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# Regional coherency of boreal forest growth defines Arctic driftwood provenancing☆

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ABSTRACT

Arctic driftwood represents a unique proxy archive at the interface of marine and terrestrial environments. Combined wood anatomical and dendrochronological analyses have been used to detect the origin of driftwood and may allow past timber floating activities, as well as past sea ice and ocean current dynamics to be reconstructed. However, the success of driftwood provenancing studies depends on the length, number, and quality of circumpolar boreal reference chronologies. Here, we introduce a Eurasian-wide high-latitude network of 286 ring width chronologies from the *International Tree Ring Data Bank* (ITRDB) and 160 additional sites comprising the three main boreal conifers *Pinus*, *Larix*, and *Picea*. We assess the correlation structure within the network to identify growth patterns in the catchment areas of large Eurasian rivers, the main driftwood deliverers. The occurrence of common growth patterns between and differing patterns within catchments indicates the importance of biogeographic zones for ring width formation and emphasizes the degree of spatial precision when provenancing. Reference chronologies covering millennial timescales are so far restricted to a few larch sites in Central and Eastern Siberia (eastern Taimyr, Yamal Peninsula and north-eastern Yakutia), as well as several pine sites in Scandinavia, where large rivers are missing though. The general good spatial coverage of tree-ring sites across northern Eurasia indicates the need for updating and extending existing chronologies rather than developing new sites.



## 1. Introduction

Large boreal river systems are known to transport a large amount of wood timbers into the Arctic Ocean. There, perennial sea ice can prevent some of the logs from sinking and may transport these over thousands of kilometers within the prevailing ocean currents. After several years of sea ice drifting, the wood might be

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deposited at shallow Arctic coastlines along Greenland, Svalbard and Iceland (Hellmann et al., 2013b and references therein). Such Arctic driftwood (ADW) was intensively used by early settlers as the main construction resource and fire fuel, as well as for boat frames, weapons and other tools (Alix, 2005). To date, ADW is still an essential resource in the high-northern latitudes for firewood and to build fences or power poles (Alix and Brewster, 2004; Morris, 1991; Steelandt et al., 2013).

ADW can serve as a basis to potentially reconstruct floods, storms and river bank dynamics, but also climatic conditions such as summer temperature variability in the source areas (Büntgen et al., 2014; Eggertsson, 1994b; Giddings, 1952). Anthropogenic activities including logging and floating are important causes for ADW formation, strongly influencing its species and age composition (Eggertsson, 1993; Hellmann et al., 2015). Dendrochronological assessment of ADW ideally supports the understanding of past settlement history and current activities in northern North America and Siberia (Alix, 2005; Alix and Brewster, 2004).

Within the marine environment, changes in the strength of the Transpolar Drift and the Beaufort Gyre (Morison et al., 2012; Proshutinsky and Johnson, 1997), as well as variations in Arctic sea ice extent were reconstructed (Dyke et al., 1997; England et al., 2008; Funder et al., 2011; Tremblay et al., 1997). Analyses of fossil ADW in the best case even yield insight on past sedimentation processes and hence also on past water temperatures (Selmeier and Grosser, 2011). Techniques for ADW investigation include wood anatomical species identification, tree-ring width (TRW) measurements and radiocarbon dating. Wood identification is essential and should be realized not only macro-, but also microscopically to distinguish on the species-level where possible (i.e. *Pinus*) (Hellmann et al., 2013a). TRW measurements enable dating and also provenancing of ADW, as long as reliable reference chronologies from the boreal forest zone are available and cross-dating is possible (i.e. Eggertsson, 1993; Hellmann et al., 2015; Johansen, 2001; Steelandt et al., 2015). In case long boreal chronologies are missing, radiocarbon measurements are inevitable to estimate the age of old ADW (Dyke and Savelle, 2000; Funder et al., 2011). Beside these classical approaches, further analyses are necessary to achieve more insight in and to understand the complexity of the ADW system. Density measurements of presumably climate sensitive ADW samples should be considered to improve temperature reconstructions (Esper et al., 2012b). Even though studies about the improvement of dendro-provenancing by density measurements are missing, it would most likely not merit the effort due to few reference chronologies.

