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Tree planting is no climate solution at northern high latitudes

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Planting trees has become a popular solution for climate change mitigation, owing to the ability of trees to accumulate carbon in biomass and thereby reduce anthropogenic atmospheric CO_2 enrichment. As conditions for tree growth expand with global warming, tree-planting projects have been introduced in regions of the highest northern latitudes. However, several lines of evidence suggest that high-latitude tree planting is counterproductive to climate change mitigation. In northern boreal and Arctic regions, tree planting results in net warming due to increased surface darkness (decreased albedo), which counteracts potential mitigation effects from carbon storage in areas where biomass is limited and of low resilience. Furthermore, tree planting disturbs pools of soil carbon, which store most of the carbon in cold ecosystems, and has negative effects on native Arctic biota and livelihoods. Despite the immediate economic prospects that northern tree planting may represent, this approach does not constitute a valid climate-warming-mitigation strategy in either the Arctic or most of the boreal forest region. This has been known for decades, but as policies that incentivize tree planting are increasingly adopted across the high-latitude region, we warn against a narrow focus on biomass carbon storage. Instead, we call for a systems-oriented consideration of climate solutions that are rooted in an understanding of the whole suite of relevant Earth system processes that affect the radiative balance. This is crucial to avoid the implementation of ineffective or even counterproductive climate-warming mitigation strategies in the Arctic and boreal regions.

Since the global tree-planting potential was estimated half a decade ago[1], afforestation and reforestation initiatives have accelerated across the world[2]. Controversially, Bastin et al.[1] have identified large areas of well-functioning open ecosystems as areas that are suitable for tree planting, leading to severe recent pushback, particularly from scientists and conservationists working in open temperate and tropical ecosystems[3], for example, in savannas[4,5], drylands[6] and rangelands[7]. This criticism is twofold: (1) these ecosystems are ancient and well-functioning homes of the largest diversity of remaining megafauna species; and (2) drylands are generally becoming drier and thereby increasingly unsuitable for tree growth. At high latitudes, however, warming and carbon dioxide (CO_2) fertilization can expand the areas that are suitable for tree growth in the Arctic region[8,9] and increase tree growth rates in parts of the boreal zone[10]. Nonetheless, the natural realization of this expanded environmental niche space via the northward advancement of the treeline has been slower than

