# Point-by-point responses to the reviewers' comments

## ANONYMOUS REFEREE #1

### General comments

This study investigates the effect of disturbance type (harvest, fire) on boreal forest albedo, based on in situ albedo measurements. The authors conclude that i) post- harvest albedo is higher than post-fire albedo, ii) albedo saturates at ~50 years' age after both disturbance types (which is later than the authors expected: they expected saturation at ~25 years' age or earlier), and iii) successional changes in species composition are a key driver of age-related patterns in albedo. I see high risk that the conclusions are not valid because:

**1.** The authors complement their data with data taken from previously published papers (which they call 'secondary sources'). When looking at those papers in detail it is noticed that they used pyranometers working at full range of the solar spectrum (from approx. 300 to 2800 nm), while the data collected by the authors is recorded at visible and near infrared spectral regions (300–1100 nm). This can result in substantial differences between the data sets. Another problem is that the effects that are seen may be due to differences in climate (particularly snow depth, snow properties, and extent of snow-covered period), rather than forest structure or species proportions. The most distant study site (Alaska) is thousands of kilometres away and located in different latitudes than the main study site (~65°N compared to 49.55°N). Therefore, it is likely that not only climate, but also the forest structure (e.g. height, canopy closure) as function of age, differs notably from the forests measured by the authors.

***Authors' response to #1:***

*In this revision, we have excluded data from the Alaskan site and used data only from the stands (secondary sources) that closely matched with our study sites (figures from new analyses: 1, 4, 5, 6, 7, 8). This reanalysis did not affect our conclusions drawn from the previously used dataset. Additionally, we have conducted a direct field comparison of albedo measurements from the Si-based (300–1100 nm, used in this study) and thermopile-based CNR1 pyranometers (305–2800 nm, used in the studies providing secondary data) (please see the supplementary materials). Results from this experiment indicate that the average difference in albedo estimates between these pyranometers was negligible (0.0028; not significantly different from zero). Therefore, we concluded albedo measurements from these sensors are comparable and no further corrections are necessary.*

**2.** The amount of data is relatively small (only 15 plots + those obtained from secondary sources). For example, the conclusion that wintertime post-harvest albedo is higher than wintertime post-fire albedo seems to be due to some post-harvest plots showing very high albedos. The variation in albedo among post-harvest plots is large (Figure 4a). Removing some of the post-harvest plots with high albedo would probably result in notably different conclusions. Another example is the conclusion that albedo saturates later than at 25 years' age (but at no later than 50 years' age). I think that it is impossible to make such conclusion, because there is no data measured for stands aged 20–50 years.

***Authors' response to #2:***

*Maintaining 15 plots in a spatially dispersed remote location throughout the year for 5 years is a difficult and expensive task. This is one of the main reasons why there are not many long-term field measurements of boreal albedo.*

*Each data point in Fig. 4 is not a single measurement; it is the seasonal average albedo of a stand for the particular year – the individual sensors logged at 10-minute intervals, so each data point shown integrates thousands of individual measurements. In a long-term measurement, variations in stand structure and composition (particularly at the stand initiation stage) are obvious, which in turn make albedo responses more variable. This is not uncommon in published studies (for e.g., figure 2, Amiro et al. 2006). In fact, the present study presents the single largest data set of ground-based field measurements of albedo from the mixedwood boreal region in terms of sensor-years of data.*

*We agree that there are no direct measurements between 20–50 years: this is an outstanding data gap globally. However, looking at albedo trends with stand age from our analyses, and data from remote sensing studies suggest that albedo tends to saturate at ~ 50 years in the mixedwood boreal forest. We did not claim this is precisely 50 years: the precise wording used is "at no later than 50 years' age".*

**3.** The error sources and quality control of the measurements are not described in detail enough. The highest summer- and wintertime forest albedos measured by the authors are towards the higher end of what has been reported earlier. This may be because of limited spectral range in the measurements (i.e. not a measurement error), but it is difficult to say for sure, because this is not discussed by the authors.

***Authors' response to #3:***

*In this revision, we have provided the details of quality control for the measurements of irradiance and reflected solar radiation in subsection 2.2 of the Materials and Methods section. This concern is also addressed in the Supplementary Materials of this revised manuscript.*

**4.** From 1 it follows that the secondary data sources are not comparable with the authors' measurements and should be left out. I appreciate value of in situ data and the effort that the authors have put in the experiment. It might be possible that the authors' measurements alone would result in interesting conclusions. However, this is difficult to evaluate based on the data and figures presented. I provide specific comments below to help the authors improve their work.

***Authors' response to #4:***

*Thank you for appreciating our efforts to conduct this long-term field campaign. On comparability of our measurements with the secondary data, we have provided a detailed response previously during the discussion. In addition to that, we have conducted a field comparison of the two sensor types (Si- vs. thermopile-based) used in our study and the studies providing secondary data. Results from this study indicated that measurements from these sensors are highly comparable. Please see the Supplementary Materials for full details.*

**Specific comments**

**5.** L17-18: It would be useful to state which stand ages these values (63%, 24%) apply.

***Authors' response to #5:***

*Thank you. For winter it's 0–19 years old stands and for spring it's 7-19 years old stands. We have clarified this in the Abstract.*

**6.** L21: It is not clear what is meant by "seasonal albedo". I suggest defining the concept before its usage.

***Authors' response to #6:***

*Here 'seasonal albedo' refers to the average albedo over a season. We substituted the wording "*seasonal averages of albedo".

**7.** L21-23: I agree that change in 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 shadow 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 that it is a "key driver".

***Authors' response to #7:***

*We agree that species composition is 'a key driver' not 'the key driver'; we have "tweaked" the wording in the manuscript at a couple points to be clear on this point. Our data suggest that species composition is a better predictor than stand age and other stand structural properties: overall lower RSE of regression models with % deciduous broadleaf species as a predictor (Fig. 6) compared to models with other stand characteristics (Fig. 5, 7, 8). Here we would also like to emphasize that this study is in a mixedwood boreal forest (in mesic sites) which has different successional pathways than a pure jack pine (in dry sites) or black spruce (in wet sites) stand. In these pure boreal stands, it is very common that species composition does not change with stand age, but for a mixedwood stand that is uncommon.*

**8**. L34: It might be useful to clarify what is meant by "the relative stability of the atmospheric temperature profile".

***Authors' response to #8:***

*We have revised the wording as follows to be more precise: "…the relative stability of the atmospheric temperature profile due to weak latent-heat-driven convection".*

**9.** L70-72: I doubt that the legacy charcoal from fires that happened several years or decades ago would influence albedo at the time of harvest.

***Authors' response to #9:***

*Charcoals (and other forms of black carbon) are highly recalcitrant and can persist for a very long time (~1000+ years) in boreal soils. Because of soil scarification during harvesting, legacy charcoals from the previous wildfire can easily be exposed and can reduce surface albedo. Over the last century, fire frequency has increased so much that average fire cycle in* *the Canadian boreal forest is now ~80 years compared to the previous ~150 years. In this scenario, it is not surprising that a post-harvest site had a wildfire some 100 years ago. We did notice frequent legacy charcoals in essentially all recent post-harvest stands. Another PhD project is currently analyzing samples from the project sties to quantify legacy charcoal abundance.*

**10.** L73-75: This sentence is also a bit unclear. It needs more clarification how (through which physical mechanisms?) decomposition processes and plant colonization would influence albedo.

***Authors' response to #10:***

*We have clarified the sentence.*

**11.** L96-97: The first hypothesis is a bit contradictory to what is stated on L65-68 (that post-harvest stands typically have higher proportion of broadleaved species). Large proportion of broadleaved species should lead to higher albedo.

***Authors' response to #11:***

*Post-fire stands can have higher proportions of deciduous broadleaf species depending on legacy stand characteristics and fire frequency/intensity. In our study sites, however, we had a higher percentage of deciduous broadleaf species in the post-harvest stands. We have revised the sentence to avoid the confusion.*

**12.** L105: I think it is important to explain (in qualitative, descriptive terms) what kind of structure do the post-fire stands have. Do they have lots of standing dead trees? How severe were the fires?

***Authors' response to #12:***

*Fires in all sites (including secondary data sites) were severe which killed all previous vegetations. We have explained this in more detail in subsection 2.3 of Materials and Methods.*

**13.** L107: It is not clear whether all three replicate plots were in separate stands or in the same stand?

***Authors' response to #13:***

*The replicated plots were in separate stands. We have revised the text to make this point more explicit.*

**14.** L111-119: Would it be possible to show the forest structural variables for each study plot in a table? This way the reader would get better understanding of the forest structure and species composition and their development through stand age.

***Authors' response to #14:***

*We already had some information on forest structural variables in subsection 2.1 of the Materials and Methods section. We have added Table 1 to provide more general information on these variables.*

**15.** L117: What does the abbreviation LFH stand for?

***Authors' response to #15:***

*'LFH' stands for 'Litter, Fermentation, Humus'–a common acronym used in soil science literature to describe soil organic horizons develop in forests. We have elaborated the abbreviation in parenthesis.*

**16.** L121-124: How was the placement of the albedo measurement towers? I guess that the stands were surrounded by older (higher) forests? How far from the stand edges the towers were placed? Did the surrounding forests block a portion of the incoming diffuse radiation and is there a possibility that this would have affected the measurements?

***Authors' response to #16:***

*The selected stands were at least 5 ha in size and the towers were set up in the middle of the stands. There were no older/taller forests within a few hundred meters in every direction. So, there was no possibility of any older/taller forest being within the footprint of the pyranometers or blocking incoming solar radiation. We have added more explanations in the subsection 2.2 of the Materials and Methods section, where we write: "Selected stands were at least 5 ha in size, and plots were established at least 100 m from any older or taller stand to avoid edge effects".*

**17.** 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 to #17:***

*We have responded to this query previously as a 'short response' during the discussion (also, please see the Supplementary Materials)*

**18.** L126-127: What kind of quality control procedures were applied in the data processing? The explanation in the manuscript gives an impression that data from all days were useful and no outliers etc. needed to be removed. Did you remove some observations/days due to low quality?

***Authors' response to #18:***

*We followed the standard protocols for data quality control, and have added a description of the quality control procedure in the 'Experimental Setup" subsection of the "Materials and Methods". The full paragraph read as follows:*

*"Quality control for the irradiance and reflected solar radiation measurements was conducted following guidelines of the World Meteorological Organization (WMO). Any unusually high/low values were replaced by interpolated values by taking the average of preceding and subsequent measurements. Daily total irradiance data were compared against the WMO-provided maximum possible daily sums of clear-sky irradiance for 50°N latitudes (Annex V, Page 26, WMO 1986). If measured the daily total irradiance was higher than the maximum possible value, we excluded the measurements for that day. For reflected solar radiation, if the daily total of reflected solar radiation was higher than the daily total irradiance, we also excluded the measurements for that day. In addition, we excluded measurements for any snowy day; snowfall was detected using data from the closest available weather station (Environment Canada, 2018)"*

**19.** L131: "deciduous broadleaved area". Does this refer to basal area, or something else?

***Authors' response to #19:***

*Yes, it refers to the percentage of deciduous-broadleaf basal area of the total basal area. We had already explicitly mentioned this in the Materials and Methods section (which states: "The proportion of deciduous broadleaf species of a plot* *was calculated as the ratio of basal area of the deciduous species to the total basal of area of the plot"), so no change seems necessary.*

**20.** L132-133: The diameter limit is much stricter than the height limit. Usually trees with 5 cm diameter at breast height have height at least ~5 meters. This means that you do not need the height limit at all, because the diameter limit already excludes all trees with height less than 5 m. The diameter limit is also quite high considering the young age of the forests. I do not know exactly how fast the trees grow in the study area, but I would guess that forests with ages from 0 to 10 years have only few trees (if any) with diameter at breast height exceeding 5 cm. Is the high diameter limit the reason why some stands are missing in Figure 6 (that shows the albedo dependence on broadleaved proportion)?

***Authors' response to #20:***

*Trees in the study area actually grow relatively rapidly, but generally have a low height-diameter ratio (5-cm DBH trees are only about 2-3 m in height). In the study area, stand density for the 0–19 years old stands averaged ~7000 stem/ha. We have included information on stem density in Table 1.*

*Post-harvest stands with high albedo were 0–4 years old, which had only a few seedlings of deciduous broadleaf species. If we included those seedlings, the % deciduous species became 100%, which was misleading (compared to other plots, they were not zero either). These youngest stands were excluded from the % deciduous broadleaf species calculation and were included as ground vegetation cover. Additionally, % deciduous broadleaf species of some secondary-data sites were not reported, so were excluded from the analysis. That is why some stands are missing in Figure 6.*

**21.** L137-140: Which of the measurement years (2013-2017) were used in calculation of the age? Or did you treat each year as separate observation and thus the age differed depending on which year was used?

