Dendro-provenancing of Arctic driftwood

Lena Hellmann[1,2], Willy Tegel[3], Jan Geyer[3], Alexander V. Kirdyanov[4,5], Anatoly N. Nikolaev[6,7], Ólafur Eggertsson[8], Jan Altman[9], Frederick Reinig[1], Sandro Morganti[1] & Ulf Büntgen[1,2,10]

[1]Swiss Federal Research Institute, WSL, Birmensdorf, Switzerland
[2]Oeschger Centre for Climate Change Research, Bern, Switzerland
[3]Institute for Forest Sciences IWW, University of Freiburg, Freiburg, Germany
[4]V.N. Sukachev Institute of Forest SB RAS, Krasnoyarsk, Russia
[5]Siberian Federal University, Krasnoyarsk, Russia
[6]North-Eastern Federal University, Yakutsk, Russia
[7]Melnikov Permafrost Institute, Yakutsk, Russia
[8] Iceland Forest Service Mogilsa, Reykjavik, Iceland
[9]Institute of Botany, Czech Academy of Sciences Třeboň, Czech Republic
[10]Global Change Research Centre AS CR, Brno, Czech Republic

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Abstract

Arctic driftwood represents a unique proxy archive at the interface of marine and terrestrial environments, which will likely gain in importance under predicted global climate change. Well-replicated, circumpolar network analyses that systematically investigate species-specific origin areas, transport routes and deposition characteristics of Arctic driftwood, are, however, still missing. Here, we compare tree-ring width (TRW) measurements of 2,412 pine, larch and spruce driftwood samples from Greenland, Iceland, Svalbard, the Faroe Islands, as well as the Lena Delta against 495 TRW site chronologies from the high-northern latitudes in Eurasia and North America. The southern Yenisei region in central Siberia is the main source for recent pine driftwood at all Arctic sampling sites, whereas spruce mainly originates in western Russia and central Siberia as well as in northern North America. Dendro-provenancing for the first time proves larch driftwood to originate in central and mainly in eastern Siberia, where a larch chronology extends the middle Lena river reference chronologies to the past and now covers the period 1203-2012 CE. Supplementary, six floating larch driftwood chronologies that need radiocarbon dating most likely cover time periods throughout the late Holocene. Our study demonstrates the relevance of massive sample size at both the driftwood source and sink regions for successfully provenancing Arctic driftwood. Combined dendrochronological and wood anatomical attempts of reconstructing summer temperature variations and ocean current dynamics, as well as changes in sea ice extent and relative sea level, should overcome disciplinary boundaries and routinely involve radiocarbon dating, isotopic tracing and aDNA processing.

Introduction

The Arctic, where temperatures rapidly rise and sea ice significantly decreases, is the world's most sensitive region to recent climate change (IPCC, 2013; Räisänen, 2001). With the current retreatment rate of ice as one of the Earth's elements, a 'cryo-historical' moment has been reached, caused by human influence (Sörlin, 2015). Rising temperatures and reduced sea ice in the Arctic Ocean have strong implications on a wide range of environmental systems (Pearson et al., 2013; Smol, 2012).

Biodiversity changes are caused by the northward moving of animals and plants due to increasing temperatures and decreasing sea ice (Parmesan, 2006; Post et al., 2009; Sala et al., 2000). Vegetation composition and cover will change and expand further northwards, a phenomenon known as Arctic greening (Forbes et al., 2010; Macias-Fauria et al., 2012; Tape et al., 2006). The boreal rivers show higher discharge rates due to various factors (McClelland et al., 2004; Peterson et al., 2002), such as increasing precipitation and/or permafrost thaw (Osterkamp and Romanovsky, 1999; Schuur and Abbott, 2011). Apart from these environmental changes, shrinking sea ice extent has also economic consequences since new shipping and trading routes are expected to become accessible (Stephenson et al., 2013). To better predict future changes, models need highly resolved observational and/or proxy data for their calibration (Anderson et al., 2006; Schmidt et al., 2014). Such direct and indirect environmental evidence is, however, limited in space and time across most of the high-northern latitudes and particularly scarce in the Arctic region (Johannessen et al., 2004; Pages 2k Consortium, 2013). Most instrumental station measurements (ref) and satellite images (ref), do not extend prior to the mid- and late-20th century, respectively (ref). Sampling of ocean sediment cores or ice cores, for instance, is elaborate and expensive and therefore the spatial density as well as the temporal resolution of these proxies is low (ref).

Originating in the boreal forest zone and being transported to the Arctic Ocean via the large boreal rivers, Arctic driftwood can drift within sea ice over long distances before its deposition along shallow coastlines (Eggertsson, 1993, 1994; Hellmann et al., 2013; Hellmann et al., 2015; Johansen, 1998; Johansen, 2001). It therefore represents a unique proxy archive at the interface of marine and terrestrial environments that can provide annually resolved information over millennial time-scales (Funder et al., 2011; Nixon et al., 2016). Changing conditions in the Arctic also have high effects on the transport and accumulation of driftwood. Since sea ice is the essential transport medium for timber that reach the Arctic Ocean via one of the large boreal river systems (Häggblom, 1982), an expected decrease in sea ice extent will reduce the amount of wood that is transported over long distances across the ocean. At the same time, coastlines that have formerly been characterized by permanent sea ice, preventing the deposition of driftwood (Funder et al., 2011), will very likely obtain more wood under warmer conditions. Wood enters the boreal rivers either due to natural processes such as river bank erosion and storm surges, or due to loses of industrial timber floating activities along the rivers.

Arctic driftwood is mainly transported from the boreal coastlines across the Arctic Ocean via the Transpolar Drift Stream (TPD), which results from an anti-cyclonic circulation in the Beaufort Sea (Beaufort Gyre; BG) and a cyclonic circulation in the Laptev Sea (Proshutinsky and Johnson, 1997). Sea ice and wood as well as other material can be intermixed between these currents (Melnikov, 1997). Wood originating in northern North America first enters the BG before potentially being transported further within the TPD in direction to the Fram Strait. Transport times for ice and hence also for wood are with a minimum of 4-5 years longer than for material from the Siberian coasts, where stems may enter the TPD directly and reach the Fram Strait within a minimum of 2-2.5 years (Rigor, 1992).

