Dendro-provenancing of Arctic driftwood

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Abstract

Arctic driftwood may represent a cross-disciplinary proxy archive at the interface of marine and terrestrial environments, which will likely gain in importance under future global climate change. Circumpolar network analyses that systematically consider species-specific boreal origin areas, transport routes and deposition characteristics of Arctic driftwood, are, however, missing. Here, we present tree-ring width (TRW) measurements of 2,412 pine, larch and spruce driftwood samples from Greenland, Iceland, Svalbard, the Faroe Islands, and the Lena Delta in northeastern Siberia. Representing the largest Arctic driftwood TRW compilation, these data are compared against 495 TRW reference chronologies from the boreal forests of Eurasia and North America. The southern Yenisei region 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. Larch driftwood is, for the first time, dendro-provenanced to central and eastern Siberia. A new larch driftwood chronology extends the middle Lena River reference chronology back to 1203 CE. Annually resolved radiocarbon measurements further date six larch driftwood chronologies between 1294 and 2013 CE. Although being highly replicated, our study emphasizes the importance of interdisciplinary research efforts including radiocarbon dating, isotopic tracing and aDNA processing for improving Arctic driftwood provenancing in space and time. If successful, Arctic driftwood studies will contribute to the reconstruction of past boreal summer temperature variations and ocean current dynamics, as well as changes in sea ice extent and relative sea level over the last centuries to millennia.

Keywords:

driftwood, Arctic Ocean, boreal forest, dendro-provenancing, *Larix* sp.

Introduction

The Arctic, where temperatures rapidly rise and sea ice extent significantly decreases, is worldwide the region reacting most sensitively to climate change (IPCC, 2013; Räisänen, 2001). Higher temperatures and reduced sea ice in the Arctic Ocean have and will have strong implications on different environmental systems all over the Arctic and beyond (Pearson et al., 2013; Smol, 2012; Sörlin, 2015). An increased knowledge on both, the extent of ongoing and future changes as well as their effects is essential to elaborate and apply effective mitigation and adaptation measures. Predictive models, which are used to better calculate future climatic and environmental changes, rely on highly resolved observational and/or proxy data for 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 (Johannessen et al., 2004; Pages 2k Consortium, 2013). Most of the existing instrumental station measurements and satellite images do not extend prior to the mid- and late-20th century, respectively (Esper et al., 2010; Gordov et al., 2013). Moreover, sampling of Arctic proxy archives, such as ocean sediment cores or ice cores, is time consuming and expensive. The spatial density as well as the temporal resolution of most proxy records in this region is therefore low (McKay and Kaufman, 2014).

Tree rings represent one of the most reliable, best resolved and often easily accessible source of palaeoenvironmental information (e.g. Briffa et al., 2002; Büntgen et al., 2005; Cronin, 2009; Esper et al., 2012; Fritts, 1976; Fritts, 1991). The Arctic, even though characterized by treeless landscape, provides wood that can be used as a proxy archive: Driftwood from the boreal forest zone, which has been carried to the north via large boreal river systems, is deposited along shallow Arctic coastlines after a several year-long transport within the sea ice across the Arctic Ocean (Eggertsson, 1993, 1994; Hellmann et al., 2013; Hellmann et al., 2015; Johansen, 1998; Johansen, 2001). It therefore represents a unique record at the interface of marine and terrestrial environments that can provide annually resolved information over millennial-long time-scales (Funder et al., 2011; Nixon et al., 2016).

In its source region, i.e. the northern-hemispheric boreal forests, Arctic driftwood enters the large rivers either due to natural processes such as river bank erosion and storm surges, or due to losses of industrial timber floating activities along the large rivers (Hellmann et al., 2013). Once the wood has

reached the Arctic Ocean, it is mainly transported via the Transpolar Drift (TPD), which results from an anti-cyclonic circulation in the Beaufort Sea (i.e. the Beaufort Gyre; BG), and a cyclonic circulation in the Laptev Sea (Fig. 1, Proshutinsky and Johnson, 1997). Sea ice and driftwood 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. With a minimum of four to five years, transport times for ice and hence also for wood are 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). Not only the strength and direction of ocean currents, but also the extent of sea ice in the Arctic Ocean influence the distribution of driftwood. Changing conditions in the Arctic can hence have strong effects on transport and accumulation of the timber.

