Article

Effects of Boreal Timber Rafting on the Composition of Arctic Driftwood

Lena Hellmann [1,2,*], Alexander V. Kirdyanov [3,4] and Ulf Büntgen [1,2,5]

1 Swiss Federal Research Institute, WSL, Birmensdorf 8903, Switzerland; buentgen@wsl.ch
2 Oeschger Centre for Climate Change Research, Bern 3012, Switzerland
3 V.N. Sukachev Institute of Forest SB RAS, Krasnoyarsk 660036, Russia; kirdyanov@ksc.krasn.ru
4 Institute of Ecology and Geography, Siberian Federal University, Krasnoyarsk 660130, Russia
5 Global Change Research Centre AS CR, Brno 60300, Czech Republic
* Correspondence: lena.hellmann@wsl.ch; Tel.: +41-447392479

Academic Editors: Annika Nordin and Tomas Lundmark
Received: 16 August 2016; Accepted: 26 October 2016; Published: 31 October 2016

Abstract: Wood from the boreal forest represents an important resource for paper production and sawmill processing. Due to poor infrastructure and high transportation costs on land, timbers are often transported over long distances along large river systems. Industrial river rafting activities started at the end of the 19th century and were intensified in western Russia and central Siberia from the 1920s to the 1980s. After initial single stem rafting, timber is today mostly floated in ship-guided rafts. Lost wood can be transported further to the Arctic Ocean, where it may drift within sea ice over several years and thousands of kilometers before being deposited along (sub-)Arctic coastlines. Here, we introduce dendro-dated tree-ring width series of 383 driftwood samples from logged timber that were collected along different driftwood-recipient coastlines in Greenland, Iceland and Svalbard. The majority of driftwood is *Pinus sylvestris* from the southern Yenisei region in central Siberia, whereas *Larix* sp. and *Picea* sp. from western Russia and eastern Siberia are rare. Although our results are based on a small sample collection, they clearly show the importance of timber rafting on species, age and origin of Arctic driftwood and indicate the immense loss of material during wood industrial river floating.

Keywords: Arctic driftwood; boreal rivers; timber logging; industrial floating; Siberia

1. Introduction

The boreal forest zone accounts for 16% of the Earth's landmass, of which 61% is located in Russia, one of the five most forest-rich countries [1–3]. Up to 31.6% of global carbon storage in forests occurs in the boreal zone [4]. Boreal forests also make an important contribution to biodiversity, representing a total of 22% of the Northern Hemispheric landmass and being a habitat for rare wildlife species [5–8]. Natural events such as storms and wild fires as well as human wood industrial activities have a high impact on the development of boreal forests [9]. The huge extent of this biome not only has a large ecological relevance [4,10] but also high economic importance [11,12]. Timber from the boreal forest zone is exported and used in many parts of the world. The major part of the northern forest is located in Russia, even though only about 45% is located in accessible regions for harvesting [13], but globally, the country has the highest export rates of round timber [14,15]. A large portion (39%) of the total Siberian land area of 12,766 $\times$ 10^6 km^2 is represented by forested land [16]. The forest industry in Siberia grew with its share of the industrial gross production increasing during 1960–1980 from 12% up to 16%, but at the same time, the forest sector declined in comparison with other industries in Siberia during this time period [16]. Growth of the forest sector was reduced to -14.6% at the end of the Soviet Union by 1992 [16]. More recently, in 2011, the forest sector had a share of the total industrial production of 3.7% and a share of the Russian gross domestic product of just 1.3%, employing around 1% of the population [13]. Due to long distances to the next harbors, few roads, partly in poor conditions and high costs for transport on land, harvested timber was often transported along the big river systems [17], of which most run northward to the Arctic Ocean. Single stem floating was widely used in the 20th century, causing the loss of huge amounts of wood [18]. Better techniques including binding together of timber to rafts that were guided by ships reduced the loss of wood later on [19]. Timbers that get lost during floating either sink down or are transported further and might get stuck somewhere along their way in direction to the north or they reach the open water of the Arctic Ocean. These driftwood stems can be included in the Arctic sea ice and be transported over long distances by ocean currents [20,21]. The sea ice prevents the wood from sinking to the bottom of the ocean. After being transported across the ocean for several years, the wood can thaw out of the ice at its edges and float further to the coastlines of sub-Arctic and Arctic islands. Driftwood is found on islands such as Greenland, Iceland, Svalbard, or the Canadian Arctic Archipelago. In addition to losses from log transport, driftwood can enter boreal rivers from natural riverbank erosion and storm surges. Driftwood in the Arctic was not only a highly important resource for local people in ancient times but still is nowadays [22–24]. Additionally, it represents a unique palaeoenvironmental proxy archive that may provide insight into past sea ice conditions and current dynamics over several thousand years [25–28]. Collection of driftwood samples at different altitudinal levels along Arctic coastlines with subsequent radiocarbon dating, in combination with geomorphological analysis of beach ridges, can enable the reconstruction of past sea ice extent and variation [25,26,28–30]. Sampling sites in the northern Arctic are characterized by a high probability of finding millennial-old wood samples due to minor human impact [25]. Recent Arctic driftwood, mainly collected at sea-level and more southern sites, additionally reflects forest management and logging activities in its source regions, the boreal forest zone [18,31]. A systematic, circumpolar assessment, that not only investigates age and composition of Arctic driftwood, but also the link to forest management activities in the origin areas, is, however, still missing.