***Authors' response to #21:***

*Stand age was calculated as the difference between the year of disturbance (fire/harvesting) and the year of measurement (2013–2017). So, yes, we treated each year as separate observations and stand age was based on the year of measurement.*

**22.** L143-153. How does the climate in the secondary sites (particularly snow depth, snow properties, extent of snow-covered period) differ from the site in Ontario? This is very important because if the climate differs markedly, then the observed differences between post-fire and post-harvest stands are not solely due to stand structure and species composition.

***Authors' response to #22:***

*Weather data from Environment Canada (2018) indicated that climate conditions of the secondary data sites are similar to our study sites. In all these sites average snow duration is 5–6 months. We do not have snow property data, but average snow depth in the Lake Nipigon study area is ~ 11cm, and in Saskatchewan and Manitoban sites 10–15 cm. So, we do not expect large differences in albedo due to geographic differences in the snow regime.*

**23.** L165: "top-surface-specular-included (diffuse and direct) reflectance" is a bit awkward definition. If the reflectance values were measured with integrating sphere setup (collimated light used for illumination, and the reflected radiation collected over the hemisphere), then I would express it something like: "directional-hemispherical reflectance factor of the top-surface of the soil sample".

***Authors' response to #23:***

*Thank you. We have revised the text according to your suggestion.*

**24.** L169: Does "ten different locations" refer to ten different locations within the sample? How is a location defined (how large area is covered by one measurement)?

***Authors' response to #24:***

*Yes, ten different locations of a single sample to accommodate spatial heterogeneity in reflectance of the sample. The size of each location was dependent on the diameter of the opening of the integrating sphere on the spectrometer, which was 10.32 mm. We have added this detail in the methods as follows: "Every sample was measured ten times in ten different locations (each 0.84 cm$^2$ in area) …".*

**25.** L169: What does "Boxcar width 5" mean? It needs more explanation.

***Authors' response #25:***

*Boxcar is a spatial averaging method to remove noise by averaging reflectance/absorbance values of adjacent pixels (of the Charge-Coupled Device [CCD]) and hence improves the signal-to-noise ratio. Here, by "Boxcar width 5" we mean that reflectance values were calculated by spatial averaging of 5 CCD pixels (2 to the left + 1 center + 2 to the right) to enhance signal-to-noise ratio. We have added an explanation in the manuscript as follows: "(with Boxcar width 5 [spatial averaging of 5 pixels] and 100 millisecond integration time)".*

**26.** L187-196: Are the selected model shapes based on physical nature of the phenomena studied, or are they just chosen to give the best model fit to the observed data? For example, in Figure 6g it is difficult to imagine a physical reason why albedo would first increase as function of broadleaved percentage, and then decrease again as the broadleaved percentage approaches 100%.

***Authors' response to #26:***

*We used a purely statistical basis for model selection (i.e., minimum AIC), but we tested candidate models that potentially provide a good description of physical processes. The patterns presented in Fig. 6 show a saturating response in all but one case, and was our expectation based on physical processes. We agree that the decline in albedo shown in figure 6g (fall patterns for post-harvest stands) at high proportions of deciduous species is not intuitive. However, this could be related to leaf senescence patterns in conjunction with leaf litter reflectance properties: in particular aspen leaf litter is quite black, and if not covered by snow could certainly reduce albedo in nearly pure aspen stands in the fall.*

*To address this point, we have added the following to the results section: "In the case of fall albedo in post-harvest stands, there is an apparent decline in nearly pure stands (Fig. 6g), with a better fit of the double exponential model. We speculate that very dark post-senescence leaf litter of aspen may account for this effect".*

**27.** L209-210: Variability of albedo in post-harvest stands in winter and springtime is indeed very high. For example, in Figure 4a it is seen that the albedos of the young forests (<50 years) vary from approx. 0.2 to almost 0.9. I think that 0.9 is very rarely observed except for pure snow surfaces with no vegetation. Are you sure that the variation is not caused by measurement errors? This is why I suggest reporting the details of your measurement and quality control procedure in detail. Another thing that caught my attention is the high albedo (approx. 0.3) of some stands in summertime (Figure 4c, d).

Albedo values 0.2 (at solar noon) are rarely reported in boreal forests. Your values are approx. 50% higher than that. Is this because of the limited spectral range of the pyranometer?

***Authors' response to #27:***

*Some of the youngest stands had very little vegetation, and had prolonged periods of 100% show cover. In this revision, we have provided detailed information on measurement quality control in the Materials and Methods section. We have also provided data from field measurements comparing performances of both Si-based and high-end pyranometers (please see Supplementary Materials). On albedo variances, we have discussed in Authors' response to #2.*

**28.** Figures 2, 4–8: The number of observations varies between figures. It is not clear what constitutes an observation? There were 15 plots, but the number of observations can be much higher than this. Is each year treated as a separate observation? Text on line 128 suggests this. If each year is treated as a separate observation, how does it affect/violate assumptions (independence of observations) in the statistical models?

***Authors' response to #28:***

*This is a good point. We treated seasonally averaged measurements from the same stands as independent measurements, so the reviewer is correct that this does raise issue of non-independence of measurements – as might be handled by treating observation sites as a random effect in a linear mixed effects model. For the general linear models (i.e., ANCOVAs as described in methods) we have conducted parallel analyses that incorporate a random effect for stand. These analyses yield essentially identical results to those presented, and in all cases the random effect term is not significant. We note these parallel analyses in the methods section but present only the (simpler) analyses.*

**29.** Section 3.2: It might be possible to weight the observed ground spectra with incoming solar radiation, to calculate albedos of the ground surface. This way, it would be easier to link age-related changes in ground albedo to age-related changes in forest albedo.

***Authors' response to #29:***

*Albedo of the ground surface depends on many factors (moisture content, presence/absence of trees etc.) in addition to incoming solar radiation. Stand structure and species composition are also likely to have strong interactive effects on ground surface albedo. We respectfully argue that this would not be a viable approach to use any simple weighting scheme to separate ground albedo from vegetation albedo effects.*

**30.** Figure 6: Why Figure 6 does not contain all data presented in Figure 4 (high winter albedo values close to 0.9 are not presented in Figure 6)?

***Authors' response to #30:***

*The youngest stands (without enough trees to estimate proportion of deciduous species) were omitted from these analyses. Please see response to # 20*

**31.** L254-255: Earlier (in Section 2.5) you state that only fall albedos were modelled with double-exponential model, but here you say that also summer albedo was modelled with double-exponential model. Which one is true?

***Authors' response to #31:***

*In section 2.5, at L192–194 we were describing why we could not use generalized linear models for some stand attributes to predict fall albedo, as they were only related to fall albedo nonlinearly (double exponential). If we included these stand attributes with other attributes in a generalized linear model (GLM), the model structure became very complex (a mixture of linear and non-linear families). An immediate challenge of this modeling exercise was to decide how to define a GLM family that can handle both double exponential and exponential families at the same time. To avoid this complex modeling exercise, we chose to model these stand attributes separately. In L254–255 we were describing how summer albedo was related to the stand age only (not in the GLM with other stand attributes).*

*So, to summarize, both statements are true and are referring to two different contexts as discussed above.*

**32.** L275: Please explain in more detail what is meant by "to avoid modelling complexities". Does it mean that the model did not converge if it was too complex?

***Authors' response to #32:***

*Please Authors' response to #31*

**33.** L287-288: I think word "dramatic" is too strong.

***Authors' response to #33:***

*A difference in albedo of >0.2 is really large: larger than differences between, say, generalized albedo values typically given for grasslands (~0.25) vs. forests (0.08-0.18). It seems essential to emphasize the surprising magnitude of the differences an albedo values with disturbance type as described in the study.*

**34.** L290: I doubt that the conclusion that albedo saturates at 50 (rather than at ~25) years' age is valid. You do not have any measurement data between 20-50 years (Figure 4).

***Authors' response to #34:***

*Please see Author's response to #2.*

**35.** L291: Please explain in more detail how you determine that the effect of broadleaved proportion is larger than the stand age effect?

***Authors' response to #35:***

*This conclusion is based on the lower RSE values of the regression models for broadleaf proportion compared to other regression models. Also, please see Authors' Response #7.*

**36.** L306-308: I think this sentence is a bit misleading. I would expect that from an energy balance perspective late spring is more important than winter, because the amount of incoming solar radiation is larger in late spring.

***Authors' response to #36:***

*Snow starts melting in late spring because of high incoming solar radiation. Melting snow is usually dirty and has lower albedo compared to regular snow (as reported, for example, in Conway et al. 1996). During this time of the year, latent heat flux from the melting snow usually very strong and thus dominates the surface energy balance.*

**Technical corrections**

**37.** L177-178: Near-infrared range must have a typo [700–100 nm].

***Authors' response to #37:***

*Yes, it should be [700-1000 nm]. Thank you. We have corrected this typo.*

**38.** L206-207: "post-harvest" repeated two times.

***Authors' response to #38:***

*Thank you. Corrected.*

**39.** Table1: It is a bit difficult to see the difference between italic vs. regular font. Perhaps bold vs. regular would be a better choice?

***Authors' response to #39:***

*Thank you. We changed italic fonts to bold.*

**40.** L357: "albedo" repeated two times.

***Authors response to #40:***

*Thank you. Corrected.*

## ANONYMOUS REFEREE #2

By combining literature data with novel in-situ measurements and via chronosequencing, the study by Halim et al. analyzes temporal trajectories in surface albedo following harvest and fire disturbances in southern boreal mixedwood forests. The main findings are that i): winter and spring surface albedos following harvest disturbances are higher than those following fire disturbance; that ii) both winter and summer surface albedos "saturate" at around 50 years, and that iii) successional changes in species composition are a key driver of post-disturbance albedo dynamics.

**1.** I have several major concerns about the study methods that call to question these findings. My first and largest concern surrounds the extensive use of albedo data sourced from the literature (referred to as "secondary data") which are connected to sites located hundreds to thousands of kilometers away. Although the dominant species com- positions across sites may be similar, stand structure and other important site-specific attributes affecting the surface albedo may differ greatly across sites. These include differences in geology and soils (affecting albedo via their controls over understory vegetation compositions, soil moisture retention, growth rates), differences in latitude (affecting the direct albedo component via differences in solar geometry), and – most importantly – differences in local climate (affecting albedo via controls over soil moisture, vegetation growth and phenology, length of snow season, and important snow physical attributes such as snow depths, snow age, snow water contents). Without controlling for differences in these important site-specific factors it is difficult to arrive at robust conclusions regarding albedo-age dynamics, albedo-species composition dynamics, albedo-canopy height dynamics, and albedo-ground cover dynamics. Regarding the albedo-age dynamic, for instance, asymptotes of the presented exponential models in Figure 4 seem to be heavily influenced by the "secondary" data comprising all data points beyond 19 years. Regarding the albedo-species composition dynamic, the "secondary" data points in Figure 6 for "Summer" and "Winter" seem to be heavily influencing the y-intercepts and thus affecting the model functional form and shape parameters. Secondary data points in Figure 7 also appear to heavily influence the model fits (or lack thereof) for the "Summer" albedo-canopy height dynamics.

A second methodological concern which is also related to the augmentation of the in-situ sample with literature ("secondary") data is the difference in the definition of albedo. Much of the secondary albedo data are for a broader spectral range (e.g., 295-2800 nm) than what is measured in-situ at the authors' own study sites (i.e., 300-1100 nm). This is important given the high albedo of vegetation in spectra above 1000 nm and given the sensitivity of the shortwave near-infrared broad band (1300-2500 nm) to differences in boreal tree species (see Hovi et al. 2017 → https://doi.org/10.14214/sf.7753 ).

I also have some concern about the study's scientific value, irrespective of my concerns about the methods. None of the three major findings listed above are novel and can be distilled from a diligent review of the boreal forest albedo literature (e.g., post-fire: Lyons et al. 2008; Randerson et al. 2006; Amiro et al. 2006b; Liu et al. 2005; Wang et al. 2016 → https://www.sciencedirect.com/science/article/pii/S0034425716300888 post-harvest: Kuusinen et al. 2016; Kuusinen et al. 2014; Bright et al. 2013; Hu et al. 2018 → https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018MS001403 ).

