Tracing the origin of Arctic driftwood

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[1]   Arctic environments, where surface temperatures increase and sea ice cover and permafrost depth decrease, are very sensitive to even slight climatic variations. Placing recent environmental change of the high-northern latitudes in a long-term context is, however, complicated by too short meteorological observations and too few proxy records. Driftwood may represent a unique cross-disciplinary archive at the interface of marine and terrestrial processes. Here, we introduce 1445 driftwood remains from coastal East Greenland and Svalbard. Macroscopy and microscopy were applied for wood anatomical classification; a multi-species subset was used for detecting fungi; and information on boreal vegetation patterns, circumpolar river systems, and ocean current dynamics was reviewed and evaluated. Four conifer (*Pinus*, *Larix*, *Picea*, and *Abies*) and three deciduous (*Populus*, *Salix*, and *Betula*) genera were differentiated. Species-specific identification also separated *Pinus sylvestris* and *Pinus sibirica*, which account for ~40% of all driftwood and predominantly originate from western and central Siberia. Larch and spruce from Siberia or North America represents ~26% and ~18% of all materials, respectively. Fungal colonization caused different levels of driftwood staining and/or decay. Our results demonstrate the importance of combining wood anatomical knowledge with insight on boreal forest composition for successfully tracing the origin of Arctic driftwood. To ultimately reconstruct spatiotemporal variations in ocean currents, and to better quantify postglacial uplift rates, we recommend consideration of dendrochronologically dated material from many more circumpolar sites.

1.   Introduction

[2]   The Arctic is one of the world's most sensitive environments to climate change [*Duarte et al.*, 2012], where ecological responses have been reported among various spatiotemporal scales [*Post et al.*, 2009; *Spielhagen et al.*, 2011; *Macias-Fauria et al.*, 2012]. Surface temperatures of the high-northern latitudes increased by ~0.9°C during the twentieth century [*ACIA*, 2005], whereas circumpolar sea ice cover and permafrost depth significantly decreased [*Anisimov et al.*, 2007].

[3]   Generally too short and too few meteorological observations across the high-northern latitudes emphasize the importance of natural proxy archives to provide information on Arctic climate variability during preindustrial times [*Overpeck et al.*, 1997; *Naish and Zwartz*, 2012]. Circumpolar paleo-evidence derives either from terrestrial (e.g., tree rings, lake sediments, ice cores) or marine (e.g., sediment records, bivalves increments, water isotopes) archives, or ideally even a combination thereof [*Kaufmann et al.*, 2009]. A long-term, high-resolution record from the interface of marine and terrestrial processes is, however, still missing.

[4]   At the same time, massive driftwood deposits characterize many Arctic coastlines. This material entered the Arctic Ocean through one of the large boreal river systems before being ice-drifted to its final deposition (Figure 1a). Driftwood exclusively originates from the circumpolar boreal forest zone where trees generally grow near their northern and thus temperature-limited distribution range [*Fritts*, 1976]. Given this climatologically induced growth constraint, Arctic driftwood likely appears suitable for dendroclimatological investigations [*Häggblom*, 1982]. However, driftwood not only can contain information on past environmental conditions that occurred during a trees' lifespan but may also reflect changes in forest management strategies and associated logging and floating activities [*Johansen*, 1998]. Insight on past changes in river runoff, ocean current, and postglacial uplift might be further gained from large driftwood collections if the absolute age and precise origin of each sample is known. Hence, a systematically collected,