Here, we present 383 dendrochronologically dated driftwood samples that were collected along sub-Arctic and Arctic coastlines on Greenland, Iceland and Svalbard. These driftwood samples are all results of human forest management, i.e., loss of floating or rafting activities. We show the spatiotemporal distribution of these samples and the link to regional wood industrial activities that cause a high amount of timber delivery to the Arctic Ocean and hence play an important role in the Arctic driftwood system.

2. Materials and Methods

Driftwood was collected in Svalbard in 1996, in eastern Greenland in 2010, 2011 and 2012 and in Iceland in 2012 (Figure 1) [18,31]. Samples were taken as discs from driftwood stems and all wood was classified as logged or natural material (Figure 1). Natural material as a result of river bank erosion or storm surges contains a rootstock and/or branch bases, while logged stems that got lost during wood industrial floating activities have a clear cut surface. Subsequently, all samples were sanded or their surface was cut using a box cutter for macroscopic genus classification. Microscopic wood identification based on unstained radial cuts can reveal the genus or even the species of the wood samples (Figure 1) [18]. Ring widths of *Pinus sylvestris*, *Larix* sp. and *Picea* sp. were measured, combined to floating chronologies and, if possible, cross-dated against reference chronologies from the boreal forest zone (for further details see [31,32]). Successful cross-dating not only reveals the age but also the boreal origin of the wood samples, and is hence referred to as "dendro-provenancing", i.e., the comparison of sample and reference ring-width series based on statistical criteria and visual control [33,34]. All measured tree-ring width series were analyzed and thereafter separated by logged and natural samples. Our study focuses on logged Arctic driftwood samples and does not account for the natural material. A minimum number of ten successfully cross-dated logged driftwood samples per region from the three species together was set for the analysis. Very low numbers of logged samples from other origin areas did not allow further interpretation. For an overview of all logged driftwood samples that have been cross-dated per region, see Table 1.

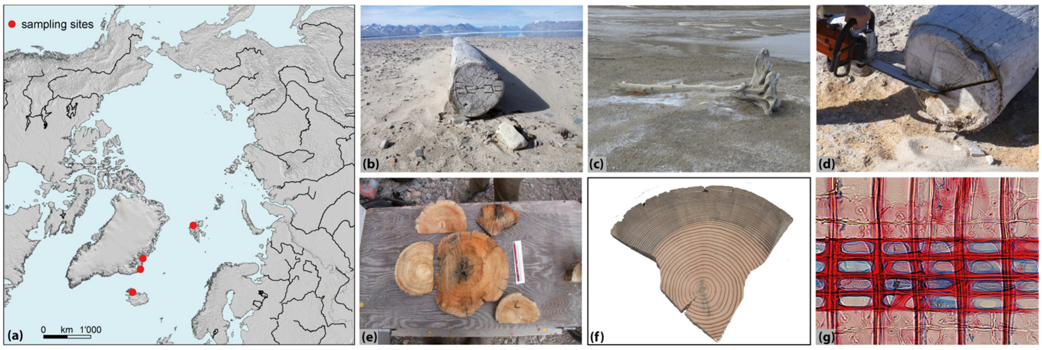

Figure 1. Driftwood sampling and wood identification: (**a**) Sub-Arctic and Arctic driftwood sampling sites (**b**) Logged driftwood timber in Greenland with a clear cut surface (credit: Willy Tegel); (**c**) Naturally fallen driftwood stem with a root collar; (**d**) Sampling of a driftwood disc (credit: Willy Tegel); (**e**) Variety of driftwood samples (credit: Willy Tegel); (**f**) Sanded *Pinus sylvestris* driftwood sample; (**g**) Stained radial cut of *Pinus sylvestris* for microscopic species identification.

