State and future of boreal forest natural climate solutions

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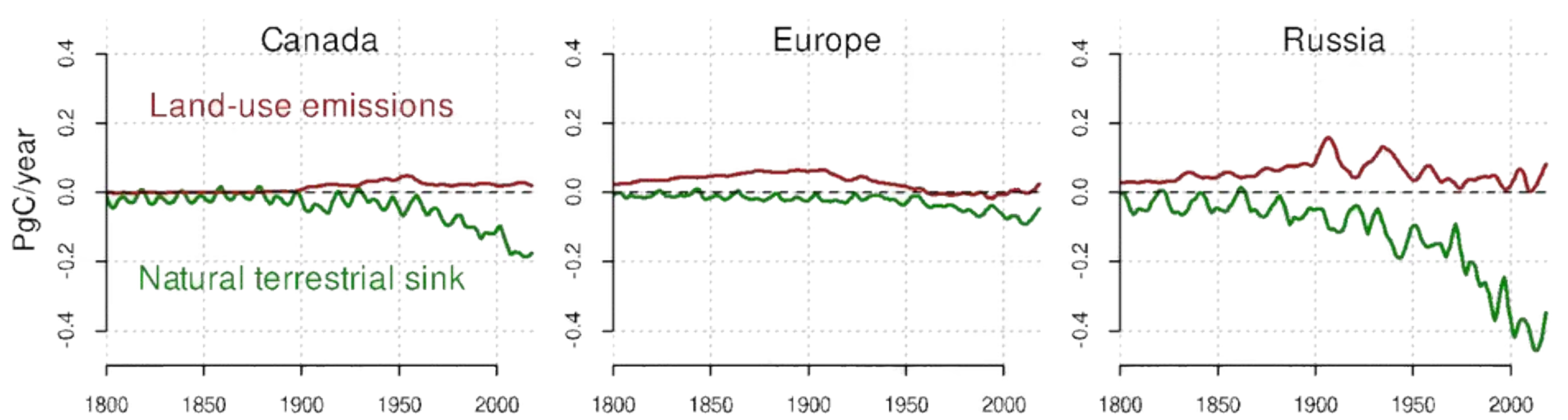
Boreal forests are strong carbon sinks but show signs of weakening

The 20th century saw a **decrease in land-use emissions and an increase in CO_2 uptake on managed and unmanaged boreal ecosystems due to climate change, effects of rising CO_2, and nitrogen deposition** (Fig. 2). The net effect of both is an increase in net CO_2 uptake to about 0.6 PgC/year (>50N) in the last decade. The increase is consistent with the increased northern land sink found from inversions (Ciais Nature 2019), and larger than inventory-based estimates (Pan et al Science 2011) due to carbon export by rivers and trade (Ciais et al, NSR, 2021).



Net sink = environmental + anthropogenic effects = natural terrestrial sink + land-use fluxes

Fig. 2 Natural and anthropogenic drivers of boreal (>50°N) CO_2 fluxes from vegetation, soil, litter and products, average over 11 vegetation models [5].

However, the sink per unit area is only half that of temperate forests, and in the recent decade signs emerged that the **net CO_2 sink may be weakening**, e.g. browning trends in vegetation activity become discernible (Fig. 3).