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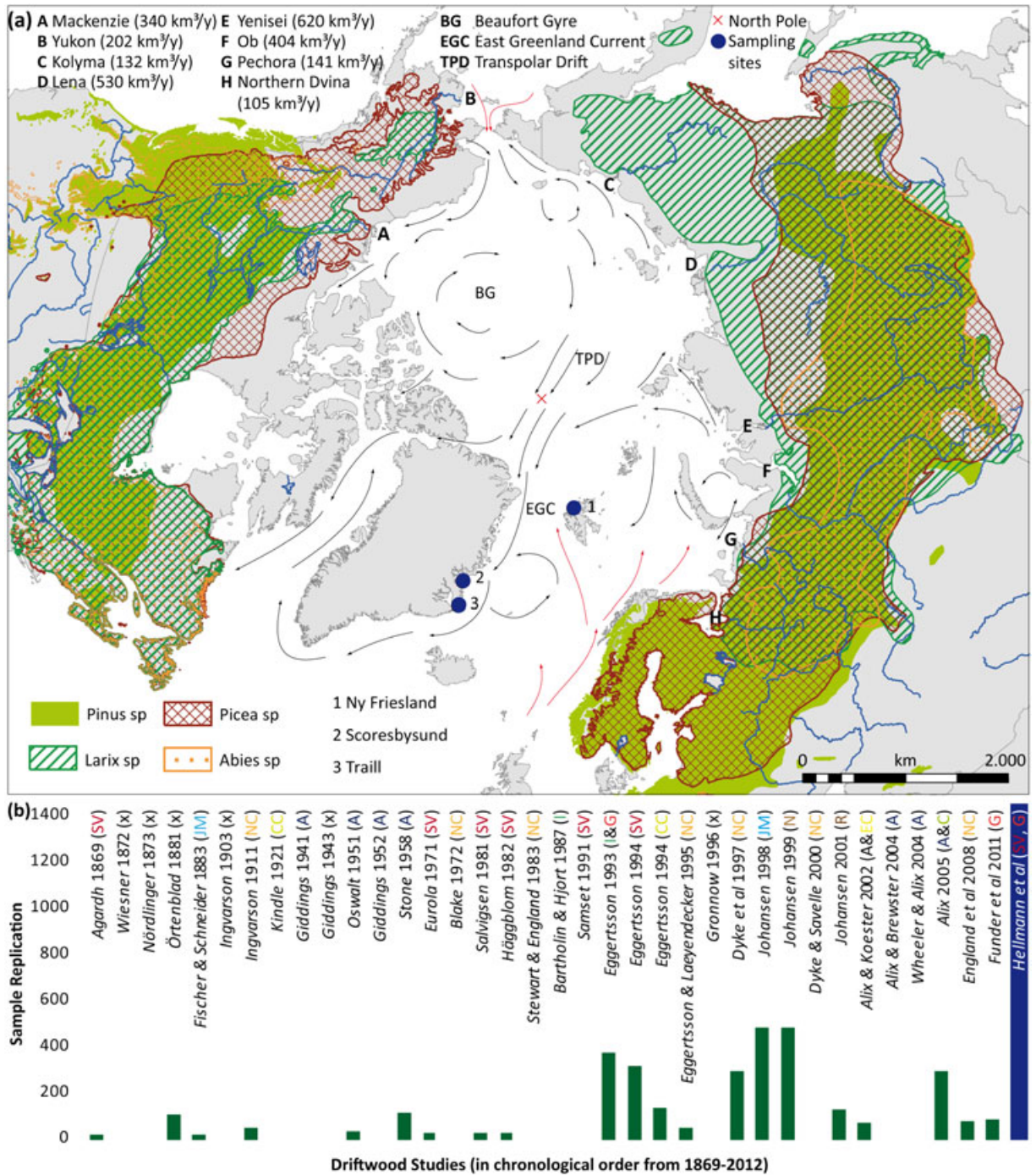
Figure 1. (a) Driftwood sampling sites and boreal forest composition with the large river systems (Projection: North Pole Lambert Azimuthal Equal Area). (b) Sample replication and region of Arctic driftwood research between 1869 and 2012 [*Agardh*, 1869; *Wiesner*, 1872; *Nördlinger*, 1873; *Örtenblad*, 1881; *Fischer and Schneider*, 1883; *Ingvarson*, 1903; *Ingvarson*, 1911; *Kindle*, 1921; *Giddings*, 1941; *Giddings*, 1943; *Oswalt*, 1951; *Giddings*, 1952; *VanStone*, 1958; *Eurola*, 1971; *Blake*, 1972; *Salvigsen*, 1981; *Häggblom*, 1982; *Stewart and England*, 1983; *Bartholin and Hjort*, 1987; *Samset*, 1991; *Eggertsson*, 1993; *Eggertsson*, 1994a; *Eggertsson*, 1994b; *Eggertsson and Layendecker*, 1995; *Gronnow*, 1996; *Dyke et al.*, 1997; *Johansen*, 1998; *Johansen*, 1991; *Dyke and Savelle*, 2000; *Johansen*, 2001; *Alix and Koester*, 2002; *Alix and Brewster*, 2004; *Wheeler and Alix*, 2004; *Alix*, 2005; *Fitzhugh et al.*, 2006; *England et al.*, 2008; *Funder et al.*, 2011], with color codes referring to the same study areas (SV: Svalbard, JM: Jan Mayen, NC: Northern Canada, CC: Central Canada, A: Alaska, I: Iceland, G: Greenland, N: Norway, R: Russia, EC: Eastern Canada, and C: Canada).

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Pine	Larch	Spruce	Fir
Resin ducts large	small	small	no/small traumatic
Colour bright/blue stain	reddish	bright	bright/brown
EW-LW medium-intense	intense	medium	medium/intense

Figure 2. Macroscopic features of coniferous stem sections.

adequately replicated, and carefully analyzed driftwood compilation would likely allow linking dynamic aspects of marine and terrestrial ecosystems at annual precision over most of the Holocene.

[5] The first driftwood was collected for scientific studies during early Arctic expeditions at the end of the nineteenth century (Figure 1b). At least 19 pioneering voyages, mainly interested in revealing the geographic origin of driftwood, were conducted between 1869 and the end of the 1980s [e.g., *Agardh*, 1869; *Kindle*, 1921; *Eurola*, 1971]. The amount of driftwood considered in these studies, however, was restricted to only few samples (Figure 1b). From the 1990s onward, more sophisticated surveys with enhanced sample replication took place with an expanded interest in exploring sea-ice variations, palaeoenvironmental changes, and/or unraveling the linkage between driftwood abundance and human settlements [e.g., *Giddings*, 1943; *Eggertsson*, 1993, 1994a, 1994b; *Dyke et al.*, 1997; *Johansen*, 1998, 1999; *Alix*, 2005, 2009]. Estimates of Arctic sea-ice cover and modern ocean current dynamics throughout the Holocene were recently obtained from ~80 radiocarbon dated driftwood samples in tandem with the analyses of shells, plants, and lake isolation lines from Northeast Greenland [*Funder et al.*, 2011]. Nevertheless, a sufficiently replicated driftwood study that comprises wood anatomical details and provides a circumpolar overview of the forest composition though owes.