Table 1. Origin areas of logged cross-dated driftwood samples for pine, spruce and larch.

Region	Origin Area	Pine	Spruce	Larch
Western Russia	Northern Dvina	19	18	-
Central Siberia	Yenisei North	-	1	-
Central Siberia	Yenisei South	296	6	14
Eastern Siberia	Lena North	-	-	3
Eastern Siberia	Lena Middle	-	-	13
Eastern Siberia	Lena South	9	-	2
North America	Mackenzie	-	2	-

3. Results and Discussion

3.1. Species and Origin

The main driftwood genera in our collection of logged samples are the conifers Scots pine (*Pinus sylvestris*), larch (*Larix* sp.) and spruce (*Picea* sp.). Dendro-provenancing of these samples shows that logged driftwood has been mainly transported to the coastlines of sub-Arctic and Arctic islands from western Russia and Siberia (Table 1). A total of 383 pine, larch and spruce driftwood samples from logged trees were successfully dendro-dated. Scots pine represents 84.6% (324 samples) of all dated logged driftwood timber. This pine species only grows in Eurasia and wood anatomically differs from the other Eurasian pine species *Pinus sibirica* and from the two main North American pine species *Pinus contorta* and *Pinus banksiana*. A total of 32 logged larch series (8.4% of all dated logged series) were dated and dendro-provenanced. Of the logged spruce driftwood samples, 27 were cross-dated, representing 7.0% of all dated logged driftwood material.

Regions of driftwood origin that are described in detail are western Russia (i.e., Northern Dvina river), central Siberia (i.e., southern Yenisei river) and eastern Siberia (i.e., middle and southern Lena river; Lena South herein describes the region around Yakutsk since the southernmost references that we used along the Lena river are located there). Considering all three species together, the southern Yenisei river is the main origin area for logged driftwood at our sampling sites. The majority of all dated logged Scots pine samples with 91.4% (296 samples) originate in the southern Yenisei region (Table 1, Figure 2). A total of 14 logged larch and six logged spruce samples are also assigned to this region.