***Authors' response to #1:***

*We responded to these concerns previously as a 'short response' during the discussion/review process. In response to Reviewer #1's comments, we have also discussed in detail above. For measurement comparability between Si-based and thermopile-based pyranometers, please see the Supplementary Materials.*

**2.** Further, the study is motivated by the need to "improve climate model parameterizations" but the authors have made no attempt to explain how their results can/will achieve this. How will the presented statistical functions or empirical insights be applied in a climate modeling context, either for improving existing parameterizations in a climate model directly or for use as a climate model benchmarking/evaluation tool? Albedo parameterizations in most climate models are process-oriented and intimately tied to important forest structural attributes like leaf area index which the authors have not included. Model parameterizations are also largely oriented around important local meteorological state variables (i.e., near surface air temperatures, wind speeds, precipitation type and frequency, snow depth, etc.) which are absent in the paper. This makes it difficult to discern the conditions under which the reported findings may be applied to evaluate climate model predictions. Further, since the reported albedo dynamics for the post-harvest case are intimately connected to the specific management practices of the study region, without providing any detail about the prevailing management regime(s) of the study region it will be difficult for modelers to assess accuracy of simulated post-harvest albedo dynamics. As for the post-fire case, the finding that the near-term (< 25 yr) increases in summertime albedo are connected to pioneer birch succession (a finding reported in several of the references listed above) implies that any "improvement" to the albedo prediction capability of a climate model would need to target the vegetation dynamics routines of the model and not necessarily the "albedo parameterization" itself.

***Authors' response to #2:***

*We also responded partly to this concern during the discussion. In this revision, we have revised the Discussion (subsection 4.2) to focus on "improving albedo prediction capability' than on "albedo parameterization". We have also provided information on current forest management practices in the study area (Subsection 2.1), as suggested by the reviewer.*

**3.** Given my concerns about the study's methods and low scientific significance, I find it difficult to recommend publication in BG. I also find it difficult to encourage a major revision involving a new analysis that excludes the use of "secondary" data given the limited number of field plots and given the narrow spectral band of albedo data that has been measured at those plots.

***Authors' response to #3:***

*Please see points made above: the present study more than doubles that number of sensor-year measurements available for field measurements of albedo in boreal forests, and we show that there is no detectable difference in albedo measurements made by the pyranometer used and the measurements based on broadband pyranometers (that have high energy demands and would be exceedingly difficult and expensive to deploy and maintain in remote field sites).*

## EDITOR'S COMMENTS

**1.** Halim and co-authors present an interesting analysis on the age and species effect on albedo.
In the introduction previous reports are cited to list possible drivers. Stand age is, however, not among the listed drivers. In the discussion the authors do a reasonable good job in focusing the discussion on the physical drivers (fraction of deciduous trees, charcoal, stand structure, ...). From this perspective it is surprising that the results section uses stand age as one of the independent variables to explain the changes in albedo (as reflected in the statistical models and the table). In my opinion, the authors should better explain that the analysis with age is simply to describe the temporal evolution but that the additional analysis are intended to explain the physical drivers of these age trends. If this indeed reflects the thinking of the authors, the paper should be edited towards this message, e.g. no models should be fitted against age and several sentences throughout the manuscript should be rephrased. Nevertheless, if the authors interpret their results as an indication that age itself is a physical driver of albedo, it should be discussed how stand age (rather than structure) affects albedo.

***Authors' response #1:***

*In our previous 'short response' during the discussion, we discussed why stand age is an important predictor in addition to stand structure and composition (regardless of their dependency on stand age).*

**2.** The importance of this study for climate modelling should be rewritten in line with the state of art of albedo modelling through canopy radiative transfer models and the simplified canopy radiative transfer schemes that are used in the land surface schemes of climate models. The authors seems not be aware of recent work (Naudts et al 2016, Luyssaert et al 2018) that does account for the effect of stand structure, tree species, and forest management on albedo and the climate (including not only albedo but also transpiration and roughness). The impact on modelling efforts of the albedo observations presented in this study is largely overstated. Canopy radiative transfer schemes combine scattering parameters and simulated canopy structures to simulate the albedo. The albedo values reported in this study can be used to evaluate existing models but are unlikely to be useful to improve existing models as claimed in the text. It may be best to delete all references to model developments and focus the discussion and conclusions on the underlying processes and the remaining unknowns.

***Authors' response #2:***

*We agree that the relevance of direct surface albedo measurements is mainly to land surface schemes and sub-models in the climate modeling community. Existing efforts, including the recent papers cited, are limited by data availability, given the lack of data from mixedwood boreal forests and for harvest impacts as distinct from fire. The link to modeling efforts is made mainly in the final paragraph of the paper. We have revised the final paragraph so as to emphasize model evaluation. However, one would hope that there is ultimately a constructive feedback between modeling and empirical studies.*

*The revised final paragraph reads as:*

*"In climate modeling studies albedo estimation for boreal forests have commonly been achieved by highly simplified representations of vegetation dynamics (Thackeray et al., 2019). In a recent study, Bright et al. (2018) pointed out that overlooking stand structural and compositional properties over the successional trajectory is likely to substantially bias radiative forcing estimates in the boreal forest. Ground-based estimates such as those presented are essential: at high latitudes when solar zenith angle is high (> 70°), satellites such as MODIS often provide poor-quality albedo data due to spatial heterogeneity of the landscape pixel signature and performance degradation of atmospheric correction algorithms (Bright et al.,*

*2015b; Wang et al., 2012). Our findings based on field data are thus important in evaluating and potentially improving albedo predictions in land surface characterizations with climate models, and in improving albedo estimates derived from remote sensing. In addition, our results point to the importance of slow ecological succession as a driver of age-related patterns in albedo, suggesting that future models should explicitly incorporate these ecological processes to better predict long-term trends in climate forcings in boreal forests."*

# Stand age and species composition effects on surface albedo in a mixedwood boreal forest

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**Abstract.** Surface albedo is one of the most important processes governing climate forcing in the boreal forest and is directly affected by management activities such as harvesting and natural disturbances such as forest fires. Empirical data on the effects of these disturbances on boreal forest albedo are sparse. We conducted ground-based measurements of surface albedo from a series of instrument towers over four years in a replicated chronosequence of mixedwood boreal forest sites differing in stand age (year since disturbance) in both post-harvest and post-fire stands. We investigated the effects of stand age, canopy height, tree species composition, and ground vegetation cover on surface albedo through stand development. Our results indicate that winter (0-19 years) and spring (7-19 years) albedo values were 63 and 24 % higher, respectively, in post-harvest stands than in post-fire stands. Summer and fall albedo values were similar between disturbance types, with summer albedo showing a transient peak at ~10 years stand age. Winter and summer albedos saturated at roughly 50 years stand age in both post-harvest and post-fire stands. The proportion of deciduous broadleaf species showed a strong positive relationship with seasonal averages of albedo in both post-harvest and post-fire stands. Given that stand composition in mixedwood boreal forests generally shows a gradual replacement of deciduous trees by conifers, our results suggest that successional changes in species composition are likely a key driver of age-related patterns in albedo. Our findings also suggest the efficacy of increasing the proportion of deciduous broadleaf species as a silvicultural option for climate-friendly management of the boreal forest.

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**Keywords**

Stand age, species composition, canopy height, ground vegetation cover, harvesting, forest fire, succession, surface albedo, boreal forest.

## 1 Introduction

Surface albedo, the fraction of incoming solar energy reflected from the surface in all directions, is one of the most important biophysical factors affecting both local and global climates. In boreal forest, the magnitude of albedo-related forcing on climate is even more important than in other ecosystems because of snow-related feedbacks, low sensible heat flux, and the relative stability of the atmospheric temperature profile due to weak latent-heat-driven convection (Bright et al., 2015a; Hansen et al., 2005). Even though albedo is increasingly used as an important state variable in climate models (Brown and Caldeira, 2017; Bala et al., 2007; Betts, 2000), forest disturbance effects on net radiative forcing due to local albedo changes and related feedbacks with regional/global mean surface temperature remain highly uncertain (Bright et al., 2015a; Lee et al., 2011). Harvest and fire suppression may differ substantially in their effects on albedo, but empirical data on albedo responses to disturbance type remain particularly sparse.

Following disturbance events, albedo of boreal forests is expected to change with stand age due to changing surface properties, and forest structure and composition. Age-related stand structural attributes (e.g., tree species composition, leaf area index [LAI], canopy height, and ground vegetation cover) can substantially influence surface albedo of a stand throughout the year. Studies have generally found higher albedos in young stands than in mature stands in the boreal forest (Bright et al., 2015a; Kuusinen et al., 2014; Amiro et al., 2006b), and it has been suggested that albedo stabilizes ~ 25 years after a disturbance event (during the 'stem exclusion' phase in the ecological succession trajectory). Early in stand development boreal mixedwood forests are commonly dominated by deciduous broadleaf species (Madoui et al., 2015; Brassard and Chen, 2010; Johnstone et al., 2010), which have higher leaf and canopy reflectance than conifers (Lukeš et al., 2013a; Linacre, 2003), contributing to high summer albedo in young stands (Lukeš et al., 2013b; Betts and Ball, 1997). These deciduous species shed leaves in the winter, which increases canopy openness (lowers LAI) and allows snow albedo to dominate, contributing to the high winter albedo in young stands. Available data suggest that at this stage both LAI and ground vegetation cover usually increase with stand age, depending on site quality and silvicultural practices (Amiro et al., 2006b; Uotila and Kouki, 2005). Low LAI can increase canopy background reflectance both in snow-covered and snow-free conditions, and thus can contribute to the high albedos in young stands (Amiro et al., 2006b). LAI effects on albedo in young stands may be highly modulated by ground vegetation cover in the summer, but probably not much in the winter as ground vegetation is generally leafless or covered with snow (Kuusinen et al., 2015; Lukeš et al., 2013b; Betts and Ball, 1997). In conjunction with other factors, surface albedo tends to decrease with increasing canopy height (Hovi et al., 2016; Linacre, 2003). In the later stages of stand development, albedo is expected to saturate non-linearly as conifers dominate the stand and canopy cover and stand attributes change gradually, but data describing this pattern remain sparse (Amiro et al., 2006b).

Harvesting and fire are the major stand-replacing disturbances in the boreal forest (Brassard et al., 2008). These disturbances may differentially affect surface albedo of post-disturbance stands in complex ways by altering ground surface spectral properties, species composition, and stand structure (Lukeš et al., 2013b; Liu et al., 2005), but field data directly addressing this issue are essentially limited to a single study in Europe (Kuusinen et al., 2016). Structure and composition of post-fire stands are generally more heterogeneous than post-harvest stands; for example, post-fire stands are more likely to show a bimodal vertical structure and a mixture of conifer and hardwood species during early stand development stages (Brassard and Chen, 2010; Chen et al., 2009). Charcoal residues may also strongly reduce albedo in snow-free conditions in the first years following fire disturbances (Amiro et al., 2006b). Both charcoal effects and stand heterogeneity might be expected to reduce surface albedo in post-fire stands relative to post-harvest stands. However, the magnitude of this difference in surface albedo might be less than expected due to the presence of legacy charcoals from historical fires in post-harvest stands (Hart and Luckai, 2013). Immediately after harvesting, the albedo of a post-harvest stand can also be reduced because of the presence of coarse woody debris (CWD) and high soil moisture content (Linacre, 2003). In the years following a disturbance event, CWD might be expected to further reduce albedo by becoming darker in color due to decomposition processes (Brassard and Chen, 2008) and plant colonization (Kumar et al., 2018).

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Despite the important roles of stand age, and stand structure and composition as determinants of boreal forest albedo, field measurements are scarce (Kuusinen et al., 2014) and particularly limited for early stand ages that show high variability in surface properties (Bright et al., 2013). This has contributed to poorly constrained estimates of the local albedo changes on net global radiative forcing (Bright et al., 2015a). Although some recent studies (e.g., Luyssaert et al., 2018; Naudts et al., 2016) have incorporated vegetation structure and composition in albedo estimation for land surface models, scarcity of field measurements is still a challenge for proper attribution of boreal forest albedo in climate models (Li et al., 2016; Thackeray et al., 2019). Thus, to estimate the net change in surface temperature as a function of albedo change from deforestation in boreal forests, a number of climate models (e.g., Bala et al. 2007, Betts 2000) have used a 'biome replacement' approach (replacing boreal forests with grassland or agricultural land cover types) and approximated boreal forests' albedo as a single value from mature stands (~ 60-year old). Early stand dynamics is reported to determine which mechanism, albedo vs. carbon storage, dominates the net forcing for the boreal forest (Kirschbaum et al., 2011). Such simplifications in climate models that do not explicitly consider stand age and successional effects on albedo will likely result in strongly biased estimations of boreal forests' albedo over the rotation (harvesting/fire) period (Bright et al., 2018).

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Given the complex nature and limited understanding of underlying processes (Lukeš et al., 2013b), it is important to conduct field studies to better quantify forest albedo in relation to stand age and disturbance type in boreal forests. Deeper understanding of the local mechanisms that account for variation in albedo will not only enhance global climate models (e.g., by improving the land-surface model: Bright et al., 2018), but also help to design climate-friendly silvicultural practices (Astrup et al., 2018; Matthies and Valsta, 2016; Bright et al., 2015a). In the present study, we set up micrometeorological towers with pyranometers in a replicated chronosequence of post-harvest and post-fire sites to study stand age, disturbance type, and species composition effects on albedo in a mixedwood boreal forest of northwestern Ontario, Canada. We hypothesized: (1) that post-fire stands would show lower albedo values than post-harvest stands as a consequence of stand composition, legacy structures, and fire residues; (2) that all stands would approach albedo values similar to mature stands within ~ 25 years, soon after crown closure; and (3) that stands with higher dominance of deciduous broadleaf species would show higher albedo than conifer-dominated stands, with this effect being most pronounced under snow-covered conditions.