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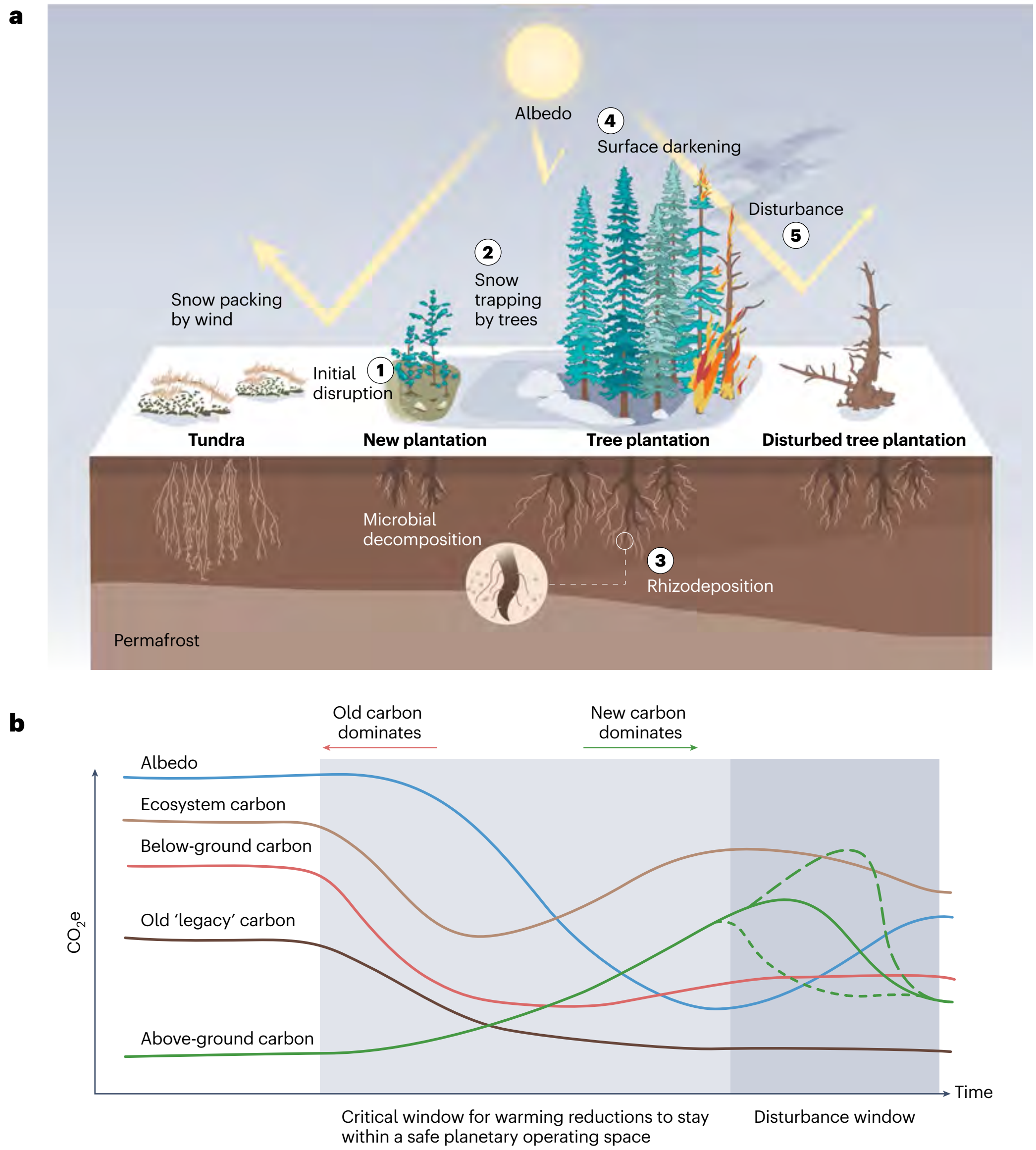

Fig. 1 | The direct and indirect effects of afforestation on climate forcing at high latitudes and their relative magnitudes over the lifetime of a plantation. **a**, Plantation establishment disrupts the previously intact soil, leading to increased decomposition of soil carbon by microbes (1), which is exacerbated by enhanced soil insulation caused by increased snow trapping and reduced snow packing (2). Growing trees exude carbon from their roots accelerating the turnover of soil carbon by root-associated microbes (3). As the plantation matures, trees darken the surface and diminish the proportion of energy reflected to the atmosphere (4). When a plantation is disturbed, the albedo increases while carbon stored in biomass decreases (5). **b**, The approximate relative magnitudes of the different responses to conversions are exemplified by the coloured lines (see Extended Data Tables 1–3 for justification). These magnitudes are expressed via the carbon dioxide-equivalent (CO_2e), a commonly used metric to compare various forcings on the energy balance, showing the equivalent mass of CO_2 needed to cause the same amount of global warming over a given period, often 100 years. See the main text for further explanation.

expected from the temperature increase[11,12]. Still, given the projected expansion of areas suitable for tree growth, the carbon farming industry has shown growing interest in high-latitude regions. For instance, the state government of Alaska has passed carbon offset legislation that encourages tree planting[13], which has readily been adopted by landowners[14]. Tree-planting initiatives for climate change mitigation have also emerged in Greenland[15] and Iceland[16]. However, northern tree planting is no solution to climate change mitigation. Below we outline the main reasons, supported by the most recent developments in this field.

High-latitude tree planting exacerbates climate warming

Several independent lines of evidence have demonstrated that planting trees at high latitudes tends to enhance climate warming. In a conceptual figure (Fig. 1), we summarize how the mechanisms behind the reduced capacity for mitigating climate warming vary along the lifespan of a plantation.