For people living in the Arctic, driftwood was and still is a highly important resource for fire, as well as for the construction of houses, tools, weapons and boats (Alix, 2005; Alix and Brewster, 2004), for instance. Investigations on the rise and fall of human settlements in the Arctic so far mainly focus on climatic conditions and sea ice extent (Bennike et al., 2008; Young et al., 2015). However, the availability of wood might have represented a key limiting factor for the suitability to inhabit a region: Distribution of settlements was influenced by the availability of driftwood or alternatives, such as whalebones, along the Arctic coastlines (McCartney and Savelle, 1993; McGovern, 1985). Inuit have specific names for driftwood based on its shape, color, or texture and hold extensive knowledge of the best places for collecting driftwood in different seasons, proving the past and present necessity of wood for these people (Steelandt et al., 2013).

At the same time, driftwood is strongly influencing the biodiversity on Arctic Islands that are characterized by harsh growing and reproduction conditions (Klein et al., 2008). Dispersal of plant diaspores over large distances from continent to continent within the sea ice, but also within driftwood, during the early Holocene resulted in the isolated occurrence of some plant species in northern Scandinavia and eastern Greenland, such as *Draba sibirica, Potentilla stipularis* or *Trisetum subalpestre* (Alsos et al., 2007; Hultén and Fries, 1986; Johansen and Hytteborn, 2001). The role of driftwood in the dispersal of various wood decaying fungi species is not fully understood yet (Blanchette et al., 2016). The investigation of Arctic driftwood offers the chance to increase our knowledge on past changes in sea ice extent (Funder et al., 2011), Arctic Ocean currents (Dyke et al., 1997), and boreal growing conditions (Hellmann et al., 2015). A highly replicated and spatiotemporally extensive sample record is the key for drawing reliable conclusions over various scales.

Here, we present the so-far largest record of Arctic driftwood TRW series of 2,412 Scots pine (*Pinus sylvestris)*, larch (*Larix* sp.) and spruce (*Picea* sp.) samples from four sub-Arctic and Arctic islands, as well as from the eastern Siberian Lena River. After precise wood anatomical identification of all samples, TRW series were compared against each other to build floating driftwood chronologies that were then dendro-provenanced by cross-dating against a spatiotemporally highly replicated network of boreal references from northern Eurasia and northern North America.

Material and Methods

Driftwood was collected along the coastlines of Svalbard in 1996, eastern Greenland in 2010, 2011 and 2012, north-western Iceland in 2012, and on the Faroe Islands over several years (Fig. 1, Hellmann et al., 2013; Hellmann et al., 2015). Subfossil and driftwood samples were collected along the Lena River and its delta in 2013 and 2015 (Fig. 1).

All samples were wood anatomically identified and prepared for TRW measurements by sanding in several steps from 80-400 grains cm^{-1} or the surface was cut with a box cutter after sanding with 100 grains cm^{-1}. Ring widths of in total 969 *Pinus sylvestris*, 563 *Larix* sp., and 351 *Picea* sp. samples from the Arctic Islands and 539 *Larix* sp. samples from the Lena region were measured by using a Lintab measuring device with a precision of 0.01 mm and the program TSAPwin (Rinntech, Heidelberg, Germany). From the Lena River only *Larix* sp. and from the Faroe Islands only *Pinus sylvestris* was analyzed. At least two radii were measured per disc and then combined to sample-specific mean curves that were used for further analyses.

We compiled 495 site chronologies ≥ 60°N as reference data from the boreal forest zone for the genera pine (n=186), larch (n=187), and spruce (n=122) from the *International Tree Ring Data Bank* (ITRDB) as well as from individual data provided by Russian colleagues (Hellmann et al., 2016a). Chronologies of all three genera were used for Eurasia, whereby for North America only spruce data were available, thus representing the boreal species distribution of spruce dominated North American forests. Regional reference chronologies were built by combining several sites to mean chronologies per genus based on common growth patterns. Six groups for pine, eleven groups for larch, and twelve for spruce (six for northern Eurasia, six for northern North America) resulted and the mean curves were further used for cross-dating (Fig. 1; Fig. S1-S4; Hellmann et al., 2016b; Hellmann et al., 2015).

A comparison of all driftwood series per genus resulted in several floating, i.e. undated chronologies that were then cross-dated against the mean reference chronologies from the boreal forest zone. Cross-dating was realized based on the raw series by using the program PAST4 by SCIEM (Scientific Engineering and Manufacture, Vienna) that uses statistical criteria, mainly the t-value after Baillie and Pilcher (TBP; Baillie and Pilcher, 1973) for the synchronization of reference and sample chronologies and allows visual cross-checking for dating. Minimum t-values for cross-dating were set to four, however, all datings were in addition carefully controlled visually. Final chronologies were built with the program ARSTAN (ARSTAN_41d for Windows (Cook and Krusic, 2007)), where age trend was removed from the power transformed data by applying negative exponential detrending (Cook and Kairiukstis, 1990) with variance stabilization (Osborn et al., 1997). Additional standardization was achieved by subtracting the mean of each series from their corresponding values and dividing by their standard deviation with the program R (R Core Team, 2014). All reference chronologies were cut at a sample depth of five series. For the northern North American driftwood chronologies from the Yukon and Mackenzie River the five series threshold was not applied since the single series were not available.