Driftwood is often affected by fungi, most of them likely already introduced in the origin areas of the trees (comm. R. Blanchette). Survival of these fungi is often limited in high Arctic regions. Analyses of fungi infestation may hence help to clarify duration of ADW deposition times in its source and/or sink areas (Jurgens et al., 2009). Additionally, dendrochronological ADW research can be used to supplement reconstructions of past forest disturbance events (Altman et al., 2014; Chapin et al., 2004).

A precise determination of the age and origin of ADW is, however, indispensable for any further analyses (Hellmann et al., 2015). Since the beginning of ADW research in the late 19th and 20th century (Agardh, 1869; Eurola, 1971; Fischer and Schneider,

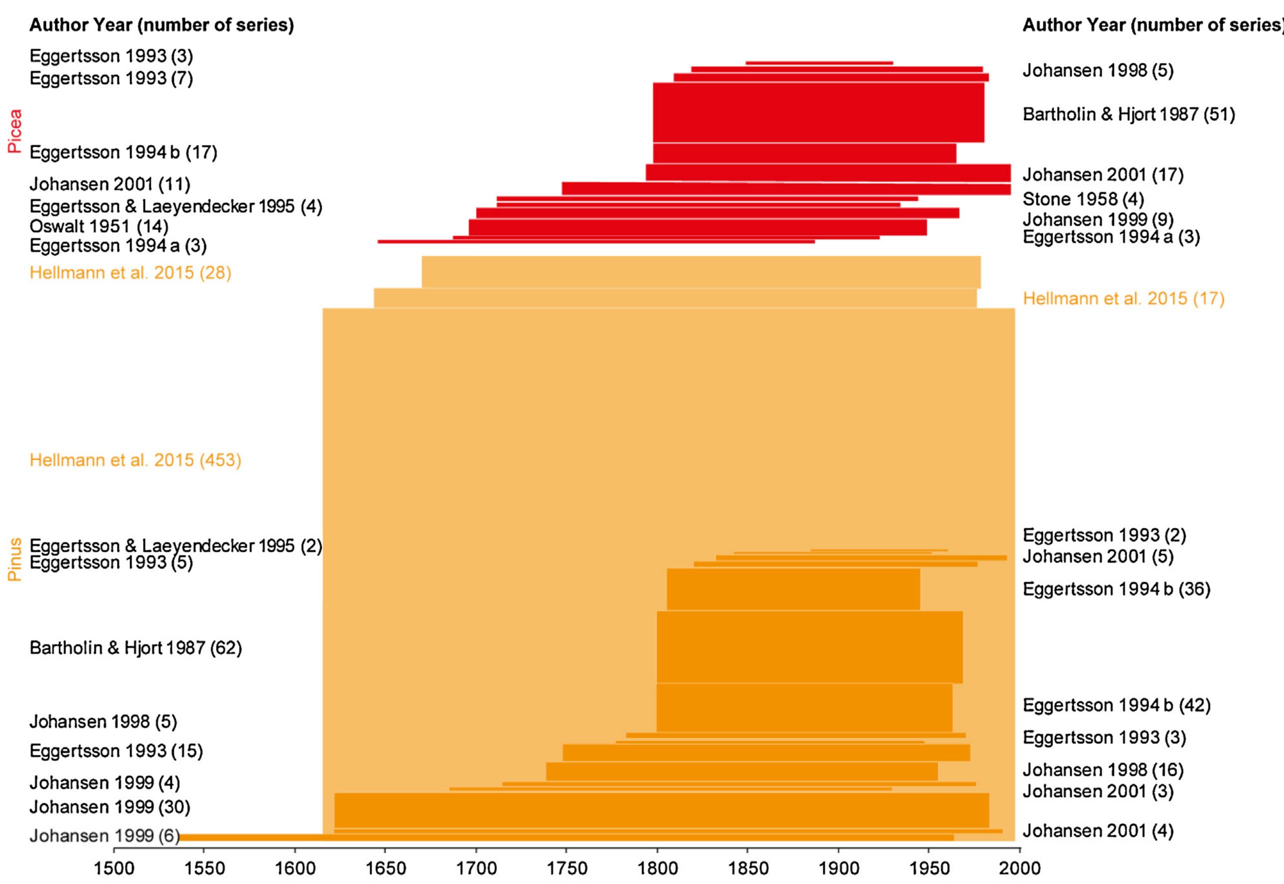



**Fig. 1.** Dendrochronologically dated ADW series (Bartholin and Hjort, 1987; Eggertsson, 1993, 1994a,b; Eggertsson and Laeyendecker, 1995; Hellmann et al., 2015; Johansen, 1998, 1999, 2001; Oswalt, 1951; Stone, 1958). Each bar represents one absolutely dated ADW chronology. Chronologies of different origin from the same study are displayed as single bars with their height referring to the number of tree-ring width series included.

1883; Kindle, 1921), several studies considered dendrochronological techniques (Bartholin and Hjort, 1987; Eggertsson, 1993, 1994a; Johansen, 2001; Oswalt, 1951; Stone, 1958), and/or radiocarbon dating (Dyke and Savelle, 2000; England et al., 2008; Funder et al., 2011; Häggblom, 1982). Most driftwood was analyzed from Svalbard, Greenland, Northern Canada and Alaska (see Hellmann et al., 2013a for an overview). Dendrochronological studies so far mainly focus on the origin and age of ADW, often in combination with human use and activities, while radiocarbon analyses, due to the longer time span covered, yield insight in past sea ice and current variations.

