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Arctic driftwood proposal for durable carbon removal

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Various geoengineering approaches have been proposed for carbon dioxide (CO_2) removal but their viability at scale remains unclear. Here, we consider the natural behaviour of driftwood, the warming-induced acceleration of sea-ice loss and tree growth, as well as the stability of cellulose in subfossil wood under cold-anoxic conditions, to introduce the concept of sinking timber from the boreal forest for durable CO_2 sequestration at the deep Arctic Ocean floor.

Capture and storage of atmospheric CO_2 offer a means to stabilise climate alongside emission-reduction efforts. However, it is estimated that over 10 gigatonnes (Gt) of CO_2 would have to be removed and sequestered each year over the 21st century to mitigate legacy effects of anthropogenic greenhouse gas emissions and compensate for those sources expected to remain hard to decarbonise[1–3]. While reductions of fossil fuel burning must be prioritised at national and international levels[3,4], different hybrid nature-engineering technologies have been recommended to capture and store CO_2 from the Earth's atmosphere. Although frequently presented as viable strategies for mitigating the effects of greenhouse gas emissions[1,2], many approaches face questions regarding their scalability and the risk of counterproductive consequences for humans and the environment[5].

Among proposed solutions is 'Wood Vaulting' (WV) or 'Wood Harvesting and Storage' (WHS)[1,2,5], which involves burying woody biomass in engineered enclosures that inhibit decomposition under anaerobic or frozen conditions, thereby ideally sequestering carbon on multi-millennial or even longer timescales. A prototype Wood Vault Unit (WVU) of 1 ha spatial extent and 20 m soil depth could store around 10^5 m^3 of timber, which is equivalent to approximately 0.1 Mt CO_2. It would therefore take annual construction of 10^4 WVU to operate at 1 Gt yr^{-1} of CO_2 removal, corresponding to a roughly 25% increase in global logging (currently around 4×10^9 m^3 of wood annually[6]). Substantial ecological and societal trade-offs can be expected from operating at such scale, including lasting impacts on soil carbon and mycorrhizal networks, biodiversity loss, and co-emissions associated with deforestation, transportation and vault construction[5,7]. Further, the putative benefits of WV would be offset if only a fraction of methane generated from decaying wood reaches the atmosphere[8,9].

Here, we examine the natural occurrence and behaviour of driftwood from the boreal forest to introduce a variant of WHS that would involve durable carbon storage on the deep, near anoxic floor of the Arctic Ocean.

Driftwood solution for carbon sequestration

The circumpolar boreal forest zone stretches across northern North America and Eurasia, from Alaska and northern Canada through Scandinavia and across the Siberian taiga. Characterised by cold climates, slow growing conifers, widespread peatlands, extensive permafrost soils, and gigantic river systems[10–12], the world's largest terrestrial biome also represents an enormous carbon pool[13,14], with as much as 10^3 Gt (10^{18} g) of carbon stored in living trees, dead wood, soils and peat[15]. Unlike wildland tropical forests, the estimated carbon stocks of boreal forest ecosystems are likely to increase under global warming[16], though whether the taiga as a whole becomes a net source or sink of carbon under warming remains unclear[15]. Parts of the boreal forest export large quantities of organic matter to riparian zones and fluvial networks, which ultimately reach the Arctic Ocean via surface runoff, riverbank erosion and mass wasting[17,18]. This drainage includes substantial but unquantified amounts of coarse woody material, known as driftwood[19], some of which accumulates in the vast delta systems of large boreal rivers and along Arctic coastlines[20,21].

Riverbank erosion strongly controls the amount of natural driftwood transported to the Arctic Ocean (Fig. 1A–C). In open ocean conditions, intact stems typically remain buoyant for 1 yr depending on species, but when entrained in sea ice they can be transported for several years before being released[19]. Timescales for wood to sink to the deep floor of the Arctic Ocean depend on density contrast, ocean depth and currents but are likely significantly shorter than floating time. This natural process is accelerating due to the combined effects of warming-induced permafrost thaw and forest expansion[22,23], as well as rapid sea-ice loss and increased river discharge[24,25] (Fig. 1D, E).