## 2 Materials and Methods

### 2.1 Study area

The study was conducted in the boreal forest of the Lake Nipigon region (49.55° N and 89.5° W), Ontario, Canada, approximately 200 km north of Thunder Bay. A series of circular (10-m radius) chronosequence plots were established in the post-harvest (full-tree harvest) and post-fire stands in the study area. Three plots were set up in each of three cutblocks (in separate stands) harvested in 1998, 2006, and 2013. Selected stands were at least 5 ha in size, and plots were established at least 100 m from any older or taller stand to avoid edge effects. Recent (2013) post-fire stands were not present, so we set up three plots only in post-fire stands dating from 1998 and 2006 fire events (Fig. 1). Replicate stands were spatially interspersed to the extent feasible. For each of the 15 plots, albedo and stand attributes (stand age, percentage of deciduous broadleaf species, canopy height, and percentage of ground vegetation cover) were measured from July 2013 to June 2017.

The mesic mixedwood study area is dominated by jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) BSP), white spruce (*P. glauca* (Moench) Voss), trembling aspen (*Populus tremouloides* Michx.), eastern white cedar (*Thuja occidentalis* L.), balsam fir (*Abies balsaema* (L.) Mill.), and paper birch (*Betula papyrifera* Marsh.) (Chen and Popadiouk, 2002). The management regime in the region is based on clearcut silviculture modified to include live tree retention in harvested stands (OMNRF, 2015); typical rotation lengths are 80 years (Colombo et al., 2005). In study plots over the study period canopy height ranged from 0–7.7 m, ground vegetation cover ranged from 1.8–96.7 %, LAI ranged from 0–2.1, and the proportion of deciduous broadleaf basal area ranged from 10.6–100 %, and stand density range from 0–11556 stem/ha (Table 1). The study area has an average elevation of 416 m a.s.l. The soil is a moderately deep Brunisol (coarse-loamy texture) with 1–15 cm thick organic layer (i.e., the total litter, fermented, and humic [LFH] layers). The area remains snow covered for 5–6 months with an average snow depth of ~10 cm (Environment Canada, 2018; Sims et al., 1997) and the mean annual air temperature of the study plots was –1.1 °C (Halim and Thomas, 2018).

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### 2.2 Experimental setup

In the center of each circular plot a pair of upward- and downward-facing pyranometers (Silicon [Si] pyranometer; Onset, Massachusetts, USA; measurement range 0–1280 Wm$^{-2}$ over a spectral range of 300–1100 nm, accuracy ± 5 %, resolution 1.25 Wm$^{-2}$) were set up on a mast 3.5 m above the canopy (above the ground for 2013 post-harvest stands) to measure incident and reflected solar radiation every 10 minute. The plot and tower locations were selected to avoid trees from surrounding stands falling within the footprints of the pyranometers or blocking incoming solar radiation. Instrument masts consisted of extendible galvanized steel poles and were set in concrete bases and guyed to mitigate instrument sway. At least once a year pyranometer heads were cleaned and realigned to make sure they were normal to the ground. Average daily albedo was calculated as the ratio of daily total incident and reflected radiation for each plot. The average daily albedo was used to calculate average monthly albedo, which was finally used to calculate mean seasonal albedo for each year in each plot.

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Quality control for the irradiance and reflected solar radiation measurements was conducted following guidelines of the World Meteorological Organization (WMO). Any unusually high/low values were replaced by interpolated values by taking the average of preceding and subsequent measurements. Daily total irradiance data were compared against the WMO-provided maximum possible daily sums of clear-sky irradiance for 50°N latitudes (WMO, 1987, p.26). If measured the daily total irradiance was higher than the maximum possible value, we excluded the measurements for that day. For reflected solar radiation, if the daily total of reflected solar radiation was higher than the daily total irradiance, we also excluded the measurements for that day. In addition, we excluded measurements for any snowy day; snowfall was detected using data from the closest available weather station (Environment Canada, 2018).

In addition to albedo, winter (December–February)/spring (March–May) and summer (June–August)/fall (September–November) proportion of deciduous broadleaf area (%), canopy height (m), and ground vegetation cover (%) were measured every year in late October and early July, respectively, in each plot. The proportion of deciduous broadleaf species (%) were determined for trees with diameter at breast height ≥ 5 cm and height > 1 m. Canopy height was determined as the mean height of all trees sampled; the young stands sampled were at stages of development prior to and just after canopy closure, so essentially all trees were "canopy dominants". The proportion of deciduous broadleaf species of a plot was calculated as the ratio of basal area of the deciduous species to the total basal of area of the plot. In each plot, four 1-m$^2$ subplots were set up and percent ground vegetation cover was determined visually (Kumar et al., 2018). Stand age was determined as the time (year) since the last disturbance (fire/harvesting) for each plot. Fire maps (from the Ontario Ministry of Natural Resources, Canada) and forest management plans (from Resolute Forest Products, Canada) were used to verify type and year of disturbances.

### 2.3 Sources of secondary data

Since we did not have recent post-fire stands (0–6-year old) in the study area, we used secondary albedo data from studies in post-fire boreal forests with similar stand characteristics in Saskatchewan and Manitoba (Canada) (Fig. 1). We also used secondary albedo data for old stands (> 70 years) from these sites along with primary data to develop regression models for both post-fire and post-harvest stands. Here we assumed that at this stage of stand development, there is negligible difference in stand attributes (e.g., species composition, height, LAI) between post-fire and post-harvest stands (Moussaoui et al., 2016). We did not use satellite-based albedo data as secondary sources as they tend to diverge from field measurements depending on a number of factors including stand age, latitude, and cloud cover effects (Halim and Thomas, 2017; Bright et al., 2015b).

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Data for Saskatchewan sites were retrieved from  Amiro et al. (2006a), and for Manitoban sites from Amiro et al., (2006b) by digitizing data points from relevant figures using the WebPlotDigitizer software (Rohatgi, 2018). These stands were dominated by jack pine and black spruce with some intermixing of trembling aspen. All post-fire sites (including this study) had severe fires that completely killed previous vegetations. There were a few burned snags in the Saskatchewan and Manitoban sites and none in the present study sites. These areas remain snow covered for ~ 6 months with average snow depths of 10–15 cm (Environment Canada, 2018). Pyranometers were located in Saskatchewan sites at 18–20 m, and in Manitoban sites at 6 m heights. There was no detailed information on how proportions of broadleaf deciduous species were calculated for these sites; however, we assumed they were basal-area based. A detailed description of the study areas and methods can be found in the respective articles.

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### 2.4 Accuracy assessment of albedo measurements

To test the relative accuracy of albedo measurements from Si-based pyranometers (Onset Computers' Hobo, used in this study) in comparison to thermopile pyranometers (Kipp and Zonen's CNR1, used in the studies providing secondary data), we conducted a field calibration study over nine days under variable sky and ground conditions (see Supplementary Materials). Results from this study showed a very close agreement between the measurements of Hobo and CNR1 pyranometers (Fig. S1). The difference (CNR1 – Hobo) in daily albedo over the study period ranged from –0.0601 to 0.064, and the mean difference in daily albedo was 0.0028 (± 0.031). The mean difference was negligible and the range in differences was well within the previously reported error ranges (~ 5–7 %) for similar pyranometers (Myers, 2010; Stroeve et al., 2005). We also did not observe any detectable pattern in deviations between the pyranometers under different sky and ground conditions. We therefore concluded that albedo measurements from Si-based Hobo and thermopile-based CNR1 pyranometers are closely comparable, and corrections to the Si-based albedo estimates presented are not warranted.

### 2.5 Measurements of ground surface reflectance

To examine effects of disturbance type on ground surface reflectance, three soil samples (top 10 cm including LFH layer, surface area 78.5 cm$^2$) from each plot were collected in fall 2017 to measure the ground surface reflectance. Samples were all collected within a two-day precipitation-free period, and were brought to the lab in airtight packaging without disturbing the top surface. A spectrometer (SD 2000; Ocean Optics, Florida, USA; measurement spectral range 338.7–1001.8 nm) equipped with an integrating sphere was used to measure the directional-hemispherical reflectance factor of the top surface of the soil samples. As there were no recent post-fire stands in the study area, we collected charcoal samples (of twigs, branches, barks, and stems) from the forest floor of a jack pine dominated post-fire (fire occurred in 2011) stand in summer 2015 from near the Musselwhite mine (52.61° N and 90.37° W), Ontario, Canada. Every sample was measured ten times in ten different locations (each 0.84 cm$^2$ in area), and each measurement was performed by scanning 10 times (with Boxcar width 5 [spatial averaging of 5 pixels] and 100 millisecond integration time) to get an average reflectance for each location of a sample. Details of the spectrometer and integrating sphere used can be found in the Materials and Methods section of Baltzer and Thomas (2005). Forest floor reflectance values from the Musselwhite stand (4-year old) were compared to soil sample reflectance values from recent (2013) post-harvest stands (4-year old). For older stands (1998 and 2006 post-harvest and post-fire stands), soil sample reflectance data were compared using samples from the main study plots.

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### 2.6 Data analysis

Robust t-tests (Wilcox, 2016) were used to compare mean differences in ground surface reflectance (in visible [400–700 nm] and near-infrared [> 700–1000 nm] spectral bands) and seasonally averaged albedo between post-harvest and post-fire stands. Mean seasonal albedo values of post-harvest and post-fire stands were also compared using Analysis of Covariance (ANCOVA) controlling for the effects of stand age as a covariate. Secondary albedo data for 0–6-year-old post-fire stands were only available for winter and summer seasons. Therefore, in the t-tests (and in ANCOVA) for winter and summer albedo, data from 0–19-year old post-harvest and post-fire stands were used. For spring and fall, albedo data from recent (0–6-year-old) post-harvest stands were omitted (since there were no data from post-fire stands for these seasons), and data from 7–19-year-old stands were used to make the comparisons unbiased. Secondary data from old stands (> 70 years) were not used in the t-tests/ANCOVA. These analyses treat seasonally averaged albedo values from the same stands as independent. We also conducted parallel analyses using linear mixed models that included plot as a random variable; in all cases, the random effect was not significant, and thus only the simpler linear model results are presented.

Generalized linear models (GLMs) with the log-linked gaussian family (additive-observation-error model with constant variance) were found to be the best fitted to model seasonal albedo as a function of stand attributes (stand age, proportion of deciduous broadleaf species, canopy height, ground vegetation cover, and their interactions) for both post-harvest and post-fire stands. Best models were chosen using an AIC-based stepwise algorithm. Asymptotic chi-square statistics based on deviance were calculated for each best-fit model to test if the model was significantly better than its counterpart null model. In fall months, some stand attributes were only nonlinearly (double exponentially) related to albedo. To avoid model complexity, for each of these fall attributes a separate nonlinear model was fitted, and for other attributes GLMs with identity-linked gaussian family were found be the most suitable. The ΔAIC for each best-fit model is calculated as its AIC difference with the corresponding null model (AIC of the best-fit model – AIC of the corresponding null model). Sample-size corrected AIC values were used in all cases.

Data were analyzed using the R platform (R Core Team, 2018) and graphs were prepared using the 'ggplot2' package (Wickham, 2016). Robust t-tests were done by 10,000 bootstrapped samples considering mean as an estimator for group comparison, and implemented by the *pb2gen* function of the WRS2 R-package (Mair and Wilcox, 2018). Adjusted $R^2$ values for GLMs were calculated using the *rsq* function of the R-package 'rsq' (Zhang, 2018).

## 3 Results

### 3.1 Seasonal albedo in post-harvest and post-fire stands

Albedo differences between post-harvest and post-fire stands varied among seasons. Albedo values in periods of the year with appreciable snow cover were significantly higher in post-harvest stands than in post-fire stands (for winter: 0.56 vs. 0.34, $p < 0.01$; for spring: 0.32 vs. 0.24, $p = 0.11$). Summer albedo values were also marginally higher in post-harvest stands ($p = 0.24$), and fall albedos were similar between disturbance types ($p = 0.73$) (Fig. 2). Considering stand age as a covariate, ANCOVA results also indicate higher albedo of post-harvest stands in winter ($p = 0.02$), spring ($p = 0.15$), summer ($p = 0.04$), and similar in fall ($p = 0.77$) compared to post-fire stands. Data also suggest higher variability in albedo in post-harvest stands than in post-fire stands (Fig. 2).