Figure 1: Boreal wood is delivered to the Arctic Ocean by the large river systems in northern Russia and northern 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). Ocean currents (blue arrows) transport the driftwood further to the coastlines of sub-Arctic and Arctic islands, where it was sampled (pink diamonds). (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 (Hägglom, 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).

The investigation of Arctic driftwood offers the chance to improve our understanding of past historical, ecological, climatic, cryospheric and hydrological conditions and processes in its source, transport and sink regions (Alix, 2005, 2009; Alix and Brewster, 2004; Blanchette et al., 2016; Dyke et al., 1997; Funder et al., 2011; Hellmann et al., 2015; Rämä et al., 2014; Wheeler and Alix, 2004). A highly replicated and spatiotemporally extensive sample record is hereby key for drawing reliable conclusions over various scales. Earlier studies on Arctic driftwood most often focus on one region and analyze a very limited number of samples. Dendro-provenancing of driftwood has not yet been realized in combination with a systematic collection and analysis of reference chronologies for the main driftwood species (Hellmann et al., 2013). The temporal restriction in dendro-dating can partly be solved by radiocarbon analyses, but missing knowledge on the origin of the driftwood again limits further conclusions.

In seeking to overcome these limitations, we developed the so-far largest record of Arctic driftwood, containing 2,412 tree-ring width (TRW) series of Scots pine (*Pinus sylvestris*), larch (*Larix* sp.) and spruce (*Picea* sp.) from four sub-Arctic and Arctic islands, as well as from the Lena River in eastern Siberia. After precise wood anatomical identification of all samples, TRW was measured and the resulting series compared against each other to first build floating driftwood chronologies. These were then dendro-provenanced by cross-dating against a highly replicated network of 495 boreal reference TRW chronologies from northern Eurasia and northern North America. Additional radiocarbon dating of certain samples was applied to reveal the age of dendrochronologically undated chronologies.

Material and Methods

Disc samples from driftwood were 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 in the 1990's (Fig. 1; Hellmann et al., 2013; Hellmann et al., 2015). Subfossil and driftwood samples were collected along the northeastern Siberian 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 their surface was cut with a box cutter after sanding with 100 grains cm⁻¹. Ring widths of 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 using the program TSAPwin (Rinntech, Heidelberg, Germany) and a Lintab measuring device at a precision of 0.01 mm. 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 sample and combined to a sample-specific mean curve that was used for further analyses.

As reference data from the boreal forest zone, we compiled 495 site chronologies $\geq 60^\circ\text{N}$ 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 our Russian colleagues (Hellmann et al., 2016a). Chronologies of all three genera were used for Eurasia. For North America only spruce data were available, thus representing the boreal species distribution of spruce dominated forests there. Regional references were created by combining several sites to mean chronologies per genus based on common growth patterns (Hellmann et al., 2016a; Fig. S1, S6; Table S2). Six groups for pine, eleven groups for larch, and twelve for spruce (six for northern Eurasia, six for northern North America) were developed and their mean curves were further used for cross-dating the driftwood series (Hellmann et al., 2016a; Hellmann et al., 2015; Fig. S2-S5).

A comparison of all driftwood series per genus resulted in several floating, i.e. undated chronologies that were then cross-dated against the mean regional reference chronologies from the boreal forest zone. This so-called dendro-provenancing (Bonde et al., 1997; Eckstein and Wrobel, 2006) is based on a statistical and visual comparison between sample and reference ring-width curves and was realized based on the raw series using the program PAST4 by SCIEM (Scientific Engineering and Manufacture, Vienna). The program applies statistical criteria, mainly the t-value after Baillie and Pilcher (TBP; Baillie and Pilcher, 1973) for the synchronization of reference and sample chronologies