A few very large river systems drain broad sectors of the circumpolar boreal forest and deliver the majority of terrestrial freshwater and dissolved and particulate organic carbon to the Arctic Ocean[17,18,25,26]. The most important catchments (and their discharge) of the Russian taiga from west to east are those of the Ob (400 km^3 yr^{-1}), Yenisey (590 km^3 yr^{-1}), Lena (540 km^3 yr^{-1}), and Kolyma (70 km^3 yr^{-1}), while the Mackenzie in Canada (290 km^3 yr^{-1}) and Yukon in Alaska (210 km^3 yr^{-1}) drain most of the taiga in northern North America[17,26]. Collectively they represent an estimated 11% of global freshwater runoff[26]. While increasing their discharge rates, and hence the amount of driftwood that can reach the Arctic Ocean, recent anthropogenic warming is also affecting the capacity of individual trees and entire forest ecosystems to sequester CO_2 from the atmosphere. Total ring width and maximum latewood density values of conifers across the boreal forests of northern North America and Eurasia have been increasing since a period of reduced growth at the end of the 20th century[27,28] (Fig. 1F).

A key aspect of our thought experiment on using driftwood to sequester atmospheric carbon is the negligible rate of wood decay after sinking (Fig. 1C). Extremely low decay rates under near anoxic and freezing conditions[29,30] suggest the deep Arctic Ocean floor would be highly suited for