[6] Here we assess the largest ever-compiled gathering of 1445 Arctic driftwood samples to discuss its boreal origin. We therefore also consider macroscopic and microscopic wood anatomical techniques and combine this high-resolution cell-level evidence with digitized information on hemispheric-scale vegetation patterns, river systems, and ocean currents.

2. Materials and Methods

[7] A collection of 1445 Arctic driftwood samples was made at three different sites along the coastlines of East Greenland (Traill, 72°32′N 23°10′W in August 2010; Scoresbysund, 70°30′N 25°0′W in August 2011) and Svalbard (Ny Friesland 78°54′N 18°1′E in August 1996). Only discs were taken at all three shoreline locations. Each sample was labeled and identified as being from natural or logged material in the field. Natural stems generally enter the rivers due to storm events, erosion processes, or changing soil conditions like permafrost thawing. Visual indication of root collar and/or branch bases characterizes this material type and clearly distinguishes it from logged timbers that are free of rootstocks and snags and often with cut ends.

[8] Data from Ny Friesland exclusively contain tree stems with >50 rings. Data from Traill also include smaller remains and partly decomposed wood. The Scoresbysund collection is most heterogeneous and compiles everything from small branches and roots to large stems. All samples

were archived following a thorough identification key [*Schweingruber*, 1990], repeatedly sanded, and macroscopically categorized. Morphological features were considered to differentiate between deciduous and coniferous wood (Figure 2), as well as pine, spruce/larch, and fir. Macroscopic characteristics include the sap-to-heartwood contrast, wood color, resin ducts, and the type of transition from early wood to latewood. Odor and gloss of driftwood samples did not provide reliable information and were therefore not used as indication key. A few distinguishing features utilized for the macroscopic characterization include the following: Reddish heartwood refers to larch and pine. Spruce and fir are bright colored without sapwood. Large resin ducts exist in pine, and small resin ducts are common in larch and spruce [*Gärtner and Heinrich*, 2009]. Fir is characterized by the absence of resin ducts or solely contains rows of traumatic resin ducts. Sharp boundaries between bright early wood and reddish latewood refer to larch.

[9] Microscopic techniques were additionally applied to determine the genus-level and to further identify the wood from different tree species. Radial sections were cut for all samples. Tangential- and transverse-orientated sectioning was performed on a subset of 20 samples for extra verification [*Hoadley*, 1990]. These samples were double stained with safranin and astrablue to enhance the contrast within anatomical structures. Samples were rinsed with ethanol and finally embedded in "Canada Balsam" to create permanent slides [*Gärtner et al.*, 2001]. Another subset of samples, obviously penetrated by fungi, was further investigated with scanning electron microscopy to determine the specific fungal types involved and to also assess patterns of degradation resulting from wood decay [*Arenz and Blanchette*, 2009].

[10] A North Pole Lambert Azimuthal Equal Area projection was utilized as a base-map to visualize the circumpolar distribution of the main boreal conifer species (Figures 1 and 5). Online forest inventory data [*Little*, 1971; *EUFORGEN*, 2009; *Malyshev*, 2008] were combined with historical Russian registers [S. Shyatov, personal communication] and documentary environmental evidence [*Berg*, 1950]. The analogue maps were scanned and subsequently geo-referenced in ArcGIS. The different species-specific areas were joined to their genus abundance by data management tools. Different color and hatching codes were generated to display up to five spatially overlapping species, accompanied by the main Eurasian and North American river systems and dominant Arctic Ocean currents, resulting in a unique circumpolar perspective that was so far missing.