The carbon in an ecosystem is made up of above-ground (stems, twigs, leaves, fauna) and below-ground pools (roots, soil animals and microbes, 'dead' soil carbon) (Fig. 1). In the Arctic, a large fraction of the soil carbon is stored in permanently frozen soils, which alone hold an estimated 800–1,580 PgC in the upper 3 m of the soil[17,18]—more than all standing plant biomass on Earth[19]. These stores are the result of tens of thousands of years of the slow biological fixation of atmospheric CO_2 via photosynthesis exceeding ecosystem respiration at low temperatures. However, the resulting soil carbon (that is, old 'legacy' carbon in Fig. 1) is rather labile and highly vulnerable to disturbance[20,21]. Consequently, the physical disruption of the intact soil as a result of

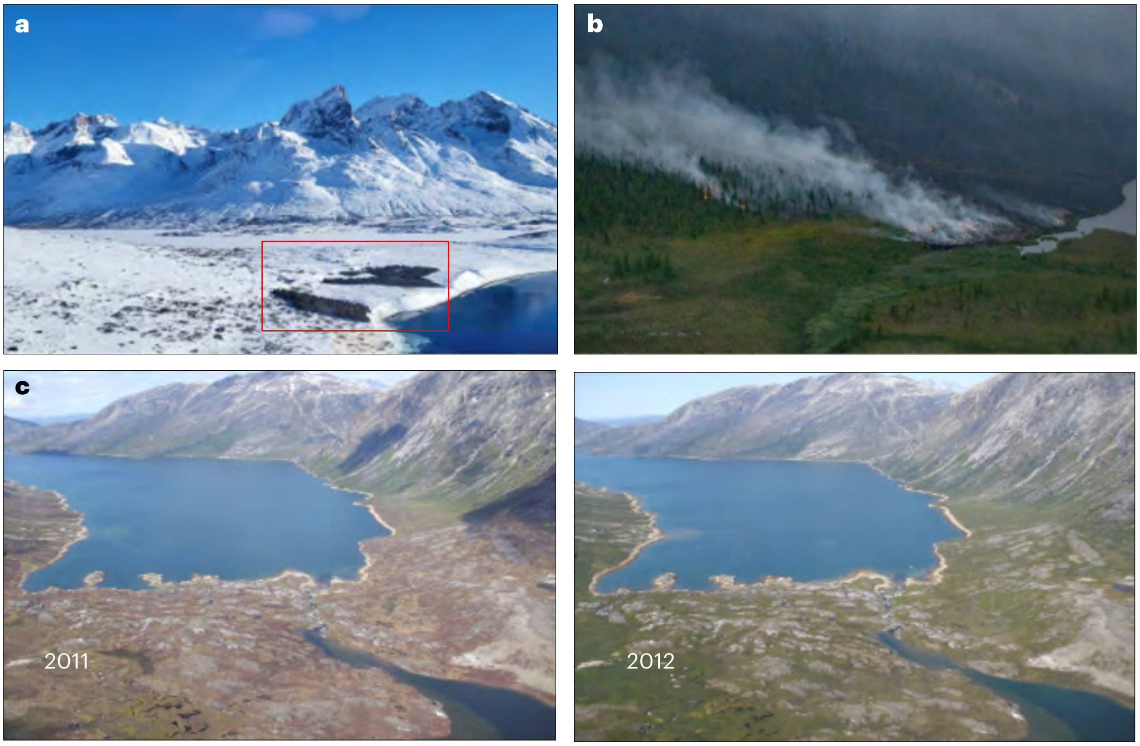

Fig. 2 | Examples of climate risks posed by northern tree planting. a, Albedo reductions due to plantation establishment in South Greenland (red box). **b**, Boreal forest fire in Russia. **c**, The landscape at Kobbefjord, southwestern Greenland, during (2011, left) and one year after (2012, right) a moth (*Eurois occulta*) outbreak (images taken on 20 July 2011 and 21 July 2012). Panel **c** reproduced with permission from ref. 58, Springer Nature Limited.