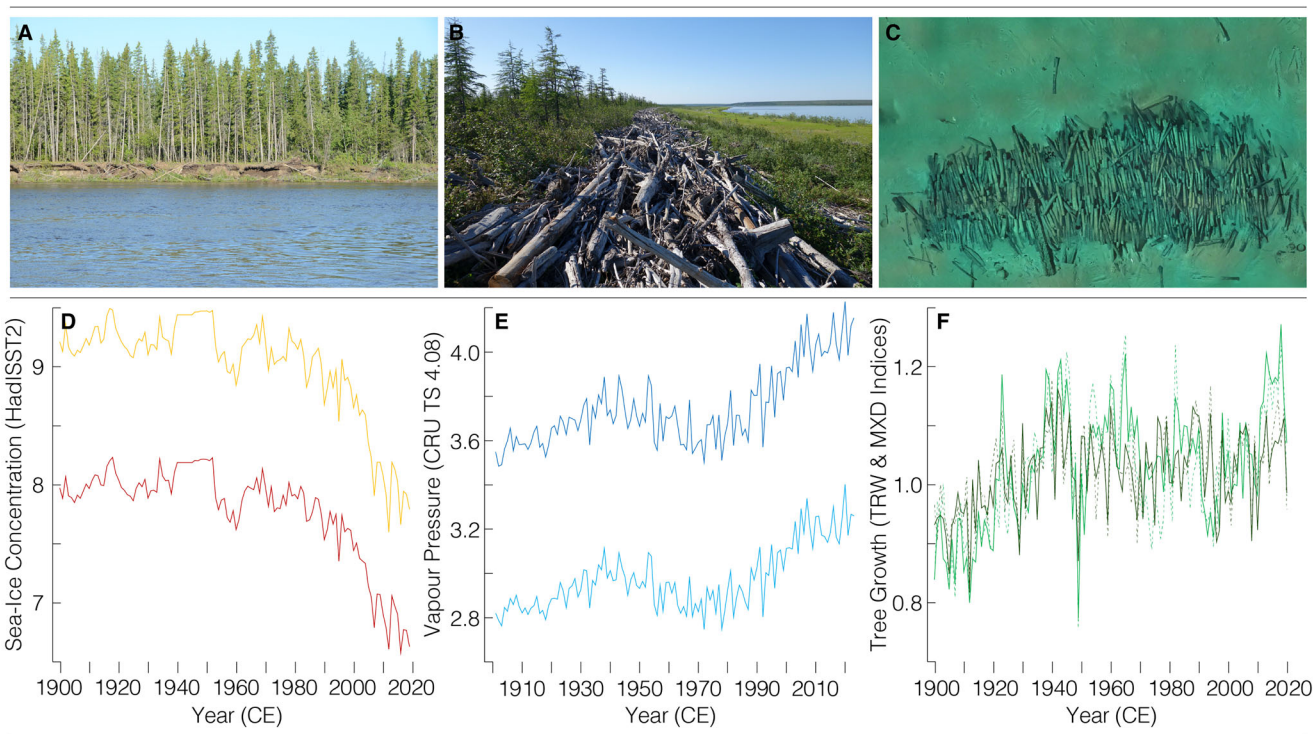

Fig. 1 | Arctic amplification and driftwood solution. A natural erosion and tree tipping, as well as (**B**) driftwood accumulation along the Indigirka river in north-eastern Siberia (taken by Ulf Büntgen in July 2016). (**C**) Underwater logs on the ocean floor of the northwest continental shelf of the Chinese Sea[51]. **D** changes in sea-ice concentration >60 and >66° North (red and orange, respectively) expressed as total annual sums of sea-ice cover anomalies[52], (**E**) changes in vapour pressure (warmer and wetter conditions) >60 and >66° North (dark and light blue, respectively) expressed as average hPa anomalies[53], and (**F**) changes in tree-ring width (TRW; light green) and maximum latewood density (MXD; dark green) expressed as mean and median (thin dashed lines) timeseries after 'signal-free age-dependent spline' detrending of eight undisturbed boreal forest sites in northern North America and northern Eurasia (https://climexp.knmi.nl and https://www.monostar.org).

long-term storage. This is supported by measurements of circa 200 living and relict, dry-dead and subfossil trees from different cold, oxic and anoxic environments in the European Alps (e.g., talus, lakes and peat), which revealed no systematic decline in α-cellulose content over the past 8000 years[31] (Fig. 2). The centennial to multi-millennial scale stability of wood carbon is further corroborated by decades of worldwide dendrochronological research on dry-dead and subfossil wood samples from historical buildings, archaeological excavations, and sediments spanning Holocene and even Pleistocene contexts[32]. While the composition and deposition of boreal driftwood should be confirmed, we expect the combination of low temperature, reduced oxygen and limited wood-borer activity to characterise large parts of the Arctic shelf and deep basin[33–35].

Conclusion and projection

Though widely discussed (and frequently criticised)[36–38], planting trees for carbon removal and storage has limited impact beyond their lifespan (captured by the adage "grow fast and die young")[39]. Evidence also suggests that afforestation of Arctic tundra is likely to result in net warming due to reduced surface albedo[38], negating perceived climate change mitigation benefits of high-latitude tree planting on previously unforested terrain. Instead, we suggest further exploration of the potential of harvesting and rafting large quantities of boreal timber into the Arctic Ocean for CO_2 removal and multi-millennial scale storage (Fig. 3). Given access to carbon rich, and economically unimportant boreal conifer trees with short transit routes to large river systems, combined with efficient monocultural reforestation practices, the cold Arctic Ocean could store vast quantities of carbon from Siberia and northern North America where biodiversity is low and the risk of wildfires high[40]. The burning-induced succession of boreal forests has almost tripled during the first two decades of the 21st century as the biome became warmer [41].

To achieve significant CO_2 drawdown, we propose, for the purposes of our thought experiment, three units of circa 10,000 km^2 (comparable to the size of Lake Onega in northwestern Russia near the Finnish border) for extensive harvesting and reforestation along each of the five main rivers and their tributaries in Russia, Alaska and Canada: Ob, Yenisey, Lena, Yukon, and Mackenzie. Due to high fire risk (and low human population), these regions carry ~10–30 t/ha of larch, pine or spruce timber for harvesting (at decreasing mass per unit area with increasing latitude). Taking 15 t/ha stand carbon content, annual logging and rafting of circa 180,000 km^2 timber could remove up to 1 Gt/y of CO_2. The total area of harvesting would represent around 1% of the boreal forest zone, comparable with the area consumed annually by wildfires[42,43]. All target regions should be even-aged, biodiversity-poor and fire-prone monocultural coniferous stands of low economic and cultural value. If logging is mainly carried out in winter, access may be facilitated by extensive ice roads, clearing can be performed on solid ground, and timber can be placed directly on the frozen rivers. Mulching small branches and other wooden remains can decrease fire risk, increase soil development, and enhance nutrient availability.