Nevertheless, no ADW sample older than 500 years was so far successfully dated against boreal reference chronologies (Fig. 1). Only pine and spruce but no larch ADW samples could yet be provenanced based on cross-dating against boreal reference chronologies from northern Russia (pine and spruce) and northern North America (spruce) (Eggertsson, 1993, 1994a; Eggertsson and Laeyendecker, 1995; Hellmann et al., 2015; Johansen, 1998, 1999, 2001). Despite these few examples of precise ADW provenancing against single boreal reference chronologies (Fig. 1), more systematic assessments that consider widespread networks of many boreal TRW sites are still missing and imply the lack of knowledge on the spatial precision of ADW provenancing.

Here, we compile and analyze a Eurasian-wide network of high-latitude (>60°N) TRW chronologies from the three main boreal conifers pine, larch and spruce. Aiming to define the potential of ADW provenancing in space and time, we evaluate how hydrological catchment areas and biogeographic zones reflect patterns of common growth variability, and should or should not be considered as preferred reference units.

## 2. Material and methods

TRW chronologies of pine (*Pinus sylvestris* and *Pinus sibirica*), larch (*Larix gemlinii* and *Larix sibirica*), and spruce (*Picea abies* and *Picea obovata*) were collected for the area 0–180°E and >60°N. A total of 160 new, mostly unpublished site chronologies complemented 286 records from the *International Tree Ring Data Bank* (ITRDB, http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring (Grissino-Mayer and Fritts, 1997) (Fig. 2). The resulting northern Eurasian TRW network contains measurements from 187 pine (127/60, ITRDB/non ITRDB), 187 larch (112/75), and 72 spruce (47/25) sites.

The longest chronology, a larch site (Yamal) from the ITRDB, spans from BC 764 to 2005 AD, whereas the shortest record, also larch from the ITRDB (Markovo) covers the 1976–1998 AD period. All site chronologies were truncated at a minimum replication of five series and age trends inherent to the raw TRW measurements were removed using the ARSTAN software (ARSTAN_41d for windows) (Cook and Krusic, 2007). Cubic smoothing splines with 50% frequency-cutoff at 30 years were applied after power-transformation (Cook and Peters, 1981, 1997). The final TRW chronologies were calculated using bi-weight robust means and considering the standard ARSTAN routine (STD). Additional calculations were realized with the program R (R Core Team, 2014) and site distribution maps were produced with ArcGIS.