3. Results and Discussion

3.1. Driftwood anatomy

[11] A combination of harsh environmental conditions of the boreal forest zone where all the driftwood originates,
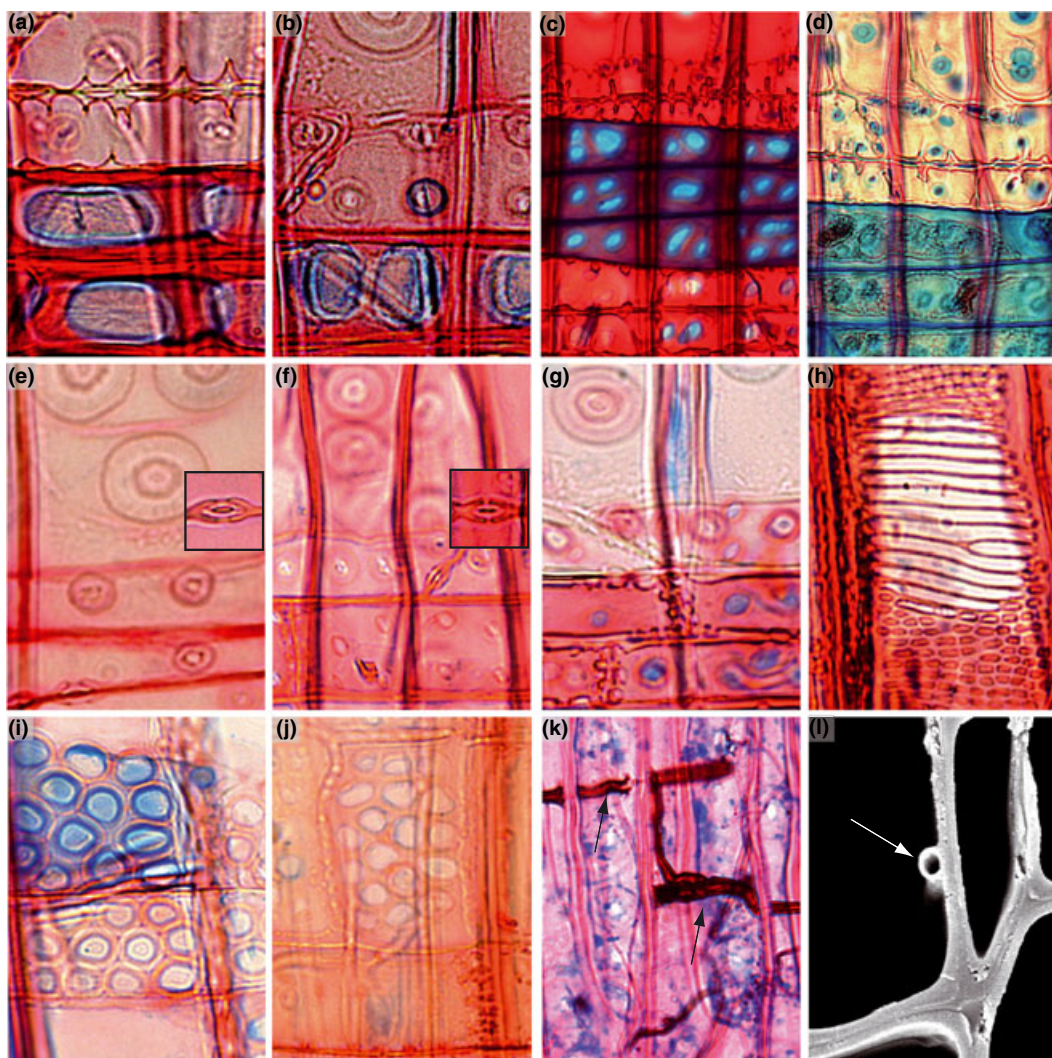
Figure 3. Microscopic identification features and fungal colonization: (a–g) coniferous wood, (h–j) deciduous wood, and (k–l) fungi invaded conifers: (a–b) large pinoid pits in the rays, stained blue. (a) *Pinus sylvestris*: typical serrated tracheid walls. (b) *Pinus sibirica*: typical smooth tracheid walls. (c–d) North American pines with small ray pits and serrated tracheid walls. (c) *Pinus banksiana*. (d) *Pinus contorta*. (e–g) Small pitting in the rays. (e) *Larix sp.*: transversal tracheids present, smooth shape of exterior borders of pits. (f) *Picea sp.*: transversal tracheids present, angular shape of exterior borders of pits. (g) *Abies sp.*: transversal tracheids absent. (h) *Betula sp.*: scalariform perforation plates. (i) *Populus sp.*: homogeneous rays. (j) *Salix sp.*: heterogeneous rays (microtome radial sections, except the zoom for *Picea sp.* and *Larix sp.* (razor blade sections), stained with Safranin and Astrablue; reflected light microscope with a magnification of 400). (k–l) fungi (blue stain) invaded PISY. (k) Stained radial cut, fungi growing through the cells without destroying cell walls. Small diameter hyphae of wood decay fungi also present (reflected light microscope). (l) Unstained cross section with large diameter hyphae (arrow) in cell lumen (scanning electron microscope). All pictures refer to driftwood samples that were analyzed in this study.

several years of polar ice rift, and even more extreme conditions along the Arctic coastlines were all the material was deposited, strongly affected the samples obtained. Missing rings, holes from shipworms (*Teredinida*), wood erosion, and decomposition by fungi, as well as silver paper-like surfaces, were characteristic features of most driftwood samples. Fungal infestation and reaction wood further complicate anatomical identification. Separation between spruce and larch was found to be particularly difficult. Nevertheless, a careful consideration of various anatomical characteristics resulted in a precise classification of almost all driftwood remains.