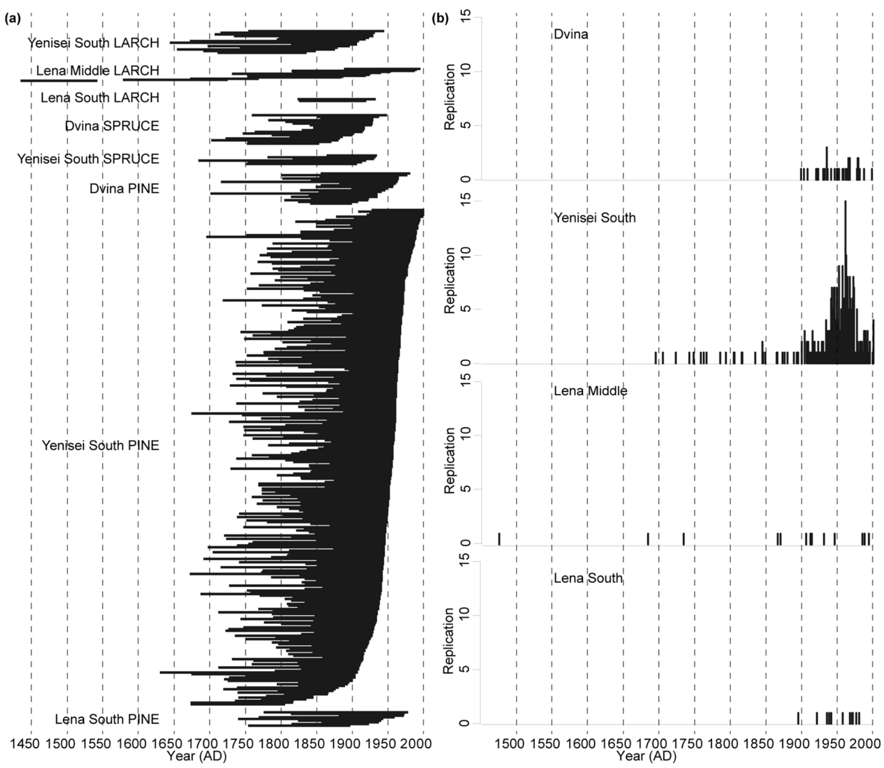

Figure 2. Temporal distribution of dendro-dated logged driftwood samples of pine, spruce and larch: (**a**) Dendro-dated driftwood series classified by species and origin area; (**b**) End-years of the dated driftwood series for pine, spruce and larch together, sorted by origin area.

Western Russia, i.e., the Northern Dvina region, is the second most relevant region for the delivery of logged driftwood to the Arctic. Fewer pine samples originate there, with 19 cross-dated series from this region. The amount of pine timber from western Russia is still higher than for spruce, for which 18 samples were assigned to the Northern Dvina, but western Russia represents the dominating origin of logged spruce driftwood. No larch originates in western Russia.

Logged larch and pine samples were assigned to eastern Siberia, but no spruce. The southern Lena region around Yakutsk is represented by nine pine and two larch samples. An additional 13 logged larch samples originate from the middle Lena river.

Our results clearly show the correlation of driftwood composition regarding species, age, and origin areas with the wood industry in Siberia. Origin areas and dates that were revealed by the logged driftwood samples very well reflect wood industrial activities in Siberia. Periods with high logging and floating activities mainly in the middle of the 20th century are well reflected by a very high amount of logged driftwood samples with the outermost ring dating in this time period (Figure 2). The Yenisei river that was most intensively used for timber transport, is at the same time the origin of the majority of our logged driftwood samples. Improved transport techniques, i.e., rafting guided by ships, caused a decline in driftwood logs reaching the (sub-)Arctic Islands. Regarding the fact that only a minority of logs is transported all the way across the Arctic Ocean and that our collection is only a small sample regarding the huge area of driftwood-recipient coastlines, the high amount of driftwood samples with wood industrial origin additionally indicates the extremely high loss of timber during single stem floating.

3.2. Central Siberia

The importance of the forest sector in the former USSR was very high in central Siberia with pine representing 34% of the harvest and hence being the preferred species for logging [16]. Pine and spruce were heavily exploited with 60% and 47% use of the annual allowable cut, respectively. Larch, of which 30% of the annual allowable cut was used in 1989, was less affected [16]. The main occurrence of larch in the far east and at the same time pine-dominated forests in central Siberia (Figure 3) are a reason for one of the main wood industrial centers in the region around Krasnoyarsk. In 1990, central Siberia had the highest commercial timber cut compared to all other regions in Russia [35]. The most important harbor for timber transport was located in Igarka at the lower Yenisei river (67°28′ N, 86°34′ E), where local timber industry processed the wood or the timber was loaded onto sea-going ships to be transported further to the Arctic Ocean [36]. Therefore, the central Siberian Yenisei was the main river for timber floating. More than 50% of the wood cut in the Yenisei region was pine [16]. Industrial logging in combination with timber floating started in the late 19th century and was considerably increased in the 1920s [19]. During the early times of industrial logging, ineffective log transport techniques, i.e., mainly single stem floating, caused more than 50% loss of timber [19]. Improved techniques, such as guiding of the floats by ships, reduced the loss of wood to less than one percent by 1975. In 1987, floating was significantly reduced on the Yenisei river [17]. Nowadays, stems are mostly transported along the rivers in rafts that are guided by ships [19].

Of the total 296 dated logged pine samples from the southern Yenisei region, 244 (82.4%) have end-years between 1920–1987 and hence fall in the time period of high logging activities in the pine-dominated forests in combination with poor floating techniques and high amounts of lost timber (Figure 2). During the long distance from the Angara and southern Yenisei region to Igarka, the destruction of floats and the probability of losing wood was high. In 1937, for example, a string of big floats (40,000 m^3), was sent to the port of Igarka and was destroyed by a storm [17]. Floating single logs is prohibited today due to damages caused by lost wood and the deposition of organic waste. However, timber is still transported with the use of advanced floating techniques and on pontoons [37].