The major catchment areas of the largest Eurasian river systems were defined by the WWF HydroSHEDS drainage basin data level 02 (Lehner et al., 2008): Scandinavia North, Scandinavia South, Dvina–Pechora, Ob, Yenisei, Kotui, Lena, and Kolyma (ordered from west to east).

Spearman correlation coefficients (Rbar) between sites were calculated per catchment, i.e. at the watershed level, as well as for each of the three genera and after combining all of them. Independently of the catchment area, genus-specific Spearman correlation coefficients were further calculated between all sites. Values of $r \geq 0.4$ were used to group the TRW site chronologies and to detect whether growth patterns within catchment areas coincide with climate-induced growth patterns. The minimum group size was set to four sites. Rbar statistics were calculated for the inter-site correlations of the resulting groups. The AD 1905–1990 period was used for all calculations to exclude as few chronologies as possible, but at the same time guarantee a representative calculation window length.

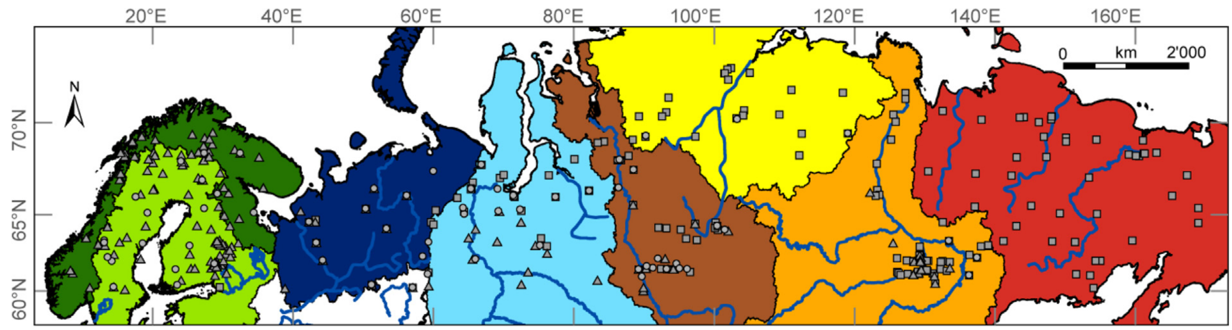
## 3. Results and discussion

### 3.1. Site distribution

The spatial and temporal precision of ADW provenancing depends on the quality, length and spatial distribution of boreal reference chronologies. Within the natural distribution areas of the main Eurasian boreal forest conifers pine, larch, and spruce, our TRW network is characterized by a dense spatial coverage (Fig. 2, St. George, 2014). A very high replication and even distribution of sites in Fennoscandia is followed eastwards by relatively few sites in the Dvina–Pechora catchment, which are mainly located along the rivers (Fig. 2). The Ob and the Yenisei basin are both represented by widely distributed sites. No sites are available for the southern Kotui and western Lena River basin. The larch sites in the northern Kotui catchment are evenly distributed. Most sites in the Lena River basin are located in the region around Yakutsk, but larch sites are also extending northwards along the river. The Kolyma catchment beyond the eastern distribution limit of pine and spruce is despite its wide spatial extension well represented by larch sites.

Site density and spatial distribution are influenced by research preferences as well as infrastructure and accessibility, which both vary substantially among the catchment areas. Sites located close to the rivers are not only most important for ADW provenancing, but are also characterized by good accessibility. Due to certain site characteristics such as wet conditions at a lake- or riverside, some stands can show different growth patterns despite being geographically close to others (Düthorn et al., 2013; Kirdyanov et al., 2013). For larch, spruce and pine, the underrepresented regions are the western part of the Lena tributary Vilyuy River and the southern part of the Kotui River. The fact that neither larch sites are available in Fennoscandia, nor pine and spruce sites in the Siberian far east and at the northernmost latitudes results from the current species distribution and not from insufficient sampling.