[12] Unstained microscopic thin sections allowed the determination of Scots pine (*Pinus sylvestris*) and Siberian pine (*Pinus sibirica*) (hereinafter PISY and PISI), as well as larch, spruce, fir, willow, poplar, and birch (Figure 3). Large pinoid pits characterize the rays of PISY and PISI (Figures 3a and 3b). Differentiation between PISY and PISI was possible by the occurrence of different ray-tracheid wall structures, being serrated for PISY but smooth for PISI. Small (piceoid) pitting in rays separates the North American *Pinus banksiana* and *Pinus contorta* from the Eurasian species (Figures 3c and 3d). Spruce, larch, and fir had small pitting in their rays.
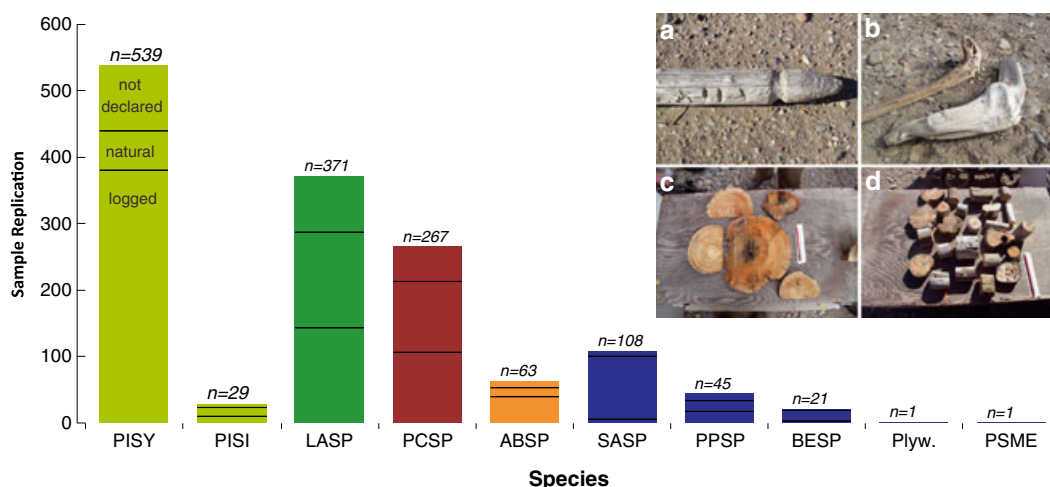
Figure 4. Species composition of the 1445 driftwood samples separated into logged, natural, and non-declared material. PISY: *Pinus sylvestris* (37.3%), PISI: *Pinus sibirica* (2.0%), LASP: *Larix sp.* (25.7%), PCSP: *Picea sp.* (18.4%), ABSP: *Abies sp.* (4.4%), SASP: *Salix sp.* (7.5%), PPSP: *Populus sp.* (3.1%), BESP: *Betula sp.* (1.4%), Plyw.: Plywood (0.1%), and PSME: *Pseudotsuga menziesii* (0.1%). Inset refers to (a) logged material (~40 cm long and ~10 cm in diameter) marked from a wood company somewhere in the boreal forest zone, and to (b) a naturally fallen/eroded stem with root collar (~50 cm long and ~5–25 cm in diameter), to (c) differences in sizes of logs sampled, and (d) branch, root, and shrub samples.

The arrangement of the bordered pits helped differentiating between *Larix sp.* (LASP, often biseriately arranged, Figure 3e) and *Picea sp.* (PCSP, uniseriately arranged, Figure 3f), but some uncertainty remained [*Anagnost et al.*, 1994]. We were able to further distinguish between spruce and larch by comparing the shape of their transversely sectioned bordered pits [*Bartholin*, 1979]. Smooth-shaped bordered pits in cross section are typical for larch and angular-shaped pits for spruce (Figures 3e and 3f, zoom). *Abies sp.* (ABSP) differs from the other species since it does not contain transversal tracheids (Figure 3g).

[13] *Salix sp.* (SASP) and *Populus sp.* (PPSP) show a somewhat similar anatomical structure. Both of these woods have uniseriate rays, simple perforation plates, and large ray vessel pits but can be differentiated by a different ray structure. Heterogeneous ray cells feature SASP; the cells at the edge are higher than the ones in the middle of the ray (Figure 3h). In contrast, the homogeneous cells in PPSP all have similar size (Figure 3i). *Betula sp.* (BESP) differs by the occurrence of scalariform perforation plates and small ray vessel pits (Figure 3j).

[14] The general tendency toward reduced wood density, caused by cellulose and lignin decomposition following fungi infestation in almost all samples, is a concern from a palaeoclimatological point of view. Maximum latewood density (MXD; g/cm^3) chronologies from northern North America and northern Eurasia are commonly used for the reconstruction of summer temperature variability over past centuries to millennia [*Büntgen et al.*, 2006, 2007, 2008, 2011; *Esper et al.*, 2012]. MXD measurements from fungal-invaded wood material, however, are less suitable for reconstructing climate due to potentially high decomposition rates [*Blanchette*, 2000] and overall reduced density values. Blue stain fungi (most frequently found in pine, Figures 3k and 3l) do not cause cell wall decay but can form penetration pegs and physically bore through cell walls. Filamentous fungal hyphae were visible in the stained wood sections when observed and photographed with a reflected light microscope (Figure 3k). Hyphae were evident in wood cells and observed by scanning electron microscopy (Figure 3l). For some of these fungi, colonization likely occurred at sites where the wood originated, but for others, indigenous fungi to Greenland or Svalbard likely colonized the wood causing decay. A common type of wood decay observed in the driftwood was soft rot. This type of attack in wood has previously been shown to be the major type of degradation occurring in Polar Regions [*Blanchette et al.*, 2010; *Jurgens et al.*, 2009].