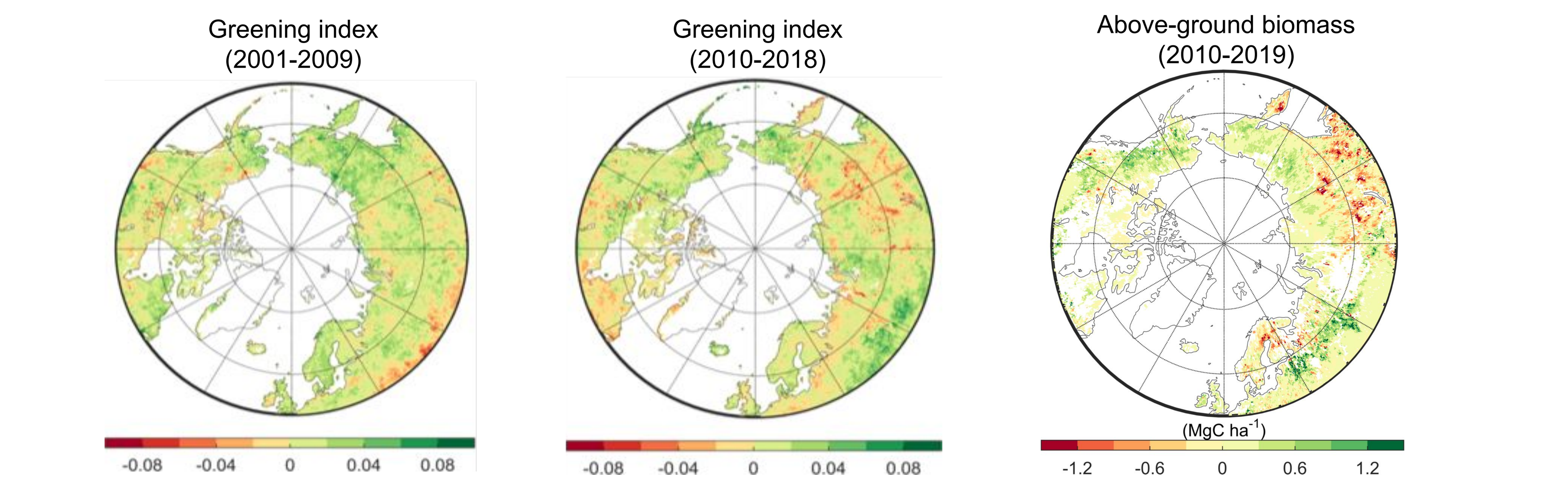
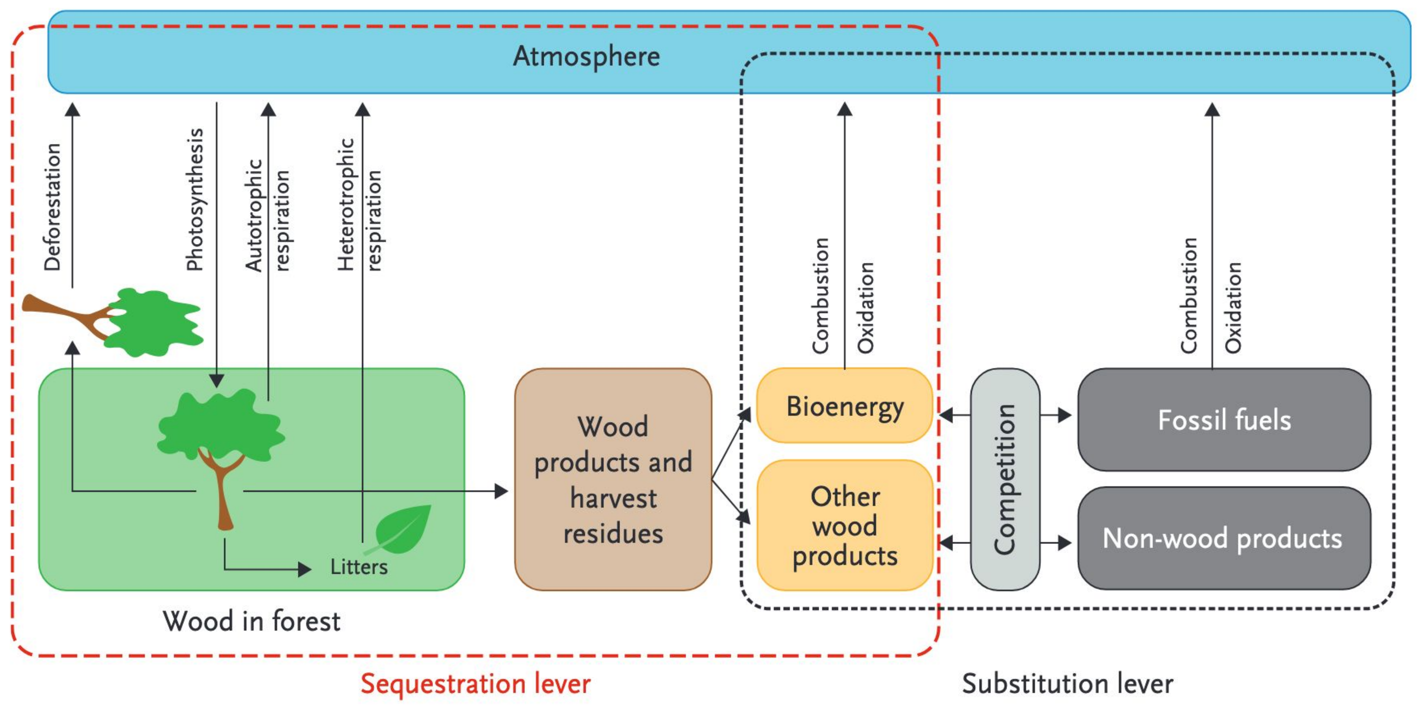


