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Holocene Fire Regime Changes in the Southern Lake Baikal Region Influenced by Climate-Vegetation-Anthropogenic Activity Interactions

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Citation: Barhoumi, C.; Vogel, M.; Dugerdil, L.; Limani, H.; Joannin, S.; Peyron, O.; Ali, A.A. Holocene Fire Regime Changes in the Southern Lake Baikal Region Influenced by Climate-Vegetation-Anthropogenic Activity Interactions. *Forests* **2021**, *12*, 978. https://doi.org/10.3390/f12080978

Academic Editors: Miguel Montoro Girona, Elizabeth Campbell and Yves Bergeron

Received: 12 May 2021
Accepted: 22 July 2021
Published: 23 July 2021

Abstract: Catastrophic fire years that have taken place during the last decade in Siberia, and more generally within the boreal forest, have been directly linked to global warming and had strong repercussions on boreal ecosystems and human populations. In this context the study of the past dynamics of these fires is essential for understanding their links with climate, vegetation and human activity changes on longer time scales than the last few decades. However, few studies on fire dynamics are available for Siberia, and none have been conducted for the entire Holocene period. This study presents the first fire history reconstruction of this area during the Holocene based on charcoals sequestered in sediments of two lakes located on the southern shore of Lake Baikal, in Siberia. The results show a similar trend in the two lakes, with high frequency and high peak magnitude during the Early Holocene and low magnitudes after 6500 cal. yr BP. This difference is interpreted as crown fires versus surface fires. According to pollen records (Dulikha, Vydrino, Ochkovoe) available near the studied lakes, a vegetation transition occurred at the same time. *Picea obovata*, which has a tree structure prone to crown fires, was dominant during the Early humid Holocene. After 6500 cal. yr BP, conditions were drier and *Pinus sylvestris* and *Pinus sibirica* became the dominant species; their tree structure favors surface fires. In addition to vegetation dynamics, the nearby pollen sequence from Dulikha has been used to provide quantitative estimates of past climate, indicating an Early to Middle Holocene climatic optimum between 8000 and 5000 cal. yr BP and an increase in temperatures at the end of the Holocene. These results have been compared to outputs from regional climate models for the Lake Baikal latitudes. Fire dynamics appear to have been more linked to the vegetation than climatic conditions. Over the past 1500 years, the greater presence of human populations has firstly resulted in an increase in the fire frequency, then in its maintenance and finally in its suppression, which may possibly have been due to very recent fire management, i.e., after ca 500 cal. BP.

Keywords: Siberia; charcoal; fire regime; crown fires; surface fire; pollen record; quantitative climate reconstruction; boreal forest; Holocene

1. Introduction

Boreal forest is a major component of the world's forested area and represents around 25% of the forested ecosystem [1]. It is the world's largest terrestrial biome, and is located in the northern hemisphere, in North America (mainly in Canada) and in Eurasia (Fennoscandia and Russia) [2]. Fires are the main natural disturbance of boreal forests and modify its vegetation composition and functioning [3]. Each year, since the 21st century, between 5 and 20 million hectares of boreal forest in the world are burned and people face catastrophic damage to both personal and public goods [4,5]. Fire regimes differ in the American and the Eurasian boreal forests, depending on the vegetation characteristics. Currently, intense crown fires dominate in North America whereas surface fires dominate in Eurasia. Crown fires jump from tree foliage to tree foliage and cause severe damage to the tree canopy, whereas surface fires spread on the ground without reaching tree foliage [5]. To better understand the long-term impact of fire disturbance on boreal forests and the mechanisms linking fire, vegetation and climate, past fire activity has been widely studied, for example in Canada [6–11], in Fennoscandia [12–15] and in Russia [3,16–19]. However, very few studies cover the region of Siberia and very little is known about past fire history during the Holocene [16,17,20–22]. In eastern Siberia, a crown fire regime occurred between 11,000 and 9000 calibrated years before present (cal. yr BP) and switched to a surface fire regime at 9000 cal. yr BP [16]. In southwestern Yakutia, Glückler et al. [21] showed that during the last two millennia, fire dynamics have been particularly influenced by a combination of short-term climatic events and anthropogenic fire management. Their results showed that fire frequency has increased since 1750 CE. Siberia covers three quarters of Russia (13.1 million km^2), from the eastern side of the Ural Mountains to the Pacific Ocean. This region is currently characterized by a continental climate and a high fire frequency [23,24]. These characteristics make Siberia a sensitive place in the context of global change, as wildfires tend to be more frequent in continental areas (global fire frequency could increase by over 37.8% during the period 2010 to 2039, according to global climate models based on the A2 emission scenario) [17,25,26].

The Lake Baikal region in Siberia is a key location because it is one of the deepest, largest and oldest lakes in the world and includes sites sacred to indigenous people [17,27–29]. The Lake Baikal area is also a region of economic interest with heat and hydropower stations, tourism and forestry industries [29–31]. It is a focus of environmental concerns as it shelters more than a thousand endemic species and faces chemical contamination and land degradation from industries located in the watershed [30,32,33]. Since the 1990s, the southern coast of the region has faced increasing fire activity with more frequent and more severe crown fires [24].

Nowadays, fire management is developing and aims to reconcile preservation of the natural landscape with wood production [34]. However, to better understand current and future fire activity variations in connection with environmental parameters (for example mean annual temperature and precipitation), it is essential to understand the dynamics of past fire activity and its links with the vegetation and climatic variations.

This study therefore centers around the first Holocene fire activity reconstruction of the Southern Lake Baikal region, based on the charcoal analysis of sediments from Lake Jarod and Lake Ébène. This study aims to characterize and understand the dynamics of the fire activity in the Southern Lake Baikal region in connection with the available vegetation and climatic studies and the recent study by Dugerdil et al. [35–39]. Our assumption is that fire activity steadily increased as climatic variations became more favorable, with more fires during drier periods than during wetter periods. In addition, an increase in fire activity at the end of the Holocene is suggested by modern observations and increasing human activity [21,24].

2. Material and Methods

2.1. Study Area

The Southern Lake Baikal region is characterized by a sharply continental climate but is also the most humid area of the Lake Baikal coastal zone [36,38]. In this region, dark taiga forest is the main vegetation cover [38]. Dominant conifer forests can be classified into dark taiga and light taiga [3,40]. Dark taiga, composed mainly of *Pinus sibirica*, *Abies sibirica* and *Picea obovata*, tends to be associated with low-frequency but severe crown fires [3,40–43].

Light taiga is mainly composed of *Pinus sylvestris* and *Betula* sp. tree species and is rather more associated with high-frequency surface fires [3,40,44].

The lakes studied in this work, named Lake Ébène and Lake Jarod (unofficial names; Figure 1, Table 1), are located south of Lake Baikal in Siberia. Two meteorological stations, Vydrino and Tankhoy (Figure 1, Table 1) are nearby the studied lakes and their records indicate a continental climate. The mean annual temperature at Vydrino (the closest meteorological station) is 0.01 °C and the mean annual precipitation at Vydrino is 120 mm [45].

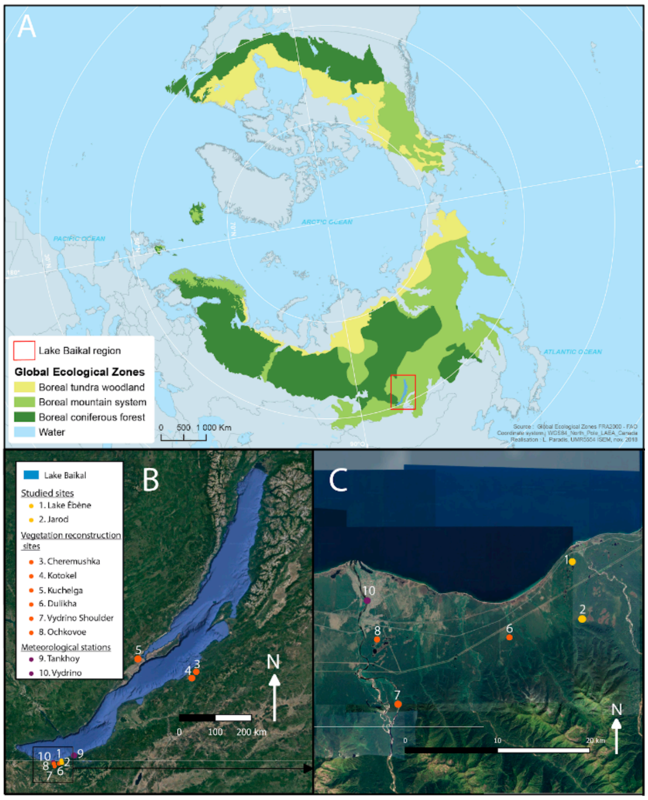

Figure 1. (**A**) Map of the boreal zone and location of Lake Baikal. (**B**) Lake Baikal and location of lakes Ebène and Jarod (1–2, this study) and available pollen records (3 to 8, orange) [36,38,46,47], and meteorological stations (pink). (**C**) Southern Lake Baikal region and location of Lake Ébène and Lake Jarod; Dulikha, Vydrino Shoulder and Ochkovoe pollen records; and meteorological stations.