[15] Our conifer driftwood composition resembles the species natural occurrence within the circumpolar boreal forest zone. Five coniferous (PISY, PISI, LASP, PCSP, and ABSP) and three deciduous species (SASP, PPSP, and BESP) were found (Figure 4). One board, likely from construction material, was determined as *Pseudotsuga menziesii* (PSME), and one other timber found was not identified. PISY accounts for 37.7%, followed by larch and spruce with 25.7% and 18.4%, respectively. ABSP and PISI only represent 4.4% and 2.0%. Deciduous samples were classified into willow, poplar, and birch (7.5%, 3.1%, and 1.4%).

[16] The ratio of logged (artificial) and non-logged (natural) materials varied between the species and was likely biased by the individual sampling strategy realized at each of the three collection sites (Figure 4). PISY represented 70.5% of the logged material, whereas 88.0% of the natural material was SASP, including a high proportion of small branches. Similar rates of logged and non-logged materials were derived from LASP (38.5% logged and 38.8% natural) and PCSP (40.1% logged and 39.7% natural). Within the other species, the ratio of logged to non-logged material ranged from 14.3% (BESP) over 34.5% (PISI) to 61.9% (ABSP), whereby the total number of these species was fairly low. The results for the three sites slightly differ due to different sampling protocols regarding the percentage of deciduous wood (mainly SASP).
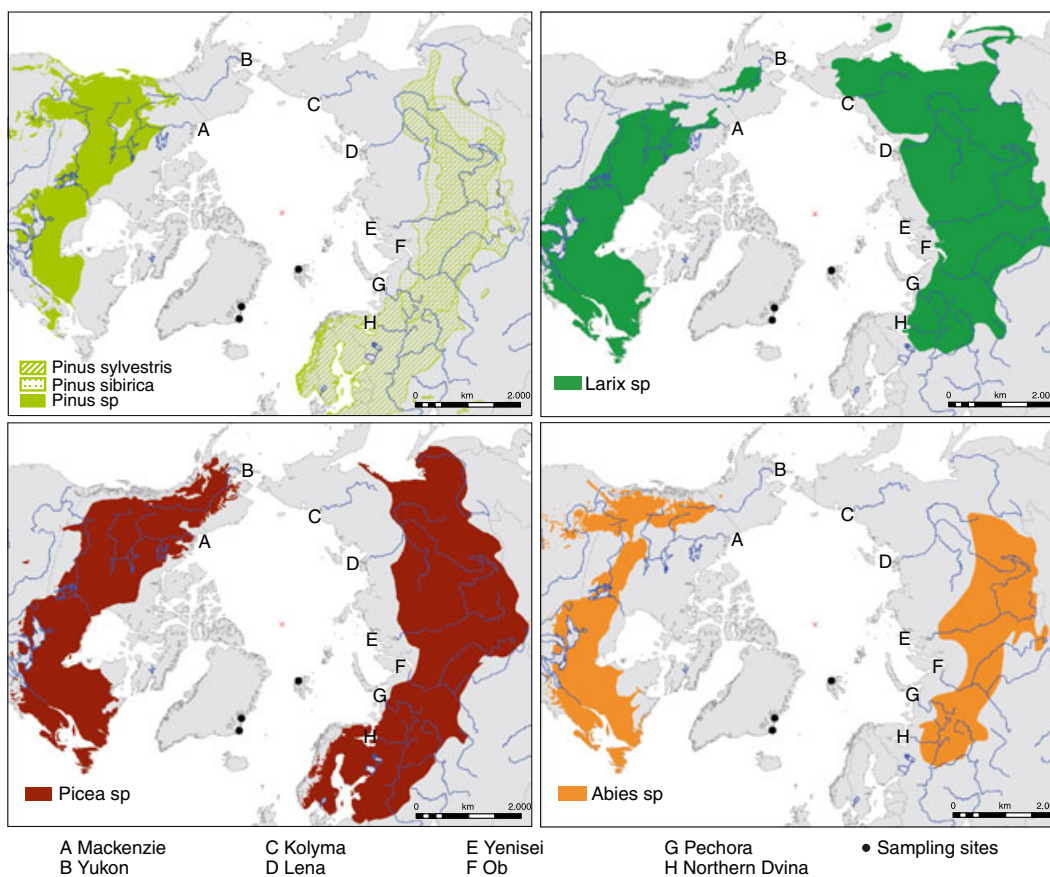
Figure 5. Distribution of boreal conifer species: *Pinus sp*. (divided in *Pinus sp*. in North America and *Pinus sylvestris*/*Pinus sibirica* in Eurasia), *Larix sp*., *Picea sp*., and *Abies sp*., together with the sampling sites and the large river systems.

The amount of small and probably local deciduous wood (mainly SASP) is higher in Scoresbysund (18.9%) and smaller in Traill and Svalbard (6.8% and 1.4%), while the rest of the species composition is approximately the same. Fungal attack was equally found in the wood from the three sites.