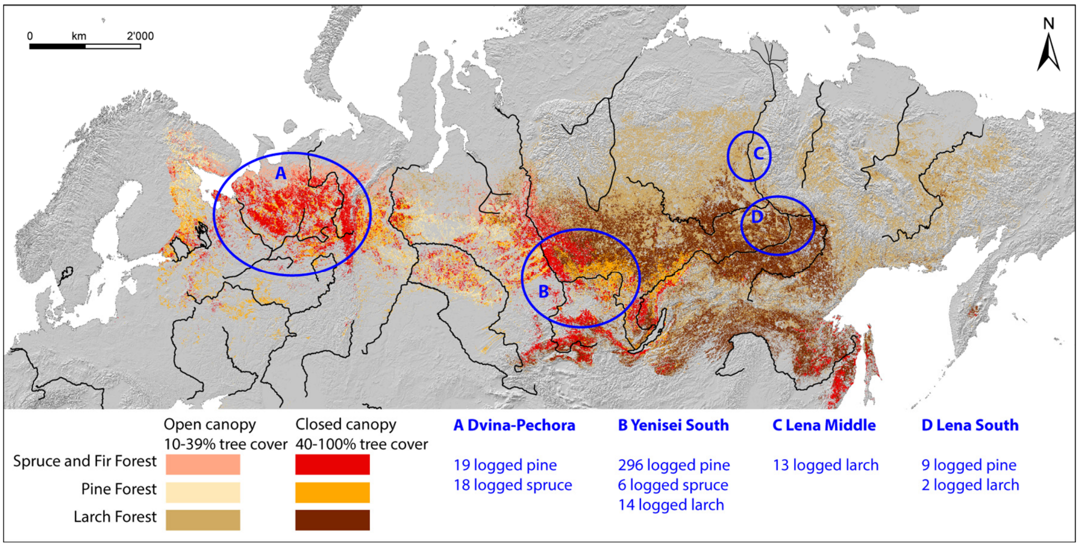

Figure 3. Dominating forest types of spruce/fir, pine and larch for Russia (adapted from [38]). Blue circles indicate the regions to which logged driftwood samples of pine, spruce and larch from sub-Arctic and Arctic islands have been dendro-provenanced to with at least ten samples for the three species.

3.3. Western (European) Russia

In the mainly spruce- and partly pine-dominated forests of western Russia (Figure 3), these two species also represent the major part of the total harvest with 38% of pine and 20% of spruce compared to only 2% of larch [16]. These wood-industrial activities are in common with our findings of logged pine and spruce driftwood samples that were assigned to western Russia (European Russia). Industrial logging in the region of the Northern Dvina and Pechora rivers started in 1840 with major exports from 1860 onwards [39]. At the turn of the 19th to the 20th century, the White Sea area accounted for 18% of the total Russian timber trade, which increased to 25% before the First World War with its main center in Archangel [40]. Floating of single logs was stopped in 1995 and is prohibited today [41]. The relatively low amount of logged driftwood samples from western Russia despite high logging activities (Figures 2 and 3) is explained first by shorter floating distances to the next harbor compared to the Yenisei river. Second, the direction of Arctic Ocean currents reduces the probability of driftwood from the western Russian Arctic coastlines being transported all the way to Greenland and Iceland, where a higher number of driftwood samples was collected for this study. A higher percentage of wood from western Siberia is deposited along Svalbard's coastlines than in Greenland and Iceland. Out of 19 logged pine driftwood samples, which were dendro-provenanced to the Northern Dvina region, eleven (57.9%) have been collected in Svalbard. For spruce, the percentage of Svalbard samples is with 13 (72.3%) out of 18 logged spruce samples even higher.

3.4. Eastern Siberia

The number of logged samples from eastern Siberia in our driftwood collection is lower compared to the western and central part and the region is characterized by less logging and in particular less floating activities. Logged larch and pine driftwood samples from the Arctic originate in the middle and southern Lena region. Only larch was dendro-provenanced to the middle Lena region with 13 logged samples, while samples from the southern Lena region were mostly pine (nine pine samples compared to only two larch samples). Despite larch being the most important species for harvest in eastern Siberia, representing 48% of the logged wood [14], floating activities there were low historically [16]. First, larch is heavy and usually not used for floating [19]. Second, the timber are often of low quality and hence used for the local industry without floating, or wood of higher quality was exported to Japan and China, to where floating was not a suitable transport method [6].