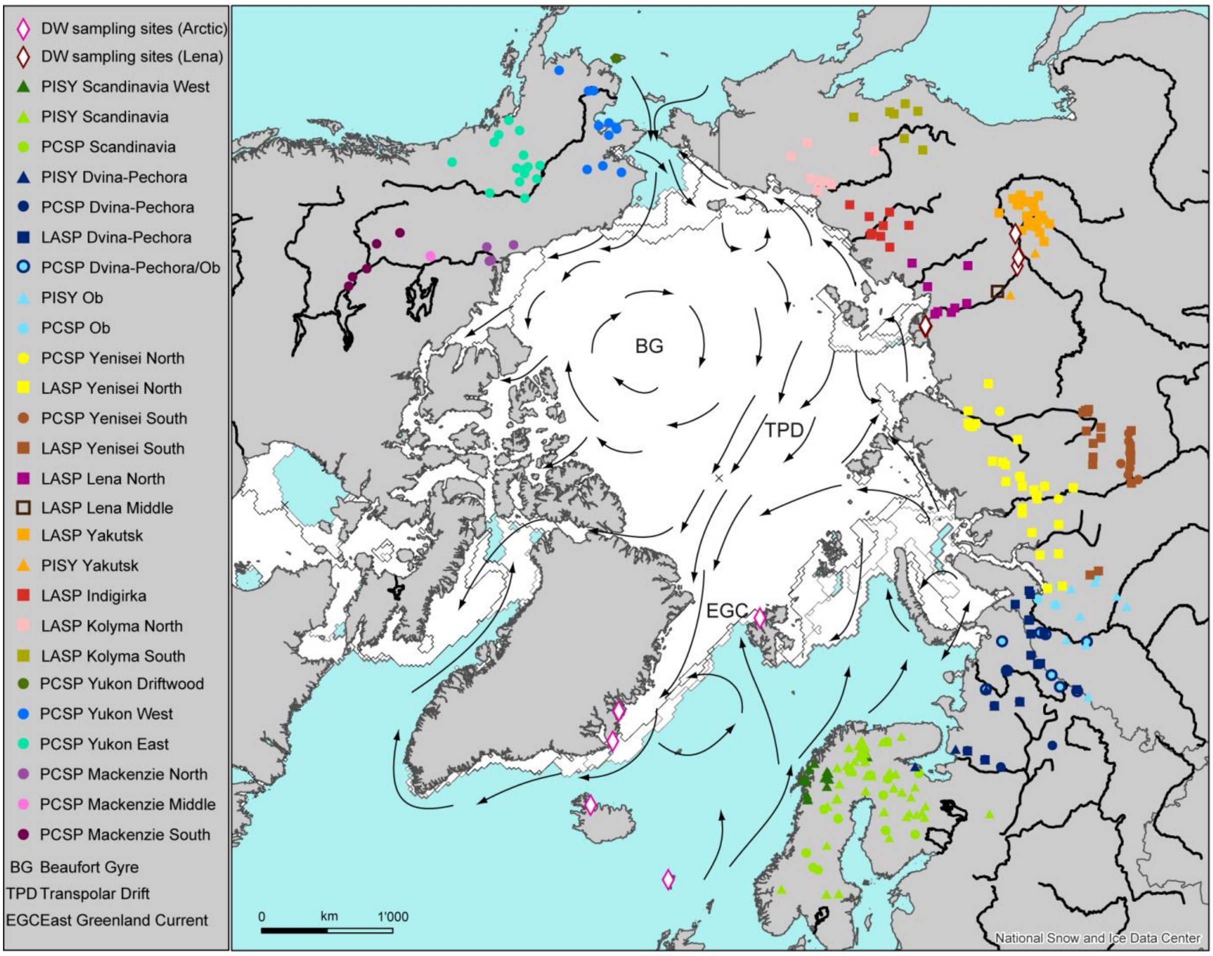

Figure 1*: Boreal wood is delivered to the Arctic Ocean by the large river systems in Russia and North America, after which it is included in the ice (white area represents the maximum July sea ice extent with the grey lines for the years 1979, 2000, 2010, 2015) and transported by the ocean currents (black arrows) to the coasts of sub-Arctic and Arctic islands, where driftwood was sampled (pink diamonds on Greenland, Iceland, Svalbard and the Faroe Islands). Driftwood and subfossil wood was also collected along the Lena River and within its delta (dark red diamonds). Colored symbols indicate the boreal reference TRW site chronologies. Triangles, circles and squares represent pine, spruce and larch, respectively. Color codes refer to common growth patterns of sites that were combined to regional reference chronologies and then used for cross-dating (Hellmann et al., 2016b).*

Results

Dendro-provenancing was possible for samples from the three main driftwood genera Scots pine (*Pinus sylvestris)*, spruce (*Picea* sp.) and larch (*Larix* sp.) from all sampling sites in Greenland, Iceland, Svalbard, the Faroe Islands, and the Lena River. Dating was achieved with different success rates depending on species and region against reference chronologies from the boreal forest zone (Table 1).

Scots pine driftwood provenancing

Pinus sylvestris originates in three different regions (Fig. 2, Table 2): A driftwood chronology including 28 series was provenanced to the Dvina catchment with a TBP of 11.9 , representing 2.9% of all Scots pine driftwood (Table 2). The Dvina Scots pine chronology covers the time span AD 1669-1980 with a mean segment length (MSL) of 128 years and an average growth rate (AGR) of 0.898 mm. The highest replicated driftwood chronology was cross-dated against the Southern Yenisei mean chronology with a TBP of 5.5 and includes 452 Scots pine series, hence 46.8% of all pine driftwood. This chronology also represents the longest pine chronology covering the period from AD 1614-1999 with a MSL of 144 years and an AGR of 0.861 mm. A driftwood chronology including 17 Scots pine series (1.8%) fits to the Southern Lena River chronology with a TBP of 6.1 and spans a time frame from AD 1643-1978 with a MSL of 174 years and an AGR of 0.758 mm . In total, 51.4% of all *Pinus sylvestris* driftwood was successfully dated (Table 1), with very little differences between the sampling sites (49.3% from Greenland, 54.0% from Iceland, 49.7% from Svalbard, 67.9% from the Faroe Islands).

Table 1*: Dated and undated driftwood per sampling site*

Genus	**Sampling site**	**Samples**	**Dated**	**% dated**
Pinus sylvestris	**All**	**969**	**498**	**51.4**
Pinus sylvestris	Greenland	452	223	49.3
Pinus sylvestris	Iceland	300	94	49.7
Pinus sylvestris	Svalbard	189	94	67.9
***Larix* sp.**	**All**	**1102**	**289**	**17.1**
***Larix* sp.**	Greenland	293	64	22.4
***Larix* sp.**	Iceland	191	29	15.2
***Larix* sp.**	Svalbard	79	8	10.1
***Larix* sp.**	Lena River	539	87	34.9
***Picea* sp.**	**All**	**351**	**53**	**15.1**
***Picea* sp.**	Greenland	170	22	13.0
***Picea* sp.**	Iceland	119	12	10.1
***Picea* sp.**	Svalbard	62	19	30.6

Spruce driftwood provenancing

Picea sp. driftwood series from Greenland, Iceland, and Svalbard originate in three Eurasian and two North American regions (Fig. 1). We assigned a chronology of 22 *Picea* sp. series to the Dvina region with a TBP of 7.8 that covers the time period AD 1753-1997. This chronology has a MSL of 111 years and an AGR of 0.875 mm. Another spruce driftwood chronology including five series cross-dated with a TBP of 8.8 against the Northern Yenisei data and covers the time period AD 1600-1977 with a MSL of 193 years and an AGR of 0.840 mm. The driftwood chronology dating with the southern Yenisei area (TBP = 9.2) covers the period AD 1735-1993 and includes eleven series. It has a MSL of 149 years and an AGR of 0.581 mm. The samples that were assigned to the Yukon driftwood chronology show a TBP of 7.4 over the time period AD 1668-1993 with a MSL of 146 years and an AGR of 0.737 mm. The series being dendro-provenanced to the Northern Mackenzie River (TBP = 8.3) represent the longest spruce driftwood chronology from AD 1594-1967 with a MSL of 159 years and an AGR of 0.427 mm. In total, we were able to date and provenance 53 (15.1%) of all spruce samples, with 41.5% from Greenland, 22.6% from Iceland, and 35.9% from Svalbard.