### 3.2 Ground surface reflectance in post-harvest and post-fire stands

Specular-included reflectance measurements of ground surface samples suggest that differences in ground surface characteristics contribute to overall surface albedo in the study sites. Summer ground surface reflectance was generally higher in old stands (Fig. 3b) than in young stands (Fig. 3a) particularly in the 600–1000 nm range. Young (4-year old) post-harvest stands showed significantly lower mean ground reflectance values (74.3 %, $p < 0.01$) in the visual spectrum (400–700 nm) and higher (32.3 %, $p < 0.01$) in the near-infrared spectrum (> 700–1000 nm) than those of young post-fire stands (Fig. 3a). Older (11- and 19-year old) post-harvest stands however showed higher mean ground reflectance in both visible (31.7%, $p < 0.01$) and near-infrared (4.6%, $p < 0.01$) spectra compared to post-fire stands (Fig. 3b).

### 3.3 Seasonal albedo in relation to stand attributes in post-harvest and post-fire stands

#### 3.3.1 Winter albedo in post-harvest and post-fire stands

Results from the best-fit GLM ($p < 0.01$, adj. $R^2 = 0.97$) for post-harvest stands indicated that stand age, proportion of deciduous broadleaf species, canopy height, and interactions among these variables were significant predictors of winter albedo (Table 2). Stand age was related to winter albedo via an exponential decay model with a horizontal asymptote ($\Delta AIC = -25.5$), and all estimated model parameters were significant (for 0.19 and 0.55: $p < 0.01$; for $-0.06$: $p < 0.05$) (Fig. 4a). The proportion of deciduous broadleaf species (Fig. 6a) and canopy height (Fig. 7a) were also related to winter albedo via negative exponential models with horizontal asymptotes ($\Delta AIC = -6.7$ and $-100.4$, respectively), and all estimated parameters for both models were significant ($p < 0.01$).

For post-fire stands the best-fit GLM ($p < 0.01$, adj. $R^2 = 0.75$) indicated that stand age and proportion of deciduous broadleaf species were significant predictors of winter albedo (Table 2). Stand age was related to winter albedo via an

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exponential decay model with a horizontal asymptote (ΔAIC = – 38.5), and all estimated model parameters were significant (p < 0.01) (Fig. 4b). Proportion of deciduous broadleaf species was related to winter albedo via a negative exponential model with horizontal asymptote (ΔAIC = – 16.3), and all estimated model parameters were significant (for – 0.27: p < 0.06; for 1.02 and 0.45: p < 0.01) (Fig. 6b).

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### 3.3.2 Spring albedo in post-harvest and post-fire stands

For post-harvest stands the best-fit GLM (p < 0.01, adj. $R^2$ = 0.99) indicated that stand age, proportion of deciduous broadleaf species, height, and the interaction of stand age and proportion of deciduous broadleaf species were significant predictors of spring albedo (Table 2). Stand age (Fig. 5a) and canopy height (Fig. 7c) were related to spring albedo via exponential decay models with horizontal asymptotes (ΔAIC = – 15.1 and – 31.2, respectively). Estimated parameters of stand age-albedo (for 0.26: p < 0.01; for 0.72 and – 0.72: p < 0.05) and canopy height-albedo (for 0.16 and 0.33: p < 0.01; for – 1.84: p = 0.07) models were likewise significant. The proportion of deciduous broadleaf species was related to spring albedo via a negative exponential model (ΔAIC = – 6.72), and all estimated parameters were significant (p < 0.01) (Fig. 6c).

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The best-fit GLM (p < 0.01, adj. $R^2$ = 0.99) for post-fire stands indicated that stand age and proportion of deciduous broadleaf species were the only significant predictors of spring albedo (Table 2). Stand age (Fig. 5b) and proportion of deciduous broadleaf species (Fig. 6d) were related to spring post-fire stand albedo via exponential negative growth models (ΔAIC = – 7.0 and – 7.5, respectively), and all estimated parameters for both models were significant (p < 0.01).

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### 3.3.3 Summer albedo in post-harvest and post-fire stands

The best-fit GLM (p < 0.01, adj. $R^2$ = 0.97) for post-harvest stands indicated that stand age, proportion of deciduous broadleaf species, ground vegetation cover and its interaction with stand age and proportion of deciduous broadleaf species were significant predictors of summer albedo (Table 2). Stand age was related to summer albedo via a double exponential model (ΔAIC = – 73.1), and all estimated model parameters were significant (p < 0.01) (Fig. 4c). The pattern described by this function indicates a sharp peak in albedo with a maximum at 10–15 years of stand age. Proportion of deciduous broadleaf species is related to summer albedo via a 3-parameter sigmoid model (ΔAIC = – 48.6), and all the estimated parameters were significant (p < 0.01) (Fig. 6e). Ground vegetation cover was related to summer albedo via an exponential model with a Gumbel distribution without a horizontal asymptote (ΔAIC = – 25.8), and all estimated parameters were significant (p < 0.01) (Fig. 8e).

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For post-fire stands the best-fit GLM (p < 0.01, adj. $R^2$ = 0.95) indicated that stand age, proportion of deciduous broadleaf species, canopy height, and their interactions with stand age were significant predictors of summer albedo (Table 2). Stand age (Fig. 4d) and canopy height (Fig. 7f) were related to summer post-fire stand albedo via exponential models with Gumbel distributions with horizontal asymptotes (ΔAIC = – 49.3 and – 53, respectively). As in the case of post-harvest stands, peak albedo was found at ~ 10–15 years of stand age.  All estimated parameters of stand age-albedo and canopy height-albedo models were significant (p < 0.01). Proportion of deciduous broadleaf species was related to summer albedo via a negative exponential growth model (ΔAIC = – 6.8), and all estimated model parameters were significant (p < 0.01) (Fig. 6f).

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### 3.3.4 Fall albedo in post-harvest and post-fire stands

The best-fit GLM ($p < 0.01$, adj. $R^2 = 0.94$) for post-harvest stands indicated that stand age, canopy height, ground vegetation cover, and their interactions were significant predictors of fall albedo (Table 2). Proportion of deciduous broadleaf species was also an important predictor that was modelled separately via a double exponential model (and was not added to the GLM to avoid modelling complexities) ($\Delta AIC = -0.9$); all estimated model parameters were significant (for 28.9 and 45.4: $p < 0.05$; for 67.6: $p < 0.01$) (Fig. 6g). Stand age (Fig. 5c) and ground vegetation cover (Fig. 8g) were related to albedo via exponential decay models with horizontal asymptotes ($\Delta AIC = -36.8$ and $-28.38$, respectively), and all estimated parameters for both models were significant ($p < 0.01$). Canopy height was also related to albedo via a negative exponential model ($\Delta AIC = -11.2$), and all estimated parameters were significant ($p < 0.01$) (Fig. 7g).

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To avoid modelling complexities, stand age and proportion of deciduous broadleaf species were fitted individually with fall albedo of post-fire stands (Table 2). Stand age was related to albedo via a double exponential model ($\Delta AIC = -3.1$), and all estimated model parameters were significant ($p < 0.01$) (Fig. 5d). Proportion of deciduous broadleaf species was generally related to albedo via a simple exponential model ($\Delta AIC = -25.4$), and all estimated model parameters were significant ($p < 0.01$) (Fig. 6h). In the case of fall albedo in post-harvest stands, there is an apparent decline in nearly pure stands (Fig. 6g), with a better fit of the double exponential model. We speculate that very dark post-senescence leaf litter of aspen may account for this effect.

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## 4 Discussion

Our results provide evidence for dramatic effects of disturbance type on the albedo of boreal forest systems, with post-harvest stands showing much higher albedo values in winter and spring months than post-fire stands. Stands of both disturbance types also showed strongly age-dependent patterns in albedo; however, analyses suggest that post-disturbance changes are more gradual than anticipated, with dynamics continuing past stand closure, up to ~ 50 years post-disturbance. The proportion of deciduous species also had large effects on stand albedo – generally larger than stand age effects – showing a positive saturating response in all seasons and for both disturbance types.

### 4.1 Albedo in post-harvest and post-fire stands

Mean albedo in post-harvest stands was significantly higher than in post-fire stands in winter and spring, marginally higher in summer, and similar in fall (Fig. 2). A similar pattern in albedo differences was also observed when the stand age effects on albedo were statistically controlled. The magnitude of differences in winter and spring values (0.22 and 0.08, or 63% and 34% increases relative to post-fire values) is large – comparable to albedo differences observed between biomes (Stephens et al., 2015). During snow-covered seasons (winter and spring), charcoal residues in post-fire stands are usually covered with snow, and thus stand structure and composition act as dominant drivers of albedo (Lyons et al., 2008; Amiro et al., 2006b; Liu et al., 2005). Deciduous broadleaf species made up 37.8 % of basal area in post-fire stands and 55.4 % in post-harvest stands: the higher percentage of dark conifer leaves is expected to result in lower winter/spring albedos in post-fire stands compared to post-harvest stands (Betts and Ball, 1997). However, immediately after a stand-replacing fire, the presence of black carbon (charcoal and soot) in the snow can reduce early winter albedo and possibly enhance spring snowmelt by absorbing solar radiation (Qian et al., 2009; Conway et al., 1996). During late spring when snow cover is shallow, it is also likely that charred branches and stems protrude through the snow and reduce albedo. From an energy balance perspective, it is important to note that albedo differences in late spring may be less important as turbulent and latent fluxes likely dominate (Conway et al., 1996).

In snow-free seasons (summer and fall) the marginal differences in mean albedo between post-harvest and post-fire stands can partly be attributed to rapid recovery of ground vegetation in post-fire stands (0–5 years old) compared to post-harvest stands (Bartels et al., 2016), and to the vegetation covering dark charcoals in older (> 5 year) post-fire stands (Randerson et al., 2006). Soon after a fire, the presence of early-successional plants (Johnstone et al., 2010) can increase surface albedo of post-fire stands because of their higher albedo relative to charcoal (Amiro et al., 2006b; Betts and Ball, 1997). This effect is expected to offset the albedo difference between post-harvest and post-fire stands. In the first year following disturbance events, we might expect lower snow-free albedo in post-fire stands than post-harvest stands because of high charcoal occurrence on the soil surface (Lyons et al., 2008; Chambers and Chapin, 2002). However, our soil reflectance data indicate that soils from 4-year old post-fire stands unexpectedly showed significantly higher reflectance in the visible spectrum than did post-harvest stands (with the pattern reversed in the NIR spectrum) (Fig. 3a). Similar patterns in spectral response were recently observed in a biochar-amended agricultural soil relative to the control (Zhang et al., 2013). Soils from older post-harvest stands (11- and 19-year old), as expected, showed higher reflectance in the visible and NIR spectra compared to post-fire stands of similar age (Fig. 3b). Most post-harvest stands exhibited patches of charcoal in surface soils, presumably originating from historical fires (personal observations). The importance of "legacy" soil charcoal on surface albedo of harvested stands has not been considered previously to our knowledge. Charcoal reflectance is highly dependent on charring conditions (e.g., temperature, oxygen content) (Hudspith et al., 2015), and may possibly change with weathering; these processes require additional study in the context of albedo and surface energy balance.

Our results from both snow-covered and snow-free seasons strongly suggest that fire residues on the ground cannot explain the observed differences in albedo between post-harvest and post-fire stands. This result is consistent with the generalization that stand structure and composition are the main drivers of surface albedo and energy balance in the boreal forest (Amiro et al., 2006a).

### 4.2 Albedo convergence with stand age in post-harvest and post-fire stands

Compiled data for winter and summer albedos from post-harvest and post-fire stands indicate that surface albedo saturates at ~ 50 years of stand age in the boreal forest (Figs. 4a–d). This finding does not support our second hypothesis that albedo saturates after ~ 25 years of stand age (during the 'stem exclusion' phase). The rationale behind this hypothesis was that a high cover of deciduous species until ~ 25 years contributes to high albedo in both snow-covered (due to leaf shedding) and snow-free (due to high canopy albedo) seasons; after this age, deciduous species are replaced by conifers and albedo tends to saturate (Kuusinen et al., 2014; Amiro et al., 2006b). Studies using remote sensing techniques also suggest that albedo in both post-harvest and post-fire stands saturates at ~ 50 years after harvest/fire (Bright et al., 2015a; Kuusinen et al., 2014; Lyons et al., 2008; McMillan and Goulden, 2008), consistent with our findings. These results thus suggest that gradual changes in species composition through later stages of succession are an important driver of stand albedo. Stand structural features such as canopy height (in winter) and ground vegetation cover (in summer) usually increase with stand age (Bartels et al., 2016) and might additionally contribute to a gradual reduction in albedo (Hovi et al., 2016) after ~ 25 years (Table 2, Figs. 7 and 8).