Table 1. Main characteristics of Lake Ébène and Lake Jarod.

Lake	Latitude	Longitude	Elevation (a. s. l. in m)	Surface (ha)	Sediment Core Length (cm)	Current Local Vegetation
Ébène	51°28′57.65″ N	104°50′12.21″ E	496	0.47	177	*Pinus sibirica*, *Pinus sylvestris*, *Betula pubescens*
Jarod	51°26′51″ N	104°50′25″ E	515	2.55	215	*Betula pubescens*, *Picea obovata*, *Pinus sibirica*, *Pinus sylvestris*, *Abies sibirica*

The main tree species currently growing around Lake Ébène and Lake Jarod are birch (*Betula* sp.), Siberian pine (*Pinus sibirica*), Siberian spruce (*Picea obovata*), Scots pine (*Pinus sylvestris*), Siberian fir (*Abies sibirica*) and larch (*Larix* sp.).

2.2. Sediment Sampling and Datation

A composite sediment core was collected from the center of each lake. As no river flows into the lakes, sedimentation is assumed to be undisturbed. Therefore, the most recent material is found at the water–sediment interface and was sampled with a Kajak-Brinkhurst (KB) gravity corer to prevent disruption of the interface [7,48]. The lower core sections were collected with a Russian corer [49]. Samples were stored in plastic tubes and wrapped in aluminum and plastic paper and then kept under dark and cold conditions (4 °C).

Age-depth models (Figure 2) were developed using the 'Bacon' v2.2 R package [50] based on Bayesian statistical methods. For each lake, five ^{14}C dates were obtained from macro-remains (twig, seed, bark, etc.) or sediment bulk (Table 2) and were used to build the chronology. Each sample was assigned an age in calibrated years Before Present (hereafter cal. yr BP). IntCal13 calibration curves were used for the Holocene period [51] and NH1 post-bomb calibration curves were used for the modern dates [52].

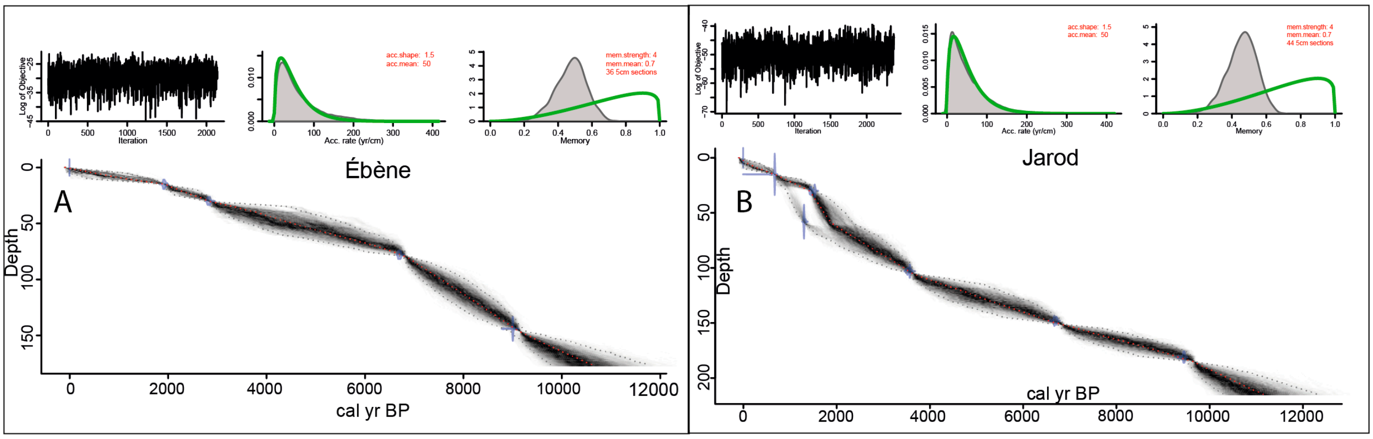

Figure 2. Bacon calibrated age-depth models [53] based on radiocarbon ages from (**A**) Lake Ébène and (**B**) Lake Jarod cores (see Table 2).

Table 2. Radiocarbon dates from Lake Ébène and Lake Jarod.

Lake	Sample Depth (cm)	^{14}C yr BP	Materials Dated	Lab. Code
Ébène	15–16	1975 ± 15	Macro-remains	ULA-8344
Ébène	30–31	2745 ± 15	Macro-remains	ULA-8345
Ébène	78–79	5880 ± 15	Macro-remains	ULA-8341
Ébène	111–112	6000 ± 20	Macro-remains	ULA-8342
Ébène	144–145	8065 ± 15	Macro-remains	ULA-8343
Jarod	15–16	720 ±15	Organic sediments	ULA-8346
Jarod	30–31	1610 ± 15	Organic sediments	ULA-8347
Jarod [a]	58–59	1390 ± 15	Organic sediments	ULA-8348
Jarod	103–104	3325 ± 15	Organic sediments	ULA-8349
Jarod	148–149	5860 ± 20	Organic sediments	ULA-8350
Jarod	181–182	8395 ± 20	Organic sediments	ULA-8351

[a] Age rejected for the age-depth model.

2.3. Reconstructing Fire Frequency with Charcoal Particles

2.3.1. Sample Preparation and Charcoal Quantification

Sediment cores were continuously sliced every 0.5 cm. One 1 cm^3 subsample was taken from the center of each slice with a punch to limit contamination risks [54]. The subsample was put in an aqueous solution of potassium hydroxide (KOH), sodium metaphosphate ($NaPO_3$) and sodium hypochlorite (NaClO, bleach). These chemicals were left to act for at least 24 h under agitation and, when possible, heated to activate KOH to facilitate deflocculation and to differentiate charcoal particles from organic matter [7].

Solutions were filtered through a 160 μm sieve to select the macro-charcoal particles. These particles are assumed to come from local fire events, within 1–3 km from the lake shores [55]. Charcoal particles were counted and measured under a dissecting microscope (×20) using WinSEEDLETM image-analysis software, Regent Instruments Inc. (http://regent.qc.ca/, accessed date 5 January 2018).

2.3.2. Fire Frequency Reconstruction

The age-depth model allows the interpretation of the charcoal records in terms of charcoal accumulation rates, CHAR ($mm^2 \cdot cm^{-2} \cdot year^{-1}$). CHAR series were statistically analyzed with CharAnalysis software v1.1 [56]. This allows the detection of past fires by decomposing CHAR series into peaks representing fire and low charcoal frequency "non-fire" events: $CHAR_{peak}$ and $CHAR_{back}$ [57,58]. $CHAR_{back}$ was estimated using a robust Lowess with a 300–600-year window width. $CHAR_{back}$ was then smoothed with a locally weighted regression. The window width was selected to maximize the signal-to-noise index (SNI, closest but greater than 3) [59]. $CHAR_{peak}$ (obtained by subtracting $CHAR_{back}$ from the raw CHAR series) was separated into $CHAR_{noise}$ (non-fire events) and $CHAR_{fire}$ (fire events) according to a Gaussian mixture model (99th percentile threshold) [57,59]. $CHAR_{noise}$ represents natural and analytical variations around $CHAR_{back}$: sediment mixing and sampling. $CHAR_{fire}$ represents the occurrence of fire events [60]. Peak magnitude, fire return interval (FRI—i.e., number of years between two fire events) and fire frequency were outputs of CharAnalysis. In addition to the CharAnalysis results, FRI data were smoothed with a Loess function using R software [61].