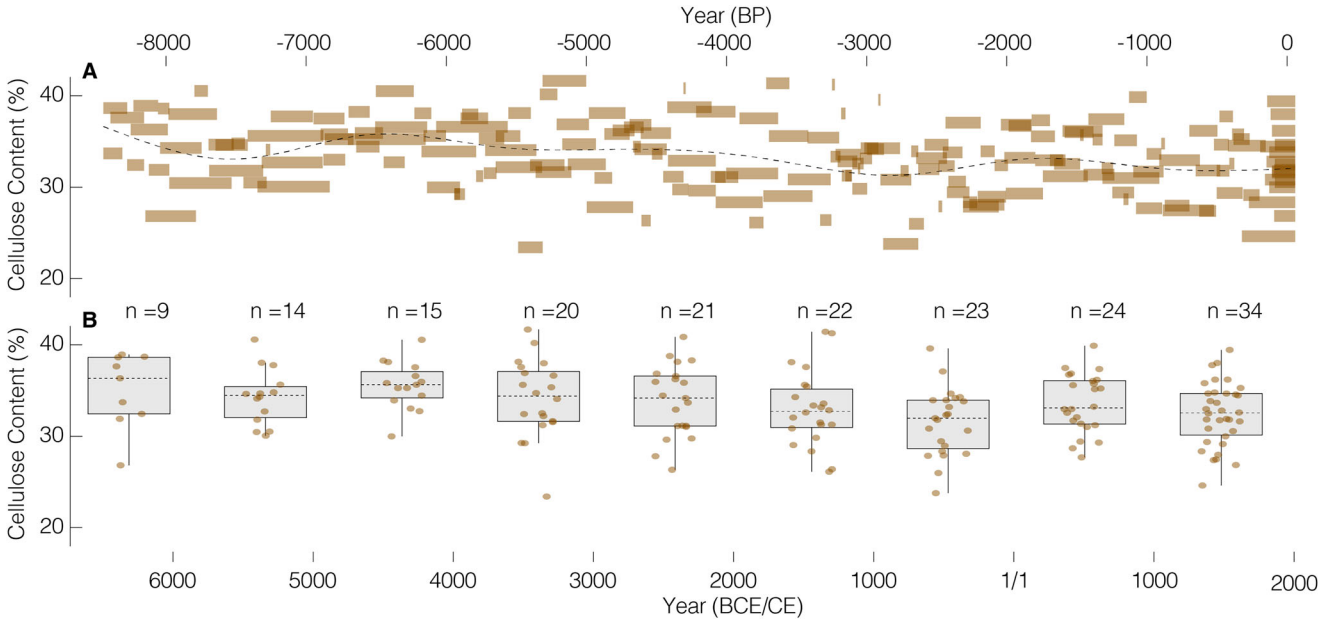

Fig. 2 | Wood preservation and carbon sequestration. A Alpha-cellulose content in 17 living and circa 183 relict, dry-dead and subfossil larch (*Larix decidua* Mill.) and pine (*Pinus cembra* L.) trees from the Austrian and Swiss Alps between 1950 and 2400 m asl, where wood preservation is promoted by near freezing conditions[31]. Brown horizontal bars show the timespan of the individual wood samples after precise cross-dating (x-axis) and the median α-cellulose content expressed in percentage and calculated from five-year blocks. The dashed line is the mean and suggests that there are no long-term effects of possible wood decay on α-cellulose content in living, dry-dead and subfossil trees over the past 8000 years (6980 BCE to 2015 CE). **B** Box plots summarise data for each millennium over much of the Holocene. We also measured 26.4% (±7.16) of remaining α-cellulose in a radiocarbon-dead subfossil tree trunk from northern Greenland (not shown).