Table 2*: Characteristics of the dated (and floating for Larix) driftwood chronologies per species for each origin area (TBP: t-value after Baillie and Pilcher 1973, Rbar: mean inter-series correlation, MSL: mean segment length (years), AGR: average growth rate (mm), AC(1): lag-1 autocorrelation). For the larch chronologies, values for all samples together are shown (Larix all), as well as separated by sampling sites (Larix Arctic and Larix Lena).*

Genus	Origin	Total length	Series	TBP	Rbar	MSL	AGR	AC(1)
Pinus sylvestris	Dvina	1669-1980	28	11.9	0.321	128	0.898	0.838
Pinus sylvestris	Yenisei South	1614-1999	452	5.5	0.305	144	0.861	0.844
Pinus sylvestris	Yakutsk	1643-1978	17	6.1	0.263	174	0.758	0.87
Larix* sp. *all	Yenisei South	1608-1993	37	12.3	0.232	173	0.586	0.831
Larix* sp. *all	Yakutsk	1651-2011	28	10.9	0.300	162	0.687	0.785
Larix* sp. *all	Lena North	1499-1997	14	20.1	0.247	170	0.376	0.760
Larix* sp. *all	Lena Middle	1203-2012	109	13.8	0.225	173	0.585	0.802
Larix* sp. *Arctic	Yenisei South	1608-1993	37	12.3	0.232	173	0.586	0.831
Larix* sp. *Arctic	Yakutsk	1855-1989	6	8.0	0.575	106	0.718	0.802
Larix* sp. *Arctic	Lena North	1549-1995	9	19.2	0.207	164	0.360	0.723
Larix* sp. *Arctic	Lena Middle	1284-1994	49	10.6	0.219	146	0.625	0.785
Larix* sp. *Lena	Yakutsk	1651-2011	22	10.9	0.247	177	0.679	0.780
Larix* sp. *Lena	Lena North	-	5	-	-	-	-	-
Larix* sp. *Lena	Lena Middle	1203-2012	60	13.2	0.243	196	0.552	0.817
Larix* sp. *all	*Floating 1*	*712 years*	*7*	-	*0.342*	*265*	*0.452*	*0.825*
Larix* sp. *all	*Floating 2*	*240 years*	*5*	-	*0.691*	*185*	*0.705*	*0.907*
Larix* sp. *all	*Floating 3*	*279 years*	*10*	-	*0.392*	*173*	*0.523*	*0.812*
Larix* sp. *all	*Floating 4*	*205 years*	*14*	-	*0.662*	*157*	*0.592*	*0.883*
Larix* sp. *all	*Floating 5*	*184 years*	*4*	-	*0.746*	*132*	*0.884*	*0.846*
Larix* sp. *all	*Floating 6*	*293 years*	*7*	-	*0.685*	*168*	*0.936*	*0.886*
***Picea* sp.**	Dvina	1753-1997	22	7.8	0.218	111	0.875	0.779
***Picea* sp.**	Yenisei North	1600-1977	5	8.8	0.308	193	0.466	0.840
***Picea* sp.**	Yenisei South	1735-1993	11	9.0	0.252	149	0.581	0.728
***Picea* sp.**	Yukon Driftwood	1668-1993	9	7.4	0.229	146	0.737	0.856
***Picea* sp.**	Mackenzie North	1594-1967	6	8.3	0.379	159	0.427	0.835

Larch driftwood provenancing

Larix sp. from the Arctic Islands (Greenland, Iceland, and Svalbard) originates in four different regions. A driftwood chronology including 37 larch series dated with the southern Yenisei region with a TBP of 12.3 and covers the period AD 1608-1993, showing a MSL of 173 years and an AGR of 0.898 mm (Table 2, Fig. 2). The main origin area of larch driftwood is eastern Siberia. A chronology including nine series from Iceland and Greenland cross-dated with the Northern Lena chronology with a TBP of 19.2 and covers the time span from AD 1549-1995 with a MSL of 164 years and an AGR of 0.360 mm. A chronology represented by 49 and therefore most larch driftwood series was cross-dated with the Middle Lena River data and also covers the longest time period AD 1284-1994. The driftwood chronology dates with a TBP of 10.6, has a MSL of 146 years and an AGR of 0.360 mm. Six larch series were combined to a chronology that was cross-dated with the Southern Lena chronology (Yakutsk) with a TBP of 8.0 over the time period from AD 1855-1989, with a MSL of 106 years and an AGR of 0.718 mm. In total, we were able to dendro-provenance 13.9% of all larch driftwood series from the Arctic Islands.

The combination of larch series from the Arctic Islands with driftwood and subfossil material from the Lena River results in an extension of the three chronologies that were dendro-provenanced to this area (for an overview on larch chronologies from the Arctic Islands, eastern Siberia and the combination of all larch sampling sites see table 2). The Northern Lena larch chronology with combined series (nine from the Arctic Islands and five from the Lena River) then covers the period from AD 1499-1997 with a higher TBP of 20.0, a MSL of 170 and an AGR of 0.376 mm. The combined chronology that cross-dated with the Lena Middle data includes 109 series and hence represents the best replicated larch chronology by also covering the longest time period from AD 1203-2012. Dating is based on a TBP of 13.8, the MSL is 173 years and the AGR 0.585 mm. The chronology of Arctic and Lena wood that was cross-dated against the Yakutsk data, includes 28 series for the time period AD 1651-2011, based on a TBP of 10.9, with a MSL of 162 and an AGR of 0.687 mm.

In total, we were able to date 188 of the 1’102 larch series and hence 17.1% all larch driftwood samples, with success rates of 21.8% for Greenland, 15.2% for Iceland, 10.1% for Svalbard and 34.9% for the Lena River (Table 1). We cross-dated the majority (37.5%) of all *Larix* sp. driftwood samples with a reference from the middle Lena River. This reference is the mean of an ITRDB chronology (russ204) covering the period AD 1519-2007 and a site chronology from living trees that resulted from an expedition along the Lena River covering the period AD 1535-2013 (own data). The reference hence has a length of 494 years from AD 1519-2013. Our *Larix* sp. driftwood chronology with a length of 809 years and covering the time period AD 1203-2012 extends the existing data by 315 years to the past. Six floating chronologies were additionally built for *Larix* sp. (Table 2, Fig. S6). These chronologies include between four and 14 series, the MSL ranges from AD 132 to 265 years and the AGR from 0.452 to 0.936 mm. The longest chronology covers 712 years with seven series, the shortest 184 years including four series.