and also allows visual cross-checking for dating. Successful dendro-provenancing, i.e. high coherence between sample and reference curves results not only in dating but also in revealing the origin of the samples by knowing the geographic location of the specific reference chronology (Daly and Nymoen, 2008; Domínguez - Delmás et al., 2013; Hellmann et al., 2015). Minimum t-values for cross-dating were set to four (4.0), and all datings were in addition carefully controlled visually. Visual control is crucial to detect false high statistical correlations that are due to one or few very large or very narrow rings. The program ARSTAN (ARSTAN_41d for Windows (Cook and Krusic, 2007)) was used to remove age trends by applying negative exponential functions (Cook and Kairiukstis, 1990) after power transformation of the data (Cook and Peters, 1997). Adaptive power transformation uses the relationship between level and spread to stabilize the variance in tree-ring series (Cook and Krusic, 2007). Narrower ring widths with increasing age of trees are defined as age-related biological growth trends that are often removed for further analyses by specific detrending methods (Esper et al., 2002). Detrending by negative exponential functions calculates the ratio of the actual ring widths and an expected, non-linear growth curve, resulting in dimensionless index-values (Z-scores) (Fritts, 1976). The final chronologies were calculated using bi-weight robust means and considering the standard ARSTAN routine. Additional variance stabilization was also performed with ARSTAN (Osborn et al., 1997) and the program R (R Core Team, 2016) was used for standardization by calculating the mean and standard deviation of the chronology and then subtracting the mean from each value and dividing by the standard deviation. All reference chronologies were cut at a minimum sample depth (i.e. number of series that are included in a chronology in a certain year) of five series to get a reliable signal on the one hand but on the other hand to avoid shortening the lengths of the chronologies too much. For the northern North American driftwood chronologies from the Yukon and Mackenzie River the five lower replication series threshold was not applied since single series were not available.

A subset of 29 *Larix* sp. single tree rings, which have been selected from samples combined to floating driftwood chronologies, were radiocarbon dated. Sample preparation followed the base-acid-base-acid-bleaching (BABAB) method (Nemec et al., 2010). Subsequent graphitization (Nemec et al., 2010; Wacker et al., 2010b) and Accelerator Mass Spectrometry (AMS) dating (Wacker et al., 2010a) was performed at the laboratory for Ion Beam Physics, ETH Zurich. At least three tree rings with a

minimum of 30 years difference were dated per floating chronology. Rings were chosen to fulfill this criteria but the exact differences between the single dates differ due to varying replications and difficulties to cut very narrow rings at the outer parts of the wood samples. The aim was to date a sufficient number of rings for reliable wiggle matching, resulting in different numbers of ^{14}C dates per chronology. Three ring samples were measured twice due to technical reasons, leading to the same results and hence confirming the dating. Calibration based on the IntCal13 curve (Reimer et al., 2013) and subsequent wiggle matching of the single dates obtained per chronology (Bronk Ramsey et al., 2001) was performed using the program OxCal 4.2 that uses Bayesian statistics and calculates the relative likelihood of each possible calendar year fit, which can then be used to calculate a range of most likely dates (Bronk Ramsey, 1995; Bronk Ramsey, 2009; Bronk Ramsey et al., 2001) (for further details see model input in table S3). Wiggle matching is a common way of reducing the range of ^{14}C dates by including other data such as stratigraphic information or further dating evidence, such as tree-ring dates (Bronk Ramsey et al., 2001).

Results

Dendro-provenancing was achieved for samples from the three main driftwood genera 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. Larch driftwood was hereby for the first time successfully cross-dated. Dating against reference chronologies from the boreal forest zone was achieved with different success rates depending on species and region (Table 1).