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The shape of best-fit curves for winter albedo vs. stand age (exponential decay) of post-harvest (Fig. 4a) and post-fire (Fig. 4b) stands are similar to other studies (Bright et al., 2015b; Kuusinen et al., 2014; Lyons et al., 2008; McMillan and Goulden, 2008; Amiro et al., 2006b); however our results diverge markedly for summer albedo. Our best-fit curves for summer albedo vs. stand age for both post-harvest and post-fire stands showed pronounced peaks in early albedo described by double exponential functions (Fig. 4c–d), whereas Amiro et al (2006b) described data with a negative linear relationship, and other remote sensing-based studies have used exponential decay curves (e.g., Kuusinen et al., 2014). However, Lyons et al. (2008) and Randerson et al. (2006) found summer albedo of post-fire stands were related to stand age via a humped-shape curve, and albedo reached peak at ~ 20 years and gradually levelled off at ~ 50 years after fire, which closely corresponds to our findings (although our observed peak is at ~10 years post-disturbance: Fig. 4c–d). We suggest that most prior studies with sparser or more noisy data sets may have missed this early peak pattern. Immediately after fires and harvesting (because of high soil moisture, decaying CWD, legacy charcoal etc.) the summer albedo of post-harvest and post-fire stands is expected to show a low value (also see section 4.1 and Fig. 3) which sharply increases as dark ground is covered with early successional pioneer species (Lyons et al., 2008; Randerson et al., 2006; Amiro et al., 2006b; Betts and Ball, 1997). This sharp increase continues until ~ 20 years of stand age but then decreases slowly until ~ 50 years and saturates – consistent with the patterns found in other seasons.

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We did not have albedo data form late-seral post-harvest or post-fire stands for spring and fall. In post-harvest (Fig. 5a) and post-fire (Fig. 5b) stands spring albedos did not show strong patterns with stand age, and the patterns were disturbance-specific (exponential decrease vs. negative exponential growth, respectively). Results from Kuusinen et al. (2014), Lyons et al. (2008), and Randerson et al. (2006) also suggest that patterns of spring albedo as a function of stand age can be disturbance-specific. In post-harvest stands, Kuusinen et al. (2014) found that spring albedo was high immediately after harvest and decreased exponentially until ~ 50 years and then saturated. However, in post-fire stands, Lyons et al. (2008) and Randerson et al. (2006), found hump-shaped patterns with a peak at ~ 10–15 years, and subsequent declines, similar to the winter albedo pattern. As discussed in Section 4.1, disturbance-specific responses may partially be attributed to the presence of black carbon (charcoal/soot) in snow immediately after a fire, which can substantially reduce snow albedo (Qian et al., 2009). Trends in fall albedo values with stand age in post-harvest (Fig. 5c) and post-fire (Fig. 5d) stands showed stronger patterns than spring, but similar disturbance-specific responses. Immediately after harvesting fall albedo was high, and exponentially decreased as stand age increased. Increased fall albedo in recent post-harvest stands may be due to contributions to senescing leaves and to snow in the late fall (Amiro et al., 2006b; Liu et al., 2005). In contrast, fall albedo immediately after a fire was low (possibly because of charcoal or soot residues as discussed above), and increased with stand age.

Predicting albedo has been a classical problem in climate simulations (Bright et al., 2015a; Kuusinen et al., 2012; Qu and Hall, 2007). Our findings indicate that there are important qualitative differences in the post-disturbance albedo patterns between seasons in boreal forests. These differences need to be considered in enhancing albedo predictability of land surface models.

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### 4.3 Deciduous broadleaf species as a key determinant of surface albedo in the post-harvest and post-fire stands

Our results indicate that the proportion of deciduous broadleaf species is a strong predictor of albedo irrespective of disturbance type, and in most cases a better predictor than stand age (Figs. 4–6). Using remote sensing techniques Kuusinen et al. (2014) also found that stand age alone was not consistently the best predictor of stand albedo in the boreal forest. We found a similar mean model residual sum of errors for snow-covered seasons and snow-free seasons (Figs. 4–5 vs. Fig. 6), indicating that the proportion of deciduous broadleaf species are similarly important in both cases. These findings strongly support our third hypothesis that stands with a higher proportion of deciduous broadleaf species show higher albedo than conifer-dominated stands, but also that this effect is pronounced under both snow-covered and snow-free conditions. Except for fall post-fire stands, the relationship between albedo and proportion of deciduous broadleaf species approximated by an exponential saturating curve in which albedo declined rapidly where the proportion of deciduous broadleaf species fell below 25–50 %. Fall albedo in post-fire stands, on the other hand, was found to be even more sensitive, with a drop in fall albedo at a proportion of deciduous broadleaf species below 80%. We speculate that this sensitivity was related to exposure of fire residues in early stand development.

Overall our results indicate a strong dependency of seasonal albedo on the proportion of deciduous broadleaf species both in post-harvest and post-fire stands. This effect provides a strong link between albedo and successional patterns in mixedwood boreal forests. Prior studies addressing this relationship (e.g., Lyons et al., 2008; Amiro et al., 2006b) have suggested that increasing deciduous tree cover results in increased albedo values from stand initiation to ~ 25 years of stand age; thereafter, conifers start dominating the canopy, canopy height increases, and albedo decreases gradually until ~ 50 years of stand age before reaching a steady state. The data presented in the current study provide a somewhat different picture of these trends, in that patterns show important quantitative differences depending on the season and disturbance type. The importance of deciduous broadleaf species in the albedo signal over ~ 50 years of stand development suggests that slow successional changes in species composition are likely the main driver of the age-related patterns in mixedwood boreal forests albedo. The dynamics of this pattern is likely to depend on the intensity and frequency of disturbance, edaphic conditions, species abundance, and climate (Taylor and Chen, 2011). For example, in dry nutrient-poor boreal stands, deciduous broadleaf species-driven albedo might never occur, as such stands are commonly dominated by jack pine (Taylor and Chen, 2011); however, in mesic moderate-nutrient-rich stands, deciduous broadleaf species can dominate for ~ 100 years (Cogbill, 1985). Future studies should prioritize robust modelling of boreal succession pathways under different biotic/abiotic conditions to properly characterize stand albedo.

## 5 Conclusions

Our findings have important implications for climate-friendly forest management practices. Since the proportion of deciduous broadleaf species is a strong predictor of seasonal albedo, stand-level albedo can be increased by enhancing the proportion of deciduous broadleaf species in a stand. Precisely this approach has recently been suggested as an adaptation and mitigation strategy to counter negative climate forcings of boreal forest (Astrup et al., 2018), but empirical data from actual managed stands have been lacking. Historically, forest managers have commonly sought to decrease or eliminate deciduous species and enhance conifers. However, there is strong evidence that local tree diversity enhances productivity in boreal forests as in other systems (Paquette and Messier, 2011), and in particular that mixedwood boreal forests including both conifers and deciduous trees show high productivity (MacPherson et al., 2001; Zhang et al., 2012). Management to increase the proportion of deciduous broadleaf species in managed boreal forests (for example, simply by avoiding chemical herbicide used to kill deciduous broadleaf species or retaining deciduous broadleaf species seed-trees) could thus be a "win-win" scenario for enhanced carbon sequestration via primary productivity, and climate mitigation via enhanced albedo.

In climate modeling studies albedo estimation for boreal forests have commonly been achieved by highly simplified representations of vegetation dynamics (Thackeray et al., 2019). In a recent study, Bright et al. (2018) pointed out that overlooking stand structural and compositional properties over the successional trajectory is likely to substantially bias radiative forcing estimates in the boreal forest. Ground-based estimates such as those presented are essential: at high latitudes when solar zenith angle is high (> 70°), satellites such as MODIS often provide poor-quality albedo data due to spatial heterogeneity of the landscape pixel signature and performance degradation of atmospheric correction algorithms (Bright et al., 2015b; Wang et al., 2012). Our findings based on field data are thus important in evaluating and potentially improving albedo predictions in land surface characterizations with climate models, and in improving albedo estimates derived from remote sensing. In addition, our results point to the importance of slow ecological succession as a driver of age-related patterns in albedo, suggesting that future models should explicitly incorporate these ecological processes to better predict long-term trends in climate forcings in boreal forests.

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## 6 Code availability

R (version 3.5.1) codes used in the data analysis can be requested to M.A.H. (abdul.halim@mail.utoronto.ca).

## 7 Data availability

Data used to produce the graphs are also available via requesting corresponding author (abdul.halim@mail.utoronto.ca).

## 8 Author contribution

M.A.H., H.Y.H.C., and S.C.T. designed the experiment. M.A.H. analysed data with inputs form S.C.T. and H.Y.HC. M.A.H. wrote the manuscript with edits and comments from H.Y.H.C. and S.C.T.

## 9 Competing interests

The authors declare no competing interests.

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## 12 Figures and Tables

### 12.1 Figures

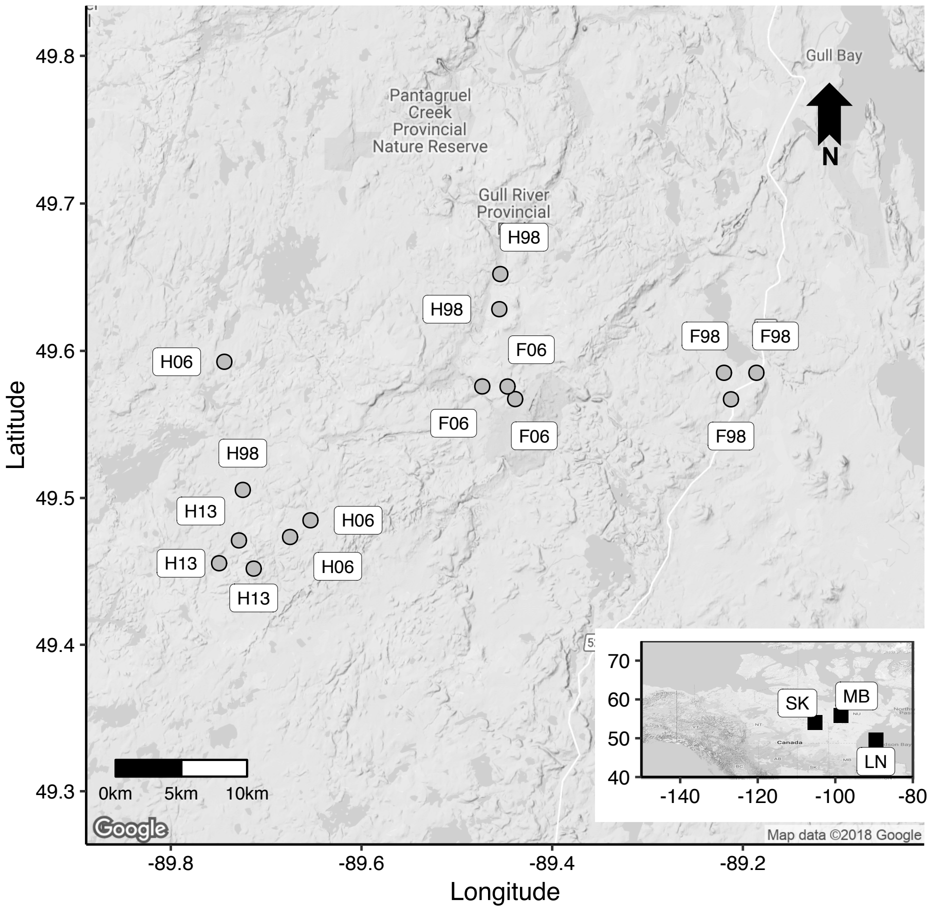

**Figure 1.** Map of the study area. Labels in the rectangular boxes indicate disturbance types (H: harvest and F: fire) and years (98: 1998, 06: 2006, and 13: 2013) for each plot (grey circles). **Inset:** black squares indicate locations of all data sources including the current study area (LN: Lake Nipigon area, Ontario, Canada; SK: Saskatchewan, Canada; MB: Manitoba, Canada).

