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Climate change and disturbance interact to alter landscape reflectivity (albedo) in boreal forests across a large latitudinal gradient in Siberia

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HIGHLIGHTS

- How will disturbances and climate interact to affect albedo of boreal forests?
- We simulated successional dynamics across a broad latitudinal gradient (57–72 N).
- We used LANDIS-II to simulate tree photosynthesis and spatial landscape processes.
- Disturbances played a key role in driving changes in albedo.
- Length of the snow-covered season (not vegetation) is the primary driver of albedo.

GRAPHICAL ABSTRACT

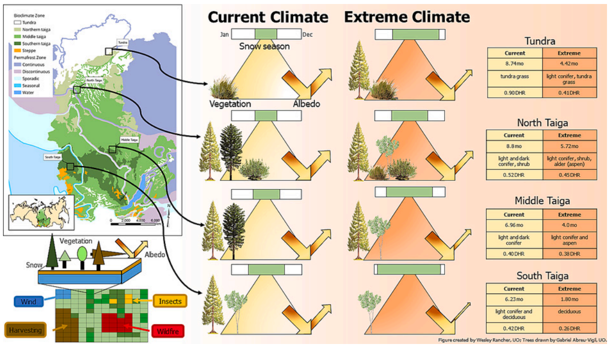

Figure created by Wesley Rancher, UO; Trees drawn by Gabriel Abreu-Vigil, UO.

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ABSTRACT

Boreal forests form the largest terrestrial biome globally. Climate change is expected to induce large changes in vegetation of high latitude ecosystems, but there is considerable uncertainty about where, when, and how those changes will occur. Such vegetation change produces major feedback to the climate system, including by modifying albedo (reflectivity). Our study used the LANDIS-II forest landscape model to project forest dynamics on four representative landscapes (1 M ha) for 280 years into the future under a range of climate scenarios across a broad latitudinal gradient in Siberia. The model estimated the albedo of the vegetation and any snow on each landscape grid-cell through time to quantify surface albedo change in response to climate change and disturbances. We found that the shortening of the snow-covered season (winter) decreased annual average albedo dramatically, and climate change facilitated the invasion of tundra by boreal trees in the northernmost landscape (reducing albedo in all seasons). However, in other landscapes, albedo increased in summer due to disturbances (fire, wind, insects, harvest), eliminating or reducing leaf area in the short-term, and in the mid-term by promoting more reflective forest types (deciduous, light conifers). This increased albedo was somewhat ephemeral and under climate change was overwhelmed by the shortening of the snow-covered season that greatly reduced albedo. We conclude that the primary driver of the overall reflectivity of boreal ecosystems is not vegetation, but rather, the length of the snow-covered season. Because climate change is likely to dramatically shorten the snow

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season, the concurrent reduction of albedo has the potential to act as a powerful positive feedback for climate change. Managing natural and anthropogenic disturbances may be the only tool with potential to mitigate the reduction of albedo by climate change in boreal ecosystems because management to encourage more reflective forest types has relatively small effect.

1. Introduction

Boreal forests are found at high northern latitudes and form the largest terrestrial biome in the world. They comprise 30–50 % of the world's forest carbon stocks (vs. 14 % in temperate forests, Pan et al., 2011). Temperatures are increasing rapidly in high northern latitudes (IPCC, 2021), resulting in modified disturbance regimes (Gauthier et al., 2015), shorter snow season length (Mellander et al., 2007), and thawing of permafrost (Chapin et al., 2010). Also, the socio-economic pressure to harvest timber is growing in currently unharvested areas (Shvidenko et al., 2007). Attempts to predict how these changes will affect boreal forests must account for interactions among multiple disturbances (e.g., wind, insects, fire, harvest), seed dispersal, species growth and competition, hydrology, and changing climate, given that uncertainty remains about how these changes will affect composition and function of this biome.

Climate change can produce direct effects (e.g., temperature effects on photosynthesis and respiration, more extreme heat and cold, changes in hydrology/permafrost) and indirect effects (e.g., alterations of disturbance regimes). Perhaps the biggest unknown is how changes in surface hydrology caused by thawing permafrost will alter species competitive interactions and whether altered hydrology, interacting with disturbances, will induce large scale conversions of biome type (e.g., tundra to forest and forest to steppe, Loranty et al. (2021)). Changes in competitive dynamics may result in a conversion of the dominant tree species to those with darker or lighter foliage, alter the mean leaf area of tree canopies, or convert land cover between forest and nonforest vegetation types, all of which could alter the reflectivity (albedo) of landscapes (Zhang et al., 2022). Additionally, it is uncertain how associated changes in land cover and its productivity e.g., forest composition, albedo, C stocks, NPP, evapotranspiration) will feed back to the climate system via changes to the energy balance to exacerbate or mitigate climate change (Betts, 2000; Schaphoff et al., 2016; Forzieri et al., 2017; Li et al., 2018).

Landscape models integrating different processes including vegetation dynamics, seed dispersal, fire disturbance, and permafrost dynamics have been applied to address such questions, particularly in Alaska (Euskirchen et al., 2020; Previdi et al., 2021). Our study was motivated by the fact that surface albedo (as determined by surface land and sea cover) is a key driver in Global Circulation Models (GCM) (Foley et al., 2000). Such land cover inputs to GCMs are typically derived from Dynamic Global Vegetation Models (DGVM) that are highly mechanistic for site-scale plant growth and competition processes, but consequently require very coarse spatial resolution (typically 0.5 lat/long degree) and significant compromises must be made for modeling taxon diversity and ecological processes that have an important spatial component (e.g., propagule dispersal, most disturbances) (Quillet et al., 2010; Shvidenko and Schepaschenko, 2014). Thus, there is some uncertainty about the accuracy of albedo estimates produced by DGVMs. Process-based forest landscape models (FLM) explicitly model spatial processes such as seed dispersal and disturbances with a spatial resolution between 10 and 250 m, restricting applications to a much more limited spatial extent (landscapes of 10^5–10^8 ha) and utilizing somewhat less mechanistic algorithms for plant growth and competition processes than do DGVMs (Gustafson, 2013). As part of a larger study to compare DGVM vegetation projections with those of a FLM, we developed new capabilities to estimate albedo from state variables within the PnET-Succession extension (Gustafson et al., 2023a) of the LANDIS-II FLM (Scheller et al., 2007). LANDIS-II has been successfully used in central Siberia to study the relative effects of climate change, timber harvesting, and insect outbreaks on forest composition, biomass and landscape pattern (Gustafson et al., 2010, 2011, 2020). It simulates growth, competition, mortality, and regeneration of tree species-age cohorts (i.e., not individuals) on grid cells that interact spatially through seed dispersal and contagious disturbances.

Our objectives for this paper were to 1) Use LANDIS-II to project forest dynamics under a range of climate and disturbance scenarios across a latitudinal gradient spanning the Siberian taiga from the arctic tundra to steppe ecotones, 2) Quantify the change in albedo across bioclimatic zones and climates, including the effect of climate change on seasonal snow dynamics, 3) Identify the factor(s) that are the strongest drivers of these changes, 4) Describe the algorithm to estimate land surface albedo in boreal and tundra landscapes within the LANDIS-II FLM, and 5) Estimate how climate-induced changes in albedo might affect the energy balance in central Siberia. Our general hypothesis was that climate change will change vegetation and therefore decrease albedo in tundra and increase albedo in the other three landscapes, and that the relative effect of climate change will be greater with increasing latitude and the direction of the effect will be the same in both summer and winter. Specifically, H1: In the tundra, forest will invade, and albedo will decline in all seasons. H2: In the northern taiga under climate change, dark conifers will increase in extent and leaf area index (LAI) will increase (reducing the exposure of snow) causing albedo to decline in all seasons. H3: In the mid-taiga under climate change, light conifers and deciduous species will increase in extent (with concomitant increase in snow exposure) and albedo will increase in all seasons. H4: In the southern taiga under climate change, deciduous species and steppe grasses will increase in extent and albedo will increase in all seasons, especially in winter. H5: Expected alteration of disturbance regimes will increase albedo, with both fire and insects likely to become increasingly more extensive from low to high latitudes under warming scenarios.

2. Methods

2.1. Study overview and model description

The latitudinal gradient needed for the study required us to use Siberia (Fig. 1) because the southern end of the analogous latitudinal gradient in North America is dominated by agriculture and other anthropomorphic land use. We conducted a factorial landscape simulation experiment (280 years duration) with a bioclimatic zone (sensu latitude) factor, a disturbance factor, and a climate factor (details below). Each bioclimatic zone was represented by a 1 M ha landscape (grid resolution 150 m) initialized (soils and forest composition) using data from the IIASA Integrated Land Information System (Schepaschenko et al., 2011).

