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Discussions

Interactive comment on "Stand age and species composition effects on surface albedo in a mixedwood boreal forest" *by* Mohammad Abdul Halim et al.

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Response to Referee #1 We would like to thank Referee #1 for their time to read the manuscript, and to make thoughtful and critical comments, which will help to improve our manuscript. In this short response, we are only addressing a few issues raised by Referee #1 and the rest will be addressed in detail in the revised manuscript.

Comparability of albedo measured in the field and from secondary sources: The two most common sensors used in solar radiation measurements are thermopile (used in secondary data, ∼300–2800 nm) and silicon-crystalline (used in this study, 300–1100 nm) pyranometers (Mubarak et al. 2017). Referee #1 has pointed out that

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Discussion paper

these pyranometers have different spectral measurement ranges and, thus, not strictly comparable. We employed silicon-crystalline pyranometers in the present study due to their substantially lower cost, lower power requirements, and better properties for shedding snow and rime; we estimate that instrumenting and maintaining the sites with thermopile pyranometers would have resulted in additional research expenses of >CAD$100,000.

We respectfully argue that even though the silicon pyranometers have narrow spectral measurement range, silicon pyranometers can measure irradiance within +/- 3% error relative to thermopile pyranometers within a solar zenith angle of +/- 60 deg (Mubarak et al. 2017 and Li-COR/Onset pyranometer specifications). The relatively good agreement is partly because most of the solar energy (within 300–2800 nm) is concentrated within 400–1100 nm, and partly because the daily variation (overestimation/underestimation) in measured irradiance is due to changes in solar zenith angle (and associated silicon sensor responsiveness), and is mostly canceled out if averaged over 24 hours. Myers (2010) concluded that silicon pyranometers, when compared against WRR (World Radiometric Reference) cavity radiometer, can offer acceptable accuracy (within $\sim$5%), and that the agreement increases if averaged over longer time period. In our study, we have reported field measurements (albedo) averaged over entire seasons (3-month periods).

Relative accuracy in albedo measurements between thermopile and silicon pyranometers can be different than in irradiance measurements. The relative measurement error can stem from differences in spectral measurement range, behavior of sensing materials used, and biases to due to snow or rime accumulation. However, studies directly comparing relative performances of silicon pyranometers to thermopile pyranometer in measuring albedo are scarce. In a wheat field experiment, Francois et al. (2002) suggested that silicon pyranometers tended to systematically overestimate summer albedo, with an average bias of $\sim$0.03, and a maximum of 0.08 (at LAI $\sim$3) compared to a thermopile pyranometer. They also found that at lower LAI ($\sim$2) the maximum albedo difference was reduced and found no bias for bare soil conditions. (We note that the Francois et al. (2002) study, however, compared different sensors in different fields – and so almost certainly over-estimated differences). In our field sites LAI ranged from 0.0–2.1 and was <1 in most sites. In another study, Inge (1968) reported that silicon pyranometers overestimated plant, sand, water, and rock albedo by $\sim$0.03, and suggested caution should be taken for measuring snow albedo as the overestimation can be as high as 0.09. Stroeve et al (2005) found that silicon pyranometers can overestimate albedo by 0.04–0.09. This overestimation is mainly during the snow-covered period because of high snow reflectivity in <1100 nm range. However, they also point out that silicon pyranometers have benefits over thermopile pyranometers in measuring albedo in cold environments owing to their resistance to rime frost error (small form factor, no dome, and fast response time). Stroeve et al. (2005) made some simple corrections to the up-facing silicon pyranometer measurements (no correction for down-facing pyranometers) and calculated albedo was used to assess accuracy of MODIS albedo product (MOD43) (620–2155 nm) along with other thermopile pyranometers (305–2800 nm / 200–3500 nm) measurements. We note that several published studies (for example, Winkler et al. 2010, and Gleason and Nolin, 2016) have previously used silicon pyranometers to measure albedo of snow-covered forest floor.