2.4. Pollen Transfer Functions for Climate Reconstruction

Dugerdil et al. [39] used the Dulikha bog pollen sequence [35,62] to reconstruct Mid-Holocene climate (0 to 4500 cal. yr BP). The Dulikha bog pollen sequence is the closest to our study sites, Lake Ébène and Lake Jarod, and we aim to reconstruct past climatic parameters from the Dulikha bog pollen sequence over the entire Holocene (0 to 11,000 cal. yr BP). The mean annual air temperature (hereafter MAAT) and the mean annual precipitation (hereafter MAP) were inferred using the modern analogue technique (hereafter MAT [63]). The MAT consists of the selection of a limited number of analogue surface pollen assemblages with their associated climatic values [64]. The dataset called the New Mongolian-Siberian Database (NMSDB, [39]) was selected as the basis for applying the transfer functions. The NMSDB is composed of pollen surface samples from 49 sites in Mongolia and near Lake Baikal [39]. For detailed methods and the surface sample training dataset, refer to Dugerdil et al. [39].

3. Results

3.1. Age-Depth Models

The cores from Lake Ébène and Lake Jarod measured 177 cm and 215 cm, respectively. For Lake Jarod, the ^{14}C date 3325 cal. yr BP for the sample 58–59 cm was rejected because of inconsistency with the age–depth model. Both sediment cores cover most of the Holocene period, from 10,655 to −92 cal. yr BP for Lake Ébène, with a mean temporal resolution of approximately 61 year/cm^{-1} (standard deviation ~31 years), and from 11,157 to −92 cal. yr BP for Lake Jarod, with a mean temporal resolution of approximately 52 yr/cm^{-1} (standard deviation ~21 years).

3.2. *Fire Activity History*

Fire events were recorded throughout the Holocene at both lakes (Figures 3A and A1). Fire activity was greater at Lake Ébène than at Lake Jarod, with a median fire frequency of 4.3 fires/1000 yr^{-1} compared to 3.5 fires/1000 yr^{-1} at Lake Jarod.

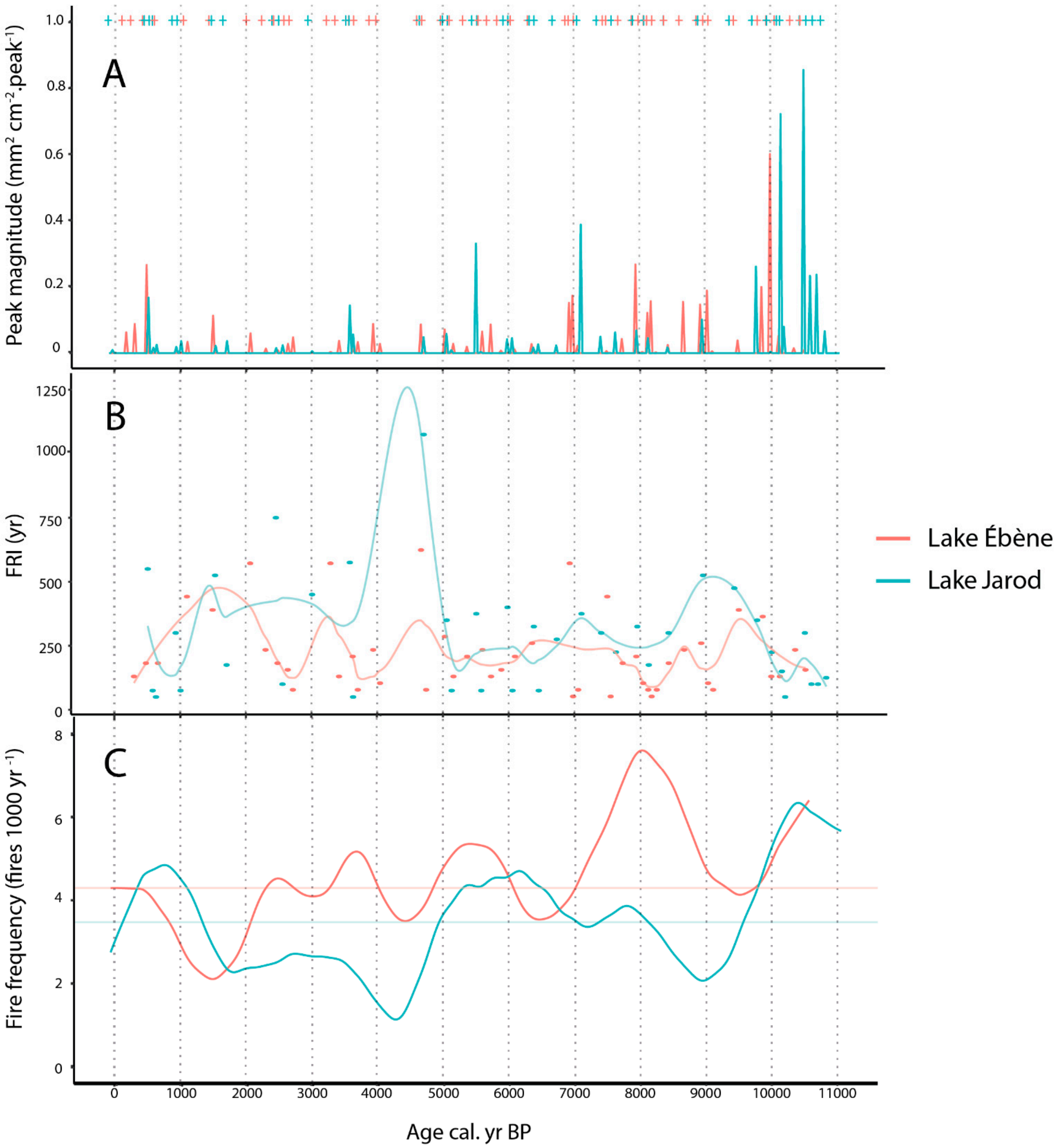

Figure 3. CharAnalysis results from Lake Ébène (pink) and Lake Jarod (blue). (**A**) Peak magnitude (lines) and fire events (crosses). (**B**) FRI (dots) and Loess smoothed FRI (solid lines). (**C**) Fire frequency (solid line) compared to its median (horizontal line).

Peak magnitude was higher in the Early Holocene (from 11,700 to 8000 cal. yr BP) than in the Late Holocene (the last 2500 years), with peaks between 0.7 and 0.9 $mm^2/cm^{-2}.peak^{-1}$ at Lake Jarod between 10,500 and 10,200 cal. yr BP and a peak of 0.6 $mm^2/cm^{-2}.peak^{-1}$ at 10,000 cal. yr BP at Lake Ébène. At Lake Ébène, most peaks remained around 0.2 $mm^2/cm^{-2}.peak^{-1}$ from 10,000 to 7000 cal. yr BP. After 7000 cal. yr BP, peaks were around 0.1 $mm^2/cm^{-2}.peak^{-1}$ or below, except for a peak of 0.28 $mm^2/cm^{-2}.peak^{-1}$ at 500 cal. yr BP. At Lake Jarod the peaks were mainly below 0.1 after 10,000 cal. yr BP. A few larger peaks appeared, namely 0.42 $mm^2/cm^{-2}.peak^{-1}$ at 7200 cal. yr BP, 0.38 $mm^2/cm^{-2}.peak^{-1}$ at 5500 cal. yr BP and two peaks of 0.17 and 0.18 $mm^2/cm^{-2}.peak^{-1}$ at 3800 and 500 cal. yr BP, respectively. Overall, higher peak magnitudes were observed before 6500 cal. yr BP and lower peak magnitudes between 6500 and the present.