Natural and silvicultural reforestation is likely to sequester most CO_2 during the first few decades of forest regeneration[44,45]. Such a multi-year, seasonal cycle of harvesting, sinking and replanting will always capture more CO_2 than any form of natural taiga succession in which trees grow slower and will either burn or decompose afterwards. Potential removal rates, however, can be expected to vary substantially between biogeographic zones, and boreal forests are less productive (but more durable) than those in warmer climates[44,45]. It should be further noted that the boreal rivers and their vast delta systems[19–21], together with large parts of the circumpolar coastlines of northern North America and Eurasia already contain significant amounts of driftwood[46].

Although our thought experiment should not distract from the priority of reducing greenhouse gas emissions, with continued economic growth undermining efforts to meet the Paris Agreement targets, carbon removal proposals are increasingly relevant[47]. As with other means for carbon capture and removal, our sylvicultural proposal is not without caveats and requires further interdisciplinary scientific investigation. We recognise significant issues must be evaluated carefully in developing and refining our concept not least concerning land ownership by indigenous peoples, infrastructure and market value, topography, hydrology, accessibility, biodiversity, and productivity of different harvest units in the boreal forest zone, as well as the species-specific sinking potential of driftwood under changing sea-ice conditions, and the locations of its final deposition in more or less anoxic parts of the Arctic Ocean floor. Undesirable environmental impacts that might arise include the release of phenols and other wood chemicals during both controlled and uncontrolled river rafting, and ocean sinking, while large quantities of floating timber may threaten riverine and maritime traffic. Geo-political questions concerning different cost factors and ownership rights of the Arctic Ocean floor would also need to be addressed, including whether seabed driftwood storage should be accounted as part of the terrestrial or marine environment, with implications for carbon sink and source budgeting at national and international scales (and hence carbon credit incentivisation). Rigorous cost-benefit modelling with a comprehensive agent-perspective for environmental and societal impact assessments is also needed (Fig. 3). Such a model must accurately address multi-scalar, cross-cultural and cross-functional/sectoral[48] tensions between the norm and value-based institutions of indigenous forest user groups and the market cost and revenue generation processes of the logging and climate mitigation industry[49,50]. A refined model is expected to define ecologically, economically and politically suitable harvesting practices, logging terrains and shipping routes (Fig. 3).

While logging at a desirable scale could hypothetically be achieved by Russia alone, we imagine a coordinated circumpolar effort that complements other mitigation strategies. Following scientific and indigenous guidance, the incentive for Moscow, Ottawa and Washington to start considering a viable concept of using driftwood to sequester atmospheric carbon could be twofold: Reductions of greenhouse gas emissions to mitigate the effects of anthropogenic climate and environmental change, in tandem with fiscal profit from carbon credit points, and international reputation for sustainable nature-based geoengineering.