Fig. 3 A satellite-based greening index suggests an increase in browning (red colors) from 2001-2009 to 2010-2018. Large areas in Siberia and Scandinavia lost biomass in 2010-2019 (data based on [6]).

The future **sink is under threat as disturbances (drought, fire, pests) increase** in intensity and/or frequency. Long recovery times and being a climate change hotspot make the boreal particularly susceptible. Feedback effects have not been comprehensively assessed and may accelerate carbon loss e.g. via increased soil respiration and permafrost thawing, but may also include negative (dampening) feedbacks [7]. Related uncertainties need to be considered in decision-making.

Overview: Natural climate solutions in the boreal forests include protection, restoration and sustainable management of the forests with the goal of mitigating climate change while also addressing other societal challenges. While the currently strong CO_2 sink in the forests shows signs of weakening, using forest products may contribute to climate mitigation. However, benefits of management are strongest on long timescales and trade-offs with other ecosystem services need careful consideration.

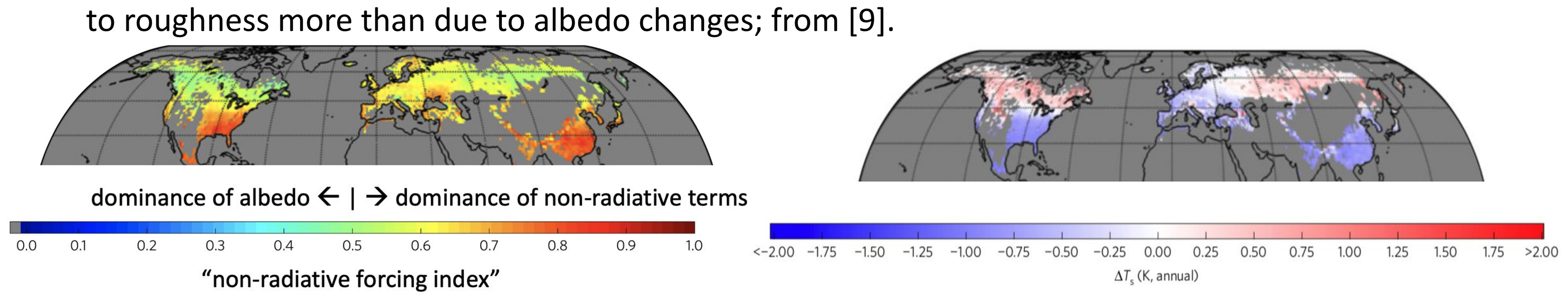
Fig. 1 Scheme of carbon stocks and fluxes between atmosphere, biosphere and fossil reservoir, and the two mitigation levers; from [1].



