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Assessing the climate benefits of afforestation in the Canadian Northern Boreal and Southern Arctic

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Afforestation greatly influences several earth system processes, making it essential to understand these effects to accurately assess its potential for climate change mitigation. Although our understanding of forest-climate system interactions has improved, significant knowledge gaps remain, preventing definitive assessments of afforestation's net climate benefits. In this review, focusing on the Canadian northern boreal and southern arctic, we identify these gaps and synthesize existing knowledge. The review highlights regional realities, Earth's climatic history, uncertainties in biogeochemical (BGC) and biogeophysical (BGP) changes following afforestation, and limitations in current assessment methodologies, emphasizing the need to reconcile these uncertainties before drawing firm conclusions about the climate benefits of afforestation. Finally, we propose an assessment framework which considers multiple forcing components, temporal analysis, future climatic contexts, and implementation details. We hope that the research gaps and assessment framework discussed in this review inform afforestation policy in Canada and other circumpolar nations.

Climate change poses a critical threat to humanity, with observed and projected warming rates unprecedented in the current interglacial period. Unless we act swiftly to reduce greenhouse gas (GHG) emissions and begin sequestering existing accumulated atmospheric GHGs, climate change impacts will likely intensify in the coming years, impacting ecosystems worldwide[1]. Some ecosystems are more vulnerable than others, with high-latitude ecosystems warming two to four times faster than the global average[2,3], making them highly sensitive areas needing stewardship. Canada is home to one-third of the boreal biome that envelops the global northern hemisphere, which is a significant store of terrestrial carbon[4], with managed boreal forests alone storing ~28 gigatonnes (Gt) of carbon[4].

The Intergovernmental Panel on Climate Change (IPCC) recognizes the vast potential of forests to sequester carbon dioxide (CO_2)[1]. Afforestation is projected to provide substantial sequestration benefits this century, estimated at ~4.9 $GtCO_2$/year globally[5]. The Canadian government's Two Billion Trees program[6] exemplifies the significant interest in afforestation, particularly in the northern boreal region[7]. However, it is essential to consider that forests impact the climate in complex ways, extending beyond carbon sequestration to influence albedo, surface energy balance, hydrological cycles, and permafrost dynamics. While significant progress has been made in understanding the impacts of forests on regional dynamics and global climate processes, many knowledge gaps remain, hindering the consideration of

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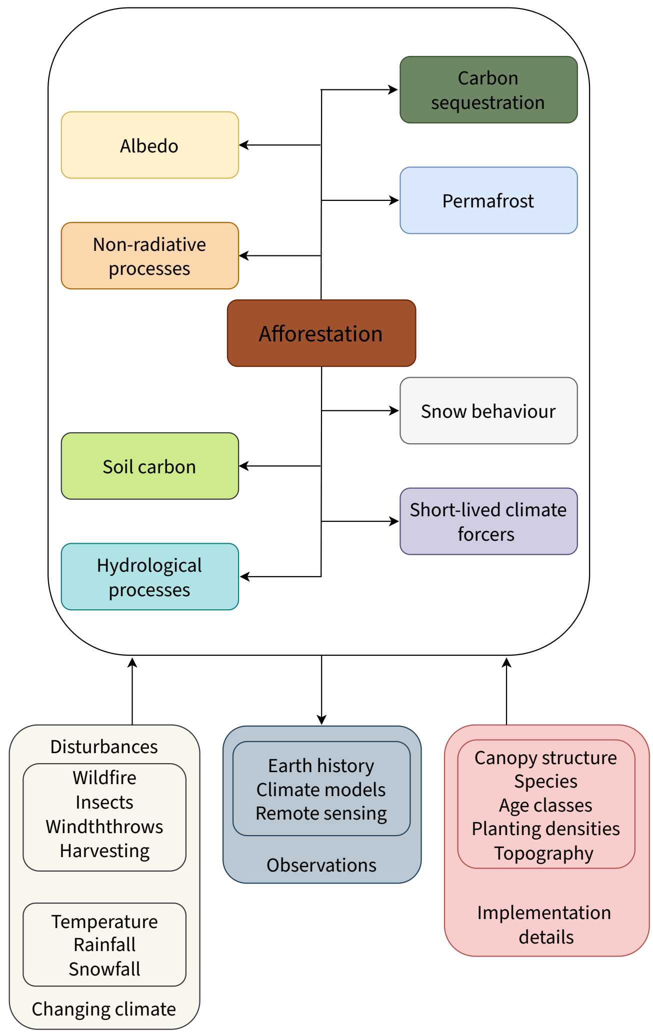
these effects in existing assessments of afforestation's climate benefits[8–10].

In this work, we explore the interconnections of forest processes (see Box 1a), revealing that afforestation is a more complex decision than it initially appears. We explore the unique realities of the northern boreal and southern arctic regions (see Supplementary Fig. 3 for land cover map[11]), including permafrost, hydrology, snow behavior, and general forest considerations such as non-radiative processes, soil carbon, forest structure, and chemical emissions (see Box 1a). In addition, we examine what can be learned from forest behavior during Earth's climatic history and the uncertainties in forest dynamics under projected climate change this century. We also highlight the need to reconcile remote sensing-based methodology with climate models and point out the methodological limitations of existing afforestation

BOX 1

Unique realities and processes that afforestation influences in the northern boreal and southern arctic regions, observations used to study these processes, and implementation details that are crucial



Apart from BGC processes such as carbon sequestration and emission of short-lived climate forcers (SLCFs), afforestation influences a variety of other processes, including albedo (radiative), non-radiative and hydrological processes, and dynamics such as permafrost, snow, and soil organic carbon (SOC) dynamics. The influence that afforestation has on these processes and dynamics can be studied using observations from remote sensing, climate model simulations, and Earth's geologic history. A changing climate is expected to affect afforestation and all its interlinked processes by altering disturbance regimes like wildfire and insects, as well as modifying climate variables such as temperature and precipitation. Implementation details, including the group of species chosen to be afforested, age distributions in a given forested area, and planting densities, change canopy structure and affect various processes linked to afforestation. Moreover, the topography chosen for afforestation affects the overall surface energy balance by altering solar illumination, snow behavior, and hydrology.

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assessments. Finally, we discuss how these insights can be used to improve afforestation project modeling and outline a path forward for analysis, planning, and policy-making. We do not discuss the details of the ecophysiology of stand transitions (from seedlings to saplings to trees) in this review but rather abstract these out to a factor like time since afforestation, and investigate the overall climate benefits. For a quick introduction to the acronyms and abbreviations used in this review, refer to Supplementary Table 1.

Results

Each ecosystem has unique characteristics and key drivers that play a crucial role in its functioning and set it apart from other ecosystems. In the subsequent sections, we expand upon these critical processes and realities central to the northern boreal and southern arctic regions.

Permafrost

Permafrost is a crucial component of northern forests. Permafrost contains substantial carbon (~1.3–1.7 teratonnes) and methane (~20 Gt) reserves, stored in frozen organic soils[12–14], far exceeding the carbon stored in the active layer and aboveground biomass[15]. As climate change accelerates, permafrost is at risk of melting, threatening to release ancient reserves in the form of carbon dioxide and methane and jeopardize ecosystem function. Permafrost thawing and large-scale GHG emissions could further exacerbate climate change, potentially initiating feedback loops[16]. Therefore, high-latitude regions require a management plan to reduce the impacts of melting permafrost on delicate ecosystems. While there is debate about which land covers will best protect ecosystem function, maintain permafrost, and ensure carbon sequestration, there is consensus that action is necessary to help ecosystems adapt to anthropogenic climate change[17].

While an overlap between Canada's boreal treeline and permafrost line may suggest that forests affect permafrost negatively, there is ample contrary evidence that forests help maintain permafrost in many ways[18] (see Box 2a). The results from the experimental station in Farmers Loop (Fairbanks) run by the US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CRREL) demonstrate the role forests play in maintaining the stability of permafrost[19] (seeBox 2b). Data from other monitoring sites across the world support this conclusion that forest removal results in an increase in active layer thickness and ground temperature[20–22]. These findings are further validated by modeling studies which reveal positive relationships between forest cover and permafrost integrity[23–25]. Even in the larger boreal, average winter soil temperatures are found to be significantly lower in forested sites compared to open lands[26], pointing to forests altering the ground thermal regime favorably.

Forests alter the ground thermal regime, reducing the impact of rising summer air temperatures on soil temperatures[27,28] (see Box 2a, b). In addition, the reduced accumulation and prolonged melting of snow on the forest floor, compared to open lands, reduces the extent of snow-trapped insulation during winter (see Box 2a, section "relationship between snow and tree cover")[27,28]. In spring, the snow albedo effect reduces soil warming by slowing down melting, more so on the forest floor due to radiation interception by the canopy. Moreover, forests reduce ground heat flux by redistributing intercepted energy towards sensible and latent heat fluxes (see Box 2a, b, Supplementary Fig. 4). Forests also influence the thermal diffusivity of the soil by creating insulating soil layers and mediating soil moisture[29]. By enhancing evapotranspiration (ET), forests reduce soil wetness, which in turn reduces thermal conductivity[27,29] (see Box 2a, b, Supplementary Fig. 4). Furthermore, mosses, constituting a substantial portion of southern arctic vegetation, form thick insulating mats that shield the soil from warmer surface temperatures[29,30], highlighting the importance of understanding interactions between forest and moss layers (see Box 2a, b, Supplementary Fig. 4). The impact of these vegetation-related effects on the depth of the active layer and various thawing regimes remains unclear. While gradual thaw can increase soil decomposition, releasing nutrients and enhancing vegetation productivity, abrupt thaw (also known as thermokarst) can occur in regions with high ice volume, causing soil collapse and affecting local vegetation growth[27] (see Box 2a, Supplementary Fig. 4).

Permafrost is going to respond to climate change, with rising summer temperatures and increased precipitation (see section "changing climatic conditions"). Understanding the response of permafrost to Earth's previous warm periods is crucial to plan for the effects of future warming. The mid-Pliocene warm period (mPWP, ~3.264 to 3.025 Ma BP) serves as a valuable analogue for projected climate change scenarios[31]. Research indicates that near-surface permafrost during the mPWP was significantly reduced, estimated to be ~93% smaller than pre-industrial levels, coinciding with elevated surface air temperatures and increased winter snow accumulation[31]. This finding indicates that permafrost will thaw significantly as the climate changes in the coming decades, with major impacts on climate, hydrology, and ecosystems[12,31,32]. Therefore, the role of forests in regulating permafrost dynamics at high latitudes is crucial and cannot be overlooked in afforestation assessments.

Observation from Earth's climatic history

Examining the historical northward expansion of boreal forests and treelines provides valuable insights into positive feedback loops between forests and the climate, as well as crucial corrective mechanisms. Regarding boreal forest expansion, the Sahtu Nation in the Northwest Territories believed that the treeline extended to the Arctic Ocean 9000 years ago, much further north than the present treeline[33]. While there is no consensus on the exact extent of the treeline during the Holocene, it is observed that trees colonized quickly behind retreating glaciers in Canada, and the treeline stabilized thousands of years ago in some areas. For example, the Quebec treeline has remained relatively stable for the past 6000 years, with varying species and temperature gradients throughout the Holocene[34]. This treeline stability supports the argument that the boreal treeline may not continually move north, reinforcing itself, but significantly influences the preferred position of the arctic front[34–37].

Some studies suggest that the mid-Holocene (6 ka BP) high-latitude warming cannot be attributed to orbital forcing alone and requires positive feedback from the northward expansion of boreal forests to explain the Holocene thermal maximum (HTM)[38]. Paleobotanical evidence supports the notion that boreal forests indeed migrated northward in response to orbital forcing[38–40] (see Supplementary Fig. 5). Global climate models estimate that this expansion may have contributed an additional 4 °C in spring and 1 °C in other seasons[38], but studies disagree on the exact contribution of vegetation to this warming[41–45]. Moreover, some studies dispute the role of vegetation feedbacks during the HTM and argue that climate models may have overestimated the positive feedbacks from the expansion of the boreal forest into the tundra[46]. Paleoceanographic observations suggest that parts of the North Atlantic were ~4 °C warmer than the present day during the mid-Holocene. Climate models that incorporate mid-Holocene North Atlantic Sea Surface Temperature (SST) and sea ice conditions estimate that a significant portion of the high-latitude warming can be attributed to SSTs, orbital forcing, and sea ice[47]. The role of vegetation feedback is further explored by studies that investigate possible equilibrium states in the Earth's climate under specific boundary conditions[48,49]. These studies observe that despite initial forest extension, warming from feedback between ocean, land, atmosphere, and sea ice is insufficient to continually push the boreal forest north into a different equilibrium state[48,49] (see Supplementary Fig. 5). This suggests that despite feedbacks between climate and land cover at high latitudes, vegetation extent may be stable in response to reasonable perturbations[48].