We used the PnET-Succession growth and competition extension (v.5.1, Gustafson et al., 2023a) of the LANDIS-II (v7, Scheller et al., 2007) forest landscape model because it is among the most mechanistic succession extensions for LANDIS-II, allowing robust simulation of forest dynamics under novel conditions by relying heavily on physiological first principles (De Bruijn et al., 2014; Gustafson, 2013). Furthermore, it can simulate permafrost dynamics and estimate surface albedo using state variables on each grid cell at a monthly time step. PnET-Succession incorporates many algorithms of the original PnET-II (Aber et al., 1995), a "big leaf" stand model simulating monthly photosynthesis and growth using physiological first principles, and tracking soil water at the site scale using a bulk-hydrology model based on precipitation, foliar interception, evaporation, runoff, percolation out of the rooting zone, and water uptake by species cohorts (Gustafson et al., 2023a). Climate inputs dynamically determine length of growing seasons (species-specific) and latitude determines average monthly daylength. Active layer thickness (depth to permafrost in summer) responds to air temperature as a function of snow cover, vegetation and soil thermal conductivity (Abels, 1892; Sitch et al., 2003; Beer et al., 2007; Jonas et al., 2009; Gustafson et al., 2020), which modifies rooting zone depth and the fraction of water that is able to percolate from the rooting zone. Precipitation is assumed to fall as snow when the average monthly temperature is $\leq 0^{o}$ C, its depth is assumed proportional to its water equivalent, and snow melts at a rate of 2.74 mm (water equivalent) per degree day (Gustafson et al., 2023a).

Cohort biomass is a surrogate for height, determining its relative access to light, and the effect of soil moisture on growth depends on the species' waterlogging and drought tolerance. When water is not limiting, the amount of photosynthesis for a given species cohort increases with available light (dependent on canopy position and leaf area), atmospheric CO_2 concentration and foliar N, and decreases with age and departure from optimal temperature. PnET-Succession accounts for plant respiration such that growth respiration depends on temperature and moisture stress, while maintenance respiration depends on temperature and biomass. Cohorts (including shrub species) compete for light and water according to their biomass (size) and species-specific shade and drought (and waterlogging) tolerance. Cold-killing (mortality from extreme cold) is simulated within the PnET-Succession extension by estimating the coldest daily temperature reached in each month using the methods of Court (1951), and cohorts die when this temperature is less than their cold tolerance. Prevalence of cold killing was calibrated to allow the survival (under historical climate) of species known to persist in each study area.

We simulated seven major tree species that dominate this region (Siberian stone pine, Scots pine, Siberian spruce, Siberian fir, larch, silver birch, and aspen (Table S1)). We also simulated three shrub species (dwarf birch, alder, willow) and three groundcover pseudo-species (*Sphagnum* spp., C3 arctic grass/lichen and C3 steppe grass). PnET-Succession has 33 species-specific input parameters, but most were given PnET-II defaults or values established in other simulation studies

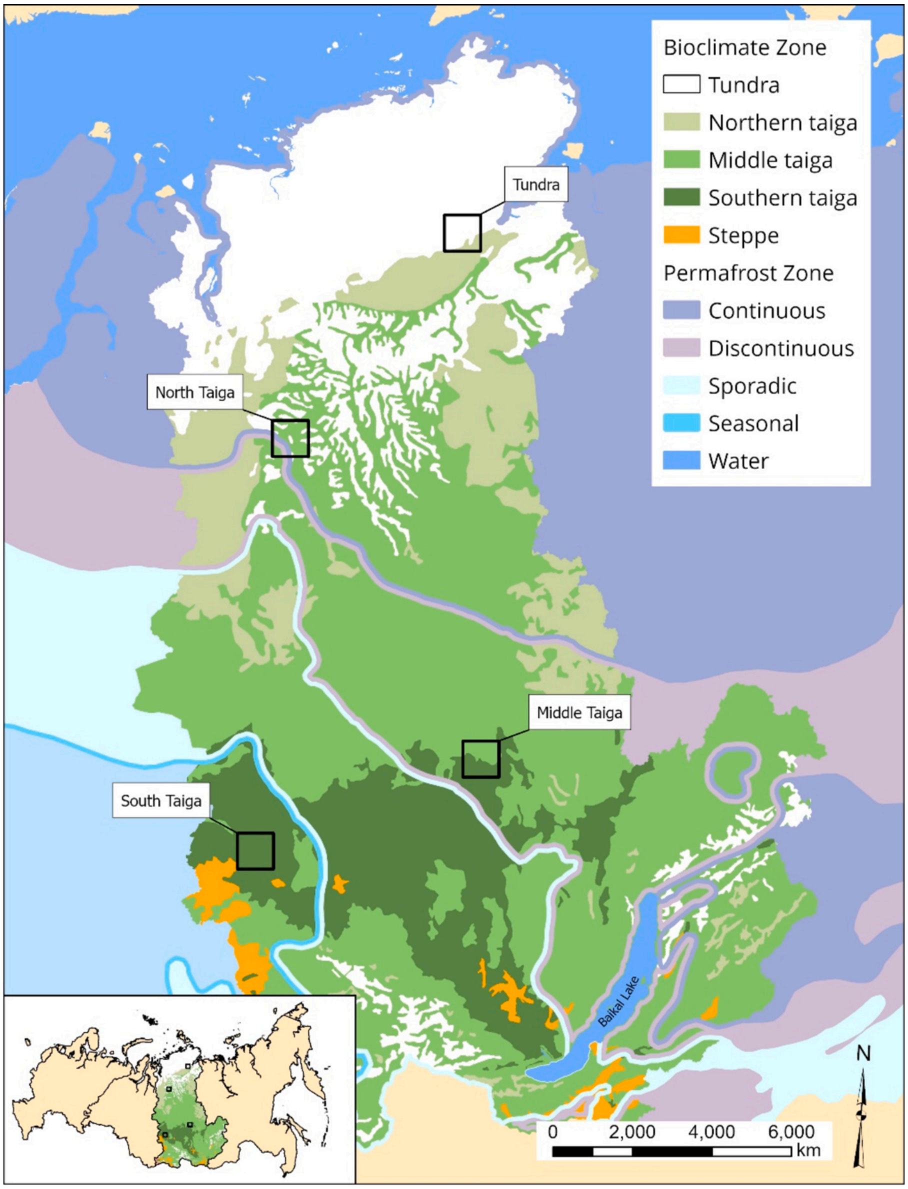

Fig. 1. Location and size of the four study sites across the large latitudinal gradient in central Siberia, in context of the spatial distribution of permafrost and bioclimatic zones (Stolbovoi and McCallum, 2002). Inset map shows the study context within the Russian Federation.

in sub-boreal ecosystems (e.g., Lucash et al., 2017; Gustafson et al., 2023b). Using published sources (e.g., Niinemets and Valladares (2006)) and expert knowledge of data available only in Russian, we explicitly estimated the following parameters for each species used in our study: longevity, fire tolerance, leaf longevity, half-saturation point (shade tolerance), four water potential parameters that define drought and waterlogging tolerance, min/max and optimal temperature for photosynthesis, and cold tolerance. Four other parameters (foliar nitrogen, specific leaf weight, foliage mass per unit of active wood mass, and a parameter that estimates active wood mass from total wood mass) were calibrated to match empirical growth curves (from the three taiga landscapes) as is required for all PnET-Succession modeling studies (see Appendix A for details).

These species parameters were set the same across all bioclimatic zones, and in general they were parameterized as a compromise to match empirical growth as closely as possible in all three forested locations (northern, middle and southern taiga). Thus, any difference in species growth and survival in different landscapes was not caused by species parameter differences, but by the abiotic environment (e.g., soil characteristics, climate, and latitudinal daylength differences). LANDIS-II input files are available in the Supplement.

Given the presence of seeds on a cell via dispersal, establishment probability was highest where light and water availability was optimal for species' competitiveness, and those conditions dynamically varied through time on each cell because of climate, disturbance and succession. Ground cover pseudospecies affect establishment of other species by consuming water and casting shade. Sphagnum was given very high waterlogging tolerance and very low drought tolerance so that it was generally restricted to water-logged conditions (Turetsky et al., 2012).

2.2. Albedo estimation

PnET-succession v.5.1 includes a new option to calculate monthly albedo in boreal ecosystems as a function of vegetation characteristics and snow cover. The algorithm to estimate monthly albedo from PnET-Succession state variables uses equations fitted to approximations of the empirical data in Lukeš et al. (2013), who measured summer albedo of pure boreal forest stands in Finland as a function of leaf area. Their measurements of mesic Scots pine were considered a reasonable proxy for all light conifers (including larch), Norway spruce (*Picea abies* (L.) was a proxy for dark conifers and birch a proxy for broadleaf deciduous species. Lesser LAI (including during leaf-off seasons) means that more of albedo is driven by the forest floor. The validity of this algorithm cannot be assumed for ecosystems other than boreal. The algorithm requires canopy type (or life form) of each species (Table S1): valid types are dark conifer, light conifer, deciduous, and ground cover (typically moss/lichen or grass), with each representing different reflectivity properties (Lukeš et al., 2013). It is important to note that these algorithms generate approximations, similar in kind to those made elsewhere in forest landscape models that are accepted to make them tractable at landscape scales of space and time.

In the following equations, y is surface albedo in units of DHR (directional hemispherical reflectance (black sky (shortwave) albedo)), which is the ratio of reflected solar radiation to incoming solar radiation.

For dark (lesser reflectivity) conifers (Lukeš et al., 2013),

$$y = -0.067^{*}ln(\mathrm{LAI}) + 0.2095$$

In the presence of snow (>10 cm), the albedo estimate for dark conifers increases by 80 % (Betts and Ball, 1997). This snow effect increases linearly as snow depth increases from 0 to 10 cm (for all life forms). When LAI is very low, the model sets LAI to 0.7 to prevent computations from extrapolating beyond the data of Lukeš et al. (2013).