At Lake Jarod, the FRI was between 100 and 200 years in the Early Holocene, before 10,000 cal. yr BP, which corresponds to a high fire frequency (6 fires/1000 yr^{-1}) (Figure 3B,C). After 10,000 cal. yr BP, the FRI at Lake Jarod increased and fluctuated between approximately 250 and 500 years, indicating a decrease in fire frequency (2 fires/1000 yr^{-1}). The FRI during the Early Holocene varied around 250 years at Lake Ébène. A drop in the FRI occurred at 8200 cal. yr BP for both lakes (to around 125 years at Lake Ébène, and around 250 years at Lake Jarod) and this corresponds with an increase in fire frequency, to almost 8 fires/1000 yr^{-1} at Lake Ébène and 4 fires/1000 yr^{-1} at Lake Jarod. Between 6000 and 5000 cal. yr BP, fire frequency was higher for both lakes, by between 4 and 5 fires/1000 yr^{-1}. Then, fire frequency decreased (and the FRI increased) at around 4200 cal. yr BP with 1 fire/1000 yr^{-1} (an FRI of over 1000 years) at Lake Jarod and at 3.5 fires/1000 yr^{-1} (an FRI of 300 years) at Lake Ébène. Thereafter, fire frequency increased and fluctuated between 4 and 5 fires/1000 yr^{-1} between 4200 and 2500 cal. yr BP at Lake Ébène and around 2.5 fires/1000 yr^{-1} at Lake Jarod. A decrease in fire frequency occurred at 1500 cal. yr BP, with 2 fires/1000 yr^{-1} for both of the lakes. Then up until 800 cal. yr BP, fire frequency rose to 4.2 and 4.8 fires/1000 yr^{-1} for Lake Ébène and Lake Jarod, respectively. Between 800 and -92 cal. yr BP, fire frequency dropped to 2.8 fires/1000 yr^{-1} at Lake Jarod, while it remained stable at 4.2 fires/1000 yr^{-1} for Lake Ébène.

As for fire frequency, two periods of high and low fire frequency were found during the Holocene. Between the beginning of the sequence and 6500 cal. yr BP, fire frequency values were mostly above the median (except for Lake Jarod around 9000 cal. yr BP). This corresponds to the period of high fire frequency in the first part of the Holocene. The following period, between 5000 cal. yr BP and −92 cal. yr BP, was characterized by fire frequency values under the median value for both lakes, except some peaks around 3750 and 2500 cal. yr BP for Lake Ébène and around 750 cal. yr BP for Lake Jarod. Thus, this corresponds to a period of low fire frequency for both lakes.

Therefore, the two lakes present similar fire regime trends. Two periods are identified: the first from 11,000 to 6500 cal. yr BP, corresponding to a high-frequency and more biomass burning likely related to more severe fire events; and the second subsequent period until 1500 cal. yr BP, corresponding to low-frequency and low biomass burning, likely related to less severe fire events. Then from 1500 cal. yr BP, fire frequency initially increased until 900 cal. yr BP at Lake Jarod where a decrease is observed, and until 600 cal. yr BP at Lake Ébène where a stabilization of fire frequency appears until the present time.

3.3. Mean Annual Temperature and Precipitations at Dulikha

The MAT transfer function at Dulikha indicates values close to the modern average annual temperature (0 °C at the Vydrino weather station). However, the modern average annual precipitation values indicated by the MAT are higher than those known at the Vydrino weather station (about 700 mm). At Dulikha a similar trend is observed for the MAAT and MAP with an increase during the early Holocene (from 11,000 cal. yr BP to 7500 cal. yr BP) followed by a decrease until approximately 4500 cal. yr BP. Then the Dulikha MAP steadily increases from 4500 cal. yr BP until the present time, whereas the

MAAT increases more slowly and seems to be reaching a threshold of 0.6 °C around the present time (Figure 4, purple and green curves).

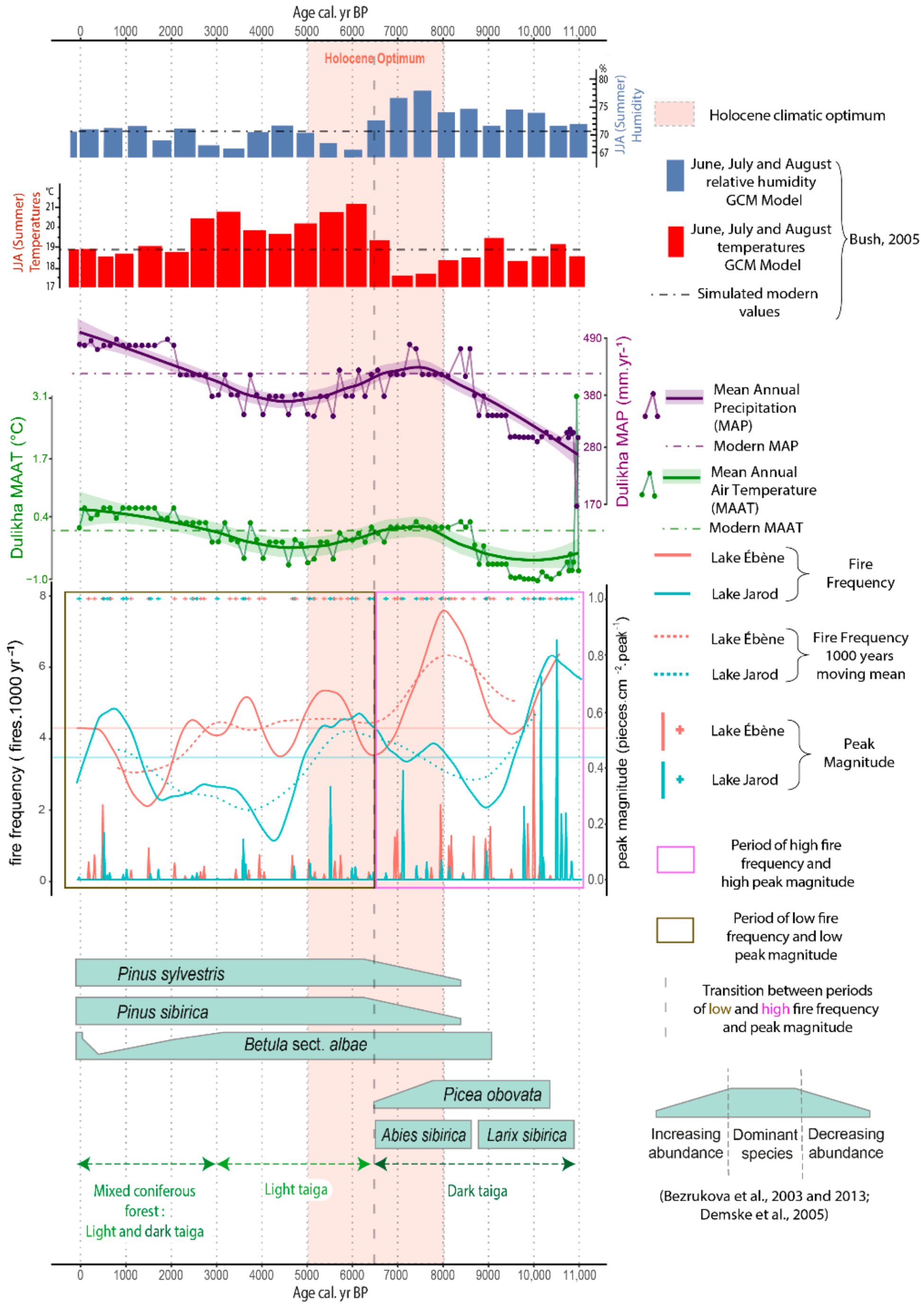

Figure 4. Correspondences in Lake Ébène and Lake Jarod fire evolutions (fire frequency, fire frequency median, fire frequency with 1000-year moving mean, fire events and peak magnitude) with summarized variations in reconstructed vegetation of the southern region of Lake Baikal during the Holocene: Vydrino (0–13,520 cal. yr BP), Dulikha (0–11,109 cal. yr BP) and Ochkovoe (0–4500 cal. yr BP) see Figure 1 [36,46,47] and reconstructed climate: temperature and precipitation for Dulikha and atmospheric general circulation model (GCM) output using a series of 500-year intervals for continental Eurasia (45–70° N, 75–130° E) that includes the Lake Baikal region [65,66].