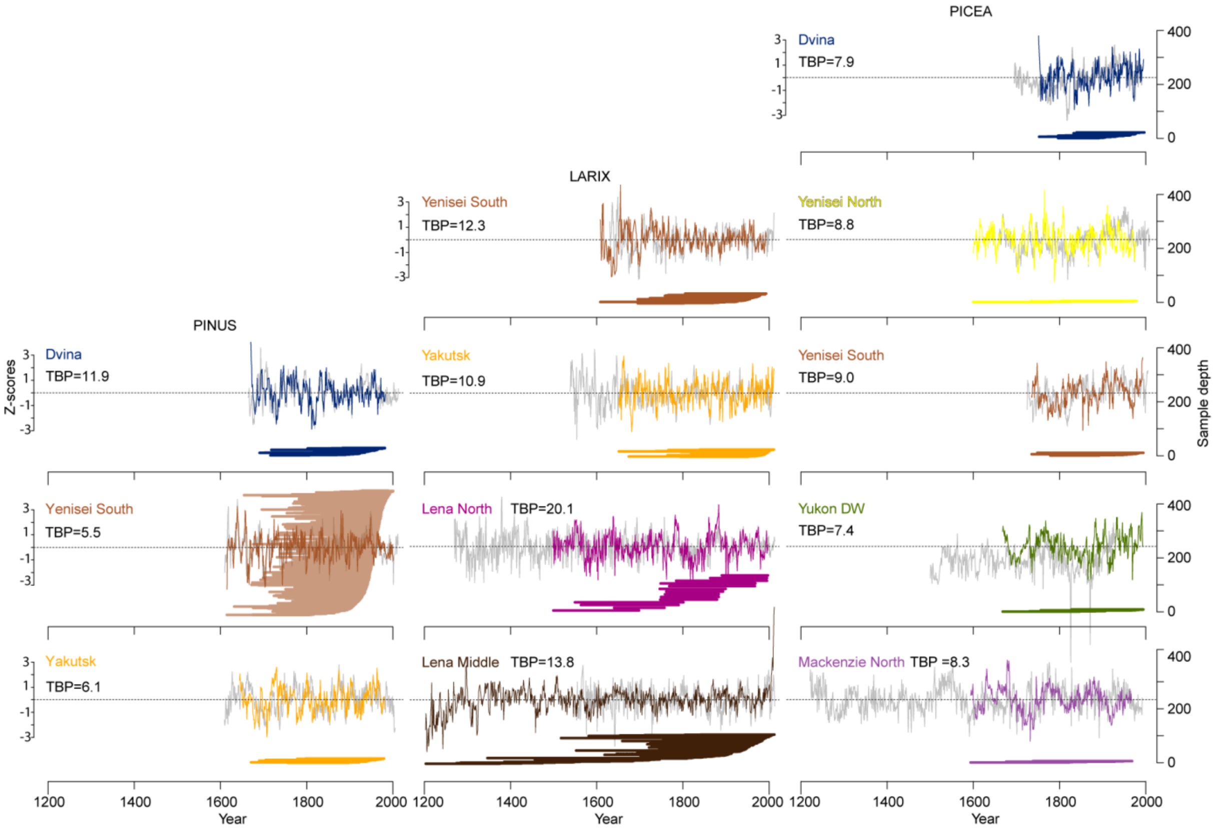

***Figure 2**: Cross-dating of driftwood chronologies with regional references for Pinus sylvestris, Picea sp. and Larix sp.. Colored curves and bars represent the driftwood data and grey curves the according references. Chronologies were detrended by negative exponential functions after power transformation in combination with variance stabilization and normalization. The bars show the temporal distribution of the single driftwood series that were successfully cross-dated. Larix chronologies include Arctic driftwood series as well as series from the Lena River.*

The classification of dated driftwood samples by collection sites shows that 44.8% of the dated pine samples were collected in Greenland, 32.5% in Iceland, 18.9% in Svalbard and 3.8% on the Faroe Islands. For larch we find that 22.4% of the dated larch samples were gathered in Greenland, 15.2% in Iceland, 10.1% in Svalbard, and 35.0% along the Lena River. For spruce, 13.0% from Greenland were cross-dated, 10.1% from Iceland, and 30.6% from Svalbard. These findings agree with the dominating forest types in the origin areas and ocean current directions that suggest more wood from western Siberia (mainly spruce) to arrive in Svalbard, and more wood from central (mainly pine) and eastern (mainly larch) Siberia to be delivered to Greenland and Iceland.

Discussion

Our dating results show that the amount of driftwood that is delivered to the Arctic Ocean from a region is highly connected to river discharge and forest composition. The Yenisei River has the highest discharge of all the rivers draining into the Arctic Ocean and more than 70% of the driftwood from the Arctic Islands is assigned to the Southern Yenisei region. Most of this wood is represented by logged pine timber that got lost during floating transportation on the river (Hellmann et al., 2015). The region is also characterized by pine dominated forests (Bartalev et al., 2004). Even 35.9% of the dated *Larix* sp. samples (excluding all samples collected in the Lena region) and 20.8% of the dated *Picea* sp. also come from the Southern Yenisei region. Further coherence is found between driftwood origin and predominating vegetation form along the boreal rivers. With 41.5% most of the spruce driftwood samples are assigned to the Dvina reference group, where spruce forests are the predominating vegetation form. Most larch samples (without the Lena samples) are with 47.6% assigned to the middle Lena region where larch forests are prevalent.

Earlier studies on Arctic driftwood dated pine and spruce samples with single boreal reference chronologies (see overview in Hellmann et al., 2016b). Our study is the first dendro-provenancing analysis that successfully cross-dated larch driftwood. This is achieved on one hand through our massive sample replication that combines driftwood from the Arctic Islands with samples from the larch dominated forests in eastern Siberia, representing the most probable origin area of larch driftwood. On the other hand, our systematic collection of references and the establishment of new chronologies from living trees for the Lena region, show the great importance of a dense spatial and long temporal distribution of references to successfully dendro-provenance driftwood samples, in particular larch.