For light conifers that have higher reflectivity (Lukeš et al., 2013),

$$y = -0.054^{*}ln(\mathrm{LAI}) + 0.2082$$

In the presence of snow (>10 cm), increase the estimate by 75 % (Betts and Ball, 1997).

For broadleaf deciduous species (Lukeš et al., 2013),

$$y = -0.0073^{*}\mathrm{LAI} + 0.231$$

In the presence of snow, increase the estimate by 35 % (Betts and Ball, 1997).

For grass or moss or open (no cohorts),

y = 0.2 (Betts and Ball, 1997).

In the presence of snow, increase the estimate by 375 % (y = 0.75) (Betts and Ball, 1997).

Cell albedo (y) is computed as a weighted average of individual cohort albedo in the topmost canopy layer (excluding cohorts with LAI ≤ 1), weighting by proportion of total leaf area of each canopy type. Albedo is not estimated for non-active cells, which are typically cells consisting of water or permanently non-forested cells.

We verified that the model generated albedo estimates consistent with reality for all four initial landscapes by comparing PnET-Succession albedo maps (cell size = 150 m) for a snowy month and a snow-free month (initial conditions approximate the year 2015) with maps of the monthly mean (years = 2001–2020) of daily MODIS albedo measurements (Jia et al., 2022, cell size = 500 m). Because the model data had finer spatial resolution than MODIS, greater extremes of albedo should be detectable on individual model cells. The MODIS data represented average reflectance (viewed from space) over an area equivalent to 11.1 model grid cells, while the equations used in our model were derived from reflectance measured directly above the tree canopy. Furthermore, the dates were only generally equivalent, possibly affecting snow and recency of disturbance, and the initial conditions reflect some uncertainty (Schepaschenko et al., 2011). Thus, we did not expect the comparisons to result in exceptional agreement, but we found that relative mean albedo varied similarly across each landscape (Fig. S1) and among the landscapes and between seasons (Fig. S2). PnET-Succession consistently estimated higher albedo in both seasons and for most landscapes (Fig. S2), which may be a consequence of the finer resolution that allows relatively small reflective openings to have a greater effect and possibly atmospheric effects on spaceborne sensors. Our verification exercise did not reveal a land cover type or snow-cover condition for which our simple algorithm was clearly biased. We concluded that, for our study area, PnET-Succession is well able to estimate relative albedo and produces credible estimates for absolute albedo.

2.3. Bioclimatic zone factor and study landscapes

The experimental bioclimatic zone factor had four levels (Tundra, N. Taiga, Mid-Taiga and S. Taiga) to represent present and future boreal ecosystems across a large latitudinal gradient. The southern part of the mid-continent latitudinal gradient we wished to study is not forested in N. America so we selected four sites in Siberia between 91 and 102^{o} East longitude and 57-72^{o} North latitude, each the same size (~1 million ha) and each straddling the ecotone between two ecosystems (Fig. 1). The northernmost study site (72^{o}N) is above the Arctic Circle in the ecotone between taiga and tundra (termed 'Tundra'). The two middle study sites are located within the transition zone between two major forest formations of the Asian north. The more northern of the two (67^{o}N, termed 'Northern taiga') is comprised primarily of light coniferous forests (larch, Scots pine) on continuous permafrost (i.e., entire area has permafrost). The site south of the Northern taiga site (59 ^{o}N, termed 'Middle taiga') has more dark coniferous forests (spruce, Siberian pine, fir) on discontinuous permafrost (i.e., permafrost is not always present). The southernmost study site (57^{o}N, termed 'Southern taiga') has sporadic permafrost and is in a zone at risk of losing forests to grasslands at a biome ecotone (forest-steppe). The location of this site is almost as far north as the middle taiga site, but we chose to avoid the Sayan Mountain range to prevent the confounding effects of elevation-induced colder temperatures and to be adjacent to current steppe ecosystems in the plains to the west. Its location was also constrained by multiple settlements, which we avoided to prevent confounding comparisons to the unfragmented forests to the north. Initial conditions were derived from the IIASA Integrated Land Information System, representing the synthesis of many empirical data sources, including remote sensing (Schepaschenko et al., 2011; Shvidenko and Schepaschenko, 2014).

2.4. Disturbance factor and disturbance extensions

Because DGVMs have relatively weak capabilities for accounting for disturbances (Shvidenko and Schepaschenko, 2014), we included a disturbance factor with two levels (all disturbances on or all disturbances off) to determine the relative importance of disturbance for determining albedo. The On-Off levels of this factor were used in an attempt to increase the independence of the climate and disturbance factors (wind and harvest are already independent of climate). We simulated the major disturbances (fire, wind, insects, harvest) that determine forest landscape dynamics in Siberia. Wildfire was simulated using the BFOLDS (Boreal FOrest Landscape Dynamics Simulator) Fire Regime extension (Ouellette et al., 2022), derived from the original BFOLDS model (Perera et al., 2008) that was designed to mechanistically simulate forest fire processes in Canada in a spatially explicit manner. We used BFOLDS because its wildfire regimes are an emergent property of climate and fuel (live and dead vegetation) – desirable because future functioning of boreal ecosystems is not expected to have a historical analog needed to parameterize other extensions. Because boreal wildfires in Eurasia are not as likely to be highly destructive crown fires as they are in North America (Rogers et al., 2015; Sitnov and Mokhov, 2018; Wooster and Zhang, 2004), the extension was modified (v2.2) to link cohort mortality to cohort species and age, and fire intensity. This allows the user to specify the fire intensity (kW/m^2) threshold necessary to kill each species by age class (see input files in the Supplement for thresholds used (based on Williams et al., 2023)). Calibration of historical fire return interval, fire size and area burned was somewhat complicated due to limited data for four very different landscapes, as described in detail in Williams et al. (2023). A daily ignition stream was generated for each year of the simulation period using the thermal hotspot archive of the MODIS Collection 6.1 active fire product (Giglio et al., 2020) as our source of observed fire ignitions combined with statistical modeling (Williams et al., 2023). BFOLDS was run at a daily time step with outputs aggregated annually. The fuel type of each landscape cell needed by BFOLDS was generated annually by the Dynamic Fuel extension (v3.0.2, Shinneman et al., 2018). For each landscape, we calculated metrics of the fire regime (e.g., mean annual number of fires and fire return interval) using publicly available datasets (Rogers et al., 2015; Andela et al., 2019). Replicated simulations were then conducted for different combinations of IgnitionDMCLimit, DMCSpreadLimitMean, and DMCSpreadAdjustment until the simulated fire regime characteristics converged on the observed fire regime characteristics.

Defoliation disturbance by a major insect defoliator in Siberia (Siberian silk moth, *Dendrolimus siberica* Chetverikov) was simulated with the Biological Disturbance Agent (BDA) extension, modified by us to produce v4.1.0 (Sturtevant et al., 2004, Appendix B). This extension simulates the effects of insect defoliators using relationships between host abundance and weather to simulate the timing, extent and duration of defoliation outbreaks. The extension was parameterized and calibrated for each landscape and climate using the literature, analyses of past outbreak patterns, and expert judgement, and run at an annual time step. Weather variables constraining outbreak activity were: mean August temperature ≥ 13.5 °C (Dergunov and Yakubailik, 2019); cumulative active insect degree days ($> +10$ °C air temperatures) >1200 and < 2400 (Kharuk et al., 2017); and cumulative drought indicated by a Standardized Precipitation-Evapotranspiration Index (SPEI) value ≤ -0.5 (Kharuk et al., 2017). Probabilistic tree species mortality was related to the “appropriateness index” of Kirichenko and Baranchikov (2007) defining host preference, and then modified to account for greater resilience of larch to defoliation and the secondary mortality agents affecting defoliated dark conifers. More details on the silk moth disturbance regimes are provided in Appendix B.

Two types of wind disturbances were simulated. Microbursts (generally smaller events) were simulated using the Base Wind extension (v3.1, Mladenoff and Hong, 1999). Tornadoes and derechos were simulated using the Linear Wind extension (v.2.0, Gustafson et al., 2018), which simulates large-scale wind events that produce a linear pattern of damage across a landscape. Whether a cohort is killed by a specific intensity of wind in these extensions depends on its relative age (% of species longevity). Both wind extensions were difficult to parameterize because of limited empirical data for Siberia. We modified parameters from other studies in Siberia (Gustafson et al., 2010) and N. America (Lucash et al., 2017) using expert judgement. Wind extensions were run at a decadal time step, simulating all wind events in that decade.

Timber harvesting was simulated using the Biomass Harvest extension (v. 4.5.1, Gustafson et al., 2000), which was run with a 10-year time step. This extension simulates removal of cohort biomass (including partial removal of individual cohorts) caused by timber harvest activities during the time step and has links to the fuel extension to account for logging activity (e.g., production of slash). Legal timber harvesting was parameterized to reflect the requirements and typical implementation of the Russian Federation Forest Code (see https://www.garant.ru/products/ipo/prime/doc/74983487 (in Russian)) in each study area (Table S2). Illegal logging is currently common in the southern landscapes, but it is under-reported in official documents. We estimated its parameters based on anecdotal understanding of the practice and expert judgement, and thus specified that the amount of illegal harvest for each forest type was 5 % of the legal harvest amount in the northern two study areas and 20 % in the southern two.