4. Discussion

4.1. Age-Depth Models

The age–depth model for Lake Jarod led to the rejection of the sample date 1390 ± 15 at depth 58–59 cm (Table 2, Figure 2). Since it was a relatively recent ^{14}C date that was rejected, the hypothesis of manual contamination of younger sediment by older sediment during core extraction in the field is favored since the carbon content of the samples is not known. This single date rejection across the entire age model does not affect the quality of the model established, relative to the total number of ^{14}C dates performed (Blockley et al., 2007).

4.2. South Lake Baikal Spatial Fire Activity

Fire frequency patterns and the distribution of magnitude peaks between Lake Ébène and Lake Jarod are markedly similar, despite being inferred from two close but different sites (Figure 3). The increase/decreases in fire frequency and FRI mainly occur in the same periods. In general, the fire frequencies recorded at Lake Ébène show higher values than those at Lake Jarod, particularly between 9500 and 7000 cal. yr BP and between 6000 and 2000 cal. yr BP, this could be due to the site spatial variability. Magnitude peaks were higher from the Early Holocene to 6500 cal. yr BP and thereafter lower until the present time. Several factors can induce magnitude peak variations and so magnitude values do not necessarily represent the fire type affecting the boreal ecosystem. Here, we have supposed that the magnitude of the peak is linked to the biomass burned (i.e., high-magnitude peaks represent a substantial volume of biomass burned) which is linked to the fire regime (surface and crown fires) [10,67]. The majority of fires in the southern Lake Baikal region, and more generally in the Eurasian boreal forest, are surface fires, i.e., low-intensity and generally non-lethal to trees [3,68,69]. The nature of these fires (i.e., surface fires vs. crown fires), as well as the sites' spatial variability, may explain the variability observed in fire events, for fire frequency and peak abundance, between Lake Ébène and Lake Jarod [70]. However, the median values of the fire frequencies for both lakes are very close (4.3 and 3.5 fires/1000 yr^{-1} for Lake Ébène and Lake Jarod, respectively). The correspondence between the fire signals of the two lakes indicates that our reconstructions are robust and suggests shared levels of fire activity in the southern region of Lake Baikal during the Holocene.

The fire signals occur at the same time periods, except between 7000 and 6000 cal. yr BP, when a shift in fire frequency is observed and, for the last 900 years, fire frequency and FRI tendencies differed between the two lakes (Figure 3A,C). The differences in fire intensity between Lake Jarod and Lake Ébène could be due to several factors, such as the spatio-temporal frame (like the place of fire departure, the type of fire ignition or the fire duration) and the direction and intensity of the winds between these two locations. Different local air currents occur around Lake Baikal, for example the Shelonnik wind [71]. This wind blows in summer, during the fire season, following a South–North direction, which corresponds to the Lake Jarod–Lake Ébène direction. Most of the fire peaks have a higher magnitude at Lake Ébène compared to Lake Jarod, which could indicate fire events that increase in intensity as we move from Lake Jarod towards Lake Ébène. However, peak magnitude was higher at Lake Jarod in the Early Holocene before 9800 cal. yr BP, and during 3 distinct peaks at 7200, 5500 and 3700 cal. yr BP, which points to other wind directions or other factors being at work.

Between 11,000 and 9000 cal. yr BP there were high-frequency but also high-intensity fires, and peak magnitudes were at their maximum for the Holocene (up to more than 0.8 $mm^2 \cdot cm^{-2} \cdot peak^{-1}$ for Lake Jarod). This more intense fire activity was also observed by Katamura et al. [16] for the Early Holocene in Eastern Siberia and may be related to crown fires because of the peaks' magnitude [3,68,69]. Further into the boreal regions, in Fennoscandia and Denmark, a higher influx of charcoal in the early Holocene was related to the nature of the fires [13]. Another study in northwest Siberia, carried out by Clark [72], showed higher levels of charcoal in the mid-Holocene, around 5000 cal. yr BP, which also corresponds to the high peak recorded at Lake Jarod for the same period and could also be related to a crown fire event. However, within the Lake Baikal region, there is no other long-term Holocene reconstruction of fire history to which our results can be compared.

4.3. Vegetation and Climate Influences on Fire History

The composition of plant communities in boreal forests (to which are related general fire characteristics such as crown or surface type) are themselves influenced by the climate [3]. For example, Canada's boreal forests are dominated by high-intensity crown fires and are characterized by forests composed of *Pinus banksiana* and *Picea mariana* [5,73–75]. As these species are serotinous, their seed dispersion is fire-dependent: tree seeds are contained in serotinous cones which open with the heat of fires [76]. Eurasian boreal forests, where most fires are surface fires, are today mainly composed of *Pinus sylvestris* and *Betula* sp. (light taiga forest). *Pinus sylvestris*, for example, self-prunes its lower branches and presents a thick more fire-resistant bark, which tends to prevent fires from rising and restricts flames to the ground surface [3].

When crown fires were probably occurring at Lake Ébène and Lake Jarod in the Early and Mid-Holocene, the vegetation was characterized by species ecologically similar to those found in Canada, composed of dark taiga forest such as *Abies sibirica*, *Picea obovata* and *Pinus sibirica* [3]. Palynological studies and climate-based results have previously shown that these species were dominant during these periods in the southern region of Lake Baikal at the sites Vydrino, Dulikha and Ochkovoe [36,46,47,77] (Figure A2). At the Dulikha site, *Picea* sp. and *Larix* sp. were the dominant tree species between 13,500 and 9000 cal. yr BP. Then *Pinus sibirica*, *Abies* sp. and *Betula* sp. became the dominant species from 9000 to 6400 cal. yr BP [36]. At the Vydrino Shoulder site, there is a clear palynological demarcation between the Early Holocene (11,600 cal. yr BP) and the mid-Holocene from 7100 cal. yr BP [47]. At the beginning of the Holocene, *Pinus sibirica* and *Betula* sp. are dominant and *Abies* sp. and *Picea* sp. show their highest percentages [47]. Thus, in the Early to Mid-Holocene, a mainly dark and humid taiga forest, dominated by *Picea obovata* and *Abies* sp., composed the forest (Figure 4). Wet conditions deduced from palynological results from the southern region of Lake Baikal [36,46,47] are regionally confirmed in general circulation model (GCM) outputs [76,77]. These simulated decreasing summer temperatures and increasing summer humidity over central Eurasia with a 500-year window (45–70° N, 75–130° E) for the Early to Mid-Holocene. The precipitation pattern from the Dulikha bog pollen sequence also shows increasing amounts of annual precipitation, although values were low, at between 250 and 400 mm per year. The pollen-based climate reconstruction carried out in the present study seems more accurate because it is based on local data (while the GCM one is a very large-scale climate reconstruction covering Eurasia) and indeed pollen reconstructions of modern climatic conditions better match actual modern conditions than large-scale GCM climate reconstructions (Figure 4). In addition, the temperature and precipitation results provide an annual estimate, while the GCM results show the summer humidity estimate, which can make a significant difference, especially with regard to precipitation, as droughts are relatively common during summer and often linked to fire occurrence [10]. In the Early-Holocene at Lake Ébène and Lake Jarod, since a high fire activity rate was recorded (high frequencies and high intensity, crown fires), summer climate conditions (related to fire season) would not be directly linked to the dynamics of the fires. One might suppose that the role of vegetation would have had a stronger effect on the dynamics of fires. It seems that the denser "dark taiga" vegetation type was conducive to high-intensity fires (as has been demonstrated in other regions [3]) and also associated with a higher frequency of fires in our study.

From 8000 to 5000 cal. yr BP, the southern region of Lake Baikal experienced its Early to Middle Holocene thermal optimum, associated with wetter conditions (Figure 4) [46,77,78]. The thermal optimum seems to be divided, with cold and humid summers from 8000 to 6500 cal. yr BP, then a reversal with hot and dry summers from 6500 to 5000 cal. yr BP (Figure 4). The first half of the thermal optimum shows the highest temperature and precipitation values of this period (0.3 °C and 420 mm) and corresponds to the period of high peak magnitudes and high fire frequency (Figure 4). This result is consistent with the presence of dark taiga and with the characteristics of the fires recorded. Indeed, at the Dulikha site, *Pinus sibirica* persists with a high percentage but *Pinus sylvestris* increases between 6400 and 5300 cal. yr BP [46]. The same is true at the Vydrino shoulders site, where the percentage of *Pinus sibirica* does not vary however *Pinus sylvestris* greatly increases [47]. However, relating fire activity to the cold summers implied by the GCM reconstructions, it can be assumed that the fire season during this thermal optimum period started earlier and/or that the majority of fires were occurring earlier in the year. Today in Russia, the fire season begins in March and the first peaks of fire occur in mid-March and mid-April [79].