More wood from the western Russian Dvina region is found on Svalbard than on Greenland and Iceland (Fig. 3, Fig. S5, Table S1). A total of 25.6% of the dated Svalbard samples are assigned to the Dvina region, in comparison to 4.9% from Greenland and 2.0% from Iceland. The wood from this region has to be included in the sea ice in the Barents Sea, and transported in a northwest direction to reach coastlines located further east. The probability of reaching the East Greenland Current that could transport material further to the eastern coast of Greenland and the Northern coast of Iceland is smaller for wood from western Russia (Fig. 1).

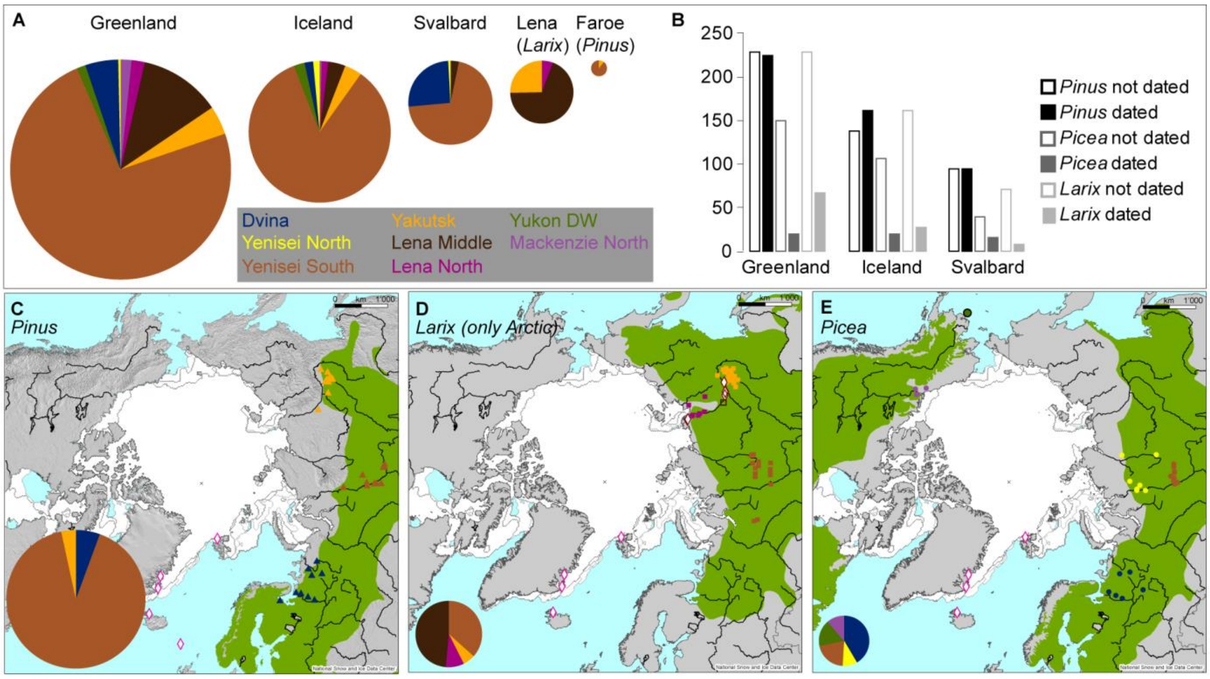

Figure 3: *Overview of the driftwood dating results: (A) shows the percentages of dated driftwood per sampling site, including the three genera Pinus sylvestris, Larix, and Picea. The size of the circles refers to the number of samples and the colors to the different origin regions. (B) illustrates the amount of dated and undated wood per sampling site and genus. (C) shows the percentages of pine driftwood cross-dated with Dvina, Yenisei, and Lena reference chronologies. (D) shows the cross-dating results of larch with Yenisei South, Lena North, Lena Middle, and Yakutsk; and (E) shows the results of spruce with Dvina, Yenisei North, Yenisei South, Yukon driftwood, and Mackenzie North, respectively.*

The AGR of the dated driftwood samples is correlated with latitude. All genera show more narrow average ring-widths towards the North of their distribution area (Fig. 4). At the same time, the TBPs are higher the further North the reference chronologies are located, indicating that more narrow ring-widths patterns cross-date better than wide rings (Fig. 4). The highest TBP of 20.1 is shown by the Lena North chronology with the reference located at ~70°N, the northernmost of our references. However, in the unfavorable regions of the North the probability of missing rings is also much higher (Hantemirov and Shiyatov, 2002), which can again aggravate dendro-provenancing.

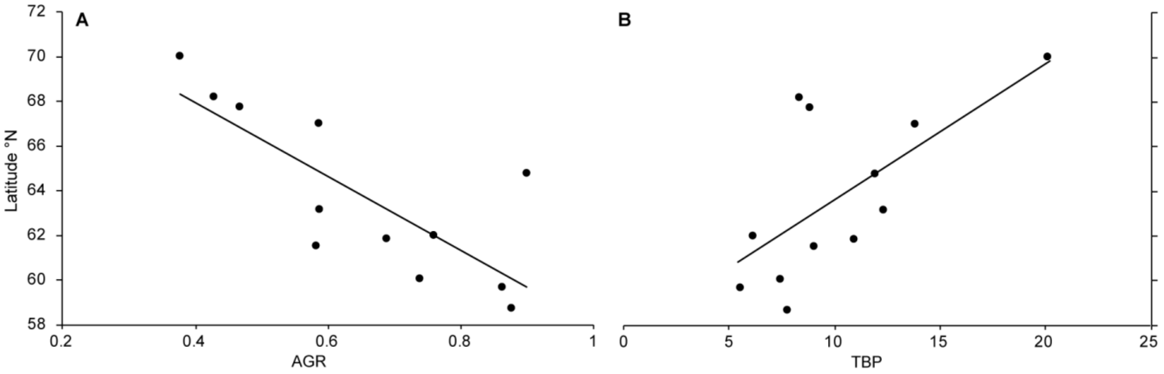

***Figure 4**: (A) Average growth rate (AGR) and (B) t-values after Baillie-Pilcher (TBP) of the dated driftwood chronologies plotted against latitude in degrees North. Lines added are linear trendlines.*

We were able to cross-date 51.3% of all our pine driftwood in comparison to 15.1% of the spruce and 17.9% of the Arctic larch samples (26.2% when including samples from the Lena region). The high amount of recently logged timbers from the Southern Yenisei region dating in the time period of high logging and floating activities (~1920-1975), when high amounts of wood got lost and were further transported to the Arctic Ocean (Hellmann et al., 2015), is the main reason for higher success rates in pine cross-dating.