Table 1: Dated and undated driftwood fractions per sampling site

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

213 *Scots pine driftwood provenancing*

214 *Pinus sylvestris* originates in three different regions (Fig. 2; Table 2): A driftwood chronology
215 including 28 series was dendro-provenanced to the Dvina catchment with a TBP of 11.9, representing
216 2.9% of all Scots pine driftwood (Table 2). The Dvina Scots pine chronology covers the time span
217 1669-1980 CE with a mean segment length (MSL) of 128 years and an average growth rate (AGR) of
218 0.898 mm. The highest replicated driftwood chronology was cross-dated against the southern Yenisei
219 mean chronology with a TBP of 5.5. It includes 452 Scots pine series, hence 46.8% of all pine
220 driftwood. This chronology also represents the longest pine chronology covering the period 1614-1999
221 CE with a MSL of 144 years and an AGR of 0.861 mm. A driftwood chronology including 17 Scots
222 pine series (1.8%) fits to the southern Lena River chronology with a TBP of 6.1 and covers a time
223 frame spanning 1643-1978 CE with a MSL of 174 years and an AGR of 0.758 mm. In total, 51.4% of
224 all *Pinus sylvestris* driftwood was successfully dated (Table 1), with very little differences between the
225 sampling sites (49.3% from Greenland, 54.0% from Iceland, 49.7% from Svalbard, 67.9% from the
226 Faroe Islands).

227 *Spruce driftwood provenancing*

228 *Picea* sp. driftwood from Greenland, Iceland, and Svalbard originates in three northern Eurasian and
229 two northern North American regions (Fig. 1). We assigned a chronology of 22 *Picea* sp. series with a
230 TBP of 7.8 to the Dvina region that covers the time period 1753-1997 CE. This chronology has a MSL
231 of 111 years and an AGR of 0.875 mm. Another spruce driftwood chronology including five series
232 was cross-dated with a TBP of 8.8 against the northern Yenisei data and covers the time period 1600-
233 1977 CE with a MSL of 193 years and an AGR of 0.840 mm. The driftwood chronology dating with
234 the southern Yenisei area (TBP = 9.2) covers the period 1735-1993 CE and includes eleven series. It
235 has a MSL of 149 years and an AGR of 0.581 mm. The samples that were assigned to the Yukon
236 driftwood chronology show a TBP of 7.4 over the time period 1668-1993 CE with a MSL of 146 years
237 and an AGR of 0.737 mm. The series being dendro-provenanced to the northern Mackenzie River
238 (TBP = 8.3) represent the longest spruce driftwood chronology spanning 1594-1967 CE with a MSL
239 of 159 years and an AGR of 0.427 mm. In total, we were able to date and provenance 53 (15.1%) of
240 all spruce samples, with 41.5% from Greenland, 22.6% from Iceland, and 35.9% from Svalbard.

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

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

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 1608-1993 CE, 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 against the northern Lena chronology with a TBP of 19.2 and covers the time span 1549-1995 CE 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 against the middle Lena River data and also covers the longest time period 1284-1994 CE. This driftwood chronology dates with a TBP of 10.6, has a MSL of 146 years and an AGR of 0.360 mm.

257 Six larch series were combined to a chronology that was cross-dated against the southern Lena
258 chronology (central Yakutia) with a TBP of 8.0 over the time period 1855-1989 CE, with a MSL of
259 106 years and an AGR of 0.718 mm. In total, we were able to dendro-provenance 13.9% of all larch
260 driftwood series from the Arctic islands.

261 The combination of larch series from the Arctic islands with driftwood and subfossil material from the
262 Lena River results in an extension of the three chronologies that were dendro-provenanced to this area
263 (for an overview on larch chronologies from the Arctic islands, eastern Siberia and the combination of
264 all larch sampling sites see table 2). The northern Lena larch chronology with combined series (nine
265 from the Arctic islands and five from the Lena River) covers the period 1499-1997 CE with a higher
266 TBP of 20.0, a MSL of 170 and an AGR of 0.376 mm. The combined chronology that cross-dated
267 against the reference from the middle Lena region includes 109 series and hence represents the best
268 replicated larch chronology by also covering the longest time period 1203-2012 CE. Dating is based
269 on a TBP of 13.8, the MSL of the chronology is 173 years and the AGR 0.585 mm. The combined
270 chronology of Arctic and Lena wood that was cross-dated against the central Yakutian reference data,
271 includes 28 series for the time period 1651-2011 CE, based on a TBP of 10.9, with a MSL of 162 and
272 an AGR of 0.687 mm.