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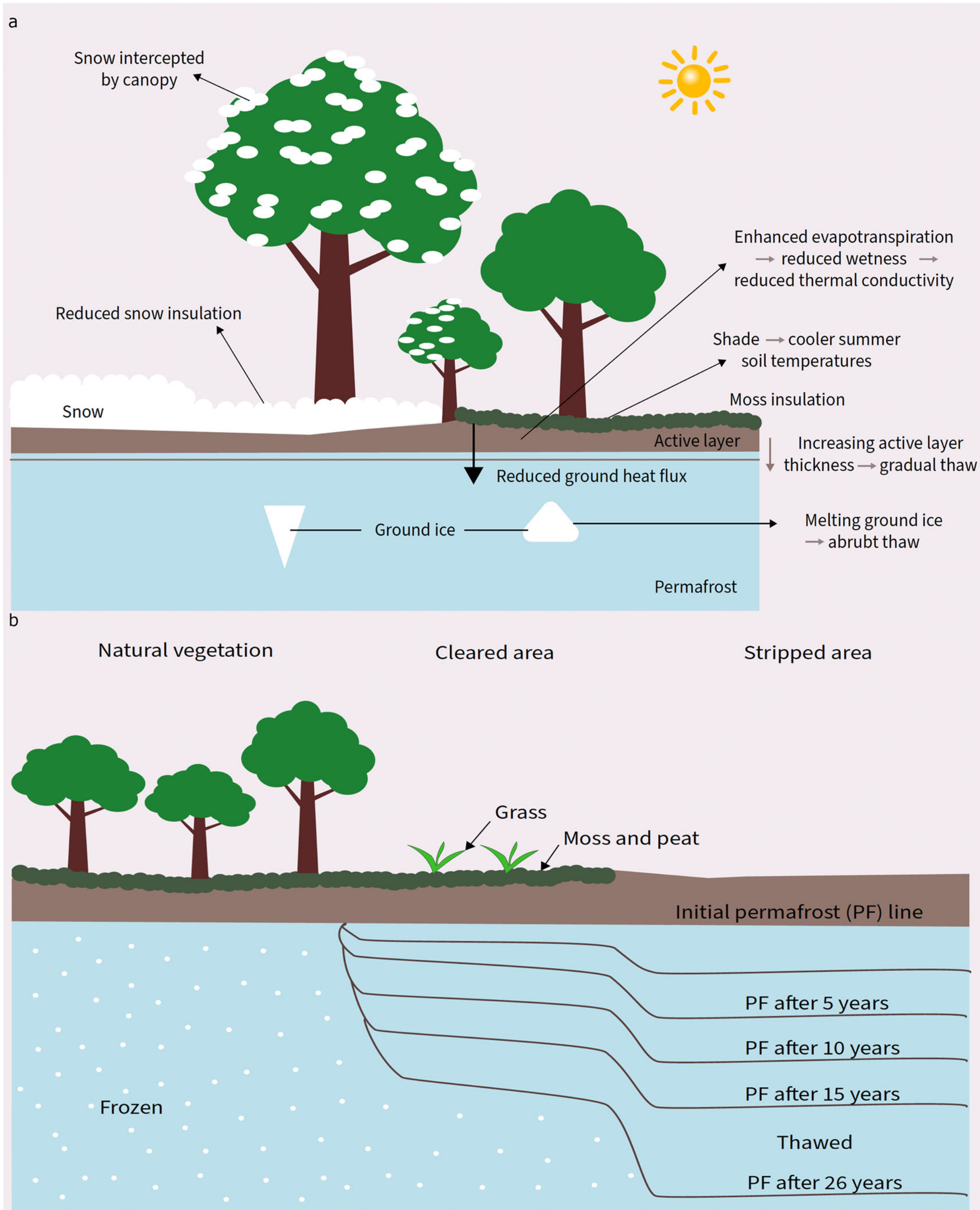
BOX 2

Forests-permafrost dynamics and the CRREL experiment



a An illustration showing forests-permafrost dynamics. Forests reduce soil temperatures during summer because of shading and reduce snow insulation during winter due to reduced forest floor accumulation. Enhanced evapotranspiration (ET) in forests reduces soil wetness and, therefore, thermal conductivity, preserving permafrost. The interaction between forests and moss layers also plays an important role in maintaining permafrost stability. **b** The CRREL experimental station in Farmers Loop that monitored different ground covers for 26 years[19]. The site was separated into three segments. A segment where the natural vegetation was untouched (left). A cleared area where trees and major growth was removed, but small shrubs, grass, and moss layers were allowed to grow (middle). A stripped area where all vegetation, including moss layers, were continuously stripped (right). Permafrost levels were measured regularly over 26 years. Results showed that forests preserve permafrost and any clearing of vegetation significantly exacerbates permafrost melt. The mature trees are only used to demonstrate dynamics. The details of these dynamics will change with tree age. Illustration made following[19].

Regardless of the ongoing debate about the role of positive vegetation feedbacks during the HTM and the extent of the boreal treeline during the Holocene, it is essential to recognize that a warmer and higher CO_2 climate state may create unprecedented conditions that have not been seen in Earth's recent geological past, leading to unpredictable responses from vegetation cover. A thorough examination of vegetation feedback during the mPWP may provide additional insights into this phenomenon[50]. On the other hand, it is also crucial to acknowledge that positive feedbacks alone cannot account for the stability of vegetation at high latitudes during the HTM and the pre-industrial Holocene, indicating that corrective mechanisms in the Earth system play a dominant role.

Non-radiative processes and energy redistribution

While the change in radiative processes like albedo after afforestation has been recently highlighted in afforestation studies[51–55] (though with large uncertainties, see Box 3c), less attention is given to how forests influence non-radiative processes and energy redistribution[56–58]. Non-radiative processes influence the temperature-based BGP effect and its CO_2 equivalent (CO_2e) contribution[56,57], which locally dominates in many afforestation scenarios. While carbon sequestration mitigates warming, the reduced albedo (a BGP effect) of forested regions can increase net available radiation, potentially offsetting the cooling effect through BGC processes[51–55]. Land covers vary in their ability to utilize the net available radiation for work including ET, turbulent heat convection, and photosynthesis[56–58] (see Box 3a). This efficiency in energy dissipation, crucial for controlling the surface energy balance, is characterized by an energy redistribution factor[57].

A portion of the net incoming shortwave radiation is photosynthetically active radiation (PAR), some of which is absorbed by trees, with a fraction used for photosynthesis (see section "forest structure and temporal analysis") and the majority converted into sensible or latent heat[59] (see Box 3a, Supplementary Fig. 6). The redistribution factor dictates how this heat is distributed, with forests typically exhibiting higher values compared to other land types, indicating more efficient ET and turbulent exchange of sensible heat[57,60]. Newly formed forests enhance the land's ability to release moisture, cooling the surroundings by altering the surface energy balance from sensible to latent heat[56] (see Box 3a), an effect observed even with small-scale tree cover gain[61]. The extent of this conversion depends on regional humidity, land aridity, and soil moisture levels[62]. Higher moisture content translates to increased sensible to latent heat conversion, also altering cloud cover and precipitation[62–67] (see Supplementary Fig. 6, section "alterations in hydrological processes"). Although non-radiative fluxes in forests contribute to local cooling, the resulting lowered land surface temperature (LST) and increased ET generate longwave RFs that can be commensurate with albedo-driven shortwave RFs[63] (see Supplementary Fig. 6). Moreover, the dominance of longwave RFs varies spatially, potentially being more pronounced in boreal and arctic regions[68].

Even after considering the merged radiative and non-radiative based CO_2e contribution, multiple uncertainties remain, including non-local effects that dominate local ones in climate models, often acting in the opposite direction[69]. Moreover, many BGP effects and their magnitudes depend on afforestation size, including variation in precipitation levels, atmospheric circulation, and cloud cover[57,66,69]. These hydrological processes, in turn, affect albedo by altering aridity gradients[62,64,65] and radiation balances at the surface[63,70] (see section "alterations in hydrological processes"). There is also a significant temporal disparity between the processes involved, as forests sequester carbon gradually over many decades, while BGP and hydrological effects manifest in just a few years. These temporal tradeoffs are often overlooked in studies, which tend to neglect the yearly variation of gradual processes like afforestation[51,55] (see section "forest structure and temporal analysis"). Furthermore, afforestation exhibits strong seasonality effects[56–58], with BGP effects being negligible during the northern summer, but potentially countering BGC benefits during the northern winter[56,57,63]. This seasonality effect poses a dual risk: minimizing cooling benefits during summer when human vulnerability to heat stress is highest while failing to account for potential adverse impacts of winter warming[56,57]. Therefore, afforestation interventions must be designed considering non-radiative effects on regional climate, as well as their potential non-local, temporal, and seasonal tradeoffs, as neglecting them can lead to policies detrimental to local climate adaptation and mitigation[57].

Relationship between snow and tree cover

Accurately assessing the climate benefits of afforestation requires considering the fine-scale spatial and temporal variations in snow cover, as snow significantly impacts albedo, non-radiative processes, permafrost dynamics, and hydrology. Modeling snow behavior in response to vegetation growth is challenging, and even climate models struggle with snow-related albedo uncertainty at high latitudes[71–76] (see Supplementary subsection "reconciliation with climate models"). Studies indicate that the spatial distribution of land cover and vegetation density predominantly influence the snow-albedo feedback in these regions[28]. Investigating snow accumulation on land cover and the mediation of processes such as interception and snowmelt is crucial to understanding the effects of afforestation on snow[77–83] (see Supplementary Fig. 7). Observations reveal that open lands generally accumulate more snow than evergreen forests in winter and undergo earlier and faster melting in spring[84] (see Box 3b), but this pattern reverses with reduced canopy density and deciduous forests[85] (see section "forest structure and temporal analysis"). The greatest snow accumulation occurs in openings to the lee of trees, partly due to forests anchoring snow and protecting it from wind erosion and solar radiation[86] (see Box 3b). As a result, snow that would otherwise be blown away is deposited in forested openings, creating zones of retention[87] (see Box 3b). This uneven accumulation and prolonged spring melting due to forests have significant implications for albedo, permafrost thawing (see section "permafrost"), carbon flux, and hydrological cycles.

An important factor modulating forest albedo and energy balance is the interception of snow by forest canopies, followed by melting, unloading or sublimation on the canopy (see Box 3b, Supplementary Fig. 7). Canopy height, age, and density control snow accumulation on and beneath the canopy, regulating the energy balance of the forest and thus melting, grain growth, and refreezing at the forest floor[88,89]. The denser the canopy, the less snow accumulates on the forest floor, and the higher the ground snow shielding, which reduces albedo[78,88,90] (see section "forest structure and temporal analysis", Supplementary Fig. 7). However, if intercepted snow sticks to the canopy for extended periods, it could increase forest albedo[91]. Snow adheres effectively to canopies in the absence of solar energy, typical of northern boreal edges where winter sunlight is minimal and the solar angle is low[86,92] (see Box 3b). The canopy also resists snow unloading by wind unless winds are strong and immediately follow the snowstorm[86,92] (see Box 3b). Therefore, the snow collected on canopies, termed 'Qali' by the Kobuk valley Inuit, may exert the most important control on forest albedo. However, a concerning finding is that although the canopy intercepts a significant percentage of snow, it does not prevent the albedo of the forest from decreasing[93]. Nevertheless, there is little consensus on this matter, and the impact of intercepted snow on albedo at high latitudes requires further investigation[91,93].

Several local factors, including topography, elevation, slope, and aspect, hinder a global analysis of the impact of forests on snow. Snow interception and accumulation vary significantly with these factors, making region-specific analysis essential. Furthermore, climate change is rapidly altering high-latitude environments, with projected increases in winter temperatures and precipitation over the coming decades.

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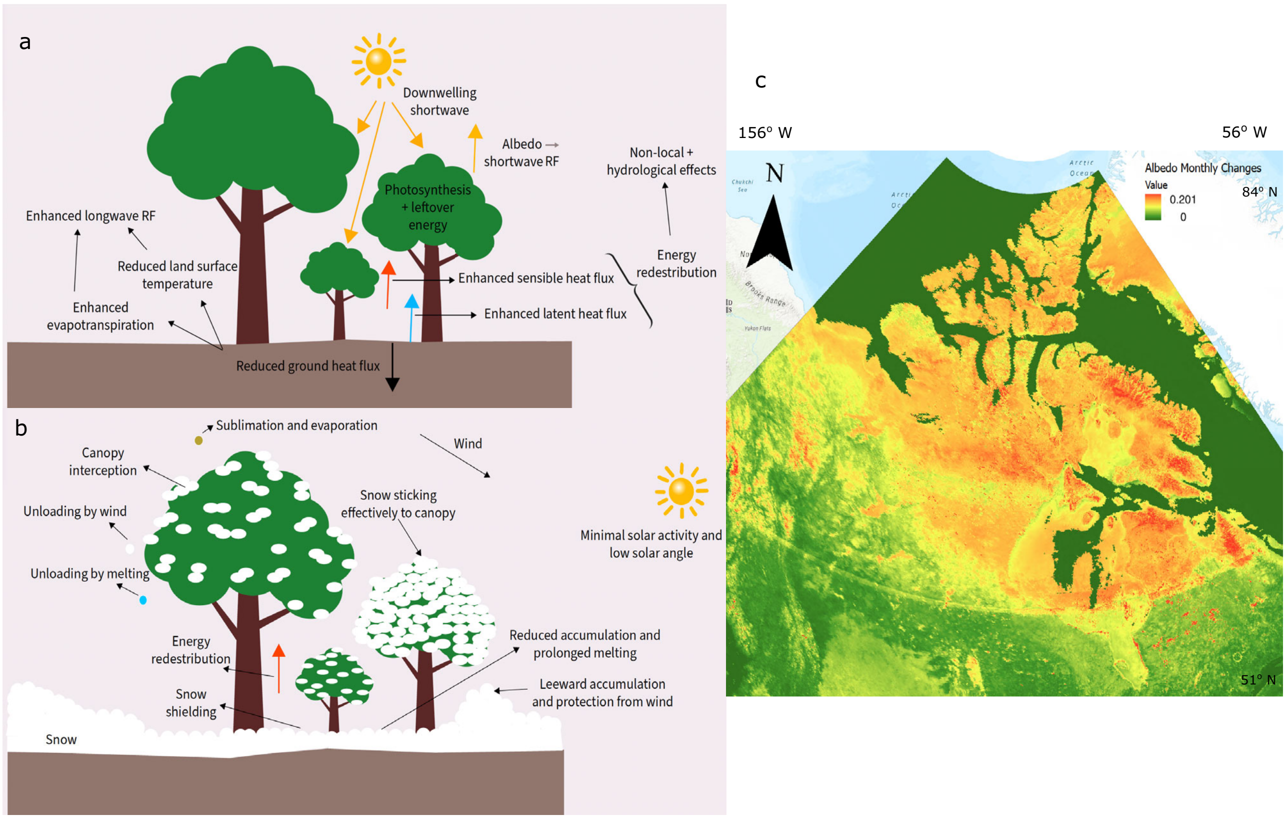
BOX 3