plantation establishment typically leads to the increased microbial decomposition of carbon in highly organic soils, which can take from decades to centuries to compensate for in cold regions[22]. After plantation establishment, the remaining soil carbon is exposed to increased decomposition that is triggered by the expansion of trees for several reasons. In ecosystems that are dominated by boreal trees, increased gains in biomass carbon due to CO_2 fertilization are often offset by the loss of below-ground carbon[23]. This is probably due to a combination of increased root penetration into deeper soil layers and the capacity of root-associated microbes to use the newly fixed carbon exuded from tree roots to decompose the soil's legacy carbon as they mine for growth-limiting nutrients. This process (the priming effect[24,25]) can, in concert with increased above-ground biomass, lead to an increasing dominance of newly fixed carbon (Fig. 1), which is reflected in a gradual decrease in the apparent mean age of the soil carbon pool (Extended Data Tables 1 and 2). Finally, compared with open landscapes, the trapping of snow by forests and the reduction in snow packing by wind result in effective soil insulation, increasing the soil temperature during winter[26] and outweighing the cooling effect of increased tree shade during summer[27]. This drives a deepening of the active layer, that is, the seasonally thawed layer above the permafrost[28], and enables the microbial decomposition of soil carbon to continue at low rates during the winter[26]. Together, these mechanisms can substantially accelerate the loss of soil carbon, occurring from the start of any tree-planting project and lasting for decades. The increased productivity of trees may eventually be on a par with increased below-ground losses after several decades, provided that no disturbances occur in between (see below). Yet, any climate mitigation project should factor in the timing of potential temporary increases in forcing. For northern tree planting that is going on now, such 'transaction costs' occur during the next two to four decades, when we most critically need reductions in warming (light grey window in Fig. 1).

As trees grow taller, surface darkening decreases the proportion of energy reflected directly back to the atmosphere (albedo) from ~75% for fresh snow to ~10% for needleleaf trees (Fig. 2a and Extended Data Tables 1 and 2). Put simply, when short-wave radiation (for example, light from the Sun) hits a surface, a proportion of it is reflected and a proportion is absorbed and emitted as long-wave radiation (heat) depending on the colour of the surface. The reflected portion does not contribute to warming the atmosphere as it is reflected as light rather than being emitted as heat. When trees are planted at high latitudes, the surface darkening alone more than offsets the climate mitigation effect from increased carbon storage in terms of atmospheric radiative forcing[29–33] (Extended Data Table 3). High-latitude systems are particularly sensitive to tall dark vegetation because of the pronounced snow and daylight seasonality. As the amount of solar energy input is very high during the spring when snow is still on the ground (semicontinuous daylight in late spring/early summer), the albedo is extremely important for overall radiative forcing at high latitudes. While the effect of this feedback is clear for the transition of open vegetation (for example, tundra) to forest (Fig. 2a), the albedo feedback will also undermine most solutions for climate warming mitigation that are based on reforestation in the boreal forest zone (Extended Data Table 3)[29,31]. The albedo sensitivity to tall vegetation will only be amplified by the projected decrease in snow depth across the Arctic during the twenty-first century, as winter precipitation increasingly falls as rain[34].

If trees make it to maturity, wildfires (Fig. 2b), droughts and pest outbreaks (Fig. 2c), which increase with climate warming[35–37], threaten the permanence of carbon stored in high-latitude ecosystems[38,39]. Boreal trees in general, and homogeneous even-aged stands in particular, are vulnerable to such disturbances when they reach a certain age[40–42] (the disturbance window in Fig. 1), whereas native tundra plants are generally more protected due to the majority of their biomass being below ground[43]. From 2018 to 2020 Arctic fires accounted for almost half of the total burned area of Arctic Siberia during the past two decades[39]. As wildfires are increasing in both area and intensity, the amount of carbon lost to flames will probably increase in the coming decades, even without plantations to fuel them. Hence, storing carbon in live