273 In total, we were able to date 188 of the 1,102 larch series and hence 17.1% all larch driftwood
274 samples, with success rates of 21.8% for Greenland, 15.2% for Iceland, 10.1% for Svalbard and 34.9%
275 for the Lena River system (Table 1). We cross-dated the majority (37.5%) of all *Larix* sp. driftwood
276 samples with a reference from the middle Lena River region. This reference is the mean of an ITRDB
277 chronology (russ204) covering the period 1519-2007 CE and a site chronology from living trees that
278 resulted from an expedition along the Lena River covering the period 1535-2013 CE (own data). The
279 reference hence has a length of 494 years spanning 1519-2013 CE. Our *Larix* sp. driftwood
280 chronology with a length of 809 years covers the time period 1203-2012 CE and extends the existing
281 data by 315 years into the past.

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 built by applying negative exponential detrending after power transformation in combination with variance stabilization and normalization, resulting in dimensionless values, i.e. Z-scores. Sample depth describes the number of series that are included in a chronology in a certain year. 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.

Six chronologies were additionally built for *Larix* sp. (Table 2), which could not be dendro-dated (Fig. S7). These chronologies include between four and 14 series, the MSL ranges from 132 - 265 years and the AGR from 0.452 - 0.936 mm. The longest chronology covers 712 years with seven series, the shortest 184 years including four series. Radiocarbon dating of at least three tree rings that are well distributed across the chronology allowed subsequent wiggle matching, hence showing the temporal distribution of these chronologies (Table 3; Table S4; Fig. 3).

Table 3: Radiocarbon dating of the dendrochronologically undated larch chronologies based on wiggle matching. 2-sigma ranges for start and end year represent a 95.4% probability for the given time range based on the combination of ^{14}C counts and tree-ring date. Rings numbers that are given in bold font were measured twice.

Chronology	Number of radiocarbon dates	Tree-ring date in chronology (from 0)	2-sigma range start year (CE)	2-sigma range end year (CE)
1	3	20, 180, 501	1294-1301	2006-2013
2	4	31, 57, 125, 211	1704-1726	1944-1966
3	4	34, 57, 85, 267	1720-1742	1984-2006
4	5	45, 46, 58, 106, 174	1765-1808	1970-2013
5	5	17, 47, 102, 153	1780-1789	1964-1973
6	8	10, 100, 114, 121, 187, 255	1642-1661	1935-1954

Radiocarbon dating reveals that the chronologies are composed of recent material (Table 3). Start years vary from 1294-1301 CE (2-sigma age range, 95.4% probability) for chronology 1, which also represents the longest chronology, to 1765-1808 CE for chronology 5. End years range from the mid-20th century to the beginning of the 21st century. The oldest radiocarbon date spanning 1312-1416 CE is found for a larch sample that was collected in the Lena delta and is part of the longest driftwood chronology 1.

Figure 3: Calibration and wiggle matching of the derived radiocarbon dates from six dendrochronologically undated *Larix* sp. driftwood chronologies using OxCal 4.2 (Bronk Ramsey, 2009; Bronk Ramsey et al., 2001; Reimer et al., 2013). Dark grey filled areas show the calculated distribution based on the restrictions given by the tree-ring dating. Light grey areas represent the temporal distribution based on the calibration of ^{14}C counts with the IntCal13 radiocarbon curve without wiggle matching. Light blue bars indicate the end sequence of each chronology based on the number of years missing to the outermost ring of the chronology.