For successful ADW provenancing not only the distribution, but also the length of reference chronologies matters. Despite of the dense spatial coverage of sites across the Eurasian boreal forest zone, only a few chronologies are several centuries long in time. A number of millennial-long pine chronologies are available for Scandinavia (Esper et al., 2012a; Linderholm et al., 2010), but no large rivers, the main driftwood deliverers from the boreal forest, are draining into the Arctic Ocean. A few millennial-long larch chronologies have so far been developed in Siberia (Briffa et al., 2008): Polar Urals (Shiyatov, 1995), eastern Taimyr (Naurzbaev et al., 2002), Yamal (Hantemirov and Shiyatov, 2002), and north-eastern Yakutia (Sidorova and Naurzbaev, 2002). However, no such dataset from Siberia was yet successfully used to cross-date larch ADW. The natural distribution of larch at the northern timberline often causes wedging and missing rings that complicate cross-dating (Hantemirov and Shiyatov, 2002). Low correlations between reference chronologies of different genera indicate that dating of pine or spruce by these long larch chronologies is not possible. The restriction of provenancing precision by number, length, and spatial distribution of reference chronologies implies the need for a systematic network analysis of TRW sites across the possible source




| ITRDB / other / Rbar | | ScandinaviaN | ScandinaviaS | DvinaPechora | Ob | Yenisei | Kotui | Lena | Kolyma |
|---|---|---|---|---|---|---|---|---|---|
| *Larix* | ■ | - | - | 7 / 1 / **.40** | 18 / 6 / **.44** | 4 / 21 / **.37** | 21 / 7 / **.42** | 14 / 38 / **.24** | 46 / 2 / **.22** |
| *Pinus* | ▲ | 28 / 7 / **.37** | 83 / 16 / **.35** | 10 / 2 / **.21** | 3 / 10 / **.37** | 0 / 10 / **.30** | - | 2 / 15 / **.44** | - |
| *Picea* | ● | 2 / 2 / **.60** | 14 / 1 / **.33** | 11 / 1 / **.41** | 8 / 5 / **.44** | 3 / 16 / **.37** | 4 / 0 / **.37** | 3 / 0 / **.22** | - |
| all | | 30 / 9 / **.33** | 97 / 17 / **.29** | 28 / 4 / **.21** | 29 / 21 / **.31** | 7 / 47 / **.23** | 25 / 7 / **.39** | 19 / 53 / **.22** | 46 / 2 / **.22** |

**Fig. 2.** Eurasian boreal forest zone with *Pinus* (PISP), *Larix* (LASP), and *Picea* (PCSP) site chronologies >60°N. The different symbols (square, triangle, and circle) represent the three species *Larix*, *Pinus*, and *Picea*. Colors indicate the large catchment areas from west to east: Scandinavia North (ScandinaviaN), Scandinavia South (ScandinaviaS), Northern Dvina with Pechora (DvinaPechora), Ob, Yenisei, Kotui, Lena, and Jana with Indigirka and Kolyma (Kolyma) (Lehner et al., 2008). The matrix shows the number of sites from the ITRDB, from other sources, and the inter series correlation (Rbar) for each species and catchment and for all species together. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regions as well as for extending existing chronologies rather than expanding the network in space (Johansen, 2001).