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biomass in high-latitude systems is a risky strategy. The intensification of disturbance regimes is particularly rapid in high-latitude regions, where extreme weather events have increased substantially in both count and severity over the past four decades[44], where the average climate warming rates were four times higher than the global average[45]. Projecting climatic changes to the end of this century shows that there will be severe knock-on effects on other growth-determining variables, notably a decrease in soil moisture[34], which already inhibits warming and CO_2-fertilization-induced tree-growth acceleration in large parts of the boreal region[10]. Consequently, the integrated long-term net carbon storage in high-latitude ecosystems may reach similar or lower levels after tree-planting projects than before, but with higher sensitivity to disturbances, decreasing its predictability. In Fig. 1, we illustrate the potential impact of this uncertainty on above-ground carbon stocks with three possible trajectories (green lines) within a 'disturbance window'. If a stand-replacing disturbance occurs late in this window or not at all, the above-ground carbon may reach levels that compensate for loss of the below-ground carbon (long-dashed line). However, if a disturbance occurs early in the disturbance window, the ecosystem carbon may never reach the initial level (short-dashed line). Moreover, interactions between disturbances and other important climate feedback should also be expected, for example, positive interactions between wildfires and permafrost thaw[46]. It is important to note that different disturbances have different outcomes. For instance, insect outbreaks or droughts may have smaller effects on both above-ground biomass reduction and albedo increase—both in magnitude and duration—than stand-replacing fires. Finally, it should be noted that, even in cases when stocks of ecosystem carbon after tree planting reach levels similar to those before planting, the net climate effect of the intervention would still enhance warming due to the decreased albedo effect.

Climate mitigation strategies beyond carbon

Achieving no net increase in radiative forcing due to human activities—sometimes referred to as net zero[47]—remains a tremendous global challenge. Because net zero has often been applied to greenhouse gas (GHG) emissions alone, that is, focussing on balancing the GHG emissions and sinks, avoiding increased GHG emissions and removing gases from historical emissions has been the main focus. This is justifiably so, as emission reduction from human activities must remain the number one priority for climate mitigation[47]. However, climate forcings other than GHGs cannot be disregarded if we truly aim to mitigate climate warming, and recent calls have been made to move towards including other effects of human activities that influence the world's energy budgets, such as land cover driven albedo changes[29,32].

Biodiversity conservation as an alternative way forward

High-latitude afforestation is still in its infancy, so this is the time to reconsider policies and strategies for climate mitigation and adaptation in this region. Science has long established that high-latitude afforestation exacerbates climate warming, and, in the wrong places and/or with the wrong implementation, it also has detrimental effects on local ecosystems and livelihoods. Fortunately, there are other strategies for climate change mitigation in this region. In fact, efforts to preserve and restore open and semi-open ecosystems with sustainable populations of large herbivores may present the most reliable way of mitigating climate change[19,48], as well as climate-driven reductions in biodiversity driven mainly by woody encroachment[49,50], while ensuring continued access to and the use of landscapes by local communities.

Beyond falling short of representing an effective strategy for climate warming mitigation, tree planting in open ecosystems carries risks for nature and societies worldwide[3,51]. The continued use by local communities of open and semi-open landscapes in northern regions for hunting, herding, gathering and ceremonial purposes poses the pertinent concern of fundamentally changing land cover at high latitudes through carbon farming. Future land use strategies should stem from local communities to ensure that they are aligned with the complex long-term goals of the many rather than short-term economic benefits for the few. This is particularly important in a region of the world with complex property rights, where communal rights to land are common[52].

Moreover, the conversion of both open tundra and boreal forests to—mostly monospecific—plantations impacts biodiversity negatively[53,54]. The global demand for restored or intact nature is expected to increase substantially in the near future. This will be driven partly by increasing the requirements of large corporations to disclose and mitigate their negative environmental footprints beyond carbon[55,56] and partly due to rising global incomes making individuals, on average, willing to pay for biodiversity conservation while, at the same time, biodiversity rapidly declines[57]. Thus, the conservation and restoration of well-functioning, biodiverse ecosystems may soon represent not just a more sustainable land use strategy but also an economically viable alternative to tree planting.