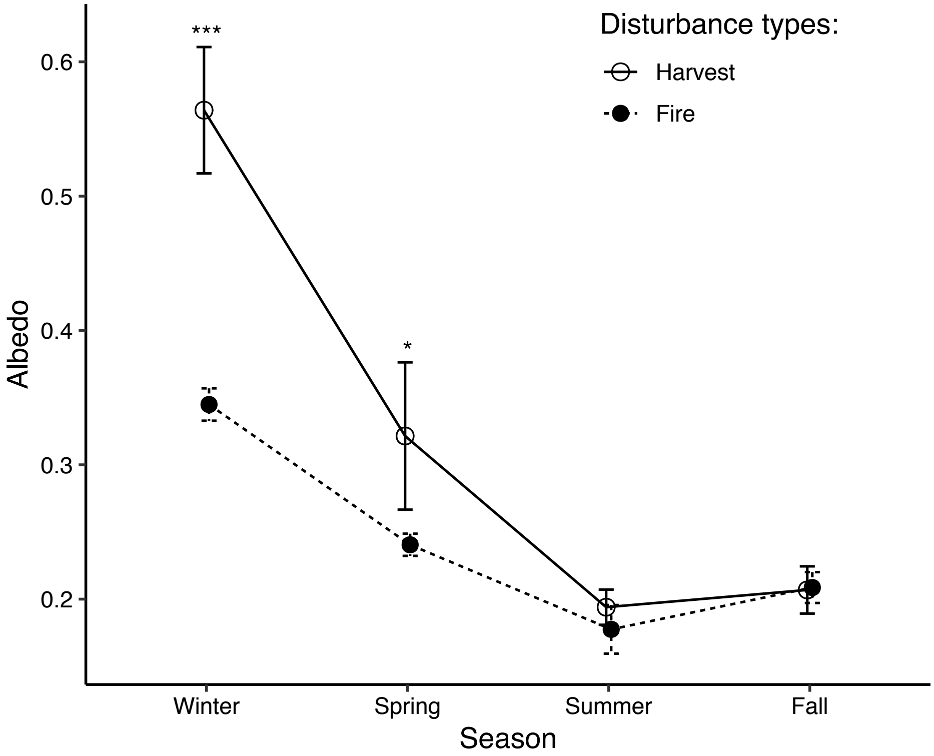

**Figure 2.** Comparison of seasonal albedo (mean ± SE) in post-harvest and post-fire stands. Winter (no. of observations for post-fire stands, $n_F = 35$; no. of observations for post-harvest stands, $n_H = 48$) and summer ($n_F = 44$, $n_H = 41$) albedo data were from 0–19-year-old stands, and spring ($n_F = 30$, $n_H = 30$) and fall ($n_F = 30$, $n_H = 30$) albedo data were from 7–19-year-old stands. Albedo of 0–6-year-old post- 760 fire stands were from secondary sources. * and *** indicate significant mean albedo differences between post-harvest and post-fire stands with $p = 0.11$ and $p < 0.01$, respectively.

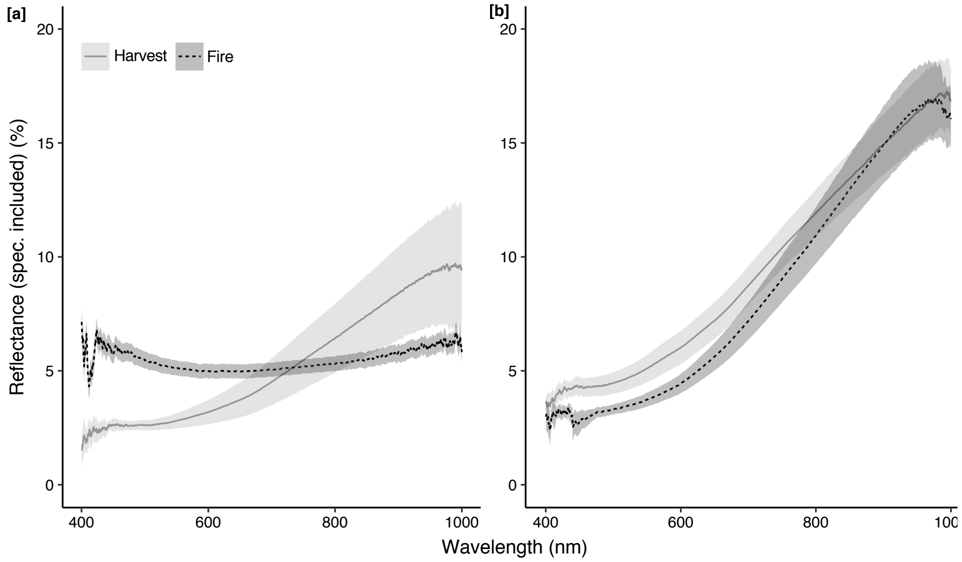

**Figure 3.** Specular-included ground surface reflectance (400–1000 nm) of post-harvest and post-fire stands. Lines indicate mean reflectance (number of sample (n) × 10 replicated measurements/sample) in the corresponding wavelengths, and shades indicate SE. **[a]** ground surface reflectance of young (4-year old) post-harvest stands (n = 9) and a post-fire stand (n = 12). **[b]** ground surface reflectance of old (11- and 19-year old) post-harvest (n = 18) and post-fire (n = 18) stands.

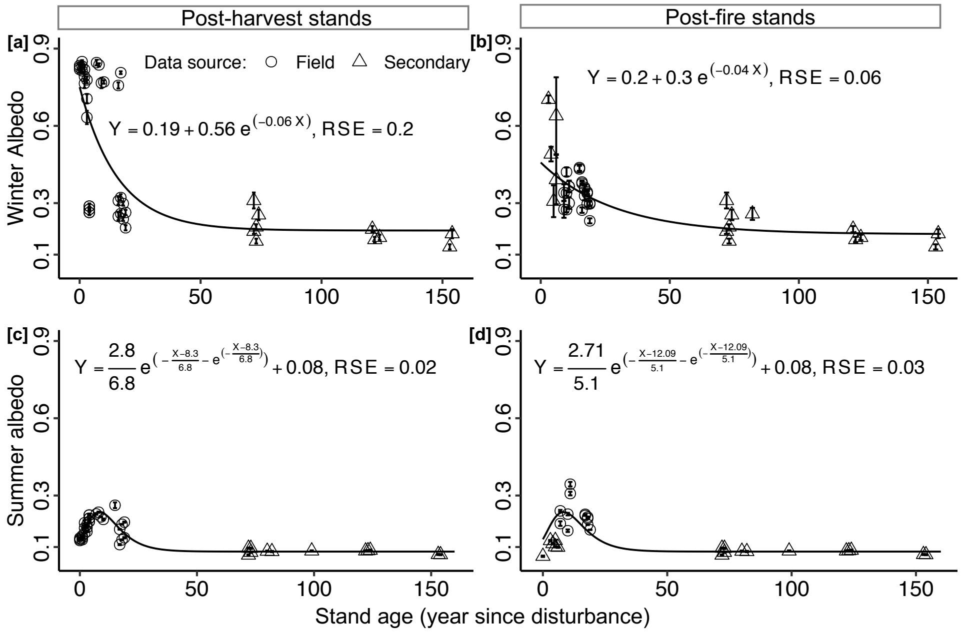

**Figure 4.** Stand age affecting mean seasonal albedo (± SE) in boreal forest over 0–150 years of stand development. Mean winter albedo as a function of stand age in **[a]** post-harvest stands (n = 42) and **[b]** post-fire stands (n = 36). Mean summer albedo as a function of stand age in **[c]** post-harvest stands (n = 41) and **[d]** post-fire stands (n = 30). Each field-data point is the average seasonal albedo (error bars indicate standard errors) of three plots from each stand-age category over the study period.

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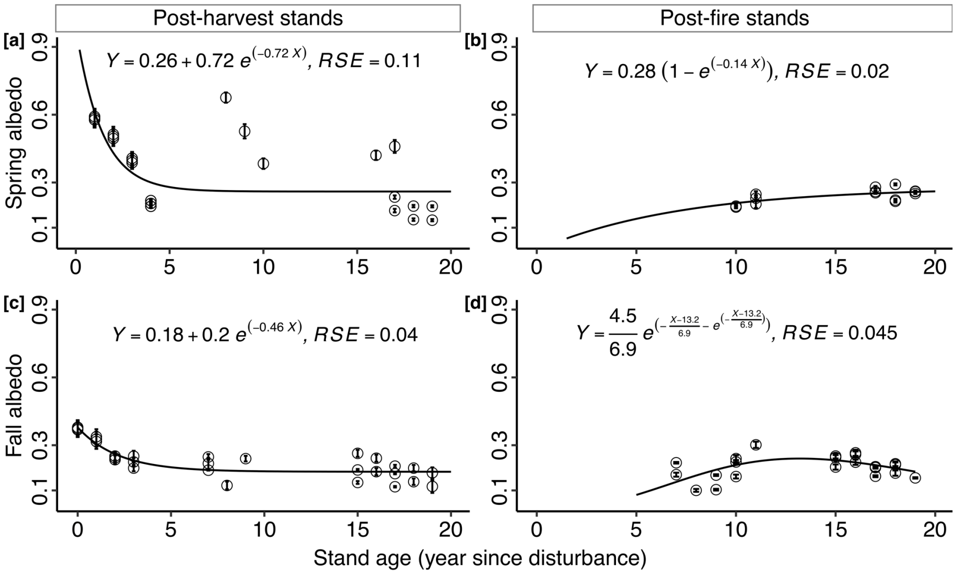

**Figure 5.** Stand age affecting mean seasonal albedo (± SE) in boreal forest in the early seral stage. Mean spring albedo as a function of stand age in **[a]** post-harvest stands (n = 26) and **[b]** post-fire stands (n = 14). Mean fall albedo as a function of stand age in **[c]** post-harvest stands (n = 29) and **[d]** post-fire stands (n = 22). Each field-data point is the average seasonal albedo (error bars indicate standard errors) of three plots from each stand-age category over the study period.

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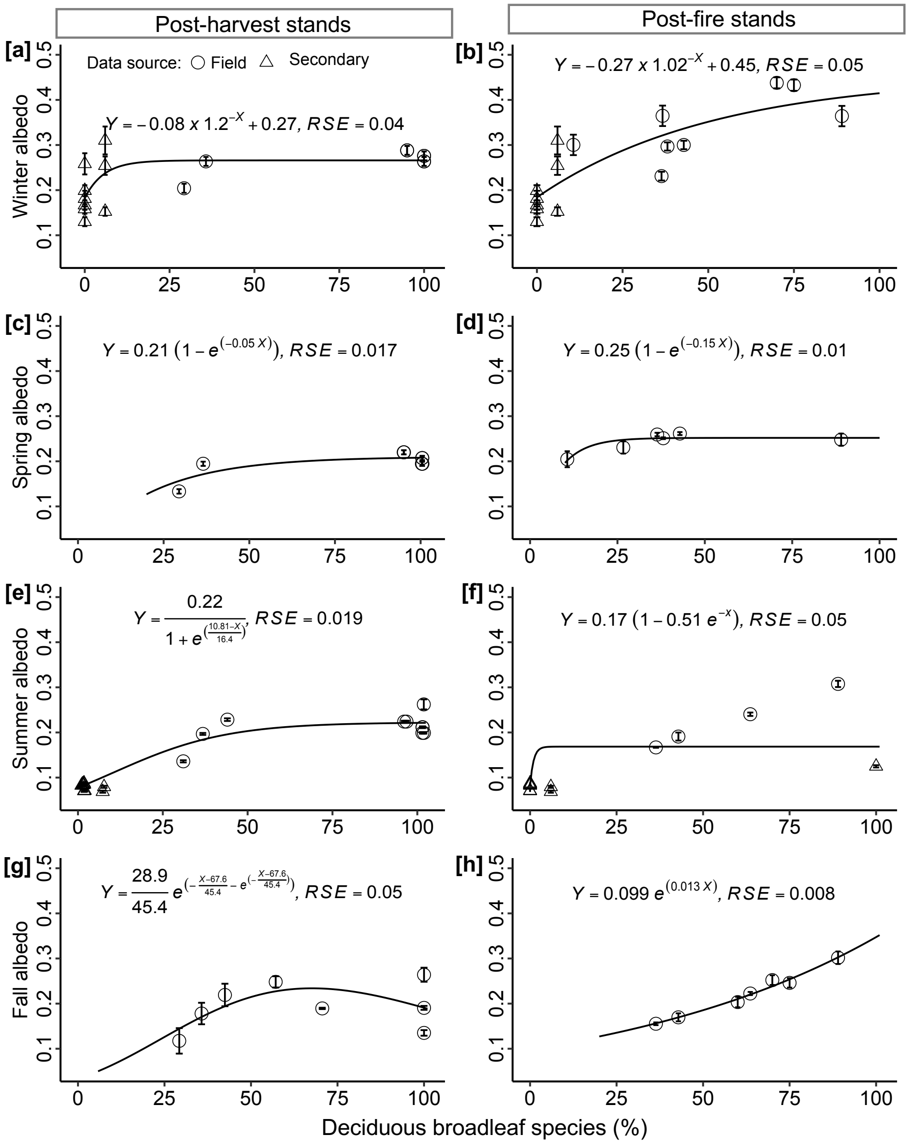

**Figure 6.** Mean seasonal albedo (± SE) as a function of deciduous broadleaf species (%) (proportion of deciduous broadleaf species) in the boreal forest. Proportion of deciduous broadleaf species affecting mean winter albedo in **[a]** post-harvest stands (n = 17) and **[b]** in post-fire stands (n = 20), mean spring albedo in **[c]** post-harvest stands (n = 8) and **[d]** post-fire stands (n = 6), mean summer albedo in **[e]** post-harvest stands (n = 20) and **[f]** post-fire stands (n = 15), and mean fall albedo in **[g]** post-harvest stands (n = 8) and **[h]** post-fire stands (n = 7).