### 3.2. Catchment related growth correlations

Even being rather small, the two Fennoscandian catchments are represented by many pine (north and south) and spruce sites (mainly in the south, being only two spruce sites in the northern catchment). Larch is only represented by one site in Southern Scandinavia. Pine sites in the northern part show a mean correlation of $r = 0.37$ ($p = 0.09$) between the sites. The only two spruce sites in Northern Scandinavia are geographically very close and correlate with $r = 0.60$ ($p < 0.01$). In the Southern Scandinavian catchment pine sites correlate with $r = 0.35$ ($p = 0.10$) and spruce with $r = 0.33$ ($p = 0.15$) (Fig. 2). The rivers Northern Dvina and Pechora in west Russia represent one catchment where larch stands correlate with $r = 0.40$ ($p = 0.15$), pine with $r = 0.21$ ($p = 0.05$), and spruce with $r = 0.41$ ($p = 0.06$). The part east of the natural border of the Ural Mountains includes the large catchment of the Ob river and the smaller one of the Tas river, with larch and spruce correlating with $r = 0.44$ (for larch $p = 0.06$, for spruce $p = 0.05$) and pine sites with $r = 0.37$ ($p = 0.07$). The Yenisei river basin borders in the east, where larch and spruce sites correlate with $r = 0.37$ (for spruce $p = 0.08$, for larch $p = 0.09$) and pine sites with $r = 0.30$ ($p = 0.05$). The northern part of central Siberia is drained by the Kotui River, where pine is absent, spruce only represented by four sites that correlate with $r = 0.37$ ($p = 0.04$), but larch by 28 stands that correlate with $r = 0.42$ ($p = 0.05$). In the adjacent Lena River catchment larch sites extend along the river to the north and show an Rbar of $r = 0.24$ ($p = 0.22$). The few spruce sites around the city correlate with $r = 0.22$ ($p = 0.30$), and the pine sites with $r = 0.44$ ($p = 0.02$). The most eastern Siberian catchment area includes the rivers Jana, Indigirka, and Kolyma. It contains only larch chronologies with a low inter-site correlation of $r = 0.22$ ($p = 0.24$), most likely due to their wide spatial distribution.

In general, the Rbar is rather low (approximately 0.2) for catchments and genera where the sites are widely distributed from the south to the north, as for instance the larch sites in the Lena or Kolyma river basin. Sites in the Northern Scandinavian, Ob and Kotui catchments have a small north-south gradient and show relatively high correlations between the sites ranging from 0.37 to 0.60.

The correlations between all sites, not taking into account the genus, are in all catchments generally low ($r = 0.2–0.3$). The highest correlation for all genera is found for the Kotui river basin with $r = 0.39$ ($p = 0.06$), but this area is dominated by larch and the sites have a relative short north-south distance (approximately 1000 km).

### 3.3. Correlation defined growth coherency

The correlation between sites decreases with increasing distance for pine, larch, and spruce (Fig. 3). The mean correlation for sites within a distance of 0–100 km is $r = 0.54$. Within a distance between 100 and 500 km, the mean correlation is $r = 0.41$ and decreases between 1000 and 2000 km to $r = 0.19$. Sites separated by distances larger than 2000 km do, on average, not correlate positively but even contain inverse signals.

Sites with a common signal often belong to different catchment areas, especially in central and Eastern Siberia (Fig. 4). Over large