Interaction between forests and radiative, non-radiative, and snow-related processes



a An illustration showing how forests alter radiative and non-radiative processes. The decreased albedo in forests induces short-wave radiative forcing (RF). However, forests also redistribute the absorbed solar energy into processes such as photosynthesis, latent heat flux, and sensible heat flux. The increased ET from enhanced latent flux decreases surface temperatures, which contributes to local cooling but also induces longwave RF. The effective energy redistribution in forests affects non-local and hydrological processes, modifying atmospheric energy balance. Forests also reduce ground heat flux because of energy redistribution to other fluxes. **b** An illustration depicting snow-related processes in forests. Forests with dense canopies contribute to ground snow-shielding, reducing snow-related albedo. On the contrary, both prolonged spring melting and leeward snow accumulation can increase snow-related albedo. Effective canopy interception and resistance of canopies to unloading by melting, wind, sublimation, and evaporation, can increase forest albedo. Minimal solar activity and low illumination angles in the northern boreal and southern arctic increases the adhesion of snow to canopies. The mature trees are only used to demonstrate dynamics. The details of these dynamics will change with tree age. **c** Average standard deviation of monthly moderate resolution imaging spectro-radiometer (MODIS) albedo data. The daily post-processed 500 m global surface blue-sky albedo climatology data is obtained at 0.05° resolution[159]. The daily data is aggregated to monthly standard deviations, and the 12-month average of the monthly standard deviations is computed. Many parts of the north have a high standard deviation of 0.1–0.2, because of the distinct snow season and lack of temporal resolution to capture the dynamic interaction between snow and vegetation.

These changes will impact snow interception, accumulation, and melting on afforested land[94] (see Supplementary Fig. 7), which must be considered in afforestation assessments.

Changing climatic conditions and disturbances

The Earth's climate is currently undergoing significant changes and will continue to change in the coming decades. Global mean surface temperatures, both over land and oceans, are surpassing previous record highs. A warmer atmosphere can hold more moisture and is expected to alter atmospheric circulation patterns (see Box 4a). Climate change is also impacting snow seasons, altering the composition of tundra biomes, and influencing wildfire and insect disturbances[94–96] (see Supplementary Fig. 8). It is crucial to understand how forests respond to this changing climate, as it has significant implications for the productivity of existing forests and new afforestation initiatives[97–99]. In higher latitudes, a warming world is expected to reduce temperature restrictions on vegetation productivity and the duration and extent of snow cover, both of which would decrease the albedo offset[51,55], and alter non-radiative processes (see Supplementary Fig. 8). Moreover, non-radiative mechanisms may dominate in a warmer climate due to their effects on leaf area, canopy conductance, and water vapor[56,57,68].

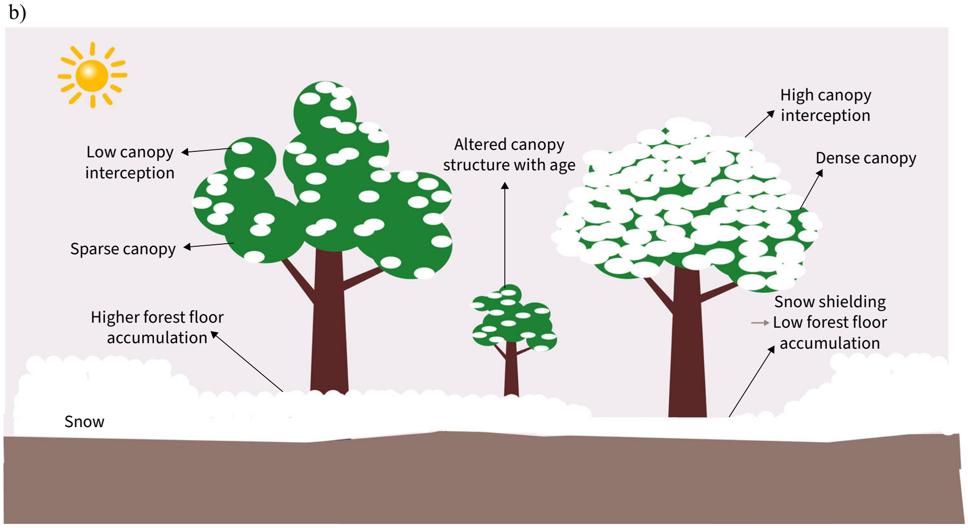
BOX 4

Projected changes in climate variables and the influence of forest density

a)

Climate related variable/event	Approximate projected change in 2100
Wildfire area burned	+ 3.5–5.5 times relative to 1991–2000
Insect disturbances	+ but unclear
Temperature	+ 4-5 °C relative to 1961–1990
Precipitation	+ 14–21% relative to 1961–1990
Permafrost thaw	+ 16–35% relative to 2000
Humidity	+ but unclear
Windthrow	+ but unclear
Drought	+ but unclear
Cloud cover	+ but unclear
Solar radiation	Unclear
Net primary productivity (NPP)	+ 50–75% for doubled [CO_2]
Respiration	+ but Unclear
Carbon storage	Unclear

b)



a Projected changes in climate-related variables in the northern boreal[95,98]. Wildfire occurrence, temperature, precipitation, permafrost thaw, and net primary productivity are projected to increase by significant percentages this century. Insect range expansions, humidity, cloud cover, and ecosystem respiration are estimated to increase, but the exact percentages of increase is unclear. The changes in overall solar radiation and carbon storage is unclear because of the uncertainty in cloud cover for the former and the uncertainty in the interplay between disturbances, temperature, and precipitation for the latter. **b** An illustration showing the difference between how sparse and dense canopies interact with snow. Denser canopies have lower snow accumulation on the forest floor and higher interception at the top of the canopy (right). Sparse canopies have higher snow accumulation on the forest floor and lower canopy interception (left). The difference in forest structure as trees age also dictates canopy-snow interception and energy redistribution (middle). The mature trees are

Wildfires are an integral part of forest ecosystems and play a crucial role in the forest carbon cycle. They regulate forests by facilitating forest succession and regeneration, and maintaining plant and animal biodiversity[95,100]. While humans and lightning strikes initiate roughly equal numbers of fires, most of the area burned in the north is due to lightning caused ignitions, and climate change is projected to increase the number of lightning ignitions[95,100,101]. Moreover, climate change is predicted to increase various fire-related variables, including frequency of fires, fire season length, severe fire weather, area burned, fire intensity, and emissions[95,100–104]. Studies suggest that fire occurrence could increase by 75% by 2100[95] (see Box 4a). While increases in area burned from wildfires are expected to be gradual, threats from population outbreaks and range expansion of endemic forest insect pests are more immediate[105]. Windthrow, the uprooting or breaking of trees due to strong winds and heavy rainfall, is a major cause of tree mortality. Windthrows can significantly alter forest structure, composition, dynamics, and impact both radiation and carbon balance[106,107], potentially shifting a forest from being a carbon sink to a carbon source[107,108]. With climate change expected to increase the frequency and intensity of storms[109] and decrease the soil frost duration[110], the incidence of windthrows is likely to rise[99,110]. Droughts pose a significant threat to the functioning of the northern ecosystems, as increased precipitation will not offset higher temperatures, leading to increased evapotranspiration[95]. They impair

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forest regeneration, and are expected to increase in frequency and duration[95,111].

Non-insect herbivores, including large mammals like caribou, muskox, and moose, play a pivotal role in shaping vegetation patterns, nutrient cycling, and ecosystem structure[112]. For example, their grazing sometimes reduces nutrients like nitrogen, leading to tree mortality under stressful conditions[112]. These effects extend to larger-scale processes, altering carbon exchange and primary production[112]. Climate change further complicates this dynamic by altering herbivore distributions and changing grazing pressures on forest communities. Additionally, ecological competition among native and non-native vegetation, intensified by the changing climate, affects forest regeneration, community composition, and successional trajectories[113]. Invasive species, ranging from certain plants (white sweetclover, narrowleaf hawksbeard, smooth brome) to exotic earthworms, are increasingly common, especially in disturbed areas[113]. Processes like self-thinning, also play a crucial role in forest stand development. Self-thinning is the density-dependent mortality that occurs as trees compete for limited resources, such as light, water, and nutrients[114,115]. As trees grow, competition intensifies, leading to mortality and a reduction in stand density, impacting forest structure, function, and dynamics[114,115]. Several factors can influence self-thinning, including species composition, functional diversity (range of traits), and functional identity (dominant traits)[115]. Climate change is impacting self-thinning by altering tree growth rates, resource availability, and disturbance regimes[114].

Disturbances in northern forests are interconnected and often reinforce each other. As wildfires become more frequent, they accelerate permafrost thaw, and in turn, thawing permafrost contributes to conditions that promote further fire[95]. Drier soils and the increased likelihood of peat burning create a feedback loop that exacerbates drought and enhances vulnerability to root pathogens, insects, and diseases[111]. This can severely diminish forest health, stifle regeneration, and reduce carbon uptake[111]. Bark beetle outbreaks initially raise wildfire risk by drying canopy fuels, though the risk diminishes once needles fall[95,111]. Similarly, mild fires can increase susceptibility to insects and pathogens, while intense, stand-replacing fires can break the cycle by removing hosts[95,111]. Windthrow often paves the way for bark beetle infestations, and drought further intensifies all these disturbances by weakening vegetation resilience[111]. The effects of climate change on disturbances and their interactions have critical implications for afforestation schemes and need to be carefully considered in assessments, particularly because of the potential reversibility of carbon stores in all pools due to these disturbances[95,111] (see Supplementary Fig. 8, Box 4a).

In addition to specific disturbances driving changes in vegetation distribution, a general trend of enhanced vegetation greening is observed at the northern boreal edge and the southern arctic, indicating shifts in recruitment, mortality, and vegetation productivity[116,117]. These early signs of boreal shift have significant implications for the taiga and tundra ecosystems[118,119], particularly permafrost thaw, due to altered ground thermal characteristics[27] (see Supplementary Fig. 8). Therefore, boreal afforestation assessments need to investigate changes in vegetation distribution and the observed greening at the northern boreal edge and the southern arctic, examine the implications of planting more trees in this context, and account for their impact on critical ecosystems like the tundra when in spatial proximity.

Forest structure and temporal analysis

Trees absorb photosynthetically active radiation (PAR), which accounts for approximately 50% of incoming shortwave radiation[59,120]. Only a small portion (around 3%) of this absorbed radiation is utilized for photosynthesis, while the remainder is converted into latent or sensible heat[59,120]. As trees mature, the net ecosystem productivity (NEP) increases, leading to denser and taller canopies. These canopies, with their intricate leaf structure, absorb more solar radiation[121], resulting in a negative correlation between albedo and canopy density[59,122] (see Supplementary Fig. 9). Studies that map the link between forest structure and albedo globally at high spatial resolution show that forest structure significantly modulates albedo, and is inadequately characterized in existing forest albedo estimation[120,123]. Moreover, forest structure also plays a crucial role in regulating sensible heat fluxes, which are higher in forests with sparse canopy structures (canopy convector effect) due to low aerodynamic resistance[62,124] (see Supplementary Fig. 9). This canopy cooling through the convector effect suppresses the longwave thermal radiation flux, which the inter-canopy latent heat flux could potentially balance due to the exposed soil surface, but also leads to higher respiration rates and lower NEP[62] (see Supplementary Fig. 9). Therefore, uncertainties exist regarding ideal forest structure for climate benefits, and further investigation is warranted.

The remote sensing-based analyses employed by most afforestation assessments substitute space for time and assume instantaneous land cover conversion, overlooking several important details, including: a) the relationship between tree age and canopy structure with albedo[59,123,125] (see Box 4b, Supplementary Fig. 9), b) The changes in snow interception and unloading with canopy structure and age[90,122,126,127] (see Box 4b, section "relationship between snow and tree cover"), c) the alterations in surface energy redistribution with forest structure and age[125,128] (see Supplementary Fig. 9), and d) the change in canopy density with planting density (see section "effects of planned afforestation projects"). Studies have shown that structural transitions with forest age lead to erroneous albedo estimation (a, b above) due to differences in canopy structure between mature and young forests[122,125]. Moreover, surface energy redistribution is strongly dependent on forest age[129]. Temporal analysis is crucial, and solely modeling instantaneous conversion for end-of-century responses is inadequate because climate change mitigation policy involves tradeoffs. While maintaining low temperatures by mid-century through cooling measures preserves the short-term climate phase space, CO_2 sequestration is essential in the long term. These arguments highlight the importance of integrating forest structure in afforestation assessments, including variation with forest age, plant functional types (PFTs) (species), and planting density, to better capture structural and temporal dynamics[122].