Wind and harvest disturbance extensions do not have direct links to climate, so within a study area they were constant across treatments, while insect outbreaks and fire dynamics emerged from the underlying climate and vegetation drivers. However, harvesting was always allowed to respond to the availability (increase or decrease) of each forest type after the first rotation. The introduction of colonizer species from the south (no seed sources currently present on the landscape) was also simulated using the Harvest extension by clearcutting a single cell and planting a single cohort of a colonizer species (not found in a study area but found in the next one to the south). This was implemented each decade on a repeated pattern (of individual colonizer species) across the row of cells on the southern edge of each study area. When the climate was too harsh for such cohorts, they were killed by cold, but when a previously planted cohort was still alive at subsequent time steps, the cell was not cleared and re-planted, allowing colonists to grow and reproduce. This method mimics a periodic arrival of propagules of new species from the south, which establish and survive only when abiotic conditions permit.

2.5. Climate factor and climate inputs

The experimental climate factor had three levels (Historical, Intermediate, Shared Socioeconomic Pathway 585 (SSP585)). Because an intermediate SSP climate scenario was not available for our study areas at the time of simulation, we generated one as described below. Climate inputs were managed by the climate library of LANDIS-II (v.4.2, Lucash and Scheller, 2021), which supplies and synchronizes climate inputs across all extensions. The “Historical” climate used the GSWP3 climate product for the years 1980–2014 (Dirmeyer et al., 2006; Kim, 2017). “Historical” data were randomly selected from this dataset (with replacement), one calendar year at a time, to create a “historical” climate stream corresponding to the full length of the 280-year LANDIS-

II run. The SSP585 climate was represented by the CESM2-WACCM_ssp585 product (Rodgers et al., 2021) for the years 2015–2300, accessed sequentially by the climate library. We generated ad hoc Intermediate climate streams in which temperature and precipitation values for each day were computed as the mean of the respective Historical and SSP585 values.

2.6. Simulation and analysis details

We simulated four replicates of each factor combination (beginning in the year 2015) for 280 years into the future to allow forest composition sufficient time to fully respond to the experimental treatments; each replicate used a different model random number seed, and the same four replicate seeds were used for all treatment combinations. We did not vary (by replicate) the climate input streams or initial vegetation conditions within each landscape. Model stochasticity affects disturbance regimes, establishment of new cohorts, and the order in which competing cohorts gain access to light and water on each cell at each monthly timestep.

To quantify the simulation results (maps output each decade) we computed landscape means and standard deviations of response variables related to forest composition, LAI, snowpack and albedo using R. To show treatment effects we plotted the trends through time (with 1 STD uncertainty ribbons) for each response variable by landscape and treatment, interpreting treatment effects as significant when uncertainty envelopes did not overlap after 100 years. This approach is generally superior to statistical tests for simulation modeling studies because *p*-values can be arbitrarily high and the null model (i.e., no difference between treatments) is invalid because parameter inputs (in this case, random number seeds) differ between model runs (White et al., 2014). We also used effects analysis with ANOVA to partition variation and quantify the relative effect sizes among the experimental factors (bioclimatic zone, climate scenario and disturbances using the 'effectsize' package in R (Ben-Shachar et al., 2020).

2.7. Quantifying radiative forcing on a global scale

Using the methodology outlined in Rutherford et al. (2017), we estimated the potential for changes in albedo in Siberia to alter radiative forcing at a global scale. Radiative forcing is defined as the change in net radiation at the top of the troposphere (IPCC, 2021). A positive radiative forcing tends to warm the earth's surface and a negative forcing cools it. We calculated the radiative forcing through time for each landscape, climate scenario, and disturbance scenario using:

$$Radiatative\ Forcing = albedo_{initial} - albedo_{mean}\frac{area_{landscape}}{area_{Central\ Siberia}} * \frac{area_{Central\ Siberia}}{area_{Earth}}$$

where radiative forcing = radiative forcing (W m^{-2}) corrected for the relative area of each landscape and central Siberia, divided by the total surface of the earth, $albedo_{initial}$ = albedo at the start of the simulation, $albedo_{mean}$ = albedo across the entire 280-year simulation, $area_{landscape}$ is the area of each landscape (1.0×10^4 km^2), $area_{Central\ Siberia}$ is the land area of central Siberia (3.62×10^6 km^2), and $area_{Earth}$ is the area of the entire earth (i.e. 5.066×10^8 km^2).

3. Results

Fire activity under historic climate was virtually nonexistent in Tundra and most prevalent in the South Taiga, with intervening Bioclimatic Zones experiencing fire rates between these two extremes (Fig. S3). By comparison, fire extent dramatically increased under both warming climate scenarios, with fire activity initiating in the Tundra because of invading trees in the twenty-first century. The effect of climate and zone on insect disturbance was more mixed, only affecting Mid and South Taiga zones under historical climate, and all zones experiencing a multi-decade pulse of silk moth outbreaks as warming scenarios passed first into and then out of the cumulative active air temperature ranges defining the silk moth's current range of outbreak activity. Static wind regimes generally affected less area than either insects or fire, and were stochastic in their impact patterns, while harvest rates ultimately declined under climate warming scenarios (Fig. S3), primarily because elevated fire kept forests below current minimum harvest age requirements (Gustafson et al., n.d.).

In the presence of disturbances summarized above, open (no trees, high albedo) sites were common and climate change generally increased the abundance of deciduous species and decreased the abundance of dark conifers (Fig. 2A). Light conifers were generally resilient to climate change in the north but less so in the south. Lowland deciduous species like alder and willow increased modestly with climate change. Arctic ground cover was mostly displaced by shrubs and trees in the north; steppe grasses increased with climate change in the south but there was not a major transformation of forest to grassland. Climate change increased the amount of open ground because more sites were disturbed (Fig. S3) and recolonization was unable to keep pace. The abrupt decline in the extent of Arctic ground cover around the year 2100 under the SSP585 climate (Fig. 2A) was caused by an increasingly chronic heat stress that resulted in low or negative net photosynthesis in mid-summer months. The lengthening of the growing season (with mild temperatures in those months) was insufficient to overcome the increased respiration costs of higher summer temperatures. The decline of photosynthesis (from heat stress) was gradual over about a 20-year period, but the mortality of most cohorts occurred in the same decade. Re-colonization of sites dominated by Arctic ground cover was quite slow, resulting in a prolonged increase of open sites.

Composition was much different when disturbances were not simulated. Without disturbances, there were many fewer open sites, dark conifers thrived, and deciduous pioneers were decidedly less abundant (Fig. 2B). In these No Disturbance scenarios, composition was not very different under climate change than under historical climate, presumably because disturbance is needed to reset succession, except in the tundra (and to a lesser extent in NTaiga) where trees were initially rare.

Leaf area is also an important driver of albedo in boreal forests. LAI generally increased from north to south (Fig. 3) because cohorts in the north had less biomass, representing smaller and more scattered individuals. Without disturbances, LAI increased markedly, reflecting invasion of cohorts into open areas and enhanced growth under climate change on the northern landscapes where LAI was initially relatively low on most cells. In the southern taiga, climate change had little effect on LAI. Disturbances generally decreased LAI on all landscapes. With disturbances under climate change, LAI was higher in the tundra, but in all the other landscapes, disturbances and climate change tended to depress LAI to levels lower than simulated under historical climate (Fig. 3), possibly due to depressed growth in the last century of the simulations.

Snow is an important driver of annual albedo in boreal forests, with changes in the length of the snow-free season having more effect than snow depth. Severe climate change caused large reductions in length of the snow-covered season in all landscapes (Fig. 4). Under climate change, snow begins falling later in the fall and it melts earlier in the spring (Fig. S4). Surprisingly, the intermediate climate produced as much snow as the historical climate, except in the tundra. Disturbance had little effect on snowpack because the parameter controlling precipitation interception (by foliage) affects only liquid precipitation (rain). This reflects an assumption that intercepted snow eventually reaches the ground (as its water equivalent) and that prior to reaching the ground it sublimates at the same rate as snow on the ground. Depth of snow has a minor impact on albedo in the model (i.e., any depth $> \sim 10$ cm has the same albedo effect).