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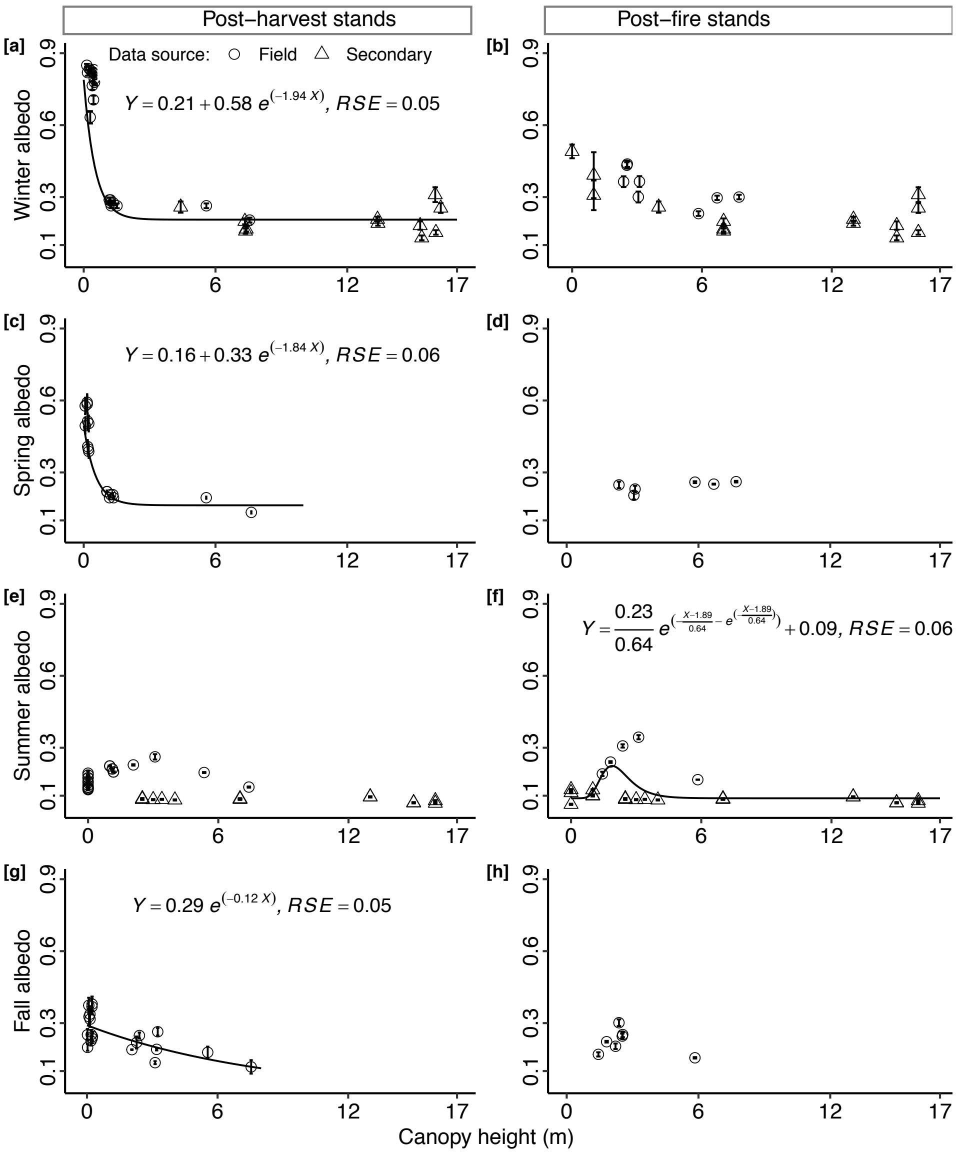

**Figure 7.** Mean seasonal albedo (± SE) as a function of canopy height (m) in the boreal forest. Canopy height affecting **[a]** mean winter albedo in post-harvest stands (n = 31), **[c]** mean spring albedo in post-harvest stands (n = 16), **[f]** mean summer albedo in post-fire stands (n = 23), and **[g]** mean fall albedo in post-harvest stands (n = 20). In **[b, d, e, h]** canopy height is not a significant predictor of the corresponding mean seasonal albedo; thus, no model is fitted to the data points.

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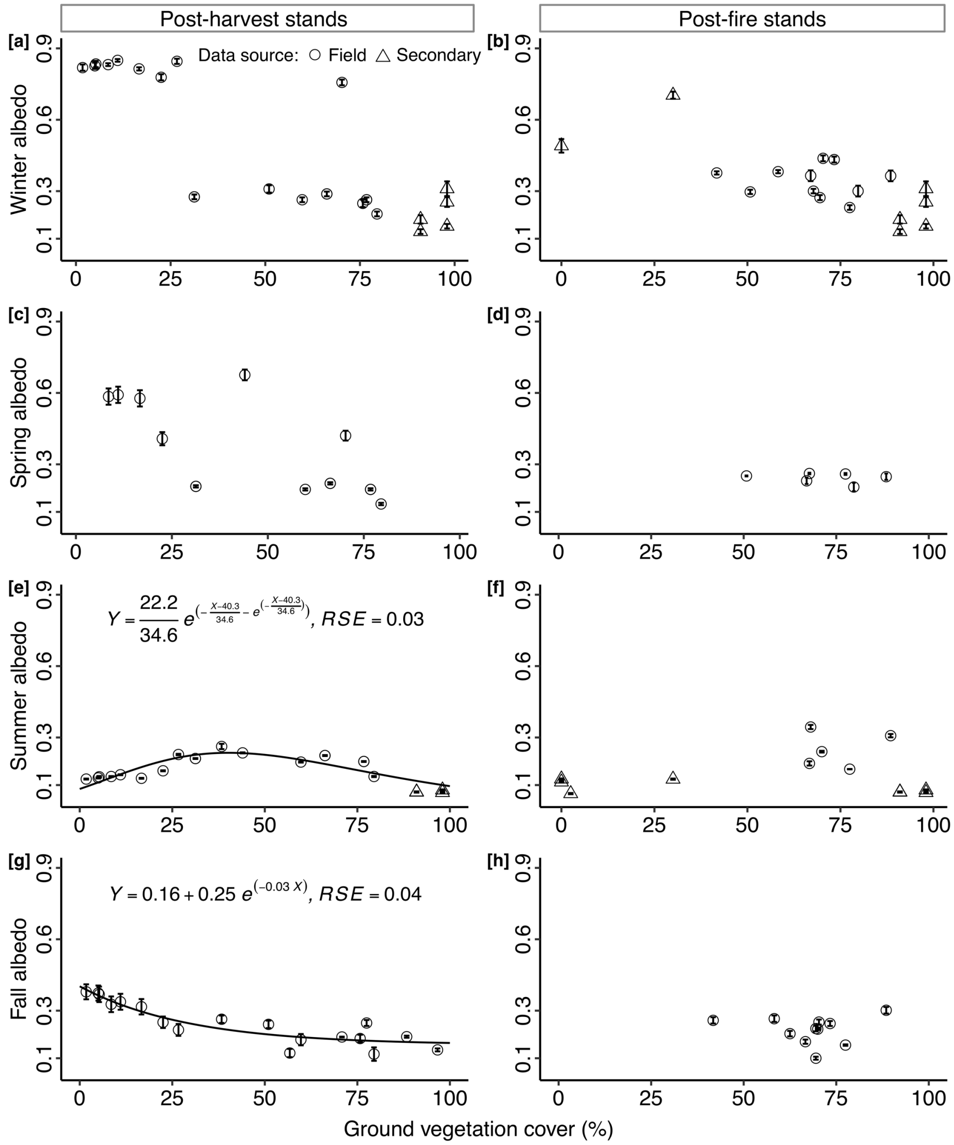

**Figure 8.** Mean seasonal albedo (± SE) as a function of ground vegetation cover (%) in the boreal forest. Ground vegetation cover affecting **[e]** mean summer albedo in post-harvest stands (n = 22) and **[g]** mean fall albedo in post-harvest stands (n = 18). In **[a–d, f, h]** ground vegetation cover is not a significant predictor of the corresponding mean seasonal albedo; thus, no model is fitted to the data points.

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### 12.2 Tables

**Table 1. Structural characteristics of post-harvest and post-fire stands sampled. Mean values (± SE) are reported across all sites of a given disturbance type.**

| **Stand type** | **Stand age (year)** | **DBS (%)** | **LAI** | **Stem density (stems ha$^{-1}$ ≥ 5 cm DBH)** | **Height (m)** | **GCV (%)** |
|---|---|---|---|---|---|---|
| Post-harvest | 0–19 | 55.4 ± 11.2 | 0.4 ± 0.3 | 6472 ± 3060 | 1.7 ± 1.3 | 51.8 ± 20.1 |
| Post-fire | 7–19 | 37.8 ± 9.1 | 0.7 ± 0.4 | 8400 ± 1902 | 2.9 ± 1.5 | 62.5 ± 14.1 |

**Notes:** DBS, LAI, and GCV indicate deciduous broadleaf species (% by basal area), leaf area index, and ground cover vegetation.

**Table 2. Regression model coefficients and fit statistics for albedo as a function of stand attributes in different seasons in the boreal forest.**

| **Season** | **Post-harvest stands** | | | | **Post-fire stands** | | | |
|---|---|---|---|---|---|---|---|---|
| | ***Parameter Estimates*** | | ***Model fit*** | | ***Parameter Estimates*** | | ***Model fit*** | |
| | *Coefficient* | *Estimate* | *ΔAIC* | *Adj. $R^2$* | *Coefficient* | *Estimate* | *ΔAIC* | *Adj. $R^2$* |
| Winter | Intercept | **1.722** | – 69.2 | 0.97 | Intercept | **– 1.25** | – 5.3 | 0.75 |
| | SA | **– 0.031** | | | SA | – 0.004 | | |
| | PDBS | **– 0.021** | | | PDBS | **0.005** | | |
| | CH | **– 0.079** | | | | | | |
| | SA:CH | **0.002** | | | | | | |
| | PDBS:CH | **– 0.007** | | | | | | |
| Spring | Intercept | **– 7.195** | – 495.4 | 0.99 | Intercept | **– 1.747** | – 18.8 | 0.92 |
| | SA | **1.298** | | | SA | 0.016 | | |
| | PDBS | **0.116** | | | PDBS | 0.002 | | |
| | CH | **– 1.264** | | | | | | |
| | SA: PDBS | **– 0.024** | | | | | | |
| Summer | Intercept | **– 1.377** | – 24.9 | 0.97 | Intercept | **– 2.996** | – 48.3 | 0.95 |
| | SA | **0.032** | | | SA | **– 0.012** | | |
| | PDBS | **– 0.003** | | | PDBS | – 0.004 | | |
| | GVC | **– 0.01** | | | CH | **0.788** | | |
| | SA: GVC | **– 0.0004** | | | SA: PDBS | **0.003** | | |
| | PDBS: GVC | **0.0001** | | | SA: CH | **– 0.004** | | |
| | | | | | SA:CH: PDBS | **– 0.001** | | |
| Fall | Intercept | **0.398** | – 6.1 | 0.94 | $\frac{4.5}{6.87} e^{(-\frac{SA-13.2}{6.87} - e^{-\frac{SA-67.62}{45.39}})}$ | | – 3.1 | 0.045¹ |
| | SA | 0.013 | | | $0.099\, e^{0.013\, PDBS}$ | | – 25.4 | 0.008¹ |
| | CH | **– 0.182** | | | | | | |
| | GVC | **– 0.007** | | | | | | |
| | SA:CH | **0.007** | | | | | | |
| | CH: GVC | **0.005** | | | | | | |
| | SA:CH: GVC | **– 0.0002** | | | | | | |
| | $\frac{28.86}{45.39} e^{(-\frac{PDBS-67.62}{45.39} - e^{-\frac{PDBS-67.62}{45.39}})}$ | | – 0.9 | 0.049¹ | | | | |

**Notes:** SA, PDBS, CH, and GVC indicate stand age (year), proportion of deciduous broadleaf species (%), canopy height (m), and ground vegetation cover (%), respectively. Parameter estimates for GLMs in bold and regular fonts indicate statistical significance at 1% and 5% level, respectively. For fall nonlinear regression models, 28.86 and 45.39 coefficients of post-harvest stands are significant at 5% level and the rest is significant at 1% level. ¹ indicates residual standard error of the nonlinear regression model. ΔAIC = AIC of the best-fit model – AIC of the corresponding null model.

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