From 6500 to 5000 cal. yr BP, the annual climate remained relatively hot and humid but temperature and precipitation decreased. However, the hotter and drier summers indicated by the GCM are in agreement with the disappearance of the dark taiga in favor of the light taiga, with species well adapted to these conditions (*Pinus sylvestris*) and to a surface fire regime taking over [36,46,47,77]. A period of generally low temperature/precipitation and hot/dry summers was maintained through the Mid-Holocene, from 5000 to 3000 cal. yr BP and the general dynamics of fires remained constant, involving the surface fire type. The Ochkovoe site also shows a dominance of *Pinus sylvestris* pollen grains during this period, indicating a drier climate [36].

From 3000 cal. yr BP, annual temperature and precipitation increased in the region but summers became colder (Figure 4). A mixed coniferous forest, composed of both light and dark taiga, became established (Figure 4) [36,46,47].

4.4. Late Holocene Human Impact on Fire History

According to a study by Kobe et al. [80] of the West Cis-Baikal coast, the first hunter-gatherer culture present after the collapse of large mammals in the region was the Kitoi culture (from 7560 to 6660 cal. yr BP). However, after 6660 and until 6060, there are no further archaeological traces of their activities, an absence which has been linked to a rapid change of climate and vegetation at that time [81]. The populations present thereafter appear to have been smaller groups, surviving on the aquatic resources of Lake Baikal [80,81]. The impact of these populations on the fire dynamics around Lake Baikal seems to have been minimal compared to the influence of climate and vegetation.

The frequency of fires at the end of the Holocene, from about 1500 cal. yr BP, shows first an increase (Figure 3) then a decrease from 900 cal. yr BP (Lake Jarod) and a stabilization from 600 cal. yr BP (Lake Ébène) from about 500 cal. yr BP onwards. These shifts seem difficult to relate to climatic and/or vegetation conditions, which were stable during this period [36,46,47]. Another hypothesis would connect these shifts to the increase in human activity in the region. Indeed, human activities and settlement have often been linked to an increase in fire frequency and severity, for example because of human-induced fire for opening landscape and sustaining grasslands [21,49,82,83]. Bezrukova et al. [36] discussed human activities around Lake Baikal over the Late Holocene period and indicated that archaeological research has shown that the region was inhabited by communities of hunter-gatherers and then pastoralists but that there were no traces of this occupation in the lake sediments for the Mid- to Late-Holocene. According to these authors, the increase in pollen of *Betula* sp. and *Pediastrum* spores at the site Cheremushka from 300 cal. yr BP could be linked to an intensification of human activities, more precisely wood harvesting.

North of Lake Baikal, in Yakutia, a recent study [21] indicates a decrease in fire activity since 1200 cal. yr BP and linked it to fire suppression by humans. This study suggests that the impact of human activities was more linked to the type of society than to the number of people; for example, slash and burn practices were linked to small populations, while in the 18th century this practice was banned in line with industrialization and fire suppression policies in Russia, in order to protect forest resources, despite the fact that human populations had increased [21,84,85]. Within our study sites, we can assume that the arrival of new human populations like hunter-gatherers and pastoralists could have increased fire frequency after 1500 cal. yr BP. Then a fire suppression strategy could have been induced by a societal change and could have resulted in a decrease in the frequency of fires, particularly at Lake Jarod from 900 cal. yr BP and more strongly from 500 cal. yr BP. However, there is a lack of multi-proxy studies in these regions to confirm the links between human activities and fire occurrence [36]. Notably, Walker et al. [86] indicate an unprecedented recent increase in fire activity, which has caused considerable human damage. This recent trend has also been observed by Sofronov et al. [24], in the same study area, with an increase in fire frequency and fire severity since 1989 along with the appearance of crown fires every year since 1994 CE, although this trend was not observed or recorded with charcoal particles within our sediment cores.

5. Conclusions

In this study we have presented the first complete Holocene reconstruction of fire dynamics around the Southern shore of Lake Baikal. In the Early Holocene, from 11,000 to 6500 cal. yr BP, the region experienced severe crown fires (based on fire frequency and peak magnitude), mainly due to the establishment of a dark taiga forest. Then a surface fire regime (indicated by the fire frequency and peak magnitude observed), more characteristic of Eurasian boreal forests, was established until the present day. This shift coincides with the light taiga implementation at 6500 cal. yr BP while temperature and precipitation decreased annually but summers became hotter and drier. Fire, climate and vegetation are very intertwined and act on each other, as the shift of fire frequency, climate conditions and vegetation types between 8000 and 6500 cal. yr BP illustrated. However, at the end of the Holocene climate Optimum, fire regime seems to be linked to climate conditions rather than the vegetation types. The impact of human activities has not yet been firmly established and the gap in knowledge and studies of human activities and their relationship to fires in these regions needs to be filled in order to shed light on practices of fire management during the Holocene in the South of Lake Baikal. However, we hypothesize that this impact was significant from 1500 cal. yr BP onwards, showing first with an increase in fire frequency, then with a decrease or maintenance of the fire frequency through fire suppression strategies. On the other hand, in recent years, the region has been marked by disastrous crown fires probably linked to climate change.

Author Contributions: Conceptualization, C.B., M.V. and A.A.A.; methodology, A.A.A., C.B., M.V. and H.L.; validation, A.A.A., S.J. and O.P.; formal analysis, C.B., M.V., H.L. and L.D.; investigation, A.A.A. and C.B.; data curation, C.B., M.V. and H.L.; writing—original draft preparation, C.B. and M.V.; writing—review and editing, C.B., M.V., A.A.A., S.J. and O.P.; supervision, A.A.A.; funding acquisition, A.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Belmont Forum Project PREREAL, grant number #292-2015-11-30-13-43-09; the consortium GDRI Cold Forests and IUF of Adam A. Ali.

Acknowledgments: We thank Benoît Brossier, Laure Paradis and Thierry Pastor for their technical contribution. We thank Simon J. Crowhurst and Alexandra Buxton for scientific language editing. We thank Alexandre Nolin and Maxence Soubeyrand from Corrige-Moi for their first reviews. This is an ISEM contribution No. 2021-167. We thank the labex Cemeb for funding the internship of Hanane Limani.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