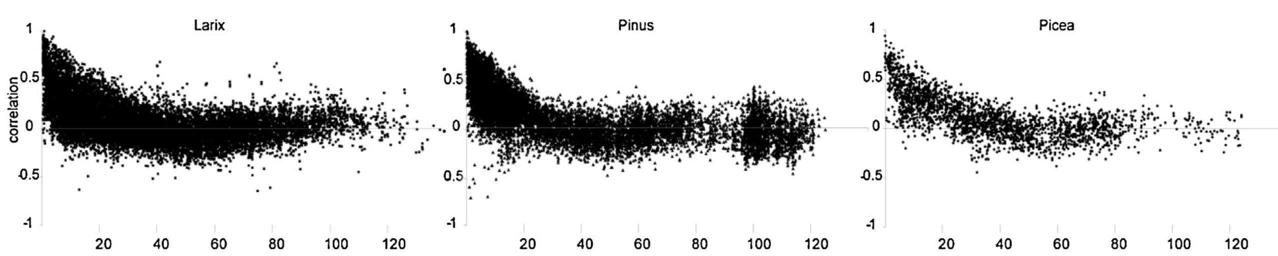



**Fig. 3.** Correlation decay with increasing distance for all sites of the three species *Larix*, *Pinus*, *Picea*.

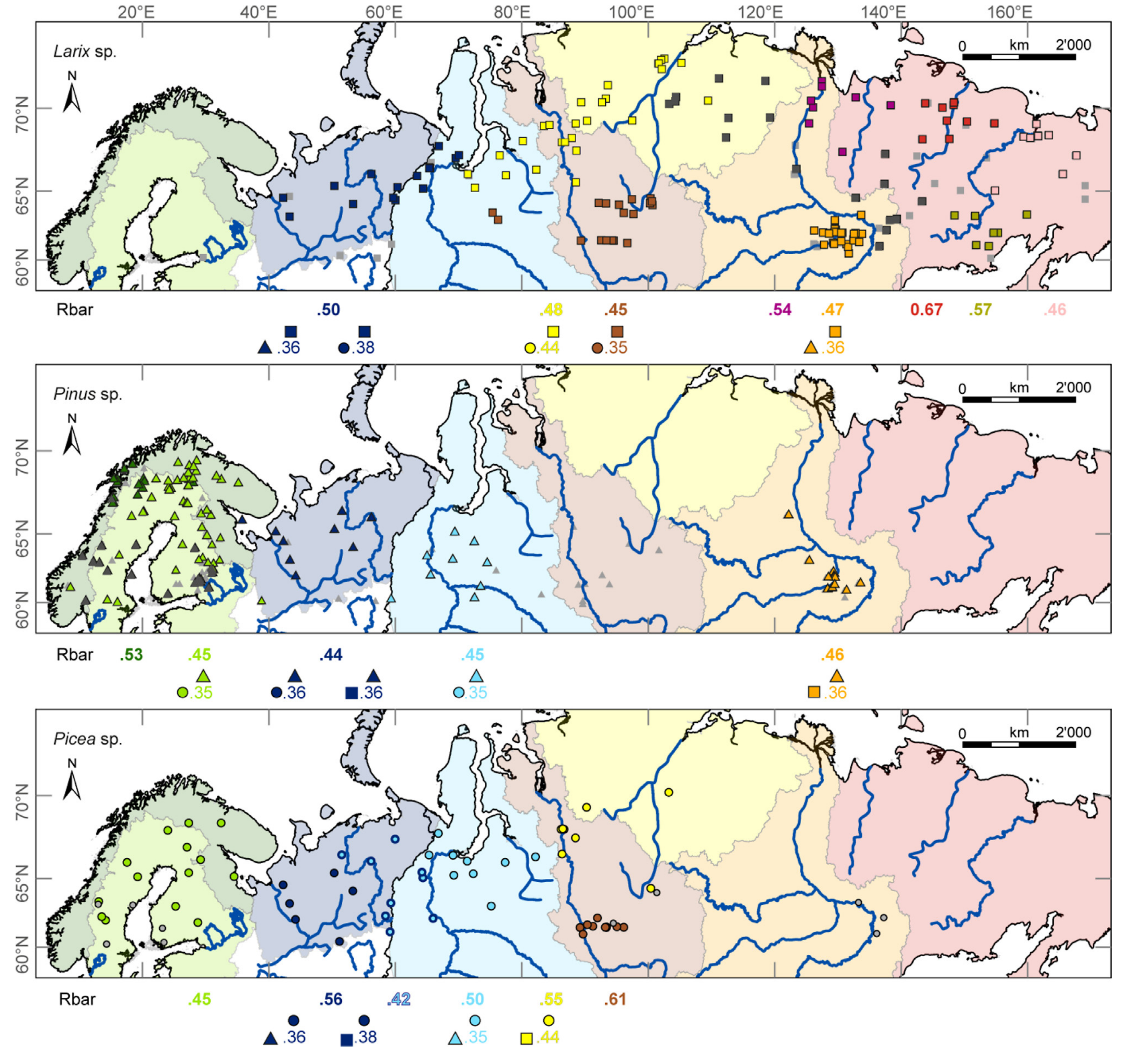



**Fig. 4.** Groups of common growth patterns based on correlation coefficients for the three main species (A–C) of the boreal forest zone, grouped by colors. Background colors indicate the catchment areas as introduced in Fig. 1. Minimum group site was set to four sites, all sites correlating higher than 0.39 with each other. Sites represented by dark symbols show ambiguous correlations and light grey symbols correlate with no or less than four other sites. Dark blue-framed light blue dots for *Picea* (C) correlate with the adjacent groups to the west and to the east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

distances (3000 km) from north to south, different growth patterns are recorded within the river basins. Besides a few pine stands in Northwestern Scandinavia that form a separate group ($r = 0.53$, $p = 0.02$), pine and spruce sites from Northern and Southern Scandinavia are combined based on Spearman correlation coefficients. The inter-site correlation is $r = 0.45$ (for spruce $p = 0.05$, for pine $p = 0.02$) and exceeds the values among chronologies within each single catchment (Fig. 4).