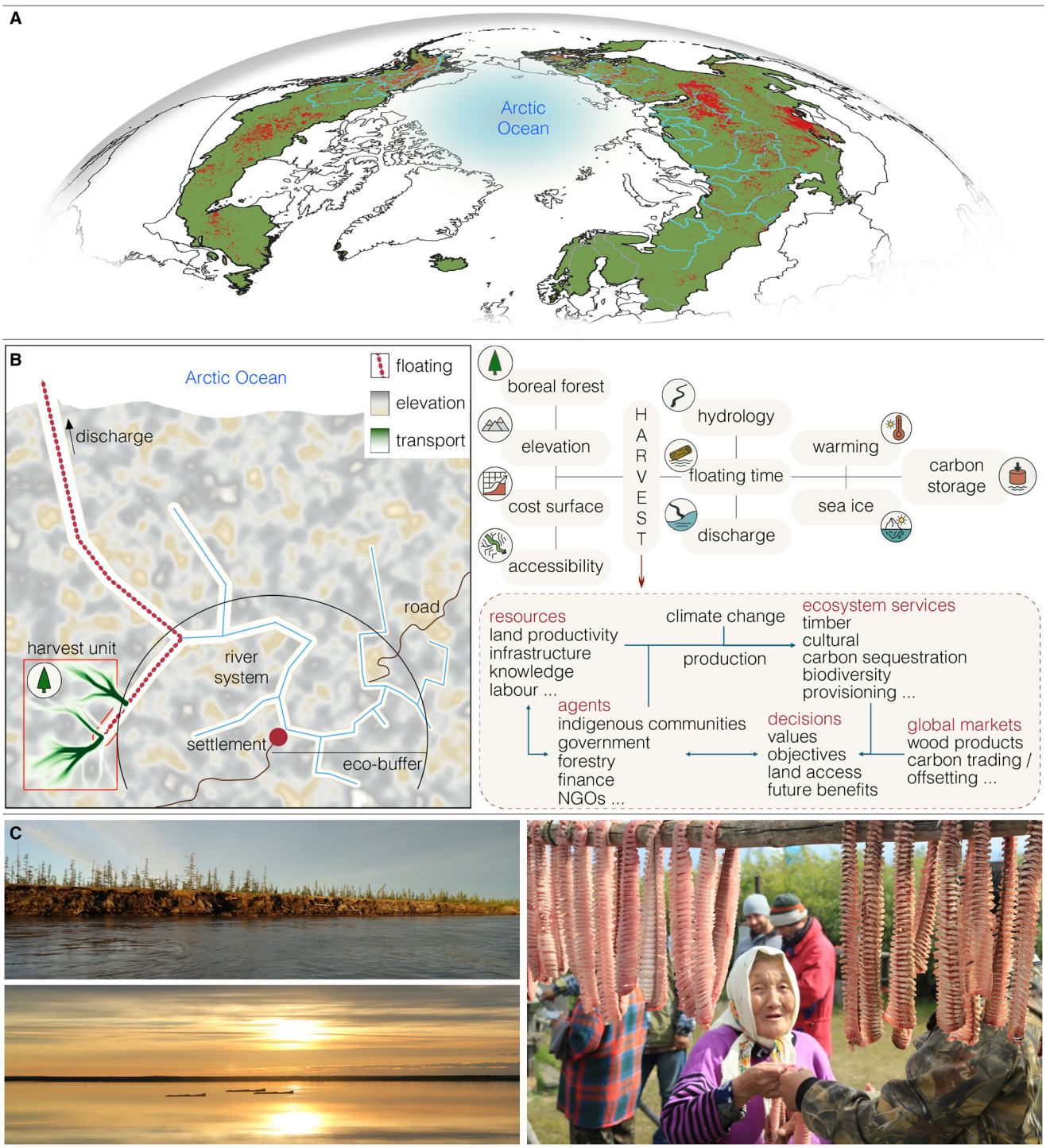

Fig. 3 | Driftwood carbon storage model with agent-perspective. A Circumpolar boreal forest zone with large river systems, and the extent of burnt boreal forest between 2002 and 2020 that amounts to circa 1,835,00 km² (red areas)[42,43]. **B** Least-cost analysis of a boreal forest patch with suitable timber harvesting parameters and optimal driftwood transportation conditions along the closest river to the nearest ocean[54]. Floating time is calculated as average downstream river run-off velocity and depending on rafting style and wood amount. An ecological buffer zone has been included around the nearest administrative centre from which labour and logistics are directed. The simplified model design includes an agent-perspective[55], in which the ability for the exogenous (e.g., harvesting for wood products and wood vaulting, and maintenance for carbon offsetting) and endogenous (e.g., cultural, herding, etc) demand for forest services to be met by spatial production depends on factors such as forest productivity, land ownership, infrastructure, human resources and the decisions of modelled agents, informed by their values, objectives and perceptions of future monetary and non-monetary value of land. **C** Pictures of natural driftwood erosion, tree tipping and driftwood rafting, as well as Indigenous people at the Indigirka river in northeastern Siberia (all taken by Ulf Büntgen in July 2016).

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

U.B. and J.E. initiated and conceived the study. U.B. wrote the manuscript together with C.O., M.T., I.H. and J.E., whereas M.K. was responsible for the model aspect of the study. T.A. provided cellulose data and T.B. contributed to discussion and revision.

Competing interests

The authors declare no competing interests.

Additional information

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