The alteration of the length of the snow-covered season is the main driver of seasonal albedo dynamics under climate change (Fig. S5). Interestingly, albedo was generally higher under the Intermediate climate than under either of the other climates except in the Tundra. The

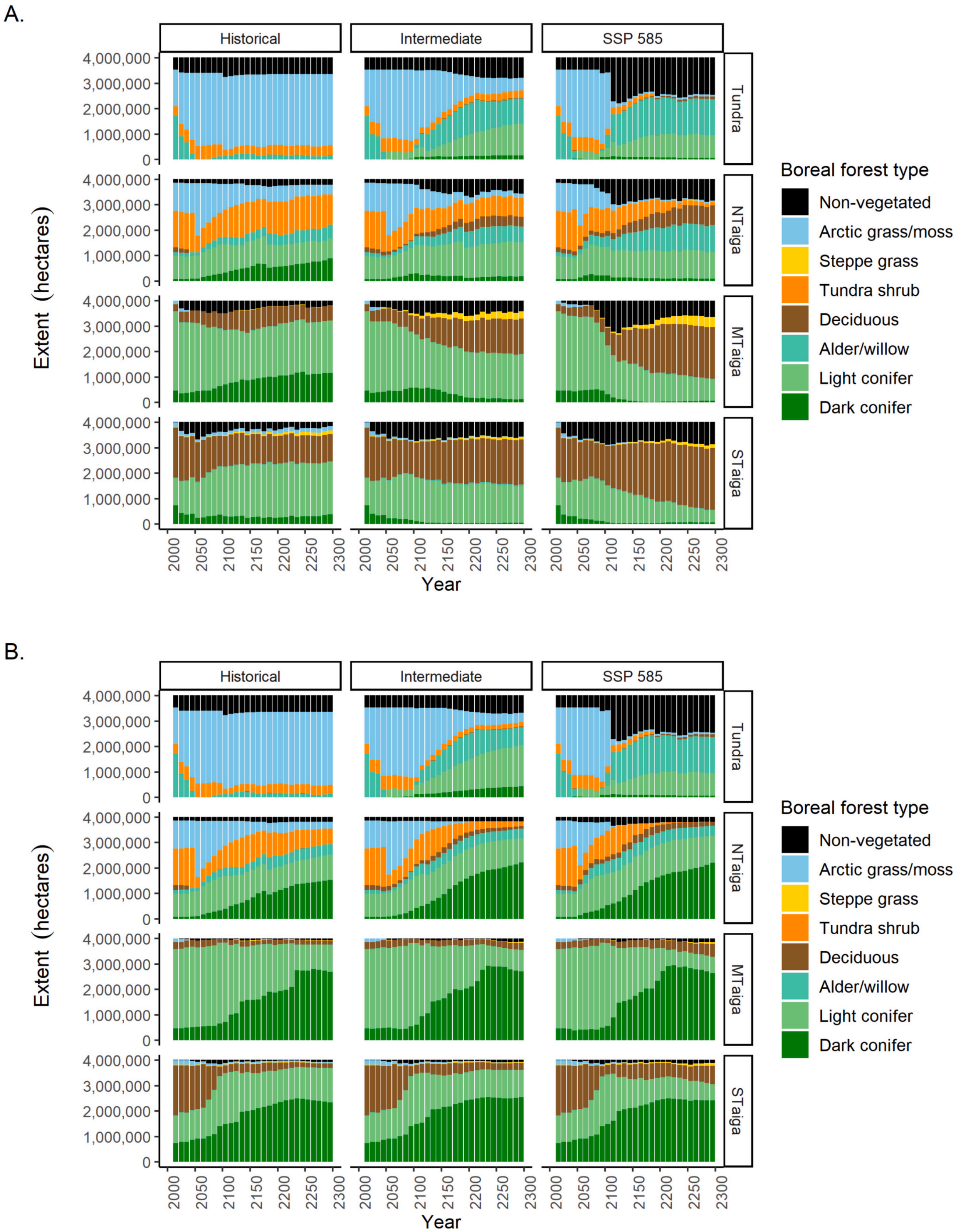

Fig. 2. Areal abundance of forest types through time by climate and landscape with all disturbances (A) or with no disturbances (B). Large, abrupt changes in the abundance of a type were usually caused by the senescence of cohorts having the same (+/− 10 years) initial age or by cold-killing (typically deciduous).

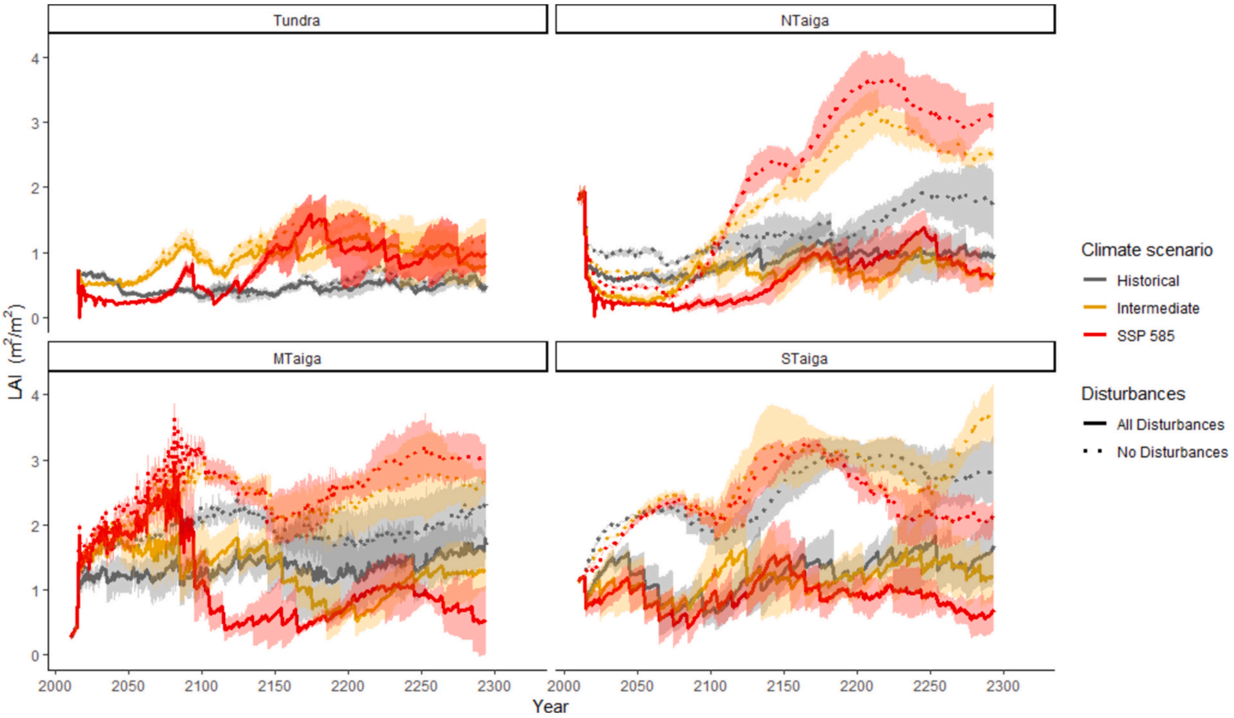

Fig. 3. Average of total (weighted average of all cohorts on each cell) LAI (in July) on all active cells of each landscape through time by climate and disturbance scenario. Ribbons show one standard deviation of four replicates.

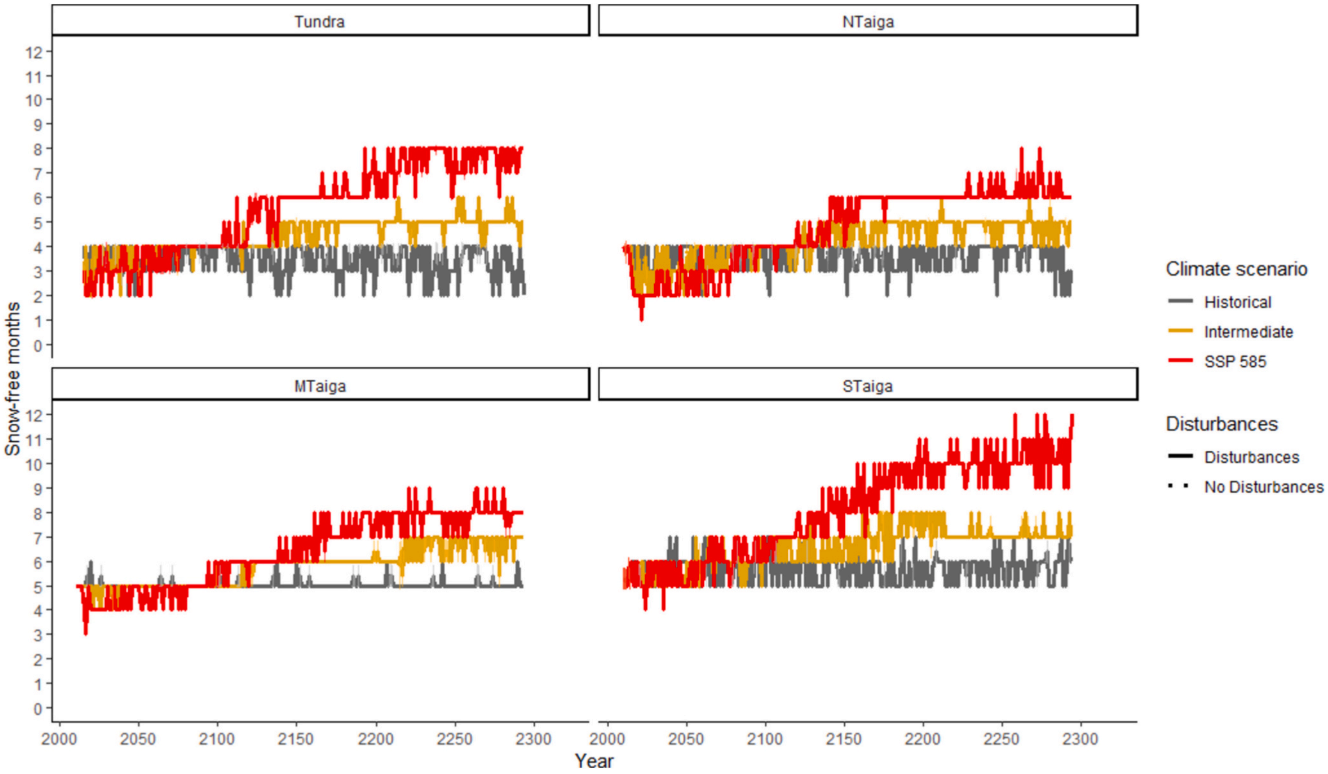

Fig. 4. Mean number of snow-free (snowpack = 0) months per year across all active cells of each landscape through time by climate and disturbance scenario. Ribbons show one standard deviation of four replicates and are less than the width of the lines because climate did not vary by replicate. Note: disturbance has a negligible effect on snowpack (Disturbance/No Disturbance curves overlap).

hypothetical No Disturbance scenario consistently produced markedly lower albedo. The dramatic reduction in winter albedo in the final century of the simulations under severe climate change on all landscapes was mostly the result of alteration of the length of seasons. Albedo was noticeably higher in winter due to increased snow and reduced LAI, and the length of the winter season shortened considerably under severe climate change (Fig. S4). However, disturbance increased albedo, in winter and with the effect increasing with decreasing latitudes, by reducing LAI and exposing more of the ground (snow-covered in winter) (Fig. S5). Sometimes warmer climates produced higher albedo than the historical climate in all but the Tundra landscape, presumably because growth (and therefore, LAI) was somewhat less optimal under warmer climates.