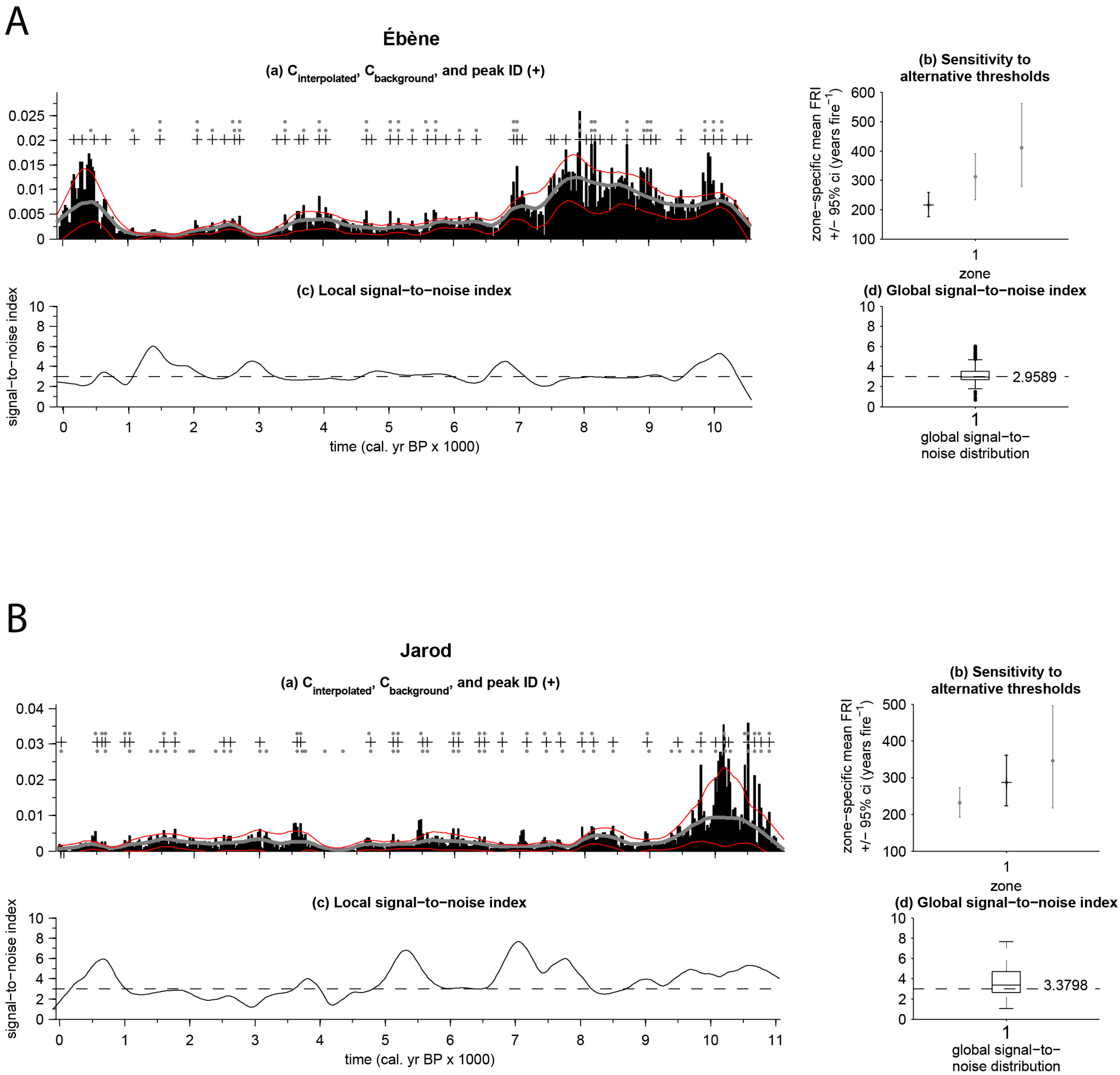

Figure A1. CharAnalysis outputs: Charcoal influx and signal-to-noise index of Lake Ébène (**A**) and Lake Jarod (**B**).

<table>
<tr><th>Periods (cal. kyr bP)</th><th colspan="3">Summarized vegetation evolution of the southern shore of lake Baikal</th></tr>
<tr><td>References</td><td>Demske et al., 2005</td><td>Bezrukova et al., 2003</td><td>Bezrukova et al., 2013</td></tr>
<tr><td>10.6 – 9</td><td>Herbs and steppe domination (tundra biome)
Duschekia fructicosa, Poaceae, Picea obovata, Artemisia and Chenopodiaceae</td><td>Larix, Picea, Betula, Salix, Equisetum, Cyperaceae and other herbs</td><td rowspan="6">No pollen data for this period</td></tr>
<tr><td>9 – 8.6</td><td rowspan="3">Picea obovata and Abies domination</td><td>Picea obovata, Larix, Abies, Betula, Polypodiaceae, Equisetum and other herbs</td></tr>
<tr><td>8.6 – 7</td><td rowspan="2">Abies sibirica, Pinus sibirica, Betula, Sphagnum and Ericaceae</td></tr>
<tr><td>7 – 6.4</td></tr>
<tr><td>6.4 – 5.3</td><td rowspan="6">Pinus sylvestris, Pinus sibirica and Betula domination</td><td>Pinus sylvestris, Pinus sibirica, Betula, Sphagnum</td></tr>
<tr><td>5.3 – 4</td><td rowspan="5">Pinus sylvestris, Pinus sibirica, Sphagnum</td></tr>
<tr><td>4 – 3.3</td><td rowspan="3">Pinus sibirica, Pinus sylvestris, Betula sect. albae and low percentage of Abies, Picea and Larix</td></tr>
<tr><td>3.3 – 2.5</td></tr>
<tr><td>2.5 – 0.63</td></tr>
<tr><td>0.63 - 0</td><td>Betula sect. albae and Pinus sylvestris, less Pinus sibirica, Cyperaceae and Sphagnum play an important role and Artemisia increased</td></tr>
</table>

Figure A2. Synthesis of the past vegetation dynamics in the southern Lake Baikal region.

References

1. Chapin, F.S.; Danell, K. Boreal forest. In *Global Biodiversity in a Changing Environment*; Springer: Berlin/Heidelberg, Germany, 2001; pp. 101–120.
2. Chapman, B.R.; Bolen, E.G. *Ecology of North America*; Wiley: Hoboken, NJ, USA, 2015.
3. Goldammer, J.G.; Furyaev, V.V. *Fire in Ecosystems of Boreal Eurasia*; Springer: Dordrecht, The Netherlands, 1996. [CrossRef]

