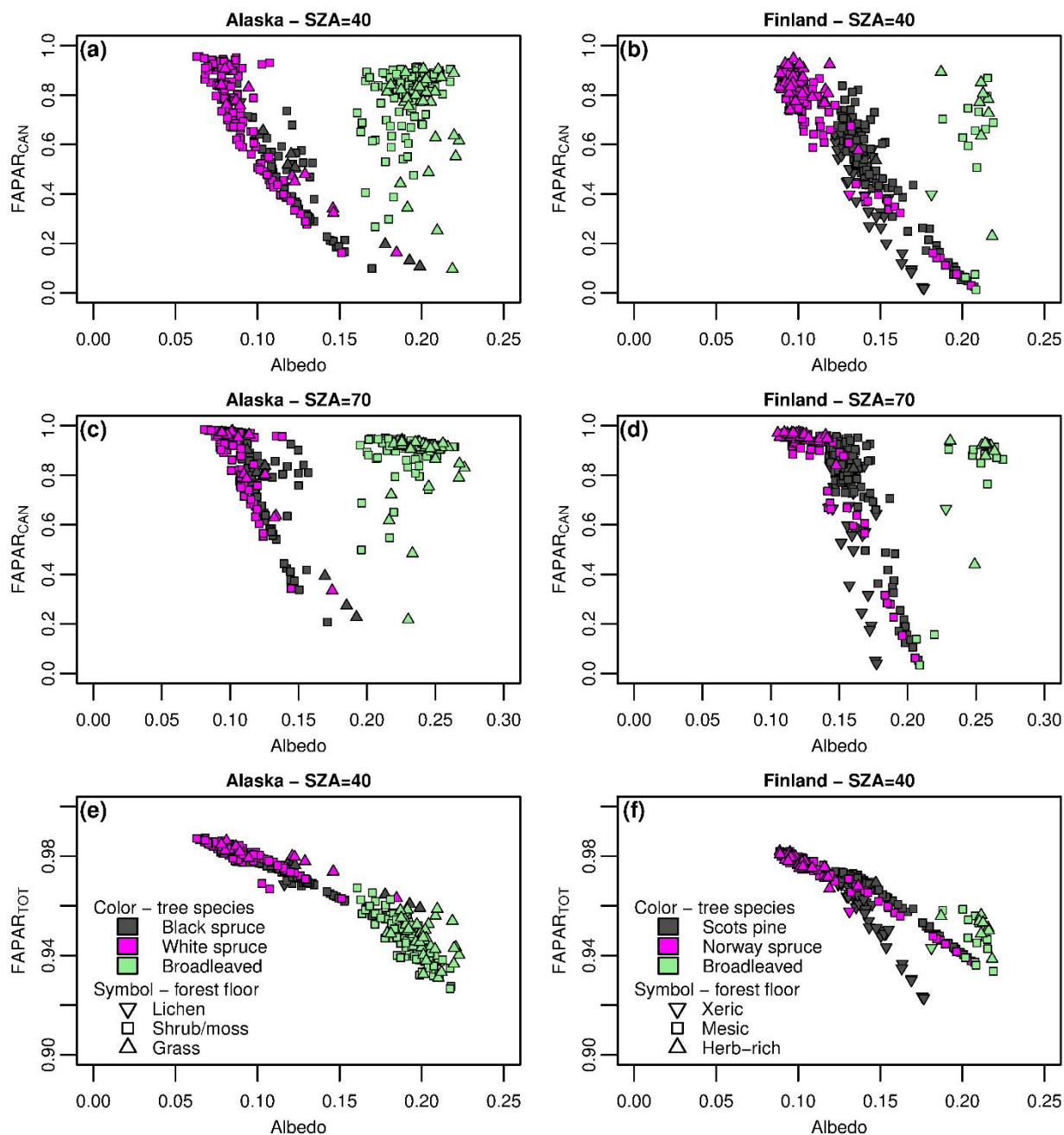
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718 Figure 6. FAPAR_{TOT} as a function of tree height at SZA of 40°. The figures show only monospecific plots i.e. plots in which
 719 the basal area proportion of one of the species exceeded 80%. For explanation of the symbols, see legend in Fig.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