Short-lived climate forcers

Land cover changes not only alter BGC processes involving CO_2 and water vapor but also impact the concentrations of short-lived climate forcers (SLCFs) including aerosol, ozone, and methane, via the emission of biogenic volatile organic compounds (BVOCs)[130–132]. These emitted BVOCs alter the atmospheric concentration of ozone and methane by reducing the atmosphere's oxidative ability via interaction with other constituents[132,133] (see Supplementary Fig. 10). Furthermore, oxidative byproducts from BVOCs contribute to the formation and expansion of secondary organic aerosol (SOA) particles, which can directly interact with incoming shortwave radiation (direct radiative forcing, DRF) and facilitate the formation of cloud droplets (indirect radiative forcing, IRF)[134,135] (see Supplementary Fig. 10).

Research has demonstrated that forests increase the concentration of SLCFs, with increased ozone and methane contributing to warming and increased aerosols contributing to cooling[130,132,134–136]. However, the net RF due to SLCFs from forests is dominated by the DRF and IRF from aerosol cooling, outweighing the warming effects of ozone and methane[130,137]. Observations reveal that the formation of aerosols and clouds from BVOCs significantly impacts high-latitude regions, with models underestimating these effects[138,139]. Therefore, it is crucial to include the RF of SLCFs in afforestation assessments, primarily because the IRF effects from aerosols alone are sufficient to shift forests from being climate-negative to climate-positive[130] (see Box 5a).

Soil carbon storage and emissions

It is vital to recognize that the natural climate solutions highlighted by the IPCC include soil carbon sequestration[1], underscored by various land model comparisons[140], SOC measurements in afforested and adjacent areas, and global meta-analyses[141–143]. Therefore, an oversight in many afforestation assessments aiming to identify climate-positive afforestation is the neglect of soil organic carbon (SOC) accumulation over the lifetime of different forest classes and potential GHG emission reductions due to land-use changes. Forest classes have significantly higher SOC storage advantages than open grasslands, croplands, shrublands, and natural vegetation[144–146]. Moreover, cropland management practices and regular disturbances like tillage worsen soil integrity and enhance organic matter oxidation[147], affecting conclusions regarding afforestation on cropland.

There are many uncertainties surrounding SOC quantification. While promoting carbon sequestration in soils is essential, it may be even more critical to manage soils in a way that prevents permafrost and wetland soils from transitioning from carbon sinks to sources as the climate changes, given that the majority of carbon in the north is stored in these reservoirs[148]. Research indicates that SOC stocks may initially decrease after afforestation[149], but typically recover over decades[150]. The recovery rate depends on factors such as soil depth[150,151], climate[151,152], previous land use[151], and the species planted[153]. Moreover, it is vital to understand how SOC stocks respond to disturbances like wildfires and how long it takes for them to recover, especially as wildfire risk continues to increase in the north[154]. The relationship between the size of the SOC pool and properties like soil moisture[155], soil Nitrogen concentrations, C:N ratios[156], and pre-afforestation soil carbon[157] is complex and needs more research.

Irrespective of these uncertainties, it is important to include SOC in afforestation assessments. For example, studies considering temperature-based BGP effects observe that including SOC in carbon storage estimates can reduce the net climate-negative regions from ~30% to 7% of the total area in high latitudes[56,57]. This significant reduction highlights the importance of including SOC in assessment frameworks, rather than omitting them to reach an overly simplistic conclusion.

Alterations in hydrological processes

Various uncertainties persist regarding the atmospheric adjustments and oceanic feedbacks following afforestation, which may be better captured by effective radiative forcing (ERF) and climate models. Research indicates that instantaneous radiative forcing (RF) overestimates net radiation changes in high-latitude regions, potentially due to forests' ability to form low-level clouds[59,69]. These clouds contribute to top-of-atmosphere (TOA) cooling effects and are also moved non-locally by convection-driven forest breeze[59]. Existing afforestation assessments neglect non-local effects, second-order effects, and large-scale climate feedbacks, such as changes in atmospheric circulation patterns (mesoscale circulation, deep convection) and cloud cover formation[56,66,69]. Contrary to previous beliefs, these effects are now recognized to be significant even at smaller areal extents of afforestation[69].

Forests are known to enhance ET, which facilitates the formation of shallow cumulus clouds[66] (see Supplementary Fig. 11). Research has shown that summertime clouds occur more frequently over forests than over surrounding non-forest regions[66,67]. Furthermore, observations reveal that clouds tend to form earlier and more rapidly over forested areas, lingering into the evening, possibly due to enhanced thermal flux and atmospheric boundary layer (ABL) moistening[66,67]. Redistribution of energy and higher sensible and latent heat fluxes are believed to be key factors driving cloud formation[66]. In addition to driving heat fluxes, forests emit BVOCs that contribute to the generation and growth of SOA particles, thereby facilitating cloud formation[134,135] (see Supplementary Fig. 11). Moreover, clouds play a crucial role in modulating energy balance by altering the quantity of energy reflected, absorbed, and emitted in the atmosphere and at the surface[67,70]. Thus, clouds influence vertical movements, large-scale circulation, and the hydrological cycle by partitioning energy in the atmosphere[63,70]. In addition, clouds mediate outgoing and downwelling shortwave (albedo) and longwave (greenhouse forcing) radiation, controlling the vertical spread of radiative heating. Although the exact impacts clouds have on surface energy balance depend on their altitude, size, and composition, they are known to produce an overall global cooling effect[70].

The impact of afforestation on surface water availability (precipitation minus ET) depends on various factors, including forest and root structure, as well as the precipitation of recycled moisture from afforestation-driven ET, both locally and from upwind locations[64,65]. While forests generally increase precipitation, they can also reduce rainfall in some regions by decreasing the land surface temperature (LST) and thereby suppressing the thermal contrast with the oceans[64,65] (see Supplementary Fig. 11). Therefore, the impact of forests on the hydrological cycle varies regionally. While altered hydrology, such as increased precipitation, protects downwind trees from mortality caused by droughts, augmenting climate benefits[51,64,65], the effects on surface energy balance are not yet fully understood. For example, both shortwave RF and suppressed longwave RF increase with aridity[62,63]. While higher net radiation is compensated by increased non-radiative fluxes in these regions, the partitioning of these fluxes also varies with aridity[62]. Sensible heat fluxes are typically higher in drier regions due to the canopy convector effect, whereas latent heat fluxes are higher in humid regions where water is available for ET[62,63]. Hydrological processes, such as cloud formation, atmospheric circulation, and precipitation, have significant feedbacks on RFs, surface energy balance, and net ecosystem productivity[56,83,94]. Therefore, afforestation assessments should make an effort to model some of these feedbacks using Earth system models and reconcile the results with satellite observations to gain a more accurate understanding of the complex interactions involved.

Methodological limitations

To conduct reliable afforestation assessments, in addition to considering the critical processes discussed in the previous section, it is essential to address methodological limitations. These limitations include uncertainties in remote sensing data and the failure to account for the deliberate and planned nature of afforestation projects, which can impact the accuracy and reliability of the conclusions drawn from afforestation assessments. While remote sensing data is a valuable asset for climate science, enabling the regular tracking of crucial climate variables at global scales, it is important to acknowledge its limitations. For instance, uncertainties in satellite-derived albedo can be as high as 9.7 W/m^2[158], affecting assessments of afforestation that consider albedo[51,52] (see Supplementary section "uncertainties in albedo-related afforestation assessments"). Moreover, the temporal resolution of remote sensing products significantly impacts final conclusions[159,160] (see Fig. 3c). Remote sensing products are also error-prone in overcast conditions with cloud cover[56], susceptible to bias when the solar zenith angle (SZA) exceeds 70° (particularly relevant at high latitudes during northern winter)[72], and lack the spatial resolution to account for finer variations in topography[51,161–163]. Finally, remote sensing land cover products such as the one from moderate resolution imaging spectroradiometer (MODIS) often misclassify land covers, which can significantly bias the final conclusions[51,52].

Most afforestation assessments use naturally formed forests as a proxy to examine the albedo impacts of afforestation. However, this approach has limitations, as afforestation projects allow for controlled

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BOX 5

Various uncertainties related to afforestation and processes arranged by spatial and temporal scale

a)

Process/parameter/method	Approximate associated uncertainty/variability in quantification
Variability in monthly temporal resolution of MODIS albedo	> 0.2[159]
Uncertainty of MODIS albedo from overcast conditions	0.01[178]
Uncertainty of albedo from SZA	0.05[72]
Variability of energy balance with topography	30%[161]
Uncertainty of energy balance from misidentified or coarse land cover	Unclear
Uncertainty of albedo from RF kernels	15%[51]
Uncertainty of ERF	20%[63]
Variability of radiation balance with cloud cover	1.6 W/m^2 [63]
Variability of albedo with forest structure	0.4 W/m^2 [122]
Albedo bias in climate models	> 0.1[72,73]
Uncertainty of CERES EBAF albedo	9.7 W/m^2 [158]
Uncertainty of downwelling shortwave radiation	10%[63]
Variability of radiation balance with precipitation	Unclear
Variability of energy balance with SLCFs	0.12 W/m^2 [134,135]
Variability of net positive afforestation area with SOC inclusion	23%[56,57]
Variability of net positive afforestation area with emission from previous land use	Unclear
Uncertainty of albedo from snow-related factors	0.1[72,73]
Difference in climate sensitivities of CO_2 and albedo	0.5 W/m^2 [63]
Variability of ET from land use change	20%[63]
Variability of longwave RF from land use change	1.1 W/m^2 [63]
Variability of latent heat flux from land use change	2.5 W/m^2 [63]
Variability of sensible heat flux from land use change	8.5 W/m^2 [63]
Uncertainty of temperature rise from vegetation feedbacks during HTM	4 °C[38,47]
Variability of temperature with permafrost thaw	12%[95]
Variability of permafrost thaw with increased surface energy	35%[95]

b)

Spatial-scale	Temporal-scale: Seconds-Minutes-Hours	Days-Weeks	Months-Seasons	Years-Decades	Centuries-Millennia
Leaf	Decreased short-wave reflectance decreases albedo Evapotranspiration affects various forest processes	Interception of snow, followed by melting, unloading, or sublimation	–	–	–
Tree	–	Control of tree height and age on snow accumulation	Variation in albedo by species type - deciduous have higher albedo than evergreen	Radiative forcing effects of short-lived climate forcers - aerosol cooling dominates ozone and methane warming	–
Stand	–	Energy redistribution to latent and sensible heat	Stand-level seasonal modification of ground thermal regime in favor of permafrost preservation	Prevention of permafrost thaw	–
			Variation in albedo and energy redistribution by forest structure - interaction with snow and high uncertainty	Variation in albedo and non-radiative processes as stands age	
		Lowered local land surface temperature generates longwave radiative forcing	Non-radiative processes affect energy balance and hydrology Snow accumulation and melting - affecting albedo, energy redistribution, permafrost dynamics, and hydrology	Soil carbon recovery as a function of soil depth, species, climate, C:N ratios, and previous land use	
Landscape	–	–	Variation in snow interception and accumulation by topography, elevation, slope, and aspect	Carbon sinks and sources - post disturbance recovery	–
			Changes in precipitation and water availability Radiative forcing changes through aridity gradients	Climate change alters disturbance regime and climatic variables	
Biome	–	–	–	Enhanced vegetation greening and shifts in recruitment	Future permafrost thaw risks derived from previous warm periods like mPWP Boreal forests may not cause positive feedbacks resulting in indefinite expansion into the arctic
Non-local	–	–	Energy redistribution affects non-local hydrology like atmospheric circulation and cloud cover formation	Cumulative radiative and climatic effects	–

a Uncertainties and variabilities in quantification associated with various processes, parameters, and methods. Percentage changes are mentioned without units, unitless parameters (such as albedo) are mentioned without units, and the rest are mentioned with their respective units (such as W/m2). MODIS - moderate resolution imaging spectroradiometer, SZA - solar zenith angle, RF - radiative forcing, ERF - effective radiative forcing, CERES - clouds and the earth's radiant energy system, EBAF - energy balanced and filled, SLCFs - short-lived climate forcers, SOC - soil organic carbon, ET - evapotranspiration, HTM - holocene thermal maximum. Significant variability exists in remote sensing products, energy balance because of topography and cloud cover, and ERF. SLCF's, non-radiative processes, and forest structure also alter overall RF to a large extent. Moreover, the inclusion of SOC increases the net climate benefits of afforestation considerably. **b** A summary of important processes and findings arranged by spatial and temporal scale, relevant for afforestation assessments. Some of these processes transcend one particular scale, operating at multiple scales. The segregation shown is a simplification for easier understanding and modeling. Refer to Box 7 for open questions and future directions related to these and Box 6 for integration of some of these into an afforestation assessment framework.

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variables such as tree species selection, topography, total afforestation area, and planting density. These factors can be optimized to minimize potential negative impacts. For instance, deciduous trees with lower albedo offset (higher albedo) than evergreen trees, could be planted in regions where albedo has a significant influence. Topography can be selected to optimize snow cover behavior and illumination angles, mitigating negative BGP effects. The extent of afforestation can be determined by modeling energy balance and hydrological mechanisms to maximize benefits. In addition, planting density can be adjusted to avoid forest snow shielding issues. Therefore, it is essential to evaluate the climate benefits of afforestation projects on a case-by-case basis, modeling best and worst-case scenarios to account for these factors.