Forests' climate impact: more than carbon and albedo

The overall mitigation potential of forests needs to also consider effects on energy and water fluxes. While boreal forests warm the globe due to their lower albedo, the local temperature signal, relevant for adaptation, is more mixed and dominated by the higher roughness of forests (Fig. 4) mixing in warm air from above in winter and night-time [8].

Fig. 4 Needleleaf forests, compared here to grasslands, tend to warm the local climate due to roughness more than due to albedo changes; from [9].



Key to sustainable forest management is a **multidimensional assessment of forests' values,** as economic benefits may provide only 5-20% of the total value when biodiversity, water and air quality, recreation and other values are factored in [10] (Fig. 5). Many non-economic values are degraded as old natural forests are cut throughout the boreal zone and converted to plantations (in Sweden, at a rate of at least 1% per year [11]).

Fig. 5 Natural, rotation and continuous cover forests fulfill ecosystem services in different respects.

Benefits of forest products vary widely

depending on how they are produced and what they substitute

Determining the net CO_2 effect of forests requires a **system perspective:** increased soil respiration may compensate aboveground growth seen by inventories, both carbon stored in forests and in wood products need to be accounted for, and the impact of using these products to replace energy-intensive material and fossil fuels needs to be considered (Fig. 1). When accounting towards a climate target, a reference level may help identifying the additional mitigation, as **CO_2 uptake on managed forests is partly due to environmental effects** (Figs. 2, 6), **not management.**

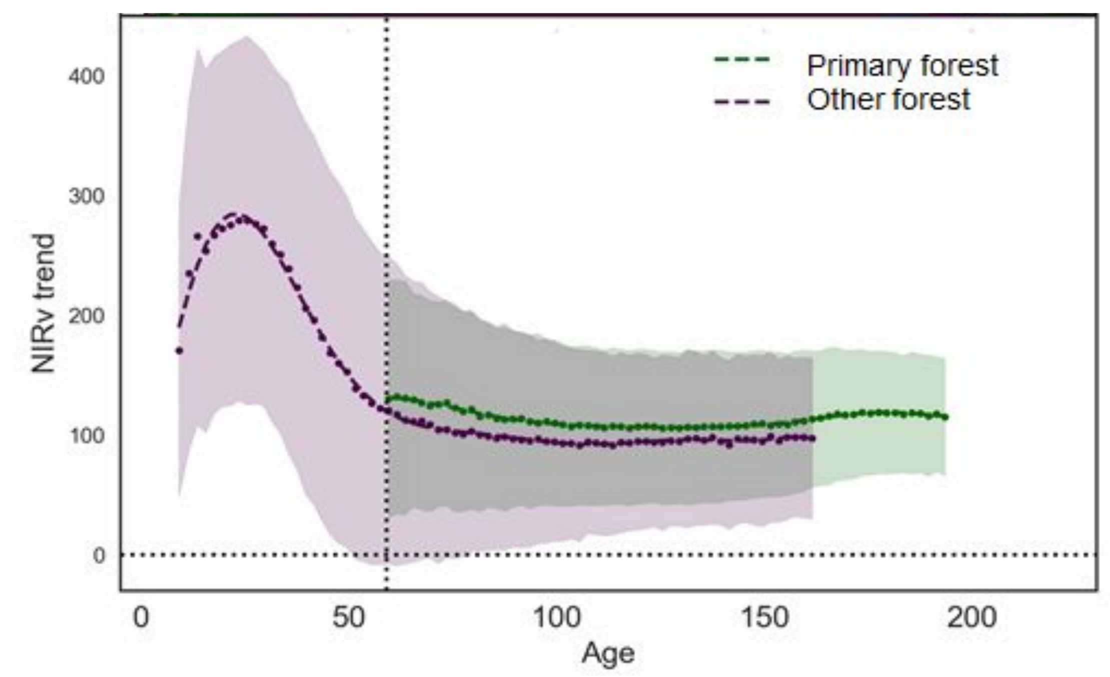


Fig. 6 Greening in adjacent pairs of managed and primary (pristine) forests in Sweden since 1984. While regeneration increases the greening, mature primary stands have greened faster than planted and managed mature stands; from [12].