Overall, the literature suggests that albedo measured by silicon pyranometers does show some systematic overestimation compared to thermopile pyranometers. Now the question is, what is the allowable error limit to make these two sensor measurements comparable? The answer is subjective. Even class one pyranometers in a lab environment typically vary by +/- 2% with respect to WRR cavity radiometer (Myers, 2010), and in field environment by +/- 5-7% (Stroeve et al 2005). Low cost and low maintenance of silicon pyranometers offer the flexibility to increase measurement replication, which is very important for stand-level albedo estimation. Given the spatial/structural heterogeneity of a forest stand, a single thermopile pyranometer measurement may not offer a better estimate of the stand albedo than albedo measured at multiple locations using silicon pyranometers.

We would also like to stress that secondary albedo data were not used in any statistical comparisons (t-tests, ANOVA) in our paper, but only used in model development to show general trends in albedo change with stand age.

On secondary albedo data usage from the Alaska (USA) site, even though stand characteristics were similar to our study area, we agree that because of different latitudes, snow cover duration, snow depth, and snow properties may strongly affect seasonal stand albedo. We will exclude Alaska data (2 data points for summer and winter each) from regression models in our revision; we have revised the analyses, and this modification does not affect any conclusion of the paper.

In the meantime, we have set up four (two down-facing and two up-facing) silicon pyranometers alongside four thermopile pyranometers (two down-facing and two up-facing) at the same height in an Ontario site to estimate relative albedo errors during winter, when it varies the most, under varying snow and sky conditions. We will report this error estimate in the Methods section (with more details on data processing) in our revised manuscript.

Referee comment: "I agree that change is species composition when the forest gets older is one driving factor of albedo changes. However, also the forest structure changes when the forest gets older. For example, increasing canopy closure reduces the visibility of ground surface, and increasing tree height/canopy closure increase the show fraction. These both reduce forest albedo. There is lots of empirical evidence (at least based on satellite albedo measurements) in literature suggesting that albedo of coniferous forest changes with stand age, even though the species composition does not change. Thus, I think that your statement here is too strong. Species composition is one driver of age-related albedo changes, but based on the data presented, I would not say it is a key driver."

Authors' Response: We agree with the point that changes in stand structure with age importantly influence albedo – and also note that this has been a main emphasis in

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a number of prior studies. However, prior boreal forest albedo studies have focused almost entirely on pure stands, such as upland jack pine or lowland black spruce. In these pure stands species composition does not change (>90% remains the same species) with stand age. In such a stand albedo variation with stand age will necessarily be due mainly to changes in stand structural properties. Our study, however, was conducted in a mixedwood boreal forest, where species composition characteristically changes with stand age. In such stands, our results suggest that species composition can dominate other age-related drivers of albedo. As noted in the manuscript, mixedwood boreal forests are generally the most productive boreal systems, and most forest management occurs in such systems.

Referee Comment L122: "Due to limited spectral range (300–1100 nm) the upper end of solar spectrum (from 1100 nm up to 4000 nm) is left out and therefore the measured albedo is not full shortwave albedo. I looked at the methods of the papers providing secondary data sources, and noticed that they used full solar spectrum: -Chambers and Chapin (2002), Liu et al. (2005): Eppley precision spectral pyranometer, 285–2800 nm -Amiro et al. (2006a): Kipp and Zonen CNR1, 305 to 2800 nm -Amiro et al. (2006b): Kipp and Zonen CM3, 305 to 2800 nm."

Authors' Response L122: Please look at Table 1 of Liu et al. (2005): they have used LI 200R silicon pyranometers (LI-COR, Inc.) (400–1100 nm) in addition to Eppley precision spectral pyranometers for their 3-, 15-, and 80-year sites. Their Methods section implies that they have used LI 200R data at least for the 15-year sites. This is an example of a study where researchers have previously used silicon and thermopile pyranometers in combination.

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