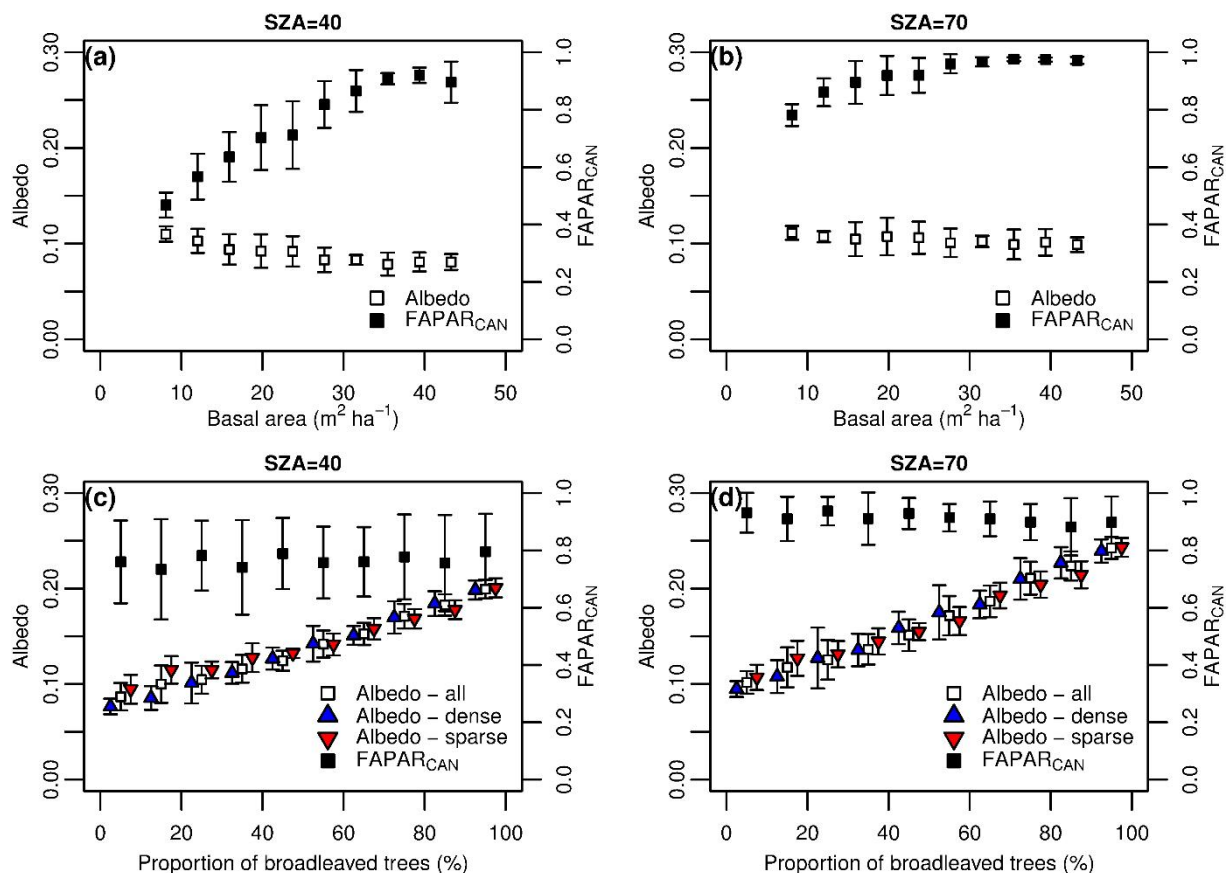
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721 Figure 7. Canopy and forest floor contributions to forest black-sky albedo as function of tree height. Canopy contribution
 722 was obtained by assuming black soil in the simulation. Forest floor contribution was obtained by subtracting the canopy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



724

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



729

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