3.5. Ecological Effects

Single stem floating along the Russian rivers mainly in the 20th century caused high losses of timber and is nowadays forbidden in most parts of the country. Ecological impacts of past floating and present rafting activities are, however, still considerable. High amounts of timber have mostly been floated after clear-cuttings in large areas. Clear-cuttings itself are ecologically problematic as they reduce the possibility of carbon accumulation in the forests and damage the existing ecosystems. Additionally, they can lead to shortages of high quality timber since being exhaustively used without selection. Rafting of timber from clear-cut areas leads to many sunken stems that become organic waste at the ground of the rivers and cause considerable damage to the environment [6,42,43].

However, sunken stems are not the only negative effect of river transport [6]. Rivers have been transformed not only to be better suitable for navigation, but also for floating timber, resulting in a channelization of the river systems [44]. In the Angara river basin, for example, recreation activities are now opposed to navigation and timber rafting [45]. Additionally, phenols, resin and acids are washed from the timber, contaminate the water and represent a large problem for the fishing industry [45].

4. Conclusions

Central Siberia was the main region for the Russian wood industry in the 20th century. Timbers were transported along the rivers over long distances from the southern logging areas to northern ports. Pine was the most important species for logging and floating in this region. Driftwood collected along the coastlines of (sub-)Arctic islands is dominated by logged pine timber that originated in central Siberia and mostly date to the middle of the 20th century, reflecting the period prior to floating in rafts guided by ships, which reduced the loss of timber considerably. Less logged timber reached the Arctic coastlines from western Russia and eastern Siberia, represented by pine and spruce in the west and pine and larch in the east, respectively.

Acknowledgments: This study was part of the "Arctic driftwood project" partly financed by the Eva Mayr-Stihl foundation. The tree-ring network in Siberia was mainly updated under support of the Russian Science Foundation (Project 14-14-00295).

Author Contributions: L.H. and U.B. conceived and designed the experiments; L.H. performed the experiments; L.H. analyzed the data; A.K. contributed materials; L.H. and U.B. wrote the paper with input from A.K.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Apps, M.; Kurz, W.; Luxmoore, R.; Nilsson, L.; Sedjo, R.; Schmidt, R.; Simpson, L.; Vinson, T. Boreal forests and tundra. *Water Air Soil Pollut.* **1993**, *70*, 39–53. [CrossRef]
2. Bonan, G.B.; Pollard, D.; Thompson, S.L. Effects of boreal forest vegetation on global climate. *Nature* **1992**, *359*, 716–718. [CrossRef]
3. Food and Agriculture Organization. *Global Forest Resources Assessment 2010*; Food and Agriculture Organization: Rome, Italy, 2010.
4. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G. A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993. [CrossRef] [PubMed]
5. Potapov, P.; Yaroshenko, A.; Turubanova, S.; Dubinin, M.; Laestadius, L.; Thies, C.; Aksenov, D.; Egorov, A.; Yesipova, Y.; Glushkov, I. Mapping the world's intact forest landscapes by remote sensing. *Ecol. Soc.* **2008**, *13*, 51.
6. Dudley, N.; Jeanrenaud, J.-P.; Sullivan, F. *Bad Harvest: The Timber Trade and the Degradation of Global Forests*; Earthscan Publications Ltd.: London, UK, 1995.
7. Usher, M.B.; Callaghan, T.V.; Gilchrist, G.; Heal, O.W.; Juday, G.P.; Loeng, H.; Muir, M.A.K.; Prestrud, P. Principles of Conserving the Arctic's Biodiversity. In *Arctic Climate Impact Assessment*; Cambridge University Press: Cambridge, UK, 2005; pp. 551–608.
8. Waide, R.; Willig, M.; Steiner, C.; Mittelbach, G.; Gough, L.; Dodson, S.; Juday, G.; Parmenter, R. The relationship between productivity and species richness. *Annu. Rev. Ecol. Syst.* **1999**, *30*, 257–300. [CrossRef]
9. Ponomarev, E.I.; Kharuk, V.I.; Ranson, K.J. Wildfires dynamics in siberian larch forests. *Forests* **2016**, *7*, 125. [CrossRef]
10. Harvey, B.D.; Leduc, A.; Gauthier, S.; Bergeron, Y. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. *For. Ecol. Manag.* **2002**, *155*, 369–385. [CrossRef]
11. Spence, J.R. The new boreal forestry: Adjusting timber management to accommodate biodiversity. *Trends Ecol. Evol.* **2001**, *16*, 591–593. [CrossRef]
12. Burton, P.J.; Bergeron, Y.; Bogdanski, B.E.; Juday, G.P.; Kuuluvainen, T.; McAfee, B.J.; Ogden, A.; Teplyakov, V.K.; Alfaro, R.I.; Francis, D.A.; Gauthier, S.; Hantula, J. Sustainability of Boreal Forests and Forestry in A Changing Environment. In *Forests and Society—Responding to Global Drivers of Change*; Mary, G., Katila, P., Galloway, G., Alfaro, R.I., Kanninen, M., Lobovikov, M., Varjo, J., Eds.; IUFRO (International Union of Forestry Research Organizations): Vienna, Austria, 2010; pp. 249–282.
13. Akim, E.L.; Burdin, N.; Petrov, A.; Akim, L. Russia in the global forest sector. In *The Global Forest Sector: Changes, Practices, and Prospects*; Hansen, E.S., Panwar, R., Vlosky, R., Eds.; CRC Press: Boca Raton, FL, USA, 2013; p. 185.
14. Russia: Forest Industry Competitiveness & Export Outlook. Available online: http://www.fao.org/3/a-ae887e.pdf (accessed on 21 July 2016).
15. Greenpeace Russia: Forests—Sustainable Forest Management. Available online: http://www.greenpeace.org/russia/en/campaigns/forests/sustainable-forest-management (accessed on 3 August 2016).
16. Obersteiner, M. Status and Structure of the Forest Industry in Siberia. Available online: http://pure.iiasa.ac.at/4562/1/WP-95-030.pdf (accessed on 21 April 2012).
17. Mitrofanov, A.A. *Wood Floating: New Technologies, Scientific and Technical Support*; Archangel State Technical University Press: Archangel, Russia, 2007; p. 492, In Russian.
18. Hellmann, L.; Tegel, W.; Eggertsson, Ó.; Schweingruber, F.H.; Blanchette, R.; Kirdyanov, A.; Gärtner, H.; Büntgen, U. Tracing the origin of arctic driftwood. *J. Geophys. Res. Biogeosci.* **2013**, *118*, 68–76. [CrossRef]