Winter (November to April) albedo declined in all landscapes relative to the severity of climate change (Fig. 5), presumably driven primarily by the length of the snow-free period within the 6-month "winter" season. Disturbance dramatically increased albedo except in the Tundra, where there was considerably less tree vegetation to be disturbed (until late in the simulations). Summer (May to October) albedo was not much altered by climate change in the southern landscapes where there is currently little snow in those months, while in the north, climate change eventually eliminated snow in those months (Fig. 5). Note that the spikes in albedo resulted from years when there was a weather anomaly of snow or no snow in the summer season (Fig. 5). Disturbances generally had less impact in the summer months except on the northern Taiga because disturbances have the greatest effect on albedo when there is snow involved and when there is relatively more leaf area to be disturbed.

Mean annual albedo (mean across all months) represents the overall reflectivity that impacts the climate system (Zhang et al., 2022). The effects analysis showed that all three experimental factors had a significant effect on annual albedo, with bioclimatic zone being by far the most important driver of albedo; disturbance had more of an impact on albedo than climate in the near-term (in the first simulated century), but climate had a greater impact than disturbance long-term (Table 1). When all the disturbances were simulated, climate change decreased

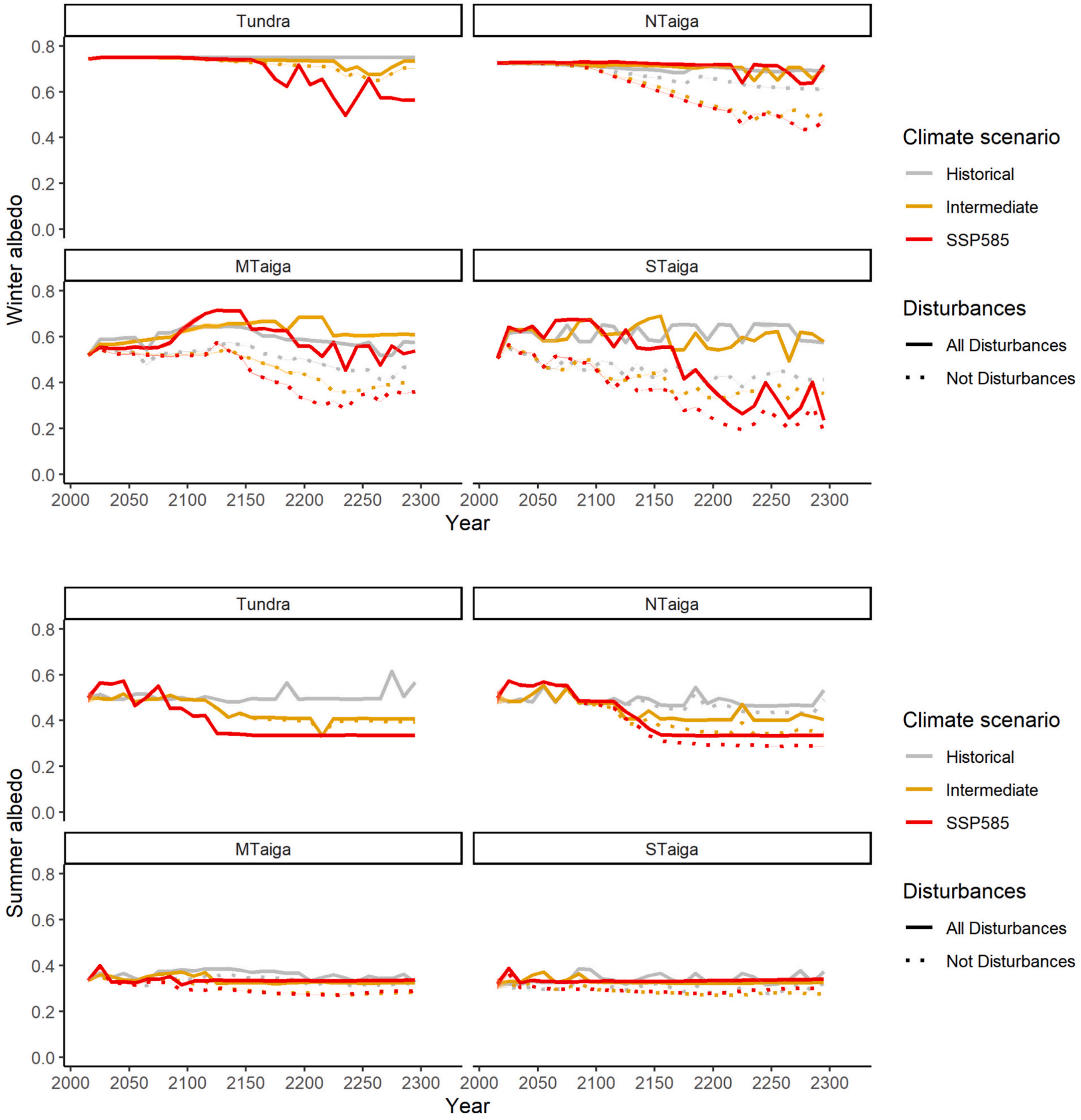

Fig. 5. Mean landscape albedo across all active cells of each landscape through time by season. The winter season was arbitrarily defined as November through April and summer as May through October to capture climate effects throughout the year. Ribbons represent one standard deviation of four replicates; variability was generally less than the width of the lines because climate was the same in all replicates of each landscape.

Table 1
Analysis of the relative effect of the treatment factors (bioclimatic zone, disturbance, climate) on mean annual albedo in the short term (the first century of simulation) and long-term (the last century of simulation). η_p^2 is the fraction of the partial variance of an individual factor after accounting for the other factors in the model.

Experimental factor	η_p^2 first century	95 % CI first century	η_p^2 last century	95 % CI last century
Bioclimatic zone	0.91	0.90–1.0	0.50	0.47–1.0
Disturbance	0.02	0.01–1.0	0.17	0.14–1.0
Climate	0.0005	0.0–1.0	0.20	0.17–1.0

albedo within all bioclimatic zones, but more so in higher latitudes (Fig. 6), presumably driven by more vegetation in north, darker conifers in south. At the cell scale, albedo sometimes increased quite dramatically after disturbance, particularly after a high intensity disturbance event (e.g., Fig. S6).

Disturbances greatly increased albedo in all ecosystems, except in the tundra. This increase was particularly large in winter (Fig. S5), and was more pronounced as latitude decreased, likely because disturbance rates increased as latitude decreased. The impact of disturbance on albedo was particularly great under severe climate change, where mean no-disturbance albedo was sometimes nearly half of the value with disturbance (see NTaiga and MTaiga in Fig. S5). Disturbances tended to remove vegetation that absorbs radiation (typically only temporarily), and this either exposed a more reflective ground cover or reset succession to a more reflective vegetation type. The difference between albedo in the Disturbance and No Disturbance scenarios was minor for the first 80 years of the simulations (Fig. 6), although their divergence was slower as latitude increased because disturbance regimes generally have longer return intervals and less intensity at higher latitudes.

Future changes in albedo in Siberia have the potential to influence radiative forcing at a large scale. Under the extreme climate scenario, we found that the radiative forcing (warming) caused by altered albedo was very high when disturbances were not simulated, ranging from 0.13 to 0.31 W/m^2 (Fig. 7). Based on our simulation of disturbances, the estimated future albedo across the latitudinal gradient of Siberia under severe climate change would produce a mean radiative forcing between -0.15 and + 0.20 W/m^2 (Fig. 7). These forcings were all positive under severe climate change except in the mid-taiga, being greatest in the tundra, cumulatively creating a positive (warming) feedback to the climate system by absorbing radiation that historically would have been reflected back to space.

4. Discussion

Overall, our results tended to support the vegetation change component of our hypotheses, but there was little support for the albedo component, suggesting that our assumption that forest cover is the primary driver of albedo was incorrect, especially in the southern two landscapes. The shortening of the snow-covered winters and lengthening of leaf-on seasons (decreased albedo) overwhelms the effects of increased disturbance that removes vegetation and resets succession to more reflective types (increased albedo). Also, the effect of changing vegetation between dark-leaved and light-leaved species on annual albedo appears to be almost negligible at landscape scale, while the ability of disturbances to reduce LAI and reset succession to an 'open' condition has a more substantial effect on albedo.