The floating *Larix* sp. chronologies (Fig. 5) indicate that the included samples might be older than existing reference chronologies. The AGR might point toward the origin areas of these samples. Based on results from successfully dendro-provenanced wood (Fig. 4), we can assume that a lower growth rate (e.g. *Floating 1* with 0.342 mm) hints at a northern origin, while a relatively high growth rate (e.g. *Floating 5* with 0.746 mm) likely indicates an origin area further South. The *Floating 3* chronology that covers 279 years with ten samples (Table 2) very likely cross-dates with a *Larix* sp. series of 272 years with the outermost rings dating around AD 25-130 (^{14}C age 1919 BP) based on radiocarbon analysis

(Fig. S6). The chronology has an overlap of 137 years with the ^{14}C dated reference sample, dating at 336-58 BC +/- 53 years with a TBP of 6.5.

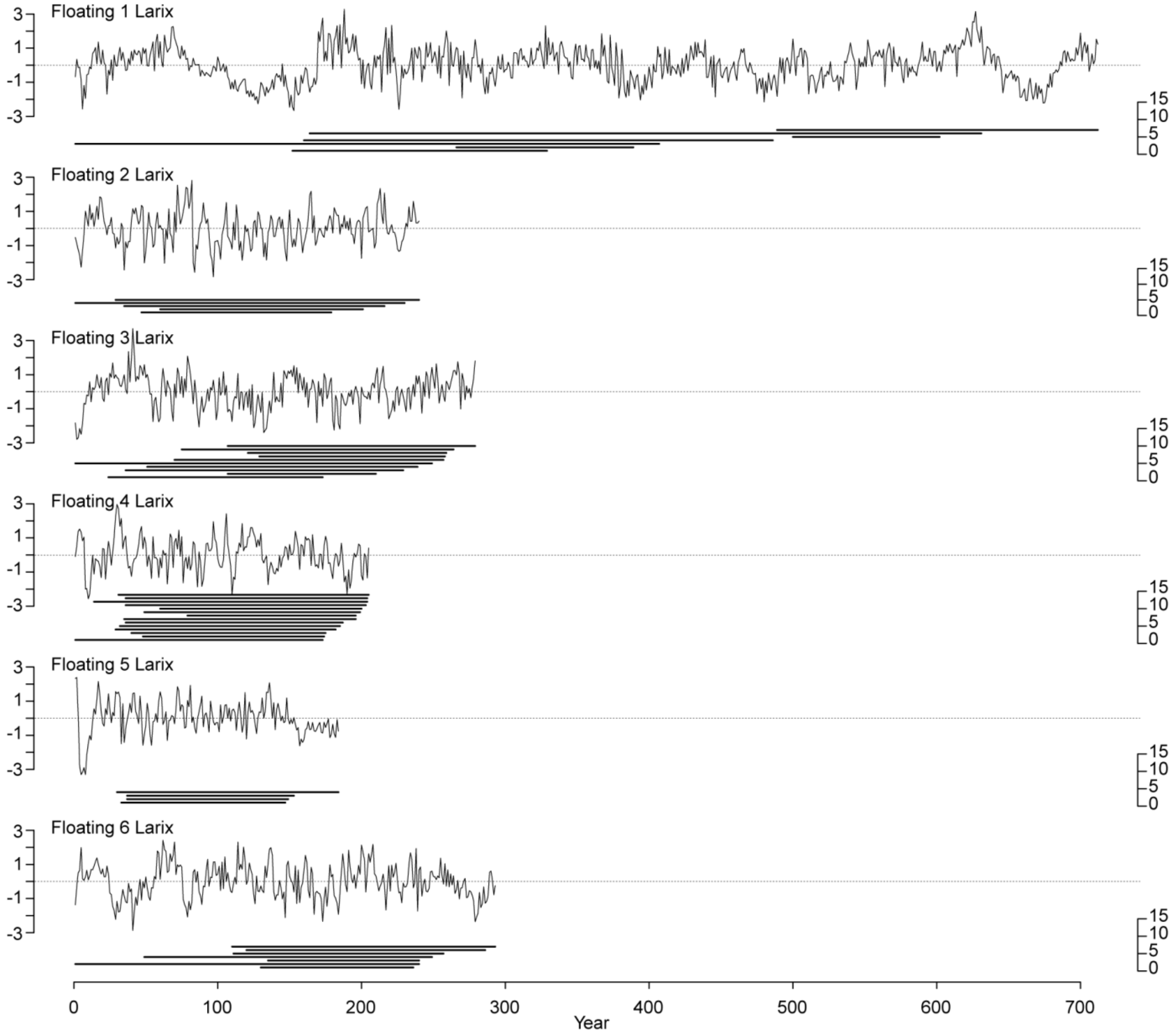

***Figure 5**: Six floating, i.e. dendrochronologically so far not datable Larix driftwood chronologies were found. Chronologies were build by applying negative exponential detrending with variance stabilization and normalization after power transformation. Bars show the number and length of single series.*

To gain better insight in driftwood delivery over more than the past few centuries, radiocarbon dating of the floating chronologies and of all dendrochronologically not datable wood samples, is required. If different origin areas would be found for different time periods over the past millennia, conclusions on variations in ocean currents (Dyke et al., 1997), as well as sea ice extent (Funder et al., 2011), could be achieved. Knowledge on the availability of driftwood based on geographically well distributed sampling sites could help explain past settlement establishment and abandonment that might not only be due to climate variations. The long-term proxy records that are possible results of Arctic driftwood analyses can be important contributions for the validation of long-term models that aim to predict the Earth's natural climate variability over 10,000 years (Clark et al., 2016).

Our results that show spruce driftwood to originate in western Russia as well as in North America and larch in eastern as well as central Siberia, question the assumption of Funder et al. (2011) that spruce originates exclusively in North America and larch in eastern Siberia, respectively. Their sites are located further North, however, the restriction is debatable regarding the natural boreal forest distribution and also regarding our cross-dating results. The low certainty of determining the origin of Arctic driftwood by species identification only, emphasizes the importance of combining dendro-provenancing and ^{14}C dating. Comparing the growth patterns of ^{14}C dated driftwood samples, will, in combination with subfossil or other millennial-old material from the origin areas, facilitate the understanding of driftwood routes over long time-scales.

Various factors in source and sink regions, but also during the transport of Arctic driftwood influence amount and properties of transported timber, direction and length of drift routes, percentage of sunk timber, as well as deposition locations (Fig. 6). These complex characteristics of the Arctic driftwood system show the importance of not only using dendrochronological and wood anatomical methods, but to involve radiocarbon dating, as well as isotopic tracing and aDNA processing, requesting interdisciplinary research efforts.

