Anonymous Referee #1

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This paper presents an assessment of the impact of forest structure (type of tree & broadleaf v deciduous proportion) on albedo and hence FAPAR as a proxy for productivity. This is an important topic given the link between productivity and climate and the use of remote sensing to estimate albedo across large areas. The paper is very well written, clear and the results are well presented. I have a few queries regarding the methods, particularly sensitivity and generality, but if the authors can address these then the paper is suitable to publish and would be of wide interest.

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

> We acknowledge that the choice of parameters has an influence on the exact values of the simulated quantities in any modeling study. The main aim of our study is to describe the general relations between forest structure, albedo, and FAPAR. Such studies have been limited by the low resolution of remote sensing data and, on the other hand, by the lack of extensive in situ measurement data. Therefore the modeling approach is a good choice for studying albedo and FAPAR in a large variety of forests, yet maintaining high spatial resolution. The advantage of FRT, when compared to many other theoretical radiative transfer models, is that it can be parameterized with standard forest inventory data and allometric models. These were used also in the current study, because the forest field inventories did not directly measure the required parameters for radiative transfer simulation (e.g. LAI, canopy cover).
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> FRT is one of the most well-known forest radiative transfer models and was originally published already in 1991 (Nilson and Peterson, 1991) and later modified by Kuusk and Nilson (2000). There are already a number of studies reporting the sensitivity of the FRT model to its input parameters. Therefore, we have not reported sensitivity analyses in this manuscript. For example, the effect of crown shape was quantified in Rautiainen et al. (2004), and based on Rautiainen et al. (2008) cone is least accurate for estimating crown volume, 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 has been reported by Lang et al. (2007).
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> We added references to the publications mentioned above in Materials and Methods section.

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.
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> Overall, the large contribution of understory implicates that, in addition to forest 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 the 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.
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> 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.
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> We checked the wordings throughout the text and modified them when necessary to avoid making the impression that too broad generalizations were made.

Anonymous Referee #2

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

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

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

> In the first version of the manuscript, we chose to simulate direct illumination only i.e. black-sky conditions, because this way the simulated albedo and FAPAR are independent of the parameterization of the atmosphere. Introducing the effect of atmosphere would make the analysis more complicated, and any differences in the modeled atmosphere, whether real or caused by uncertainty in the chosen parameters values, would affect the comparisons between the study regions located on two continents. We wanted to avoid this because the focus was on modeling the effects of forest structure.
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> However, we acknowledge that the effect of angular distribution of incoming solar radiation is important, as seen already in the differences between sun zenith angles when assuming black-sky conditions. In general, presence of clouds would reduce the relative share of short (blue) wavelengths in the incoming solar spectrum due to scattering and ozone absorption. On the other hand it would also increase the absorption by water vapor, which occurs in longer wavelengths. Because reflectivity of vegetation is higher in the infrared than in the visible region, these two phenomena have opposite effects on the simulated forest albedo and therefore would probably cancel out each other.
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> Therefore, as suggested by the reviewer, we repeated the simulations in white-sky conditions i.e. 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 certainly exist.

In the revised version, we report the simulated white-sky albedos (results regarding 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 affects 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. 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" ($f_{l}\ -$) and "downwelling (directly transmitted or downward scattered) fraction of incoming radiation" ($f_{l}\ ^{-}$).

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.

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