Under the extreme climate scenario, we found that the radiative forcing was relatively high, ranging from 0.17 to 0.54 W/m2, when disturbances were not simulated (Fig. 7). On average, these values were 2.5 times higher than scenarios with simulated disturbances, indicating that omitting disturbances likely generates unrealistically high estimates of radiative forcing under climate change. Radiative forcing was about 11 % of anthropogenic emissions (2.1 W m^2) without disturbances. When disturbances are simulated under the extreme climate scenario, the warming of Siberia could produce an estimated radiative forcing between -0.01 and 0.39 W m^2, almost 7 % of anthropogenic emissions. Under extreme climate, radiative forcing was highest in the tundra, potentially creating a positive feedback to the climate system, by absorbing radiation to the atmosphere that historically would have been reflected at the Earth surface.

Our results also suggest that climate change will produce an increasingly positive climate feedback over time by decreasing average annual albedo in boreal and tundra ecosystems. It is beyond the scope of this paper to rigorously quantify the global warming effect of the albedo changes simulated, but our results do suggest that the effect is not likely to be trivial. This was particularly strong in the tundra, where radiative forcing was 20 % of anthropogenic CO_2 emissions forcing under climate change. Our results also underscore the importance of simulating

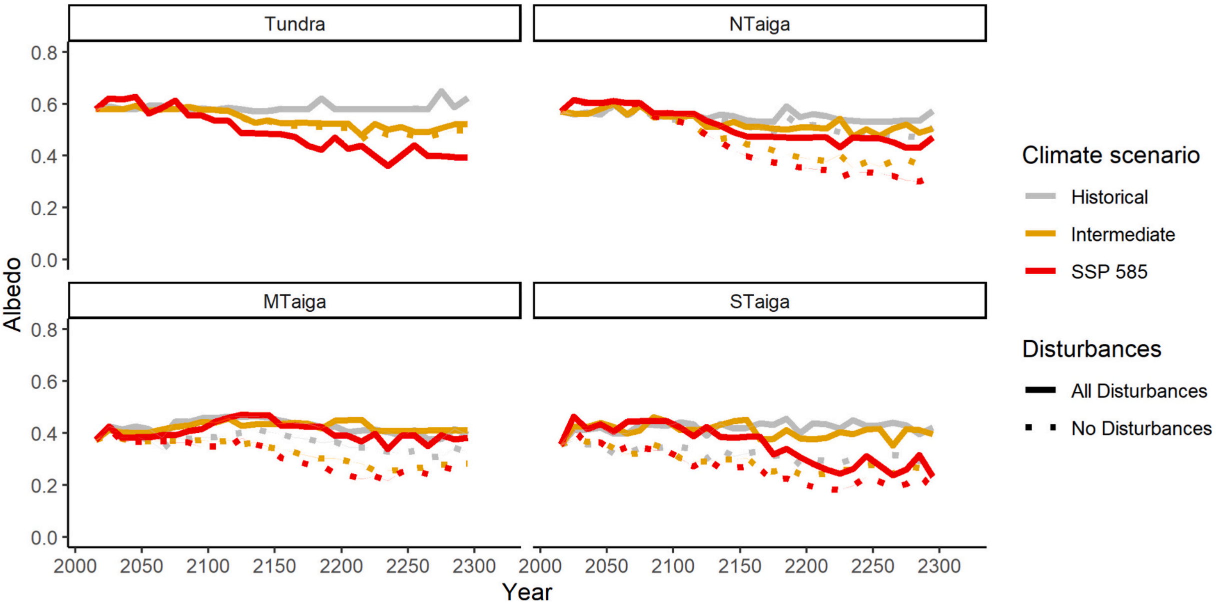

Fig. 6. Mean annual albedo (DHR; directional hemispherical reflectance) across all active cells of each landscape through time by climate and disturbance scenario. Ribbons represent one standard deviation of four replicates; variability was generally less than the width of the lines because climate was the same in all replicates.

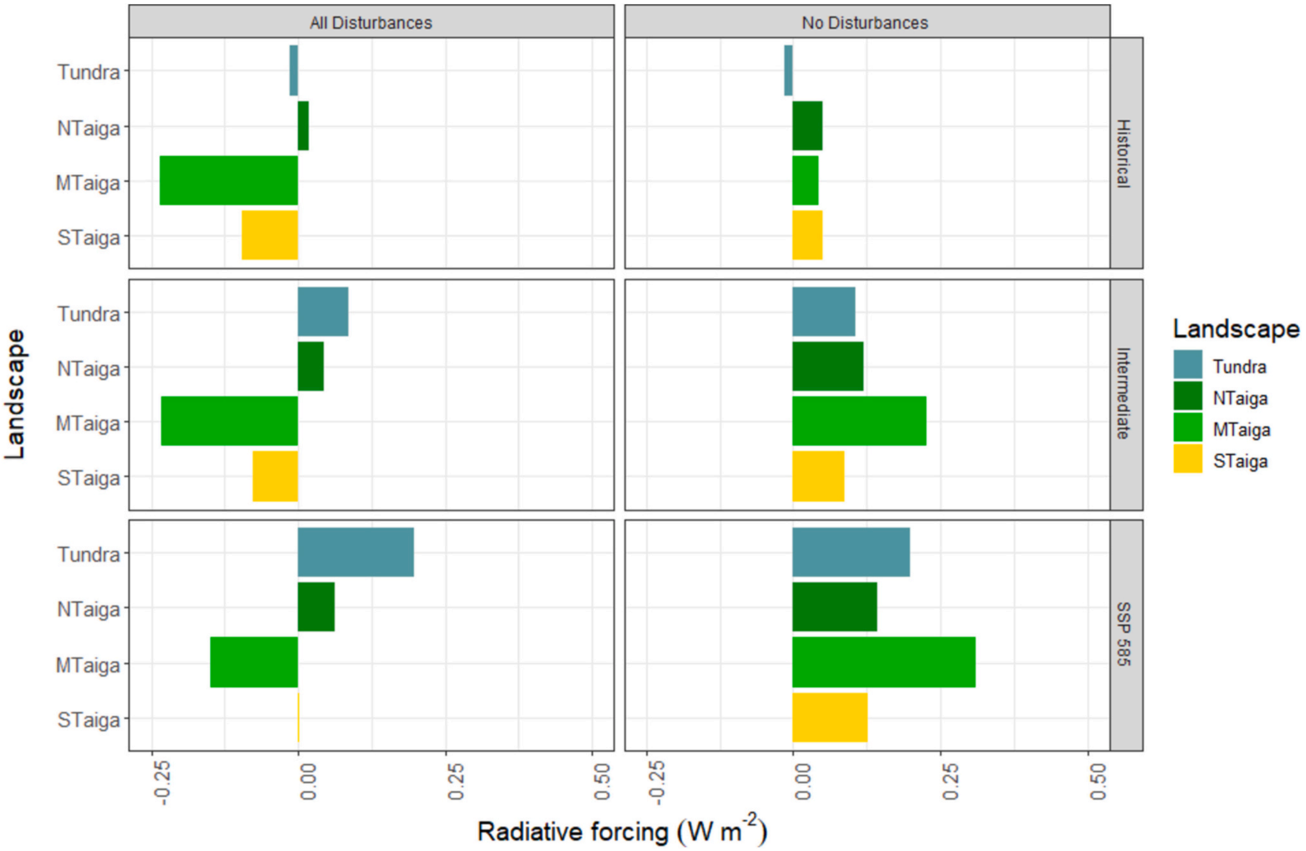

Fig. 7. Estimated mean radiative forcing for central Siberia from anticipated changes in albedo and climate from 2015 to 2085. Note: negative forcing (bars to the left) indicates cooling effect caused by altered albedo.

disturbances when quantifying albedo given that radiative forcing was >1.6 times higher when disturbances were omitted. Although this is only a heuristic exercise to estimate radiative forcing, these estimates are included to provide insight into the potential for albedo in boreal ecosystems to affect future climate via global changes in radiative forcing.

We evaluated our hypotheses against the results of simulations with "All Disturbances" scenarios because the No-Disturbance scenario is an unrealistic factor level that is useful only for estimating the effect of disturbance on albedo relative to the effect of climate. We did not compute statistical tests to evaluate hypotheses (considered unreliable for simulation results; White et al., 2014), instead visually comparing trend lines (plotted with variance ribbons). In the tundra landscape, climate change allowed an invasion of trees (primarily larch, a light conifer, displacing primarily arctic grass) which resulted in decreasing albedo through time (Fig. 6). However, climate change also increased disturbance, resulting in more open sites (higher albedo), but not enough to offset the invasion of trees. We note that Heim et al. (2021) found that Siberian sub-arctic tundra did not recover to their pre-fire state for over 44 years, suggesting that our results showing slow recovery in tundra are not unreasonable. Therefore, in the tundra, our hypothesis that the invasion of tundra by trees would reduce albedo (H1) was supported. In the northern taiga landscape, climate change greatly reduced dark conifers, contrary to our hypothesis that that dark conifers would increase (H2). Climate change also reduced light conifers, greatly increased deciduous species, and increased the abundance of grasses and open (recently disturbed) sites (Fig. 2), which collectively would tend to increase albedo. However, albedo decreased in both summer and winter compared to historical climate because of the climate-induced shortening of winter (snow season). Therefore, our proposed decline in albedo (H2) was supported, but the mechanism was incorrect.