In conclusion, the northern high-latitude region serves as a prime example of how so-called 'carbon tunnel vision' can be detrimental to achieving both the main target of a carbon farming project, that is, mitigating climate warming, and other and equally important agendas such as biodiversity conservation and thriving local communities. Truly sustainable nature-based climate solutions may only be achieved through (1) a holistic understanding of Earth system processes, (2) not sacrificing biodiversity or human livelihoods and (3) acknowledging that sustainable solutions are often system-specific.

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Author contributions

All authors contributed to the initial conceptualization. J.Å.K. wrote the first version of the manuscript with substantial inputs from M.M.-F., and L.B.-P., I.C.B., I.B.D.J., J.T.K., E.L.-B., Y.M., M.L.M., C.W.M., E.P. and K.R. provided important inputs on subsequent versions. L.B.-P. made the illustration for Fig. 1. M.L.M. and J.T.K. provided photographs for Fig. 2a,b. J.Å.K. led the manuscript revisions with inputs from M.M.-F. Input and approval of the revised manuscript before resubmission was given by L.B.-P., I.C.B., I.B.D.J., J.T.K., E.L.-B., Y.M., M.L.M., C.W.M., E.P. and K.R. The author list is presented in alphabetical order, except for the first and last authors.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Table 1 | Reference values for the tundra ecosystem in Fig. 1b

TUNDRA/OPEN											
Ecosystem	**Value**	**Coverage**	**Best estimate**	**Unit**	**Best est. description**	**Low estimate**	**Low est. description**	**High estimate**	**High est. description**	**Data type**	**Reference**
Tundra	Vegetation biomass	Canadian Arctic above treeline	0.735	kg biomass m-2	low arctic semidesert	0.018	polar desert	3.867	tall shrub	Literature review	59
Tundra	Vegetation biomass	Circumpolar	0.241	kg biomass m-2	Subzone C	0.084	Subzone A	0.564	Subzone E	Field data	60
Tundra	Soil carbon	Circumpolar permafrost zone	31.6	kg C m-2 to 1m	mean, graminoid/forb tundra	8.6	mean-SD, graminoid/forb tundra	54.6	mean+SD, graminoid/forb tundra	Field data	18
Tundra	Age of soil carbon (0-30 cm)	Global	3,490	years	median	1660	lower 95% CI	4310	upper 95% CI	Extrapolated field data	61
Tundra/grassland	Albedo -snow	Canadian boreal	20%	% radiation reflected	mean, grass	19%	mean site 2	20%	mean site 1	Field data	62
Tundra/grassland	Albedo +snow	Canadian boreal	75%	% radiation reflected	mean, grass	72%	mean site 1	77%	mean site 2	Field data	62
Tundra/grassland	Permafrost thaw (active layer) depth	Interior Alaska	68.7	cm to permafrost table	mean herbaceous 2021 Tunnel site	45.7	mean-SD herbaceous 2021 Tunnel site	91.7	mean+SD herbaceous 2021 Tunnel site	Field data	28
Tundra	Minimum soil temperature	Circumpolar	-13.8	°C	mean minimum soil temperature, graminoid tundra	-14.7	lower 95% CI	-12.9	upper 95% CI	Field data	27

Reference values[18,27,28,59–62] for the tundra ecosystem informing the relative shapes and magnitudes of the coloured lines in Fig. 1b. These values represent the characteristics of the tundra before conversion to plantation, while the forest/canopy values in Extended Data Table 2 represents the point just before harvest/disturbance. Thus, the transitional period in between is not represented by these numbers, but the general mechanisms behind our expectations are described in the main text.