Discussion

While carbon sequestration in biomass pools has garnered the most attention in discussions about the climate benefits of afforestation (for a more detailed review and analysis, see refs. 4,164,165), numerous questions remain unanswered. Over the long term, the net gain in carbon stocks is determined by the balance between carbon uptake and losses through decomposition and disturbances. One potential way to reduce these losses is through timber harvesting, which could prevent carbon loss due to tree mortality or wildfires. Optimizing both ecosystem storage and storage in harvested wood products (HWP) may offer advantages[166]. However, recent findings suggest that logging may be more emission-intensive than previously thought, potentially turning logged forests into a net source of emissions, even when considering HWPs[167]. Collecting accurate data on carbon pools is critical, and progress has been made in quantifying global carbon storage potential in biomass and soils[8,9], existing storage in Canada's managed boreal forests[4], and regional afforestation efforts in Canada[168,169]. Recent modeling efforts have aimed to estimate carbon storage in afforestation pools across the Canadian boreal using spatial reference sites[164]. However, finer spatially explicit modeling and reconciliation with on-the-ground data are needed to improve confidence in estimates and to create more detailed carbon sequestration maps.

Modeling afforestation is a complex challenge, and determining its climate benefits involves a multitude of interlinked processes and regional factors. Research has recently expanded beyond carbon sequestration, acknowledging changes in albedo due to varying tree cover, suggesting that many global biomes may exhibit a significant albedo offset, rendering afforestation climate negative[51–55]. While these studies represent a significant advancement, the form and nature of their conclusions can be misleading when interpreted by the general public and policymakers without sufficient context[170–172] (see Supplementary section "uncertainties in albedo-related afforestation assessments"). We acknowledge that it is impossible for any single afforestation assessment to account for all processes and address all methodological limitations. Therefore, we see our work as a synthesis that encourages future research to include more interlinked processes in their modeling, focus on specific regions and their realities, consider practical afforestation scenarios, and acknowledge important methodological limitations. In addition, we advocate for a separate section that elaborates on whether studies are conclusive enough for regional policy-making and what the general public needs to know. Without such exposition, oversimplified opinions like "trees are bad" may propagate in the public sphere. In some instances, offering opinions without accompanying detailed modeling can do more harm than good. For example, a recent perspective article[173] authoritatively asserts that tree planting is not a climate solution in northern regions, yet it disregards evidence for permafrost preservation[18–25], dismisses increased albedo as a dead end without considering three-dimensional energy partitioning[56–58,63], oversimplifies complex snow dynamics[84–88], ignores the inevitability of vegetation migration under warming[116–119], lacks substantial modeling evidence for soil carbon dynamics, and neglects the possibility of controlling afforestation variables to influence outcomes.

The uncertainties and variabilities arising from various non-modeled processes and methodological limitations are significant enough to preclude any definitive conclusions about the climate benefits of afforestation (see Box 5a). The variability in monthly aggregated MODIS albedo data exceeds 0.2 in many northern regions, rendering conclusions from monthly analyses questionable[159]. Topography, a factor entirely ignored by all studies, accounts for around 30% of the variability in surface energy balance[161]. Cloud cover, another overlooked factor, alters RF by ~1.6 W/m^2, while overall ERF in climate models has an uncertainty of around 20%[63,174,175]. Longwave RF, not included in any existing study, can reach up to 1.1 W/m^2[63]. Non-radiative processes, neglected by most studies, together have a variability of ~10 W/m^2[63]. We aim to tackle some of these uncertainties in the northern boreal and southern arctic regions through modeling studies in future work, with the goal of providing insights for Canadian and global climate policy.

While modeling and analysis are essential, the boreal and arctic regions face a significant shortage of field measurements. Therefore, in addition to more comprehensive modeling, we hope that future research also addresses this lack of on-ground data. With an increase in data, researchers can attempt to reconcile remote sensing observations with climate models, which is a major bottleneck in the north[71–76] (see Supplementary subsection "reconciliation with climate models"). Moreover, this improved model-data synergy, with a strong local focus across the northern boreal and southern arctic, can be highly beneficial for informing policy decisions regarding afforestation and carefully designing these initiatives. Afforestation in the north can help Canada achieve its mitigation goals while providing adaptation benefits; however, further research is necessary before it can be conclusively stated that afforestation will be climate-positive, and these climate-positive regions can be identified.

Our review focused primarily on the Canadian north, but the arguments presented are widely applicable. For example, permafrost plays a critical role in afforestation efforts across all circumpolar countries. Similarly, the interplay between forests and snow is a crucial consideration in any region with a consistent snow season. Moreover, radiative and non-radiative processes, hydrological cycles, SLCFs, SOC, GHG emissions from land use change, and a changing climate will all be essential factors in determining the climate positivity of forests worldwide, albeit to varying degrees. The key takeaway is that regional realities must be taken into account in afforestation assessments, as local conditions significantly impact the effectiveness of afforestation efforts.

Afforestation decisions involve tradeoffs. For instance, afforestation can contribute to local cooling. However, the local temperature effects due to afforestation might not harmonize with the global response required, as the primary processes dictating energy balance may differ across spatial scales. This may lead to conflicts between regional needs and global goals, which may not always align. In addition, the processes involved operate at different timescales, with albedo, temperature, and hydrology responding quickly to changes, and carbon sequestration taking longer. The full spectrum of spatial and temporal scales can be found in Box 5b. Forests operate across these scales, with leaf-scale to non-local in the spatial domain, and seconds to centuries in the temporal domain, resulting in inevitable tradeoffs. Therefore, future research must identify specific regional versus global tradeoffs and near-term versus long-term tradeoffs and provide a decision-making framework.

In this work, we primarily examined the climate benefits and drawbacks of afforestation. However, it is essential to recognize that forests also impact other vital Sustainable Development Goals (SDGs), including biodiversity, economic prosperity, and food, water, and energy security. While afforestation can lead to enhanced biodiversity, its implementation without local considerations can harm biodiversity,

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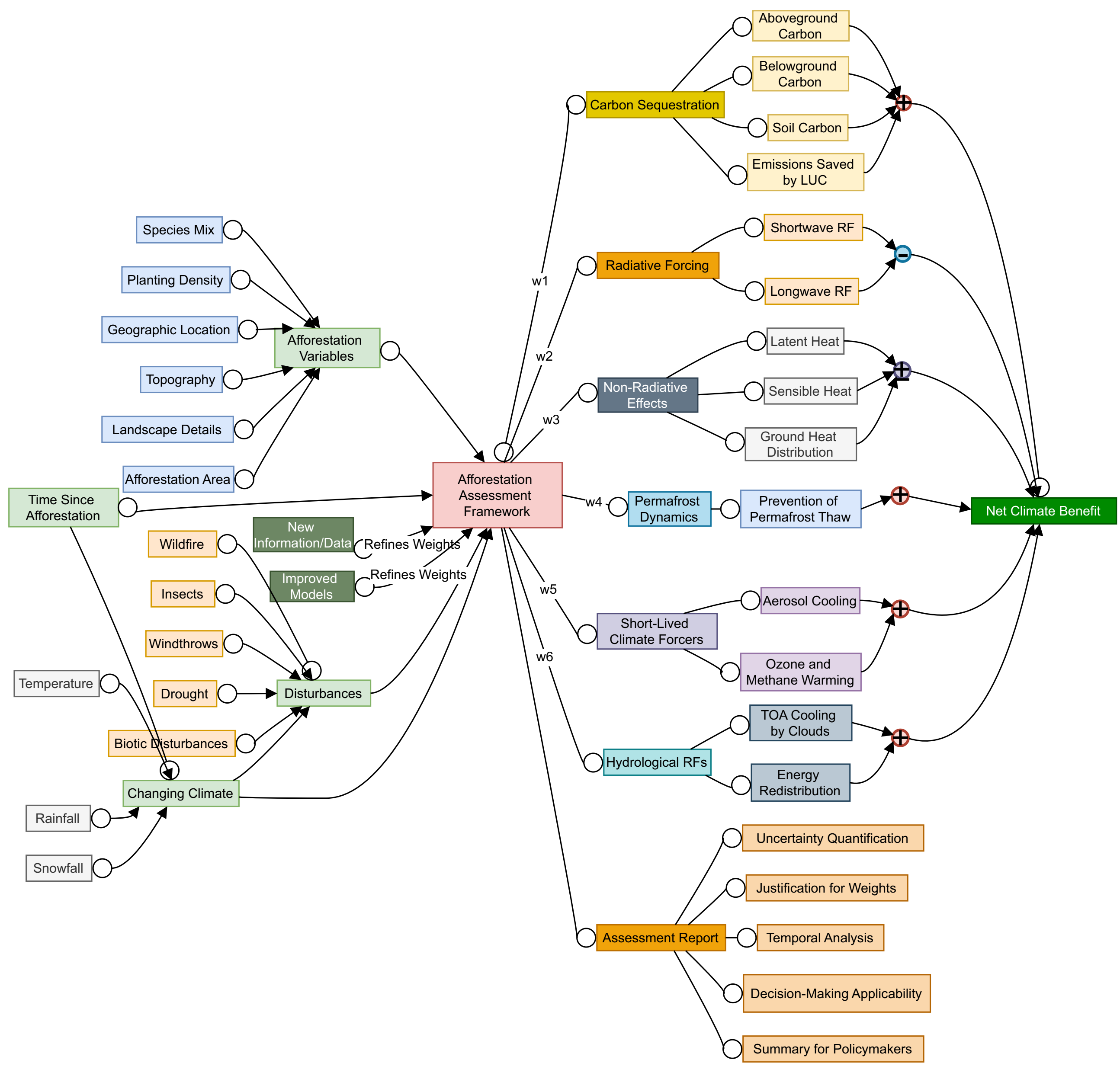
BOX 6

Proposed afforestation assessment framework



The framework has six components with their own weights, which are then added to produce a net climate benefit. It also provides an assessment report that includes justification for the weights, results of temporal analysis, and summary for policymakers among other details. Such a framework could be useful to both scientists and policy makers while determining whether afforestation should be carried out in a particular region.

as well as food and water security, depending on existing land use. These risks can be mitigated by considering regional needs and involving local stakeholders in decision-making. In addition, we have not discussed in detail the interplay between afforestation and the timber and bioenergy industries, which influence economic and energy security. These considerations raise a philosophical question about prioritizing goals, making tradeoffs, and navigating difficult decisions. We aim to address these questions in the Canadian context in future research.

However, to start the conversation around conducting more holistic afforestation assessments for climate benefits, we propose a framework in Box 6. Our proposed assessment framework consists of six components, including carbon sequestration, radiative forcing, non-radiative effects, permafrost dynamics, short-lived climate forcers, and hydrological RFs, each with their own sub-components. The effect of each component on the climate is measured in TOA RFs which are weighted, and both the weights and the RFs can vary with time. Therefore, the whole assessment has a temporal component.

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BOX 7

Important open questions and directions for future research in the context of afforestation assessments