[17] In summary, microscopic identification of all driftwood samples was possible at the genus level and for pine also at the species-level. Scots pine was most frequent among all data, followed by larch and spruce. Deciduous wood was, however, extremely rare. More than half of the Scots pine samples were logged.

3.2. Driftwood origin

[18] Both LASP and PCSP occur widespread in Eurasia and North America; PISY and PISI occur exclusively in Eurasia. ABSP is generally less frequent and more restricted to the southern boreal forest zone (Figure 5).

[19] The distribution of PISY ranges from 5°E to 135°E, but its western populations <40°E are likely less relevant for this study as no wood from this area can reach the Arctic Ocean via large river systems. The most northern Scots pine distribution in Siberia is ~67°N (Lena River). The smaller habitat of Siberian pine (48°E to 127°E), however, also reaches far north to ~67°N (Yenisei River).

[20] No samples can be assigned to North America with certainty by wood anatomical methods alone. Consideration of the species-specific relative proportion per continent is important as spruce for instance dominates the North American forests, but larch is prevalent in Siberia. Moreover, it is important to note that the overall species composition of the boreal forest zone is not necessarily representative of the river shorelines. In fact, while larch (*Larix laricina*) is indeed present in the North American boreal forest, it very rarely grows along the shores of the large "wood-producing" Yukon and Mackenzie Rivers and therefore only rarely occurs in any driftwood assemblage [*Giddings*, 1952; *Alix*, 2005, 2009; *Alix and Brewster*, 2004; *Eggertsson*, 1994a].

[21] Dendrochronological cross dating of tree-ring chronologies from the possible source areas is required to definitely determine the origin of larch, spruce, and fir.

[22] The different river discharges in Eurasia and North America are important factors influencing the amount and transport of driftwood. The Mackenzie River is the largest North American discharge into the Arctic Ocean with a runoff of $340 \, km^3/yr$, followed by Yukon River with $202 \, km^3/yr$. However, the total inflow into the Arctic Ocean is much lower from North America ($1170 \, km^3/yr$) than from Eurasia ($3300 \, km^3/yr$) [*Izmailova*, 2003; *Aagaard and Carmack*, 1989]. Three of the six large Siberian Rivers draining into the Arctic Ocean have a higher discharge than the Mackenzie River. This suggests a high probability of Arctic driftwood to originate from Siberia. With a runoff of $620 \, km^3/yr$, the Yenisei River is the largest, followed by
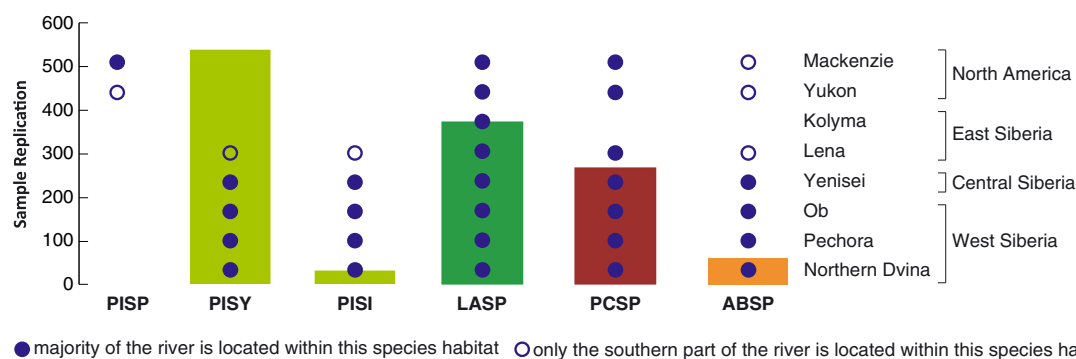
Figure 6. Relationship between boreal conifer species and river systems (PISP: *Pinus sp.* (North America), PISY: *Pinus sylvestris* (Eurasia), PISI: *Pinus sibirica* (Eurasia), LASP: *Larix sp.*, PCSP: *Picea sp.*, and ABSP: *Abies sp.*).

the Lena (530 km³/yr) and the Ob (404 km³/yr). The most eastern Siberian Kolyma River (132 km³/yr), as well as the Pechora (141 km³/yr) and Northern Dvina (105 km³/yr) Rivers in the west have relatively low drains [*Peterson et al.*, 2002]. The drainage area of Kolyma River is dominated by larch (Figure 6). All other large northern North American and northeastern Eurasian catchments contain of more than one species. Larch and spruce, for instance, occur in many catchments on both continents.

[23] The dominance of PISY would correspond with a higher influx of Eurasian Rivers into the Arctic Ocean. Nevertheless, when considering only non-logged natural wood, larch (31.0%) and spruce (22.8%) are more frequent in comparison to Scots pine (13.0%). Other factors, like vegetation cover or weather extremes, may influence the driftwood proportion relative to the different catchments [*Reimnitz and Maurer*, 1979]. River erosion occurs most frequently in delta regions of big river systems. A high degree of undercutting erosion is, for instance, known for the Yukon River. In contrast, forested delta systems such as the Mackenzie Delta are indicative for the origin of natural driftwood from North American, whereas shrub and grassland dominated delta systems, which are characteristic for most of the large Eurasian Rivers, are likely less important driftwood sources.