19. Wood Encyclopedia: Rafting. Available online: http://forest.geoman.ru/forest/item/f00/s01/e0001489/index.shtml (accessed on 5 August 2016). (In Russian)
20. Eggertsson, Ó. Driftwood as an indicator of relative changes in the influx of arctic and atlantic water into the coastal areas of svalbard. *Polar Res.* **1994**, *13*, 209–218. [CrossRef]
21. Eggertsson, Ó. Origin of the driftwood on the coasts areas of iceland, a dendrochronological study. *Jökull* **1993**, *43*, 15–32.
22. Alix, C.; Brewster, K. Not all driftwood is created equal: Wood use and value along the yukon and kuskowim rivers, Alaska. *Alask. J. Anthropol.* **2004**, *2*, 2–19.
23. Alix, C. Deciphering the impact of change on the driftwood cycle: Contribution to the study of human use of wood in the arctic. *Glob. Planet. Chang.* **2005**, *47*, 83–98. [CrossRef]
24. Alix, C. Persistence and Change in Thule Wood Use. In *The Northern World Ad*; Maschner, H., Mason, O., McGhee, R., Eds.; University of Utah Press: Salt Lake City, UT, USA, 2009; pp. 900–1400.
25. Funder, S.; Goosse, H.; Jepsen, H.; Kaas, E.; Kjær, K.H.; Korsgaard, N.J.; Larsen, N.K.; Linderson, H.; Lyså, A.; Möller, P. A 10,000-year record of arctic ocean sea-ice variability—View from the beach. *Science* **2011**, *333*, 747–750. [CrossRef] [PubMed]
26. Dyke, A.S.; England, J.; Reimnitz, E.; Jetté, H. Changes in driftwood delivery to the canadian arctic archipelago: The hypothesis of postglacial oscillations of the transpolar drift. *Arctic* **1997**, *50*, 1–16. [CrossRef]
27. Johansen, S. Origin of driftwood in north Norway and its relevance for transport routes of drift ice and pollution to the Barents Sea. *Sci. Total Environ.* **1999**, *231*, 201–225. [CrossRef]
28. Nixon, F.C.; England, J.; Lajeunesse, P.; Hanson, M. An 11,000-year record of driftwood delivery to the western queen Elizabeth Islands, Arctic Canada. *Boreas* **2016**. [CrossRef]
29. Dyke, A.S.; Savelle, J.M. Holocene driftwood incursion to southwestern Victoria Island, Canadian Arctic Archipelago, and its significance to paleoceanography and archaeology. *Quat. Res.* **2000**, *54*, 113–120. [CrossRef]
30. Häggblom, A. Driftwood in svalbard as an indicator of sea ice conditions. *Geograf. Ann. Ser. A. Phys. Geogr.* **1982**, *64*, 81–94. [CrossRef]
31. Hellmann, L.; Tegel, W.; Kirdyanov, A.V.; Eggertsson, Ó.; Esper, J.; Agafonov, L.; Nikolaev, A.N.; Knorre, A.A.; Myglan, V.S.; Churakova (Sidorova), O.; et al. Timber logging in central Siberia is the main source for recent Arctic driftwood. *Arct. Antarct. Alp. Res.* **2015**, *47*, 449–460. [CrossRef]
32. Hellmann, L.; Agafonov, L.; Sidorova, O.C.; Düthorn, E.; Eggertsson, Ó.; Esper, J.; Kirdyanov, A.V.; Knorre, A.A.; Moiseev, P.; Myglan, V.S. Regional coherency of boreal forest growth defines Arctic driftwood provenancing. *Dendrochronologia* **2016**, *39*, 3–9. [CrossRef]
33. Domínguez-Delmás, M.; Nayling, N.; Ważny, T.; Loureiro, V.; Lavier, C. Dendrochronological dating and provenancing of timbers from the Arade 1 Shipwreck, Portugal. *Int. J. Naut. Archaeol.* **2013**, *42*, 118–136. [CrossRef]
34. Eckstein, D.; Wrobel, S. Dendrochronological Proof of Origin of Historic Timber—Retrospect and Perspectives. In Proceeding of the Symposium on Tree Rings in Archaeology, Climatology and Ecology, Tervuren, Belgium, 20–22 April 2006; pp. 8–20.
35. Barr, B.M. Soviet timber: Regional supply and demand, 1970–1990. *Arctic* **1979**, *32*, 308–328. [CrossRef]
36. Resnick, A. *Siberia and the Soviet Far East: Unmasking the Myths*; GEM Publishers: Lincoln, Nebraska, 1985.
37. Mudahar, M.S. *Russia: Forest Policy during Transition*; World Bank: Washington, DC, USA, 1997.
38. Bartalev, S.; Ershov, D.; Isaev, A.; Potapov, P.; Turubanova, S.; Yaroshenko, A. Russia's Forests: Dominating Forest Types and Their Canopy Density. Available online: http://forestforum.ru/info/pictures/engmap.pdf (accessed on 29 October 2016).
39. Shegel'man, I.R. *Transformation of Forests (15th–21st Centuries)*; Publ. House of PetrSU: Petrazovodsk, Russia, 2008; p. 240. (In Russian)
40. Björklund, J.; Agnoletti, M.; Anderson, S. Exploiting the last phase of the north European timber frontier for the international market 1890–1914: An economic-historical approach. In *Forest History: International Studies on Socio-Economic and Forest Ecosystem Change, Report No. 2 of the IUFRO Task Force on Environmental Change*; 2000; pp. 171–184.
41. Termination of River Floating. Available online: http://www.kotlas.org/kotlas/northern_dvina.php (accessed on 10 August 2016).

42. Nieminen, M. Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three norway spruce forests growing on drained peatlands in southern finland. *Silva Fenn.* **2004**, *38*, 123–132. [CrossRef]
43. Shanin, V.N.; Komarov, A.S.; Mikhailov, A.V.; Bykhovets, S.S. Modelling carbon and nitrogen dynamics in forest ecosystems of central Russia under different climate change scenarios and forest management regimes. *Ecol. Model.* **2011**, *222*, 2262–2275. [CrossRef]
44. Dynesius, M.; Nilsson, C. Fragmentation and flow regulation of river systems in the world. *Science* **1994**, *266*, 753–762. [CrossRef] [PubMed]
45. Babicheva, V.A.; Rzętała, M.A. The Angara reservoir cascade as a subject of the transport and tourism concern. *Geogr. Tours* **2014**, *2*, 29–33.