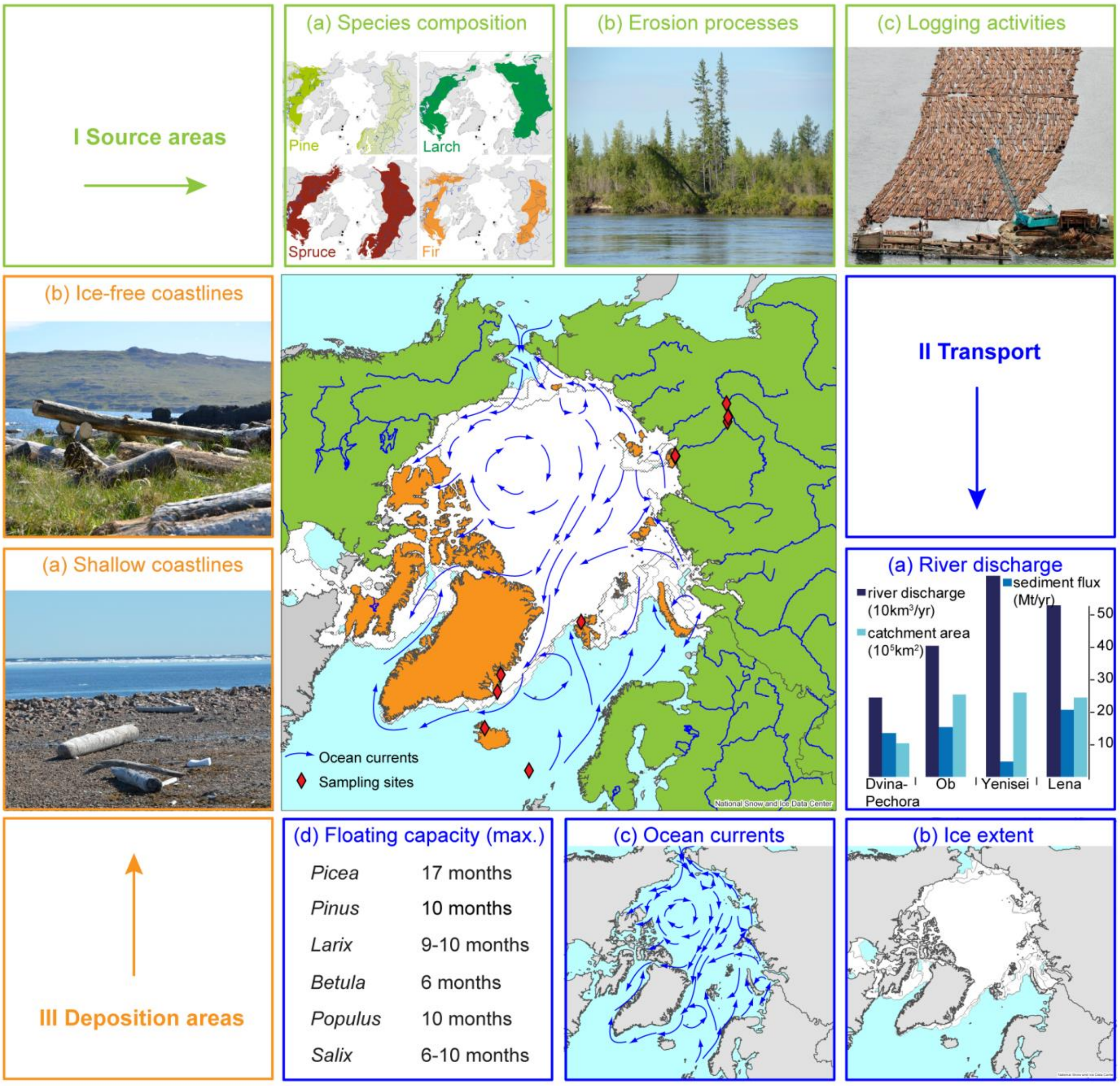

Figure 6: *Overview of the Arctic driftwood system: (I) Source areas are influenced by (a) species composition (Hellmann et al., 2013), (b) erosion processes along the rivers (Foto by W. Tegel) and (c) logging activities (Foto downloaded from: http://msnbcmedia.msn.com/j/MSNBC/Components/Photo/_new/pb-110728-timber-rafts-eg.photoblog900.jpg) and determine how much and which kind of wood is delivered to the Arctic Ocean. (II) The amount and characteristics of wood transported further across the Arctic Ocean is influenced by boreal river discharge (Hellmann et al., 2015), sea ice extent (data from the National Snow and Ice Data Center, https://nsidc.org/data/docs/noaa/g02202_ice_conc_cdr/), ocean current dynamics (ACIA, 2005), and the floating capacities of the different species (Häggblom, 1982). (III) The coastlines, where*

timber is deposited after being carried over the ocean, are generally (a) shallow (Greenland, Foto by W. Tegel) and (b) ice-free (Iceland, Foto by L. Hellmann).

Conclusions

Our study demonstrates considerable cross-dating improvement of driftwood against a unique spatially and temporally replicated boreal reference network. A total of 2,412 tree-ring series of *Pinus sylvestris*, *Larix* sp. and *Picea* sp. driftwood from Greenland, Iceland, Svalbard, the Faroe Islands and eastern Siberia were measured and 738 series were successfully dendro-provenanced. The southern Yenisei region is the main source for recent Arctic driftwood that mainly consists of *Pinus sylvestris*. *Larix* sp. and *Picea* sp. partly also originate in this region. Dendro-provenancing of *Larix* sp. driftwood is possible and most larch wood comes from the middle Lena region. *Picea* sp. driftwood originates in western Eurasia and in North America. More wood from western Eurasia is found on Svalbard than on Greenland and Iceland, where wood from central and eastern Siberia is prevalent. This spatial distribution can be explained by drift directions of the sea ice through the ocean currents.

Dendro-provenancing is restricted by the spatiotemporal availability of reference chronologies. The oldest sample found for *Larix* sp. (from the Lena River) dated AD 1203-1375, for *Picea* sp. AD 1594-1822, and for *Pinus sylvestris* AD 1614-1810. The *Larix* sp. driftwood samples that were cross-dated against the middle Lena chronology extend the reference by 315 years to the past. However, our results show the pattern of driftwood delivery over the recent period. To draw conclusions about different ocean current settings, past variations in sea ice extent, dating of even more wood samples that ideally cover a larger time period, are needed and only achievable by radiocarbon dating of our dendrochronologically not datable series.

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