Discussion

A total of 2,412 tree-ring series were measured and 738 series (30.6%) were successfully dendro-provenanced. Other, mainly dendro-archaeological studies, often show higher success rates in cross-

dating (Daly, 2007; Domínguez-Delmás et al., 2014; Domínguez - Delmás et al., 2013), however, one has to take in mind our enormous sample replication of various species in combination with the huge possible origin area, which extremely complicates dendro-provenancing. Site-specific signals, i.e. ring-widths patterns that are caused by conditions that are not influenced by the climate of a larger region (e.g. sites close to rivers or lakes or very dry sites) (Düthorn et al., 2013; Kirilyanov et al., 2013), the restricted length of the reference chronologies as well as our threshold values for dendro-dating are possible reasons for undated samples. Origin areas that are not represented by reference data are less probable since our network very well covers the boreal forest zone (Hellmann et al., 2016a). A systematic collection of reference chronologies in combination with sampling and measuring new sites, enabling the spatiotemporal extension of the network, is however needed and supported by the first success in larch driftwood provenancing. Earlier studies on Arctic driftwood dated pine and spruce samples with single boreal reference chronologies (see overview in Hellmann et al., 2016a). Our study is the first dendro-provenancing analysis that successfully cross-dated larch driftwood. This is achieved on the one hand through our massive sample replication that combines driftwood from various Arctic islands with samples from the larch dominated forests in eastern Siberia, which represents the most probable origin area of larch driftwood. On the other hand, our systematic circumpolar 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, and in particular larch.

Our dating results show that the amount and composition of driftwood that is delivered to the Arctic Ocean from a certain region is highly connected to river discharge rates and dominating forest types. The Yenisei River has the highest discharge of all 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). In addition, 35.9% of the dated *Larix* sp. samples (excluding all samples collected in the Lena River region) and 20.8% of the dated *Picea* sp. samples 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 River, where spruce forests are the predominating vegetation form. The majority of larch samples (without the Lena samples) is with 47.6% assigned to the middle Lena River region where larch forests are prevalent.

Figure 4: Percentage of the dated driftwood for the three sampling sites Greenland, Svalbard and Iceland per genus.

More wood from the western Russian Dvina region is found on Svalbard than on Greenland and Iceland (Fig. 4&5; 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 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 lower for wood from western Russia (Fig. 1). The majority of the dated spruce samples (71.7%) originates in western and central Russia, while fewer samples were found to have North American origin (Fig. 5). Even though this result might be slightly influenced by a better replication of references for Eurasia, it

gives a hint on the recent Arctic Ocean circulation systems. Proposed by Dyke et al. (1997), changes in driftwood origin mainly from North America or Eurasia could help to understand changes in the east- and westward shift of the TPD. Eurasia as main origin area for driftwood found on Greenland and Svalbard would imply a west-shifted TPD, i.e. a strong Siberian branch and a rather weak Polar branch of the stream (Dyke et al., 1997; Tremblay et al., 1997), being induced by a positive North Atlantic Oscillation and positive Arctic Oscillation mode. However, our sampling sites are generally more prone to receive material delivered from the Eurasian coastlines directly via Fram Strait, which reduces the probability for North American material compared to the Canadian Arctic Archipelago, for example.

Figure 5: Overview of the driftwood dating results: (A) shows the percentages of dated driftwood per sampling site, including *Pinus sylvestris*, *Larix* sp., and *Picea* sp.. The size of the circles refers to the number of samples and the colors to the different regions of origin. (B) illustrates the amount of dated and undated wood per sampling site and genus. (C) shows the percentages of Scots pine driftwood cross-dated against Dvina, Yenisei, and Lena reference chronologies. (D) shows the cross-dating results of larch against Yenisei South, Lena North, Lena Middle, and Yakutsk; and (E) shows the results of spruce against 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. 6). At the same time, the TBPs are higher the further north the reference chronologies are located, indicating that more narrow ring-width patterns cross-date better than wide rings (Fig. 6). Low temperatures during the vegetation period limit the growth of the trees and hence cause a stronger signal in the tree-ring series, which facilitates cross-dating. The highest TBP of 20.1 is shown by the northern Lena River driftwood chronology with the reference located at $\sim 70^{\circ}\text{N}$, representing the northernmost of our references. However, harsh growing conditions in the northern regions increase the probability of missing rings (Hantemirov and Shiyatov, 2002), which can again aggravate dendro-provenancing. Some of our so far undated larch samples might be datable when systematically searching for missing rings.