Processes/ Methods	Open Questions/Future Directions
Permafrost	Create physics/data-driven landscape-level permafrost maps
	Develop a framework using forests to regulate permafrost dynamics and prevent future permafrost thaw
	Study post-disturbance soil stability and permafrost thaw and their relationship to forest cover
	Investigate how different tree species affect permafrost through variations in canopy structure, root systems, and evapotranspiration rates.
	Examine how the combination of canopy cover, understory vegetation, and moss layers collectively influence ground thermal regimes
Radiative and Non-radiative Processes	Develop higher resolution (spatial and temporal) albedo land use change maps
	Reduce uncertainty reduction in albedo estimates during the snow season
	Develop spatial maps of energy redistribution factors and longwave forcings from non-radiative processes
	Create landscape-level maps of energy balance factoring in topography, elevation, slope, aspect, SZA, and time of day
	Study how the effects of afforestation scale with the size of the afforested area, and at what scales non-local effects become significant
	Investigate seasonality of BGP effects and relevance for mitigation and adaptation
Forest-Snow Interaction	Quantify benefits/drawbacks associated with snow accumulation and melting in forests
	Explore how different forest management strategies affect snow processes and albedo
	Study how topography, elevation, slope, and aspect influence snow interception and accumulation in forested areas
	Investigate the effects of various climate change scenarios on snow dynamics in afforested areas
	Reduce uncertainty in the role of intercepted snow in increasing forest albedo
Changing Climate	Quantify climate benefits of forests under projected disturbance regimes (wildfire, rainfall, snowfall, insects, windthrows)
	Determine the long-term implications of increased disturbance frequency and severity on the carbon balance of northern forests, and how this might shift forests from carbon sinks to carbon sources
	Investigate how shifts in vegetation distribution due to climate change affect local and global climate feedback mechanisms, such as albedo changes and non-radiative processes
	Study how afforestation initiatives can be designed to enhance resilience to climate-induced disturbances and contribute positively to climate mitigation efforts
	Determine the realistic potential of northern afforestation and reforestation in mitigating climate change, considering the risks of carbon reversibility due to disturbances
	Investigate current and past vegetation responses to changing climates, and the need for assisted migration
Forest Structure	Conduct temporal analysis of climate benefits as a function of species and stand age, focusing on the role of forest structure
	Investigate ways in which different canopy structures and ages affect snow interception, unloading, and subsequent albedo changes
	Compare the cooling effects of higher albedo in young or sparse forests with the carbon sequestration benefits of mature, denser forests
	Study what combinations of canopy density, tree species, and planting densities yield the best balance between carbon sequestration and biophysical climate effects like albedo and sensible heat flux
Short-Lived Climate Forcers	Study over what time scales the cooling effects of aerosol-induced DRF and IRF persist, and how they interact with the warming effects of ozone and methane
	Investigate why current atmospheric models underestimate aerosol and cloud formation from BVOCs in northern regions
	Study how rising global temperatures affect BVOC emissions from forests and what feedback effects might this have on climate?
	Quantify forest-related SLCF effects as a function of species and age
Soil Carbon	Reduce uncertainty in SOC accumulation over the lifetime of the forest
	Conduct longitudinal studies assessing SOC recovery post-disturbance across different ecosystems
	Investigate how increasing temperatures and altered precipitation patterns affect SOC stability and sequestration
	Study how the inclusion of SOC alters the net climate impact evaluations of afforestation projects
	Conduct comparative studies of SOC changes in afforested areas with different land-use histories
	Integrate remote sensing data and machine learning with ground measurements for SOC estimation
	Compare soil emissions in non-afforested lands with afforested lands
Hydrological Processes	Quantify TOA cooling and energy modulation via clouds formed by forests
	Create models that incorporate non-local and second-order effects to better estimate ERF in afforested regions, particularly in northern zones where RF overestimates net radiation changes
	Incorporate afforestation scenarios into Earth system models to simulate potential changes in atmospheric circulation
	Conduct studies in regions with varying degrees of aridity to understand how afforestation affects energy flux partitioning and LST
	Use climate models to quantify the overall hydrological effects of afforested trees
	Spatial maps of water availability and relationship with radiative forcing
Earth History	Investigate further the positive feedbacks from the northward expansion of forests and relevance for a climate with future forcing
	Study how northern forests will respond to future warming and CO_2 levels that exceed those of the Holocene, potentially leading to novel climate-vegetation dynamics
	Investigate the dominant corrective mechanisms that counteract positive feedbacks to maintain vegetation stability at high latitudes
	Analyze paleoenvironmental records from the mPWP to understand vegetation responses under different climate regimes, providing analogs for future conditions
Methods	Reduce uncertainty in satellite-derived albedo and remote sensing products under overcast conditions and higher SZA
	Design gap-Filling algorithms that can interpolate missing data due to cloud cover or high solar zenith angles, using spatial and temporal patterns from surrounding pixels
	Develop machine learning models that can estimate albedo under challenging conditions (e.g., cloud cover, high SZA) using inputs like land cover type, meteorological data, and historical albedo patterns
	Conduct landscape-level afforestation assessments factoring in topography, elevation, slope, and aspect
	Use deep learning techniques for more accurate land cover classification, reducing misclassification errors between forests, savannas, and other vegetation types
	Build models that account for seasonal changes in vegetation (e.g., leaf-on and leaf-off periods) to adjust albedo estimates accordingly
	Use LiDAR data to obtain detailed information on forest canopy height, density, and leaf area index (LAI), improving the representation of forests in both remote sensing products and climate models
	Design atmospheric correction models that account for aerosol scattering, water vapor absorption, and other atmospheric constituents affecting albedo measurements
	Incorporate satellite observations into climate models using data assimilation methods to update model states in real time, reducing biases
	Incorporate models that simulate changes in snow grain size over time, affecting albedo due to metamorphosis processes, and enhance representations of how different forest canopies intercept and retain snow, influencing surface albedo and energy balance.
	Use data from satellites equipped with hyperspectral sensors to obtain detailed spectral information, improving material differentiation and albedo estimation
	Collect data spanning different seasons to capture the full range of albedo variability due to snow cover and vegetation phenology
	Conduct assessments accounting for the deliberate nature of afforestation including tree species selection, topography, total afforestation area, and planting density
	Design a framework to optimize afforestation decision variables to increase climate benefits (implementing details given in Box 6)
Others	Investigate the use of logging to minimize lifetime carbon emissions due to mortality and wildfire in a changing climate
	Collect more on-ground data of aboveground, belowground, and soil carbon pools and reconcile with modeling efforts
	Reduce uncertainty of various parameters associated with afforestation (see Box 5a)
	Investigate mitigation vs adaptation, regional vs global, and near-term vs long-term tradeoffs
	Study the interaction of climate benefits of forests with biodiversity, economic prosperity, and food, water, and energy security

Future research must combine physics- and data-driven approaches to map and preserve permafrost under forested landscapes while exploring how species selection and canopy structure can regulate ground thermal regimes. Simultaneously, an improved understanding of radiative and non-radiative processes, especially albedo, sensible heat flux, and aerosol impacts, requires high-resolution remote sensing, machine learning, and data assimilation methods. Addressing snow–forest interactions, soil carbon dynamics, and the influence of SLCFs is critical to accurately assessing the net climate effects of afforestation, particularly in rapidly changing northern ecosystems. Finally, integrated frameworks that account for hydrological processes, disturbance regimes, and Earth history insights will be key to designing afforestation strategies that maintain long-term climate benefits.

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Moreover, the framework includes a changing climate component which also is a function of time, climate parameters like temperature, rainfall, snowfall, and disturbance regimes such as wildfire, insects, and windthrows. The assessment takes as input afforestation variables, including species, mix, planting density, topography, and geographic location, and combines the aforementioned components to produce a net climate benefit. In the end, it provides an assessment report that includes justification for the weights, results of temporal analysis, uncertainty quantification, the scope of the assessment in terms of decision-making, and a summary for policymakers. Determining the appropriate weights for the various components remains an area for further exploration. A potential approach is to base the weights on the uncertainties in the forcing estimates, assigning higher weights to more confident estimates, which avoids treating uncertain and confident estimates equally. Temporal analysis within this framework is essential, as it allows for the tracking of the effects of growth, from seedlings to mature trees, across different components. In addition, it facilitates the inclusion of climate variables and disturbances that evolve over time.

In this framework, we assume that given the afforestation variables and disturbances, modeling tools like the carbon budget model (CBM)[176] and the Growth and Yield Projection System (GYPSY)[177] are able to simulate the carbon dynamics (including self-thinning, mortality, etc.). Similarly, different modeling tools will be responsible for the various components like permafrost, radiative forcing, non-radiative processes, and others. We recognize that the term afforestation can bring to mind the detailed ecological and physiological shifts that occur as a forest develops, from seedlings to saplings to mature trees. While these transitions are indeed important and influence things like productivity and long-term forest dynamics, our primary focus here is different. Rather than going into the specific mechanisms that shape these developmental stages, we are interested in how the forest's condition at any given time, simply described as time since afforestation, affects climate-related outcomes. In other words, we acknowledge the ecological complexity behind forest growth, but we choose to treat it more abstractly, using the forest's age as a factor, rather than examining each developmental process in detail.

To demonstrate the value of our proposed framework, we reference studies that account for both carbon sequestration and albedo[51,55]. These studies conclude that afforestation in the northern boreal region has a negative climate impact, as the reduced albedo of forests fully offsets the carbon benefits, primarily due to the extended snow season. However, our framework reveals that this conclusion cannot be accurately reached by considering only two components while neglecting the other four. In fact, incorporating non-radiative effects and short-lived climate forcers (SLCFs) could reverse these conclusions. In addition, regional factors like permafrost preservation, a significant climate-positive factor due to the vast carbon reserves, must not be overlooked. Lastly, even within the two components considered, the exclusion of longwave forcing and soil carbon renders these conclusions premature.

Afforestation policies must account for various components to accurately calculate the net climate benefit and ensure that studies incorporate temporal analysis, changing climate conditions, and landscape-level specifics in their evaluations. Policymakers should also mandate that assessments include a summary for policymakers to clarify whether the findings are suitable for informing policy at national or global levels. This would help avoid confusion with studies that omit key implementation details and are intended solely for research, not policy guidance. In addition, policymakers should ensure that assessments consider practical factors like planting density, topography, and the uncertainties associated with their conclusions.

This review synthesizes existing knowledge on the climate benefits of afforestation, identifying gaps that prevent definitive conclusions about its climate positivity or negativity. With a focus on the Canadian northern boreal and southern arctic regions, which are highly sensitive to climate change and relevant to afforestation initiatives, we discuss regional realities and processes that must be considered in afforestation assessments, including permafrost dynamics, non-radiative processes, aerosol forcing, hydrological processes, and snow cover dynamics. We also highlight methodological shortcomings in existing assessments, including the neglect of SOC and GHG emissions changes, inadequate characterization of forest structure, limitations of remote sensing products, lack of temporal and seasonal analysis, and the failure to account for the planned nature of afforestation. We introduce an assessment framework that combines different components to calculate net climate benefit while considering temporal analysis, changing climatic conditions, and implementation level parameters. We hope that this synthesis encourages future research to address outlined research gaps and that the proposed framework drives forthcoming afforestation assessments in the north to be more holistic. Furthermore, we believe that the research gaps and assessment framework discussed in this review will spur useful discussions to inform and improve Canadian and circumpolar afforestation policy.

Data availability

No original data or code was produced during this research.

References

1. Lee, H. et al. *Climate Change 2023: Synthesis Report, Summary for Policymakers.* (2023).
2. Berner, L. T. et al. Summer warming explains widespread but not uniform greening in the Arctic tundra biome. *Nat. Commun.* **11**, 4621 (2020).
3. Lara, M. J., Nitze, I., Grosse, G., Martin, P. & McGuire, A. D. Reduced arctic tundra productivity linked with landform and climate change interactions. *Sci. Rep.* **8**, 2345 (2018).
4. Kurz, W. A. et al. Carbon in Canada's boreal forest—a synthesis. *Environ. Rev.* **21**, 260–292 (2013).
5. Doelman, J. C. et al. Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Chang. Biol.* **26**, 1576–1591 (2020).
6. Government of Canada. The 2 Billion Trees (2BT) program. https://www.canada.ca/en/campaign/2-billion-trees.html (2023).
7. Drever, C. R. et al. Natural climate solutions for Canada. *Sci. Adv.* **7**, eabd6034 (2021).
8. Griscom, B. W. et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **114**, 11645–11650 (2017).
9. Walker, W. S. et al. The global potential for increased storage of carbon on land. *Proc. Natl. Acad. Sci. USA* **119**, e2111312119 (2022).
10. Bastin, J. F. et al. The global tree restoration potential. *Science* **365**, 76–79 (2019).
11. Canada Centre for Remote Sensing, Canada Centre for Mapping and Earth Observation & Natural Resources Canada. 2020 Land Cover of Canada. *Government of Canada* https://open.canada.ca/data/en/dataset/ee1580ab-a23d-4f86-a09b-79763677eb47 (2022).
12. Miner, K. R. et al. Permafrost carbon emissions in a changing Arctic. *Nat. Rev. Earth Environ.* **3**, 55–67 (2022).
13. Treat, C. C. et al. Permafrost carbon: Progress on understanding stocks and fluxes across northern terrestrial ecosystems. *J. Geophys. Res. Biogeosci.* **129**, e2023JG007638 (2024).
14. Kokelj, S. V., Lantz, T. C., Kanigan, J., Smith, S. L. & Coutts, R. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta

region, Northwest Territories, Canada. *Permafr. Periglac. Process.* **20**, 173–184 (2009).
15. Abbott, B. W. et al. Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. *Environ. Res. Lett.* **11**, 034014 (2016).
16. Nitzbon, J. et al. No respite from permafrost-thaw impacts in the absence of a global tipping point. *Nat. Clim. Chang.* **14**, 573–585 (2024).
17. Beer, C., Zimov, N., Olofsson, J., Porada, P. & Zimov, S. Protection of permafrost soils from thawing by increasing herbivore density. *Sci. Rep.* **10**, 4170 (2020).
18. AccessScience Editors. Global climate change affects arctic treeline. *AccessScience* https://doi.org/10.1036/1097-8542.br0515171 (2017).
19. Douglas, T. A., C. A. Hiemstra, & Barker, A. J. ABoVE: End of Season Snow Depth at CRREL sites near Fairbanks, Alaska, 2014-2019. *ORNL DAAC*, Oak Ridge, Tennessee, USA (2019).
20. Fedorov, A. N., Konstantinov, P. Y., Vasilyev, N. F. & Shestakova, A. A. The influence of boreal forest dynamics on the current state of permafrost in Central Yakutia. *Polar Sci.* **22**, 100483 (2019).
21. Chang, X. et al. Thermal impacts of boreal forest vegetation on active layer and permafrost soils in northern Da Xing'anling (Hinggan) Mountains, Northeast China. *Arct. Antarct. Alp. Res.* **47**, 267–279 (2015).
22. Munkhjargal, M., Yadamsuren, G., Yamkhin, J. & Menzel, L. Ground surface temperature variability and permafrost distribution over mountainous terrain in northern Mongolia. *Arct. Antarct. Alp. Res.* **52**, 13–26 (2020).
23. Stuenzi, S. M. et al. Variability of the surface energy balance in permafrost-underlain boreal forest. *Biogeosciences* **18**, 343–365 (2021).
24. Stuenzi, S. M. et al. Thermohydrological impact of forest disturbances on ecosystem-protected permafrost. *J. Geophys. Res. Biogeosci.* **127**, e2021JG006630 (2022).
25. Stuenzi, S. M. et al. Sensitivity of ecosystem-protected permafrost under changing boreal forest structures. *Environ. Res. Lett.* **16**, 084045 (2021).
26. Halim, M. A. & Thomas, S. C. A proxy-year analysis shows reduced soil temperatures with climate warming in boreal forest. *Sci. Rep.* **8**, 16859 (2018).
27. Heijmans, M. M. et al. Tundra vegetation change and impacts on permafrost. *Nat. Rev. Earth Environ.* **3**, 68–84 (2022).
28. Yu, L., Leng, G. & Python, A. Attribution of the spatial heterogeneity of Arctic surface albedo feedback to the dynamics of vegetation, snow and soil properties and their interactions. *Environ. Res. Lett.* **17**, 014036 (2022).
29. Oblogov, G. E., Vasiliev, A. A., Streletskiy, D. A., Shiklomanov, N. I. & Nyland, K. E. Localized vegetation, soil moisture, and ice content offset permafrost degradation under climate warming. *Geosciences* **13**, 129 (2023).
30. Khani, H. M., Kinnard, C., Gascoin, S. & Lévesque, E. Fine-scale environment control on ground surface temperature and thaw depth in a High Arctic tundra landscape. *Permafr. Periglac. Process.* **34**, 467–480 (2023).
31. Guo, D. et al. Highly restricted near-surface permafrost extent during the mid-Pliocene warm period. *Proc. Natl. Acad. Sci. USA* **120**, e2301954120 (2023).
32. Rebi, A. et al. Unraveling the impact of wildfires on permafrost ecosystems: Vulnerability, implications, and management strategies. *J. Environ. Manage.* **358**, 120917 (2024).
33. Sahtu Renewable Resources Board. Boreal biome and treeline. ʔehdzo Got'ı̨nę Gots'ę́ Nákedı / Sahtú Renewable Resources Board (SRRB). https://www.srrb.nt.ca/people-and-places/sahtu-atlas/100-sahtu-atlas/the-natural-world/188-treeline (2023).
34. Gajewski, K. Environmental history of the northwestern Québec Treeline. *Quat. Sci. Rev.* **206**, 29–43 (2019).
35. Payette, S. et al. The velocity of postglacial migration of fire-adapted boreal tree species in eastern North America. *Proc. Natl. Acad. Sci. USA* **119**, e2210496119 (2022).
36. Williams, J. W. Variations in tree cover in North America since the last glacial maximum. *Global Planet. Change* **35**, 1–23 (2003).
37. Pielke, R. A. & Vidale, P. L. The boreal forest and the polar front. *J. Geophys. Res. Atmos.* **100**, 25755–25758 (1995).
38. Foley, J. A., Kutzbach, J. E., Coe, M. T. & Levis, S. Feedbacks between climate and boreal forests during the Holocene epoch. *Nature* **371**, 52–54 (1994).
39. Ritchie, J. C. & Hare, F. K. Late-Quaternary vegetation and climate near the arctic tree line of northwestern North America. *Quat. Res.* **1**, 331–342 (1971).
40. Fewster, R. E. et al. Holocene vegetation dynamics of circum-Arctic permafrost peatlands. *Quat. Sci. Rev.* **307**, 108055 (2023).
41. Thompson, A. J. et al. Northern Hemisphere vegetation change drives a Holocene thermal maximum. *Sci. Adv.* **8**, eabj6535 (2022).
42. Gallimore, R., Jacob, R. & Kutzbach, J. Coupled atmosphere-ocean-vegetation simulations for modern and mid-Holocene climates: role of extratropical vegetation cover feedbacks. *Clim. Dyn.* **25**, 755–776 (2005).
43. Wohlfahrt, J., Harrison, S. P. & Braconnot, P. Synergistic feedbacks between ocean and vegetation on mid-and high-latitude climates during the mid-Holocene. *Clim. Dyn.* **22**, 223–238 (2004).
44. O'ishi, R. & Abe-Ouchi, A. Polar amplification in the mid-Holocene derived from dynamical vegetation change with a GCM. *Geophys. Res. Lett.* **38** https://doi.org/10.1029/2011GL048001 (2011).
45. Fréchette, B., Wolfe, A. P., Miller, G. H., Richard, P. J. & de Vernal, A. Vegetation and climate of the last interglacial on Baffin Island, Arctic Canada. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **236**, 91–106 (2006).
46. Seppä, H., Cwynar, L. C. & MacDonald, G. M. Post-glacial vegetation reconstruction and a possible 8200 cal. yr BP event from the low arctic of continental Nunavut, Canada. *J. Quat. Sci.* **18**, 621–629 (2003).
47. Kerwin, M. W. et al. The role of oceanic forcing in mid-Holocene northern hemisphere climatic change. *Paleoceanography* **14**, 200–210 (1999).
48. Levis, S., Foley, J. A., Brovkin, V. & Pollard, D. On the stability of the high-latitude climate-vegetation system in a coupled atmosphere-biosphere model. *Glob. Ecol. Biogeogr.* **8**, 489–500 (1999).
49. Brovkin, V. et al. Stability analysis of the climate-vegetation system in the northern high latitudes. *Clim. Change* **57**, 119–138 (2003).
50. Paiewonsky, P., Elison Timm, O. & Rose, B. E. State dependency of the forest-tundra-short wave feedback: comparing the mid-Pliocene and pre-industrial eras. *Clim. Dyn.* **60**, 3839–3861 (2023).
51. Hasler, N. et al. Accounting for albedo change to identify climate-positive tree cover restoration. *Nat. Commun.* **15**, 2275 (2024).
52. Mykleby, P. M., Snyder, P. K. & Twine, T. E. Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. *Geophys. Res. Lett.* **44**, 2493–2501 (2017).
53. Jiao, T. et al. Global climate forcing from albedo change caused by large-scale deforestation and reforestation: quantification and attribution of geographic variation. *Clim. Change* **142**, 463–476 (2017).
54. Kirschbaum, M. U. F. et al. Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. *Biogeosciences* **8**, 3687–3696 (2011).
55. Weber, J. et al. Chemistry-albedo feedbacks offset up to a third of forestation's CO_2 removal benefits. *Science* **383**, 860–864 (2024).

56. Windisch, M. G., Davin, E. L. & Seneviratne, S. I. Prioritizing forestation based on biogeochemical and local biogeophysical impacts. *Nat. Clim. Chang.* **11**, 867–871 (2021).
57. Bright, R. M. et al. Local temperature response to land cover and management change driven by non-radiative processes. *Nat. Clim. Chang.* **7**, 296–302 (2017).
58. Eugster, W. et al. Land–atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate. *Glob. Chang. Biol.* **6**, 84–115 (2000).
59. Graf, A. et al. Joint optimization of land carbon uptake and albedo can help achieve moderate instantaneous and long-term cooling effects. *Commun. Earth Environ.* **4**, 298 (2023).
60. Zhang, C. et al. Seasonal and long-term dynamics in forest microclimate effects: global pattern and mechanism. *Npj Clim. Atmos. Sci.* **6**, 116 (2023).
61. Su, Y. et al. Asymmetric influence of forest cover gain and loss on land surface temperature. *Nat. Clim. Chang.* **13**, 823–831 (2023).
62. Rohatyn, S., Rotenberg, E., Tatarinov, F., Carmel, Y. & Yakir, D. Large variations in afforestation-related climate cooling and warming effects across short distances. *Commun. Earth Environ.* **4**, 18 (2023).
63. Zhao, K. & Jackson, R. B. Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecol. Monogr.* **84**, 329–353 (2014).
64. Cui, J. et al. Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. *Nat. Geosci.* **15**, 982–988 (2022).
65. Staal, A., Koren, G., Tejada, G. & Gatti, L. V. Moisture origins of the Amazon carbon source region. *Environ. Res. Lett.* **18**, 044027 (2023).
66. Teuling, A. J. et al. Observational evidence for cloud cover enhancement over western European forests. *Nat. Commun.* **8**, 14065 (2017).
67. Cerasoli, S., Yin, J. & Porporato, A. Cloud cooling effects of afforestation and reforestation at midlatitudes. *Proc. Natl. Acad. Sci. USA* **118**, e2026241118 (2021).
68. Swann, A. L., Fung, I. Y., Levis, S., Bonan, G. B. & Doney, S. C. Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proc. Natl. Acad. Sci. USA* **107**, 1295–1300 (2010).
69. Winckler, J., Lejeune, Q., Reick, C. H. & Pongratz, J. Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophys. Res. Lett.* **46**, 745–755 (2019).
70. Hang, Y., L'Ecuyer, T. S., Henderson, D. S., Matus, A. V. & Wang, Z. Reassessing the effect of cloud type on Earth's energy balance in the age of active spaceborne observations. Part II: Atmospheric heating. *J. Clim.* **32**, 6219–6236 (2019).
71. Levine, X. J. & Boos, W. R. Land surface albedo bias in climate models and its association with tropical rainfall. *Geophys. Res. Lett.* **44**, 6363–6372 (2017).
72. Li, Y. et al. Evaluating biases in simulated land surface albedo from CMIP5 global climate models. *J. Geophys. Res. Atmos.* **121**, 6178–6190 (2016).
73. Wang, L. et al. Investigating the spread in surface albedo for snow-covered forests in CMIP5 models. *J. Geophys. Res. Atmos.* **121**, 1104–1119 (2016).
74. Thackeray, C. W., Fletcher, C. G. & Derksen, C. Quantifying the skill of CMIP5 models in simulating seasonal albedo and snow cover evolution. *J. Geophys. Res. Atmos.* **120**, 5831–5849 (2015).
75. Thackeray, C. W., Fletcher, C. G. & Derksen, C. Diagnosing the impacts of Northern Hemisphere surface albedo biases on simulated climate. *J. Clim.* **32**, 1777–1795 (2019).
76. Essery, R. Boreal forests and snow in climate models. *Hydrol. Process.* **12**, 1561–1567 (1998).
77. Kropp, H. et al. Are vegetation influences on Arctic–boreal snow melt rates detectable across the Northern Hemisphere? *Environ. Res. Lett.* **17**, 104010 (2022).
78. Pomeroy, J. W., Gray, D. M., Hedstrom, N. R. & Janowicz, J. R. Prediction of seasonal snow accumulation in cold climate forests. *Hydrol. Process.* **16**, 3543–3558 (2002).
79. Gelfan, A. N., Pomeroy, J. W. & Kuchment, L. S. Modeling forest cover influences on snow accumulation, sublimation, and melt. *J. Hydrometeorol.* **5**, 785–803 (2004).
80. Pomeroy, J. W. et al. Physically based estimation of seasonal snow accumulation in the boreal forest. In *Proceedings of the 59th Eastern Snow Conference* 93–108 (2002).
81. Pomeroy, J. W. et al. Biome-scale representation of snow cover development and ablation in boreal and tundra ecosystems. The Mackenzie GEWEX Study (MAGS) Phase 1 (2001).
82. Raleigh, M. S. Quantification of uncertainties in snow accumulation, snowmelt, and snow disappearance dates. PhD thesis, Univ. Washington (2013).
83. Pomeroy, J. W. et al. Classification of the boreal forest for hydrological processes. In *Proceedings of the Ninth International Boreal Forest Research Association Conference* (ed. Woxholtt, S.) 49–59 (1999).
84. Pomeroy, J. W. & Granger, R. J. Sustainability of the western Canadian boreal forest under changing hydrological conditions. I. Snow accumulation and ablation. *IAHS Publication* **240**, 237–242 (1997).
85. Miller, D. H. *Interception Processes During Snowstorms*. (1964).
86. Church, J. E. *The Conservation of Snow: Its Dependence on Mountains and Forests* (1912).
87. Shankand, C. C. & Bunnell, F. L. The effects of forests on snow cover. *Integrated wildlife intensive forestry research*. Report submitted to the province of British Columbia (1982).
88. Davis, R. E. et al. Variation of snow cover ablation in the boreal forest: A sensitivity study on the effects of conifer canopy. *J. Geophys. Res. Atmos.* **102**, 29389–29395 (1997).
89. Sicart, J. E. et al. A sensitivity study of daytime net radiation during snowmelt to forest canopy and atmospheric conditions. *J. Hydrometeorol.* **5**, 774–784 (2004).
90. López-Moreno, J. I. & Latron, J. Influence of canopy density on snow distribution in a temperate mountain range. *Hydrol. Process.* **22**, 117–126 (2008).
91. Kuusinen, N. et al. Seasonal variation in boreal pine forest albedo and effects of canopy snow on forest reflectance. *Agric. Meteorol.* **164**, 53–60 (2012).
92. Miller, D. H. Snow in the Trees: Where Does it Go? Pacific Southwest Forest and Range Experiment Station (1962).
93. Pomeroy, J. W. & Dion, K. Winter radiation extinction and reflection in a boreal pine canopy: measurements and modelling. *Hydrol. Process.* **10**, 1591–1608 (1996).
94. He, Z. & Pomeroy, J. W. Assessing hydrological sensitivity to future climate change over the Canadian southern boreal forest. *J. Hydrol.* **624**, 129897 (2023).
95. Price, D. T. et al. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. *Environ. Rev.* **21**, 322–365 (2013).
96. Gauthier, S. et al. Boreal forest health and global change. *Science* **349**, 819–822 (2015).
97. Anderegg, W. R. et al. A climate risk analysis of Earth's forests in the 21st century. *Science* **377**, 1099–1103 (2022).
98. Soja, A. J. et al. Climate-induced boreal forest change: predictions versus current observations. *Glob. Planet. Change* **56**, 274–296 (2007).
99. Reich, P. B. et al. Even modest climate change may lead to major transitions in boreal forests. *Nature* **608**, 540–545 (2022).