Our hypotheses that climate change would increase albedo in the other two landscapes were not supported (H3, H4) because shorter winter (snow-covered) seasons (fewer high-albedo months) more than offset the comparatively minor effects of more reflective tree canopies and ephemeral disturbance effects. In the middle taiga, climate change increased the extent of light conifers and deciduous species (with concomitant increase in exposure to forest floor, including when snow-covered), although the effect on albedo was mixed (Fig. 6). Therefore, our hypothesis (H3) was not clearly supported. In the southern taiga landscape, deciduous species and steppe grasses increased in extent under climate change as did fire disturbance, but albedo did not increase in either season, actually decreasing in most treatment combinations. This result was driven primarily by the dramatic shortening of the winters, especially under severe climate change. Thus, hypothesis H4 was supported in terms of vegetation change, but not in terms of albedo. Although we expected that disturbances would universally increase albedo across all bioclimatic zones (H5), we found that they had a minimal effect in the tundra, likely due to very limited tree cover.

Our results suggest that accurately accounting for the seasonality of snow is the most important factor in predicting landscape albedo, and DGVMs account for snow more mechanistically than does our model. In fact, our model had a monthly timestep, so the resolution of the length of the snow-covered season was coarse, although that would make it more difficult for our model to detect an effect of snow-covered season (i.e., a subtle change would be less detectable). We found that chronic disturbance greatly increases landscape albedo in all seasons, suggesting that credibly modeling disturbance is also important to make accurate predictions of albedo. DGVMs are required to make simplifying assumptions about some major disturbance types and ignore others completely. If DGVMs predict lower albedo because they do not adequately account for disturbance, then maybe GCM temperature predictions are consequently slightly high.

Rapid change associated with warming climate at high latitudes has received much attention, in part because many interrelated processes collectively feed back into the global climate system (Previdi et al., 2021). Landscape models integrating different processes including vegetation dynamics, seed dispersal, fire disturbance, and permafrost dynamics have been applied to address the effects of rapid warming at high latitudes, particularly in Alaska (Euskirchen et al., 2020; Previdi et al., 2021). Indeed, some of those model applications include processes simulated more mechanistically (e.g., more sophisticated permafrost dynamics) than our own (e.g., Lucash et al., 2023). However, to date, albedo dynamics have only been addressed using coarser-scaled DGVMs (see Loew et al., 2014), without the benefit of the spatial interactions and multiple interacting disturbances possible only within a finer-scaled landscape model. Our modeling approach is novel in that it was implemented across an extremely broad region and accounts mechanistically for spatially and temporally defined ecological processes (e.g., seed dispersal, natural and anthropogenic disturbances) to project future forest dynamics and that it also estimates albedo dynamics at monthly and centuries time scales. The extent to which our findings are similar or dissimilar to those produced by other, less spatially explicit, approaches is useful to assess the relative importance of such spatial processes on vegetation dynamics and their concomitant effect on albedo. GCMs often use albedo estimates derived from models that may be less explicit about some spatial processes. Our approach may be useful to evaluate the consequences of such simplifying assumptions.

The results from our study seem to be unique in the literature in that they account for climate effects (temperature, precipitation, CO_2 effects on growth, permafrost hydrology, seasonality), multiple spatially interactive disturbances that may interact with climate, and vegetation change (composition and LAI), to make projections of future boreal forest cover and albedo. We were able to show the relative effect on albedo of compositional change (minor), disturbance (important) and shortening of winters (very important). Our results illustrate the outcome when all major disturbances are simulated (in interaction with climate) to capture their cumulative effect on albedo. We found that fire is the most important disturbance in these Siberian ecosystems, affirming the inclusion of fire (even when not simulated in a spatially interactive way) in most Earth System models. However, the effect on succession of other disturbance types may also be important for projecting future albedo, and our approach might be useful for assessing just how important it is and to inform methods to account for them in Earth System models.

The results of our study complement and integrate those of many others. Several studies (e.g., O'Halloran et al., 2012; Chen et al., 2018; Potter et al., 2020) also found that disturbance increases albedo in multiple biomes and that climate change is expected to reduce albedo, primarily by effects on snow. O'Halloran et al. (2012) suggest that the change in albedo from disturbance has the same magnitude of climate effect as CO_2 forcing. Our results support this view and clarify the effect of disturbance relative to other causal factors at landscape scales of space and time (centuries). Many modeling studies (e.g., Betts (2000), Shuman et al. (2011)) have shown that climate change will produce positive feedback to the climate system, with albedo being a primary driver. Wang et al. (2016) provide empirical detail about how burn severity leads to high spatial heterogeneity of spring albedo at landscape scale. Chen et al. (2018) observed a strong increase in albedo from wildfires, caused by increased exposure of snow, but worry that climate warming will eventually reduce snow and offset that effect.

The shortening of the snow-covered winter season and the trend toward earlier snowmelt has been well observed and modeled (e.g., Serreze et al., 2000; Schwartz et al., 2006; Wobus et al., 2017; Mote et al., 2018; Rhoades et al., 2022), consistent with our findings using an integrating model. However, there is at least one paper describing slower snowmelt in spring under climate warming across the northern hemisphere due to deeper snowpack (Wu et al., 2018). Similar to our motivating concerns (Introduction), Loranty et al. (2021) also question the ability of coupled climate models (e.g., DGVM and GCM) to adequately represent the snow-masking effect of vegetation in northern high latitude ecosystems.

In contrast, our results provide a different perspective about conclusions by some that managing forests to promote more reflective vegetation might substantially mitigate other factors contributing to climate change (e.g., Lutz and Howarth, 2014; Astrup et al., 2018). Our results suggest that modified forest composition would have a very small effect on mean annual albedo compared to the effect of altered growing season length or disturbances.

Our results caused us to speculate about the feedback that our simulated changes in albedo might exert on global climate. Although there were competing drivers of albedo, the shortening of the snow-covered season appears to be the dominant driver, which serves as a reinforcing feedback to the climate system. Thus, since climate already appears to be warming (especially in high northern latitudes), it seems likely that the snow-covered season is already shortening, tending to reduce albedo, which should produce an increasing warming effect. Our results are not able to address the question of when such a feedback loop might cease to increase the warming effect, at least partly because the climate futures we used as inputs were derived from GCM projections that are based on land cover projections that may not adequately account for how multiple disturbances interact with climate to alter vegetation and albedo. Nevertheless, our results seem to suggest that pessimism may be warranted concerning our ability to mitigate albedo loss to a degree that might make a significant difference. Of the available options, managing disturbances (to increase or prolong 'openness') may be the only effective tool for mitigating the reduction of albedo by climate change in boreal ecosystems because management to encourage more reflective forest types is likely to have a relatively small effect compared to that of shorter winters.

Our results suggest that altering the composition of boreal forests may not have much impact on albedo compared to other, offsetting drivers of albedo (at least in ecosystems where snow is currently present during much of the year), so more research would be required before promoting such a strategy. Accordingly, research is needed to quantify the albedo effect of individual disturbances, to begin to identify management actions that might increase or lengthen elevated albedo effects of disturbances and to estimate their ability to mitigate climate change. Some researchers have suggested that managers of boreal forests consider albedo as an ecosystem service, which might change the priority of certain silvicultural strategies (e.g., Bright et al., 2014; Lutz and Howarth, 2014; Astrup et al., 2018). Our modifications to PnET-Succession may allow forest managers to add albedo considerations to landscape-scale evaluations of climate-smart forest management strategies. Such strategies are currently focused primarily on managing forest composition to sustain traditional ecosystem goods and services from forests, but sustaining or increasing albedo could be an additional ecosystem service provided by forests. Albedo as an ecosystem service may have more merit in other biomes where snow is not such a dominant driver of albedo. However, it is not yet clear if the increase in albedo of tree harvesting activities offsets the carbon storage and emissions climate consequences of those activities (Sjølie et al., 2013).

5. Conclusions

Our study allowed us to draw several conclusions. 1) Vegetation characteristics are not the primary driver of the mean annual reflectivity of boreal ecosystems; the length of the snow season is the primary driver. 2) The alteration of albedo caused by changes in growing season length may alter radiative forcing such that it will likely act as a powerful positive feedback for climate change. 3) Managing disturbances is possibly the only effective strategy for mitigating the reduction of albedo by climate change in boreal ecosystems; managing forest type is not likely to make much difference. 4) Additional research is needed to determine the timing, extent, and location of management actions that would be most beneficial to enhance/prolong the albedo of disturbances and to assess which assisted migration strategies may be required to maintain the ecosystem goods and services currently provided by Eurasian boreal forests.

CRediT authorship contribution statement

Eric J. Gustafson: Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Melissa S. Lucash:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anatoly Z. Shvidenko:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Brian R. Sturtevant:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Brian R. Miranda:** Writing – review & editing, Software, Methodology. **Dmitry Schepaschenko:** Writing – review & editing, Validation, Methodology, Data curation. **Hana Matsumoto:** Writing – review & editing, Visualization, Investigation, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177043.

Data availability

Data will be made available on request.

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