What matters for climate change is the atmospheric perspective. Immediate emissions from bioenergy may be higher than from fossil fuels per unit energy, but they are not accounted for in the energy sector, since they are assumed to be included at harvest in the LULUCF sector. Typically, 0.5-1.0 units of fossil carbon can be avoided with one unit of biomass carbon harvested [14]. The initial increase in emissions may take decades to remove as forests regrow, which can be inconsistent with the urgency of the Paris Agreement's goals, even if in the long term there is a climate benefit (Fig. 7). Policies could enforce short payback times, which could be achieved through more efficient residue management, recycling, and a larger faction of long-lived products.

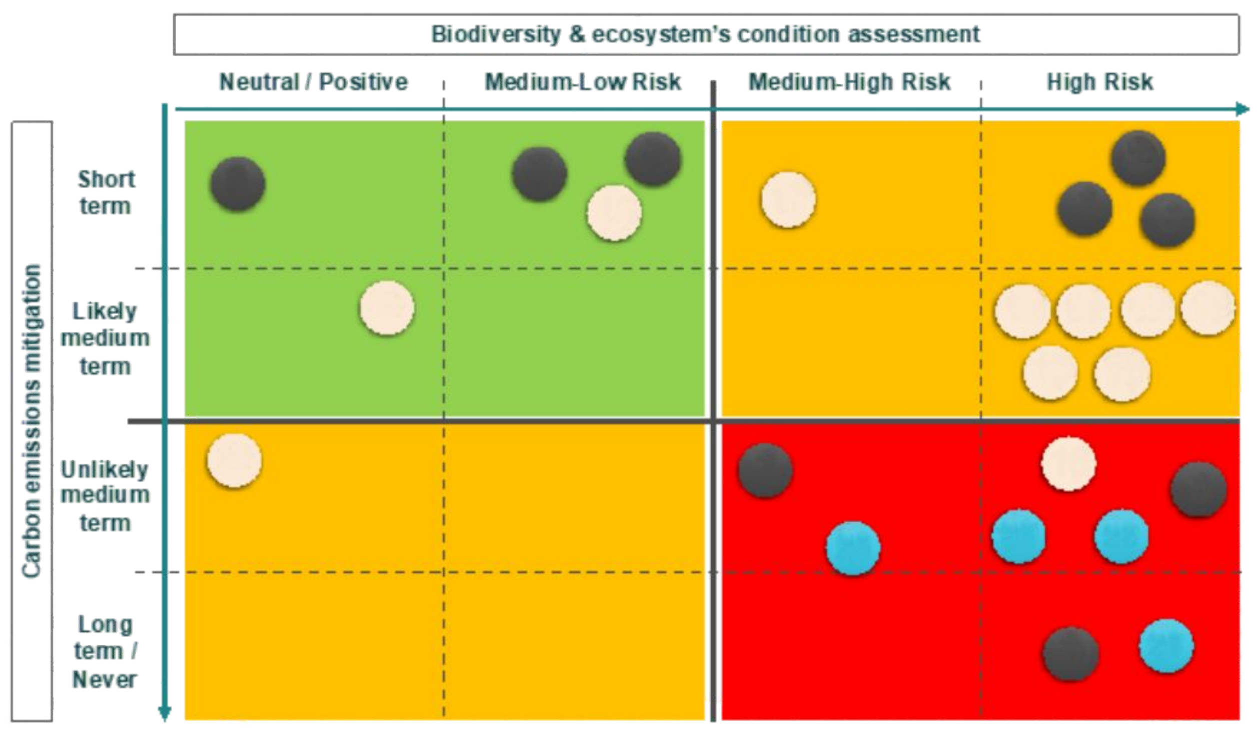


Fig. 7 Plantations (various pathways, blue) often have longer payback times, associated with risks for other ecosystem services, than afforestation (yellow) or residue removals (gray); from [13].

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