Figure 6: (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 period of high logging and floating activities (~ 1920 -1975), when large 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 Yenisei is the boreal river that is characterized by most intense wood industrial logging and floating with pine as the most important species for logging (Hellmann et al., 2015). Logging and floating activities at the other large boreal river systems were generally lower, resulting in less logged samples for spruce and larch (Hellmann et al., 2016b).

To gain better insight in driftwood delivery over more than the past few centuries, certain samples from the dendrochronologically undated chronologies were selected for ^{14}C dating. Results show that these chronologies are also composed of recent material even though they could not be dated based on our reference chronologies (Fig. S7). These first tests on radiocarbon dating of the driftwood samples in combination with the fact that most of the collected material is logged wood, show that our sites and sampling strategy that we followed did reveal mostly young material. However, further radiocarbon dating of our driftwood samples will most likely reveal spatiotemporal delivery patterns of driftwood that can then be used to reconstruct ocean current dynamics, i.e. mainly the east-/westward shift of the TPD, ideally across the Holocene. The combination with cross-dating between the tree-ring series will reduce the uncertainty range of the ^{14}C results (Kromer et al., 2004; Pearson, 1986). Driftwood series covering the 775 CE cosmic event, will very likely be datable even at an annual resolution based on the ^{14}C peak of that year (Miyake et al., 2012). Despite the fact that our driftwood record is the best replicated for the Arctic until now, the analyses of additional samples from other regions in the Arctic (e.g. where millennial old wood has already been found but not yet dendrochronologically analyzed; Funder et al., 2011; Nixon et al., 2016; Nixon and England, 2013), still offer a huge potential for building tree-ring chronologies that extend back several millennia. 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. A geographical extension of the presented sampling sites would also improve the understanding of driftwood transport routes and therefore of past ocean current dynamics. Examples of such regions include for instance the western and northern coast of Greenland or the Canadian Arctic Archipelago; i.e. regions that are influenced by different main ocean currents.

The investigated samples were mostly collected at sea level along the shorelines. A systematic search for driftwood timbers located at higher elevations along the coasts and further inland would likely offer the chance to not only find older wood samples but, when driftwood is collected at different altitudinal belts, to possibly also reconstruct postglacial uplift rates of the islands based on the timber dating. Additionally, 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 dendroprovenancing 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.

Another important issue in driftwood research is the investigation of decomposition rates of the driftwood timber in combination with their buoyancy. First tests on driftwood invading fungi (Blanchette et al., 2016) did show that most are not transported from the origin areas to the deposition coastlines. However, further analyses on driftwood decomposition during the several-year long transport in the ice, not only by fungi, but also by salt water, are essential. These could reveal further insight in the effects on buoyancy rates of the driftwood and how much these are again influenced by size and density/decomposition of the timber, salinity, water temperature, etc.

Various factors in source and deposition regions, but also during the transport of Arctic driftwood influence amount and properties of transported wood, direction and length of drift routes, percentage of timber that sink to the ground, as well as locations (Fig. 1). 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.

Conclusions

Our study demonstrates considerable cross-dating improvement of Arctic 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 Siberia is found on Svalbard than on Greenland and Iceland, where wood from central and eastern Siberia is prevalent. This spatial distribution is 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 1203-1375 CE, for *Picea* sp. 1594-1822 CE, and for *Pinus sylvestris* 1614-1810 CE. The *Larix* sp. driftwood samples that were cross-dated against the middle Lena chronology extend the reference chronology by 315 years into the past. ¹⁴C dating of 29 wood samples reveals the age of six dendrochronologically undated *Larix* sp. driftwood chronologies that also cover recent time spans from 1294-2013 CE. Radiocarbon dating of more dendrochronologically undated wood samples that ideally cover a larger time period are still needed to draw conclusions about different ocean current settings and variations in sea ice extent over the last millennia.

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Author contributions

LH, WT and UB designed the study. All authors either contributed data or helped performing the analyses. LH and UB wrote the paper, with input from all authors.

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