The signal of larch sites within the Dvina–Pechora catchment extends to the northwestern Ob basin and the combined sites correlate with $r = 0.50$ ($p = 0.02$). The signal of Dvina–Pechora pine sites is consistent with the river basin with a correlation of $r = 0.44$ ($p < 0.01$). A few pine sites, especially from the south, are still excluded as they do not show high correlations with the cluster. Spruce sites are split into two groups, one centered in the western part around the Northern Dvina reaching $r = 0.56$ ($p < 0.01$) and one in the eastern part around the Pechora River including sites located in the western Ob catchment ($r = 0.42$, $p = 0.06$). The eastern Pechora group correlates highly with the Dvina region as well as with the Ob group that follows to the east. However, these two regions do not show a common signal ($r = 0.26$), and the Pechora group is therefore kept separately. As a result, the Dvina, Pechora and Ob regions cannot be clearly distinguished as different origin areas for spruce ADW. However, in the small area of this catchment, the correlation-based groups are for all genera similar to the geographical extension of the basin area.

Central and eastern Siberian larch sites are characterized by a separation between northern and southern growth patterns. Besides the northwestern larch sites in the Ob catchment that show growth patterns similar to those found in the Dvina–Pechora group, a southern and a northern group are found. Inter-site correlation of the southern group is $r = 0.45$ ($p = 0.01$) and of the northern sites,

$r = 0.48$ ($p = 0.03$). The signal of both larch groups extends eastwards to the Yenisei, in the north also to the Kotui basin and is hence common among three catchment areas. Pine sites form a group in the central part of the Ob basin ($r = 0.45$, $p < 0.01$). Besides the few western sites belonging to the Pechora group, the spruce chronologies build a geographically river basin consistent cluster ($r = 0.50$, $p < 0.01$).

The pine sites in the central Siberian Yenisei area do not show a common signal according to the criteria used in this study (minimum group size of four sites). Spruce sites are split in two groups in this basin. Southern sites correlate with $r = 0.61$ ($p < 0.01$) and the northern sites show the same signal including two sites from the Kotui basin, correlating with $r = 0.55$ ($p < 0.01$).

Larch sites, further east, around the northern part of the Lena and Jana Rivers show the same growth patterns ($r = 0.54$, $p < 0.01$). Around the city of Yakutsk, larch ($r = 0.47$, $p = 0.01$) and pine ($r = 0.46$, $p = 0.01$) sites build one group each. Too few spruce sites (less than four) in the east inhibit grouping based on our criteria. In the larch dominated forests of the Far East the data is split in three groups. The same growth pattern is found for sites around the northern Indigirka River ($r = 0.67$, $p < 0.01$), further east around the northern ($r = 0.46$, $p = 0.04$) and the southern ($r = 0.57$, $p < 0.01$), part of the Kolyma River.

## 4. Conclusions

The spatiotemporal distribution of boreal reference chronologies defines the precision in ADW provenancing. We provide the first growth pattern assessment for the Eurasian boreal forest zone showing the spatial precision and limitations in ADW provenancing. Although comprising many long chronologies, Scandinavia is less relevant for Arctic driftwood research because large river systems that drain into the Arctic Ocean are missing. Most driftwood originates from Russia, but long chronologies are restricted to a few larch sites. Our analyses reveal that boreal catchment areas do not always coincide with the climate-induced spatial patterns of growth coherency. Within the same catchment areas, growth patterns can differ from northern to southern sites, allowing provenancing at higher resolution than the catchment level. At the same time patterns can coincide across catchment borders from west to east. As a result, biogeographical criteria rather than catchment levels should be used for clustering boreal chronologies for cross-dating.

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