Extended Data Table 2 | Reference values for the plantation ecosystem in Fig. 1b

FOREST/CANOPY											
Ecosystem	**Value**	**Coverage**	**Best estimate**	**Unit**	**Best est. description**	**Low estimate**	**Low est. description**	**High estimate**	**High est. description**	**Data type**	**Reference**
Boreal forest	Vegetation biomass	North American boreal	4.18	kg biomass m-2	mean	3.18	lower 95% CI	5.18	upper 95% CI	Field data	63
Boreal forest	Vegetation biomass	Southern Canadian boreal (w. logging)	7.3	kg biomass m-2	mean	1.6	min pixel value	15	max pixel value	Remote sensing	64
Boreal forest	Soil carbon	Circumpolar permafrost zone	14.6	kg C m-2 to 1m	mean, evergreen needleleaf forest	1.8	mean-SD, evergreen needleleaf forest	27.4	mean+SD, evergreen needleleaf forest	Field data	18
Boreal forest	Age of soil carbon	Global	1,020	years	median	650	lower 95% CI	2,750	upper 95% CI	Extrapolated field data	61
Boreal forest	Albedo -snow	Canadian boreal	8%	% radiation reflected	mean, spruce/poplar	8%	mean, spruce/poplar site 8	9%	mean, jack pine site 9	Field data	62
Boreal forest	Albedo +snow	Canadian boreal	11%	% radiation reflected	mean, spruce/poplar	9%	mean, spruce/poplar site 8	17%	mean, jack pine site 9	Field data	62
Boreal forest	Permafrost thaw (active layer) depth	Interior Alaska	88.3	cm to permafrost table	mean evergreen forest 2021 Tunnel site	46.4	mean-SD herbaceous 2021 Tunnel site	130.2	mean+SD herbaceous 2021 Tunnel site	Field data	28
Boreal forest	Minimum soil temperature	Circumpolar	-7.3	°C	mean minimum soil temperature, evergreen needleleaf	-11.6	lower 95% CI	-3.4	upper 95% CI	Field data	27

Reference values[18,27,28,61–64] for the plantation ecosystem informing the relative shapes and magnitudes of the coloured lines in Fig. 1b. These values represent the expected characteristics of a high-latitude tree-covered ecosystem at its peak, i.e. just before harvest/disturbance, while the tundra values in Extended Data Table 1 represents the values before plantation establishment. Thus, the transitional period in between is not represented by these numbers, but the general mechanisms behind our expectations are described in the main text.

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Extended Data Table 3 | The Net Climate Impact (carbon–albedo) of tree planting Fig. 1b

Units	Area Mha	Carbon only Pg CO2e	Total NCI (C+albedo) Pg CO2e	NCI avg density Mg CO2e ha-1	Avg albedo offset %	<50% AO % area	>100% AO % area
TUNDRA							
Bastin	53	7	-2 [-6 - 1]	-46 [-107 - 14]	136 [183 - 89]	11 [7 - 24]	63 [76 - 42]
Walker	198	26	-19 [-36 - -6]	-95 [-180 - -28]	174 [240 - 122]	6 [3 - 14]	76 [87 - 58]
TotalBiome	458	51	-50 [-87 - -19]	-110 [-190 - -41]	198 [269 - 136]	9 [5 - 18]	71 [81 - 57]
BOREAL/TAIGA							
Bastin	176	31	4 [-3 - 12]	24 [-20 - 66]	86 [111 - 62]	27 [18 - 41]	39 [53 - 23]
Walker	144	23	-9 [-18 - 1]	-59 [-125 - 6]	137 [178 - 96]	14 [9 - 22]	63 [75 - 45]
TotalBiome	1411	289	60 [-1 - 120]	42 [0 - 85]	79 [100 - 58]	28 [17 - 45]	34 [46 - 19]

Modelled values summarising the climate offset by carbon storage only, and the net climate impact (NCI) when albedo is considered. The last two columns show the proportion of the total area in the land cover class where albedo offsets <50% (green) and >100% (red) of the carbon storage mitigation potential, respectively. Modified from Table S2 in ref. 29. Uncertainties in square brackets reflect the maximum and minimum values across the six radiative kernels (see ref. 29 for details). Note that the Griscom opportunity map is ignored, as it does not include numbers for the tundra biome.