[24] Siberian harvest consists of 34% pine, 25% spruce, and 24% larch [*Obersteiner*, 1995]. Approximately 50% (33–43% in 1970s–1990s and 48–53% in 2000s) of the logged wood in the Yenisei drainage area was pine [*Sokolov et al.*, 2007]. This river, especially with its headwater tributary Angara River, is also the most rafted river with cut logs in Siberia. Many stems get lost while being floated within large rafts without attending ships. Lost stems are further transported along the rivers to the ocean and can then get stuck in the Arctic sea ice cover. Timber rafting started in the late 1920s and was intensified in the 1930s. In 1937, several strings of large rafts with up to 40,000 m³ of timber per string were sent from Yenisei and Angara to Igarka (67°28′N, 86°34′E), the second largest port for Russian wood transport. Floating activity at these rivers was very high until the 1990s. Industrial activities and dam constructions at the Yenisei, and in the upper Angara River region, led to more logging activities from 1950 onwards. The main species in the Angara catchment is PISY [*Korets et al.*, 2011]. Northern Dvina and its tributaries were also used for heavy timber rafting. More than 15,000,000 m³ were rafted in the 1960s. New

rafting techniques led to a decrease in wood loss from more than 50% when floating logs was just beginning at some rivers to less than 1% by 1975. Drift floating ceased in 1987 in the U.S.S.R. and almost completely stopped after 2000. However, more than 80,000 km of rivers was used for floating before this time, and floating wood guided by ships is a still commonly applied technique in Russian boreal forest zone, with up to 30% of wood harvested every year transported by water [*Sokolov et al.*, 2006]. In the larch-dominated catchments of the Lena and Kolyma Rivers, timber is mostly of lower quality and thus used for the local industry rather than for trading at the international market. Drift-floating activities are therefore of minor importance in these regions. In this context, it is important to note that timber rafting and floating was never a standard transporting technique in Alaska [*Alix*, 2005] and logging along the Mackenzie River was also quite unusual. In consequence, the majority of spruce logs might indeed originate from Siberia. However, a clear separation between logged and natural materials is not always possible, and the absence of a root collar even though the stem was not logged appears challenging [*Alix*, 2005, 2009]; such biases may result from ice-breaking events.

[25] The maximum periods of buoyancy likely range from 6 to 10 months for most of the deciduous wood, but for larch and pine, it averages 9–10 months, and up to 17 months for spruce [*Häggblom*, 1982]. Deciduous wood often sinks before entering the Arctic Ocean, or at least before its inclusion into the ice. All driftwood needs to be transported in or on the ice, mainly following the ocean currents to reach these Arctic sites where sampling took place (Figure 1). The main surface currents in the Arctic Ocean are the clockwise Beaufort Gyre, which circulates north of the Canadian Arctic Archipelago and the Transpolar Drift, from the Siberian coast over the North Pole toward the Fram Strait. The Transpolar Drift becomes the East Greenland Current by leaving the Arctic Ocean via Fram Strait and transporting wood further to the coast of Greenland and Svalbard. Variations between the two major Arctic Ocean currents may be detected in the future when much more driftwood is dendrochronologically dated and geographically provenanced—replication matters [*Büntgen et al.*, 2012].

[26] In summary, all species of driftwood that were found occur in Eurasia as well as in North America. Only PISY and PISI are restricted to Eurasia. The discharge into the Arctic Ocean is higher from the Eurasian Rivers. High

logging activities in Scots pine dominated areas result in high amounts of logged pines.

4. Conclusions

[27] A total of 1445 driftwood samples from East Greenland ~71°N and Svalbard ~78°N were anatomically classified, and a multi-species subset was additionally used for detection of fungal decay. Distribution of boreal tree species and river systems, as well as dynamics of Arctic Ocean currents, was reviewed, digitized, and mapped.

[28] Nearly half of all driftwood material was logged. Anatomical characterization at the genus-level revealed four coniferous woods (*Pinus, Larix, Picea*, and *Abies*) and three genera of deciduous wood (*Populus, Salix*, and *Betula*). Species-specific identification allowed *Pinus sylvestris* and *Pinus sibirica* to be distinguished, which account for ~40% of all samples, and this wood predominantly originated from western and central Siberia. Larch and spruce cannot be certainly assigned to an origin area, hence derived either from Siberia or North America and represented ~26% and ~18% of our compilation, respectively. Wood decay after fungal colonization complicated the anatomical assessment of almost all material.

[29] A combination of intense sample replication, careful macroscopic and microscopic anatomical analyses, as well as consideration of a complex boreal species distribution, appears indispensable for properly tracing the origin of Arctic driftwood. Even though our results realistically reflect the natural boreal species composition, more research, including dendrochronologically dated wood from various locations, could be used to further improve our understanding of changes in circumpolar ocean currents and postglacial uplift rates.

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