100. Coogan, S. C. et al. Fifty years of wildland fire science in Canada. *Can. J. Res.* **51**, 283–302 (2021).
101. Coops, N. C. et al. A thirty year, fine-scale, characterization of area burned in Canadian forests shows evidence of regionally increasing trends in the last decade. *PLoS ONE* **13**, e0197218 (2018).
102. Halofsky, J. E., Peterson, D. L. & Harvey, B. J. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecol.* **16**, 1–26 (2020).
103. Brown, P. T. et al. Climate warming increases extreme daily wildfire growth risk in California. *Nature* **621**, 760–766 (2023).
104. Jain, P. et al. Record-breaking fire weather in North America in 2021 was initiated by the Pacific northwest heat dome. *Commun. Earth Environ.* **5**, 202 (2024).
105. Pureswaran, D. S., Roques, A. & Battisti, A. Forest insects and climate change. *Curr. Rep.* **4**, 35–50 (2018).
106. Panferov, O. et al. Effects and feedbacks of Windthrow/breaks in boreal forest ecosystems. In *American Geophysical Union Fall meeting 2008*, American Geophysical Union, GC41A-GC40699 (2008).
107. Johnstone, J. F. et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **14**, 369–378 (2016).
108. Bouchard, M., Pothier, D. & Ruel, J. C. Stand-replacing windthrow in the boreal forests of eastern Quebec. *Can. J. For.Res.* **39**, 481–487 (2009).
109. Brooks, H. E. Severe thunderstorms and climate change. *Atmos. Res.* **123**, 129–138 (2013).
110. Saad, C. et al. Potential impact of climate change on the risk of windthrow in eastern Canada's forests. *Clim. Change* **143**, 487–501 (2017).
111. Foster, A. C. et al. Disturbances in North American boreal forest and Arctic tundra: impacts, interactions, and responses. *Environ. Res. Lett.* **17**, 113001 (2022).
112. Koltz, A. M., Gough, L. & McLaren, J. R. Herbivores in Arctic ecosystems: Effects of climate change and implications for carbon and nutrient cycling. *Ann. N. Y. Acad. Sci.* **1516**, 28–47 (2022).
113. Sanderson, L. A., McLaughlin, J. A. & Antunes, P. M. The last great forest: a review of the status of invasive species in the North American boreal forest. *Forestry* **85**, 329–340 (2012).
114. Forrester, D. I. et al. Self-thinning tree mortality models that account for vertical stand structure, species mixing and climate. *For. Ecol. Manag.* **487**, 118936 (2021).
115. Urgoiti, J., Messier, C., Keeton, W. S., Belluau, M. & Paquette, A. Functional diversity and identity influence the self-thinning process in young forest communities. *J. Ecol.* **111**, 2010–2022 (2023).
116. Berner, L. T. & Goetz, S. J. Satellite observations document trends consistent with a boreal forest biome shift. *Glob. Change Biol.* **28**, 3275–3292 (2022).
117. Frost, G. V. et al. Eyes of the world on a warmer, less frozen, and greener Arctic. *Glob. Change Biol.* **29**, 4453–4455 (2023).
118. Beringer, J., Chapin, F. S. III, Thompson, C. C. & McGuire, A. D. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. *Agric. Meteorol.* **131**, 143–161 (2005).
119. Jeong, J. H. et al. Greening in the circumpolar high-latitude may amplify warming in the growing season. *Clim. Dyn.* **38**, 1421–1431 (2012).
120. Bowling, D. R. et al. Phenology of photosynthesis in winter-dormant temperate and boreal forests: Long-term observations from flux towers and quantitative evaluation of phenology models. *J. Geophys. Res. Biogeosci.* **129**, e2023JG007839 (2024).
121. Luyssaert, S. et al. Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Clim. Change* **4**, 389–393 (2014).
122. Bright, R. M. et al. Inferring surface albedo prediction error linked to forest structure at high latitudes. *J. Geophys. Res. Atmos.* **123**, 4910–4925 (2018).
123. Alibakhshi, S., Naimi, B., Hovi, A., Crowther, T. W. & Rautiainen, M. Quantitative analysis of the links between forest structure and land surface albedo on a global scale. *Remote Sens. Environ.* **246**, 111854 (2020).
124. Banerjee, T., De Roo, F. & Mauder, M. Explaining the convector effect in canopy turbulence by means of large-eddy simulation. *Hydrol. Earth Syst. Sci.* **21**, 2987–3000 (2017).
125. Halim, M. A., Chen, H. Y. & Thomas, S. C. Stand age and species composition effects on surface albedo in a mixedwood boreal forest. *Biogeosciences* **16**, 4357–4375 (2019).
126. Malle, J. et al. Effect of forest canopy structure on wintertime land surface albedo: Evaluating CLM5 simulations with in-situ measurements. *J. Geophys. Res. Atmos.* **126**, e2020JD034118 (2021).
127. Pomeroy, J. & Staines, J. Influence of forest canopy structure and wind flow on patterns of sub-canopy snow accumulation in montane needleleaf forests. *Hydrol. Process.* **37**, e15005 (2023).
128. Kumkar, Y., Astrup, R., Stordal, F. & Bright, R. M. Quantifying regional surface energy responses to forest structural change in Nordic Fennoscandia. *J. Geophys. Res. Atmos.* **125**, e2019JD032092 (2020).
129. Liu, H. & Randerson, J. T. Interannual variability of surface energy exchange depends on stand age in a boreal forest fire chronosequence. *J. Geophys. Res. Biogeosci.* **113**, G1 (2008).
130. Scott, C. E. et al. Impact on short-lived climate forcers increases projected warming due to deforestation. *Nat. Commun.* **9**, 157 (2018).
131. Ward, D. S., Mahowald, N. M. & Kloster, S. Potential climate forcing of land use and land cover change. *Atmos. Chem. Phys.* **14**, 12701–12724 (2014).
132. Weber, J. et al. Chemistry-driven changes strongly influence climate forcing from vegetation emissions. *Nat. Commun.* **13**, 7202 (2022).
133. Monks, P. S. et al. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmos. Chem. Phys.* **15**, 8889–8973 (2015).
134. Rap, A. et al. Natural aerosol direct and indirect radiative effects. *Geophys. Res. Lett.* **40**, 3297–3301 (2013).
135. Scott, C. E. et al. The direct and indirect radiative effects of biogenic secondary organic aerosol. *Atmos. Chem. Phys.* **14**, 447–470 (2014).
136. Unger, N. Human land-use-driven reduction of forest volatiles cools global climate. *Nat. Clim. Change* **4**, 907–910 (2014).
137. Lund, M. T., Rap, A., Myhre, G., Haslerud, A. S. & Samset, B. H. Land cover change in low-warming scenarios may enhance the climate role of secondary organic aerosols. *Environ. Res. Lett.* **16**, 104031 (2021).
138. Spracklen, D. V., Bonn, B. & Carslaw, K. S. Boreal forests, aerosols and the impacts on clouds and climate. *Philos. Trans. R. Soc. A* **366**, 4613–4626 (2008).
139. D'Andrea, S. D. et al. Aerosol size distribution and radiative forcing response to anthropogenically driven historical changes in biogenic secondary organic aerosol formation. *Atmos. Chem. Phys.* **15**, 2247–2268 (2015).
140. Boysen, L. R. et al. Evaluation of soil carbon dynamics after forest cover change in CMIP6 land models using chronosequences. *Environ. Res. Lett.* **16**, 074030 (2021).
141. Laganiere, J., Angers, D. A. & Pare, D. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. *Glob. Change Biol.* **16**, 439–453 (2010).

142. Shi, S., Zhang, W., Zhang, P., Yu, Y. & Ding, F. A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils. *Ecol. Manag.* **296**, 53–63 (2013).
143. Ofosu, E. et al. Soil organic carbon enhancement in diverse temperate riparian buffer systems in comparison with adjacent agricultural soils. *Agrofor. Syst.* **96**, 623–636 (2022).
144. Nabuurs, G. J. et al. *Agriculture, Forestry and Other Land Ues (AFOLU)* (2023).
145. Lorenz, K. & Lal, R. Carbon sequestration in grassland soils. In *Carbon sequestration in agricultural ecosystems* 175–209 (Springer, 2018).
146. Rodrigues, C. I. D., Brito, L. M. & Nunes, L. J. Soil carbon sequestration in the context of climate change mitigation: A review. *Soil Syst* **7**, 64 (2023).
147. Congreves, K. A., Hooker, D. C., Hayes, A., Verhallen, E. A. & Van Eerd, L. L. Interaction of long-term nitrogen fertilizer application, crop rotation, and tillage system on soil carbon and nitrogen dynamics. *Plant Soil* **410**, 113–127 (2017).
148. Deluca, T. H. & Boisvenue, C. Boreal forest soil carbon: distribution, function and modelling. *Forestry* **85**, 161–184 (2012).
149. Karhu, K. et al. Effects of afforestation and deforestation on boreal soil carbon stocks—Comparison of measured C stocks with Yasso07 model results. *Geoderma* **164**, 33–45 (2011).
150. Nave, L. E., Swanston, C. W., Mishra, U. & Nadelhoffer, K. J. Afforestation effects on soil carbon storage in the United States: a synthesis. *Soil Sci. Soci. Am. J.* **77**, 1035–1047 (2013).
151. Paul, K. I., Polglase, P. J., Nyakuengama, J. G. & Khanna, P. K. Change in soil carbon following afforestation. *For. Ecol. Manag.***168**, 241–257 (2002).
152. Berthrong, S. T. et al. Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. *Ecol. Appl.* **22**, 76–86 (2012).
153. Hou, G., Delang, C. O., Lu, X. & Gao, L. A meta-analysis of changes in soil organic carbon stocks after afforestation with deciduous broadleaved, sempervirent broadleaved, and conifer tree species. *Ann. For. Sci.* **77**, 1–13 (2020).
154. Gundale, M. J. et al. The biological controls of soil carbon accumulation following wildfire and harvest in boreal forests: A review. *Global Change Biol.* **30**, e17276 (2024).
155. Larson, J., Wallerman, J., Peichl, M. & Laudon, H. Soil moisture controls the partitioning of carbon stocks across a managed boreal forest landscape. *Sci. Rep.***13**, 14909 (2023).
156. Hong, S. et al. Effects of afforestation on soil carbon and nitrogen accumulation depend on initial soil nitrogen status. *Global Biogeochem. Cycles* **37**, e2022GB007490 (2023).
157. Hong, S. et al. Divergent responses of soil organic carbon to afforestation. *Nat. Sustain.***3**, 694–700 (2020).
158. Kato, S. et al. Uncertainty in satellite-derived surface irradiances and challenges in producing surface radiation budget climate data record. *Remote Sens.* **12**, 1950 (2020).
159. Jia, A., Wang, D., Liang, S., Peng, J. & Yu, Y. Global daily actual and snow-free blue-sky land surface albedo climatology from 20-year MODIS products. *J. Geophys. Res. Atmos.* **127**, e2021JD035987 (2022).
160. Gao, F. et al. Multiscale climatological albedo look-up maps derived from moderate resolution imaging spectroradiometer BRDF/albedo products. *J. Appl. Remote Sens.* **8**, 083532–083532 (2014).
161. Hao, D., Wen, J., Xiao, Q. & Yu, W. Sensitivity of vegetation shortwave albedo to topography. In *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium* 6051-6054 (2019).
162. Klein, A. G., Hall, D. K. & Riggs, G. A. Improving snow cover mapping in forests through the use of a canopy reflectance model. *Hydrol. Process.* **12**, 1723–1744 (1998).
163. Raleigh, M. S. et al. Ground-based testing of MODIS fractional snow cover in subalpine meadows and forests of the Sierra Nevada. *Remote Sens. Environ.* **128**, 44–57 (2013).
164. du Toit, F., Coops, N. C., Mulverhill, C. & Toomey, A. Assessing the impact of afforestation as a natural climate solution in the Canadian boreal. *Environ. Res. Ecol.* **3**, 035004 (2024).
165. Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., & Cavard, X. Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. *Curr. Forest. Rep.* **7**, 245–266 (2021).
166. Lempière, T. C. et al. Canadian boreal forests and climate change mitigation. *Environ. Rev.***21**, 293–321 (2013).
167. Polanyi, M., Skene, J., Simar, A.-A. Reported greenhouse gas (GHG) emissions from logging in Canada double after revision to government data. *Nature Canada*. https://naturecanada.ca/wp-content/uploads/2024/09/2024-Logging-Emissions-Update-Report.pdf (2024).
168. Gaboury, S., Boucher, J. F., Villeneuve, C., Lord, D. & Gagnon, R. Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec's closed-crown boreal forest. *Forest Ecol. Manag.* **257**, 483–494 (2009).
169. Ameray, A., Bergeron, Y. & Cavard, X. Modelling the potential of forest management to mitigate climate change in Eastern Canadian forests. *Sci. Rep.* **13**, 14506 (2023).
170. O'Donoghue, S. Planting trees in the wrong places could be contributing to global warming, study reveals. *Euronews* https://www.euronews.com/green/2024/03/27/planting-trees-in-the-wrong-places-could-be-contributing-to-global-warming-study-reveals (2024).
171. Banerjee, P. Restoring tree cover may lead to global warming but only in some places. *Down To Earth* https://www.downtoearth.org.in/interviews/environment/-restoring-tree-cover-may-lead-to-global-warming-but-only-in-some-places--95819 (2024).
172. Graham, J. Is tree planting all it's cracked up to be? *Context News* https://www.context.news/nature/is-tree-planting-all-its-cracked-up-to-be (2024).
173. Kristensen, J. Å. et al. Tree planting is no climate solution at northern high latitudes. *Nat. Geosci.* **17**, 1087–1092 (2024).
174. Forster, P. M. et al. Recommendations for diagnosing effective radiative forcing from climate models for CMIP6. *J. Geophys. Res. Atmos.* **121**, 12–460 (2016).
175. Smith, C. J. et al. Effective radiative forcing and adjustments in CMIP6 models. *Atmos. Chem. Phys.* **20**, 9591–9618 (2020).
176. Huang, S., Meng, S. X., & Yang, Y. A growth and yield projection system (GYPSY) for natural and post-harvest stands in Alberta. *Forestry Division, Alberta Sustainable Resource Development*, (2009).
177. Kull, S. J. et al. *Operational-Scale Carbon Budget Model of the Canadian Forest Sector CBM-CFS3 Version 1.0: User's Guide* (2007).
178. Kato, S., Rose, F. G. & Charlock, T. P. Computation of domain-averaged irradiance using satellite-derived cloud properties. *J. Atmos. Ocean. Technol.* **22**, 146–164 (2005).

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