4. Shlisky, A.; Waugh, J.; Gonzalez, P.; Gonzalez, M.; Manta, M.; Santoso, H.; Alvarado, E.; Nuruddin, A.A.; Rodríguez-Trejo, D.A.; Swaty, R.; et al. Fire, ecosystems and people: Threats and strategies for global biodiversity conservation. *Arlingt. Nat. Conserv.* **2007**. Available online: https://www.conservationgateway.org/Files/Pages/Global_Fire_Assessment.aspx (accessed on 22 July 2019).
5. De Groot, W.J.; Cantin, A.S.; Flannigan, M.; Soja, A.J.; Gowman, L.M.; Newbery, A. A comparison of Canadian and Russian boreal forest fire regimes. *For. Ecol. Manag.* **2013**, *294*, 23–34. [CrossRef]
6. Macdonald, G.M.; Velichko, A.A.; Kremenetski, C.V.; Borisova, O.K.; Goleva, A.A.; Andreev, A.; Cwynar, L.C.; Riding, R.T.; Forman, S.; Edwards, T.W.; et al. Holocene Treeline History and Climate Change Across Northern Eurasia. *Quat. Res.* **2000**, *53*, 302–311. [CrossRef]
7. Carcaillet, C.; Bergeron, Y.; Richard, P.J.; Fréchette, B.; Gauthier, S.; Prairie, Y.T. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime? *J. Ecol.* **2001**, *89*, 930–946. [CrossRef]
8. Talon, B.; Payette, S.; Filion, L.; Delwaide, A. Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Québec, Canada, from charred wood in mineral soils. *Quat. Res.* **2005**, *64*, 36–43. [CrossRef]
9. Hély, C.; Girardin, M.P.; Ali, A.A.; Carcaillet, C.; Brewer, S.; Bergeron, Y. Eastern boreal North American wildfire risk of the past 7000 years: A model-data comparison. *Geophys. Res. Lett.* **2010**, *37*. [CrossRef]
10. Ali, A.A.; Blarquez, O.; Girardin, M.P.; Hély, C.; Tinquaut, F.; El Guellab, A.; Valsecchi, V.; Terrier, A.; Bremond, L.; Genries, A.; et al. Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 20966–20970. [CrossRef] [PubMed]
11. Blarquez, O.; Ali, A.A.; Girardin, M.P.; Grondin, P.; Fréchette, B.; Bergeron, Y.; Hély, C. Regional paleofire regimes affected by non-uniform climate, vegetation and human drivers. *Sci. Rep.* **2015**, *5*, 13356. [CrossRef] [PubMed]
12. Lankia, H.; Wallenius, T.; Várkonyi, G.; Kouki, J.; Snäll, T. Forest fire history, aspen and goat willow in a Fennoscandian old-growth landscape: Are current population structures a legacy of historical fires? *J. Veg. Sci.* **2012**, *23*, 1159–1169. [CrossRef]
13. Clear, J.L.; Molinari, C.; Bradshaw, R.H.W. Holocene fire in Fennoscandia and Denmark. *Int. J. Wildland Fire* **2014**, *23*, 781–789. [CrossRef]
14. Drobyshev, I.; Bergeron, Y.; Linderholm, H.W.; Granström, A.; Niklasson, M. A 700-year record of large fire years in northern Scandinavia shows large variability and increased frequency during the 1800 s. *J. Quat. Sci.* **2015**, *30*, 211–221. [CrossRef]
15. Magne, G.; Brossier, B.; Gandouin, E.; Paradis, L.; Drobyshev, I.; Kryshen, A.; Hély, C.; Alleaume, S.; Ali, A. Lacustrine charcoal peaks provide an accurate record of surface wildfires in a North European boreal forest. *Holocene* **2019**, *30*, 380–388. [CrossRef]
16. Katamura, F.; Fukuda, M.; Bosikov, N.P.; Desyatkin, R.V. Charcoal records from thermokarst deposits in central Yakutia, eastern Siberia: Implications for forest fire history and thermokarst development. *Quat. Res.* **2009**, *71*, 36–40. [CrossRef]
17. Eichler, A.; Tinner, W.; Brütsch, S.; Olivier, S.; Papina, T.; Schwikowski, M. An ice-core based history of Siberian forest fires since AD 1250. *Quat. Sci. Rev.* **2011**, *30*, 1027–1034. [CrossRef]
18. Barhoumi, C.; Peyron, O.; Joannin, S.; Subetto, D.; Kryshen, A.; Drobyshev, I.; Girardin, M.P.; Brossier, B.; Paradis, L.; Pastor, T.; et al. Gradually increasing forest fire activity during the Holocene in the northern Ural region (Komi Republic, Russia). *Holocene* **2019**, *29*, 1906–1920. [CrossRef]
19. Barhoumi, C.; Ali, A.A.; Peyron, O.; Dugerdil, L.; Borisova, O.; Golubeva, Y.; Subetto, D.; Kryshen, A.; Drobyshev, I.; Ryzhkova, N.; et al. Did long-term fire control the coniferous boreal forest composition of the northern Ural region (Komi Republic, Russia)? *J. Biogeogr.* **2020**, *47*, 2426–2441. [CrossRef]
20. Lamentowicz, M.; Słowiński, M.; Marcisz, K.; Zielińska, M.; Kaliszan, K.; Lapshina, E.; Gilbert, D.; Buttler, A.; Fiałkiewicz-Kozieł, B.; Jassey, V.; et al. Hydrological dynamics and fire history of the last 1300 years in western Siberia reconstructed from a high-resolution, ombrotrophic peat archive. *Quat. Res.* **2015**, *84*, 312–325. [CrossRef]
21. Glückler, R.; Herzschuh, U.; Kruse, S.; Andreev, A.; Vyse, S.A.; Winkler, B.; Biskaborn, B.K.; Pestrykova, L.; Dietze, E. Wildfire history of the boreal forest of southwestern Yakutia (Siberia) over the last two millennia documented by a lake-sedimentary charcoal record. *Biogeosciences* **2021**, *18*, 4185–4209. [CrossRef]
22. Safronov, A.N. Effects of Climatic Warming and Wildfires on Recent Vegetation Changes in the Lake Baikal Basin. *Climate* **2020**, *8*, 57. [CrossRef]
23. Mackay, A.W. The paleoclimatology of Lake Baikal: A diatom synthesis and prospectus. *Earth-Sci. Rev.* **2007**, *82*, 181–215. [CrossRef]
24. Sofronova, T.; Volokitina, A.; Sofronov, M. Assessing the fire hazard from weather conditions in mountain forests of the Southern Baikal region. *Geogr. Nat. Resour.* **2008**, *29*, 163–168. [CrossRef]
25. Moritz, M.A.; Parisien, M.-A.; Batllori, E.; Krawchuk, M.A.; Van Dorn, J.; Ganz, D.J.; Hayhoe, K. Climate change and disruptions to global fire activity. *Ecosphere* **2012**, *3*, 1–22. [CrossRef]
26. Hoegh-Guldberg, O.; Jacob, D.; Bindi, M.; Brown, S.; Camilloni, I.; Diedhiou, A.; Djalante, R.; Ebi, K.; Engelbrecht, F.; Guiot, J.; et al. Chapter 3: Impacts of 1.5 °C global warming on natural and human systems. In *Global Warming of 1.5 °C an IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2018. Available online: http://pure.iiasa.ac.at/id/eprint/15518/ (accessed on 18 March 2019).
27. Mikhailov, T.M. Buryat shamanism. *Sov. Anthropol. Archeol.* **1989**, *28*, 9–19. [CrossRef]

28. Kirillov, S.; Sedova, N.; Vorobyevskaya, E.; Zengina, T. Problems and prospects for tourism development in the Baikal Region, Russia. In Proceedings of the 14th GeoConference on Ecology, Economics, Education and Legislation, Albena, Bulgaria, 17–26 June 2014; Volume 2, pp. 531–538.
29. Vologzhina, S.Z.; Sutyrina, E.N.; Akhtimankina, A.V. Assessment of Anthropogenic Activities on the Tourism and Recreation Territory of Olkhon Island (Irkutsk Region, Russia). *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *204*, 012049. [CrossRef]
30. Kozhova, O.M.; Silow, E.A. The current problems of Lake Baikal ecosystem conservation. *Lakes Reserv. Res. Manag.* **1998**, *3*, 19–33. [CrossRef]
31. Kuuluvainen, T.; Gauthier, S. Young and old forest in the boreal: Critical stages of ecosystem dynamics and management under global change. *For. Ecosyst.* **2018**, *5*, 26. [CrossRef]
32. Kontula, T.; Kirilchik, S.; Väinölä, R. Endemic diversification of the monophyletic cottoid fish species flock in Lake Baikal explored with mtDNA sequencing. *Mol. Phylogenetics Evol.* **2003**, *27*, 143–155. [CrossRef]
33. Peterson, L.; Bergen, K.; Brown, D.; Vashchuk, L.; Blam, Y. Forested land-cover patterns and trends over changing forest management eras in the Siberian Baikal region. *For. Ecol. Manag.* **2009**, *257*, 911–922. [CrossRef]
34. Gustafson, E.J.; Shvidenko, A.Z.; Scheller, R.M. Effectiveness of forest management strategies to mitigate effects of global change in south-central Siberia. *Can. J. For. Res.* **2011**, *41*, 1405–1421. [CrossRef]
35. Bezrukova, E.; Abzaeva, A.; Letunova, P.; Kulagina, N.; Vershinin, K.; Belov, A.; Orlova, L.; Danko, L.; Krapivina, S. Post-glacial history of Siberian spruce (*Picea obovata*) in the Lake Baikal area and the significance of this species as a paleo-environmental indicator. *Quat. Int.* **2005**, *136*, 47–57. [CrossRef]
36. Bezrukova, E.V.; Hildebrandt, S.; Letunova, P.P.; Ivanov, E.V.; Orlova, L.A.; Müller, S.; Tarasov, P.E. Vegetation dynamics around Lake Baikal since the middle Holocene reconstructed from the pollen and botanical composition analyses of peat sediments: Implications for paleoclimatic and archeological research. *Quat. Int.* **2013**, *290-291*, 35–45. [CrossRef]
37. Fietz, S.; Nicklisch, A.; Oberhänsli, H. Phytoplankton response to climate changes in Lake Baikal during the Holocene and Kazantsevo Interglacials assessed from sedimentary pigments. *J. Paleolimnol.* **2006**, *37*, 177–203. [CrossRef]
38. Shichi, K.; Takahara, H.; Krivonogov, S.K.; Bezrukova, E.V.; Kashiwaya, K.; Takehara, A.; Nakamura, T. Late Pleistocene and Holocene vegetation and climate records from Lake Kotokel, central Baikal region. *Quat. Int.* **2009**, *205*, 98–110. [CrossRef]
39. Dugerdil, L.; Joannin, S.; Peyron, O.; Jouffroy-Bapicot, I.; Vannière, B.; Boldgiv, B.; Unkelbach, J.; Behling, H.; Ménot, G. Climate reconstructions based on GDGT and pollen surface datasets from Mongolia and Siberia: Calibrations and applicability to extremely cold-dry environments over the Late Holocene. *Clim. Past Discuss.* **2020**, *2020*, 1–39. [CrossRef]
40. Schulze, E.-D.; Wirth, C.; Mollicone, D.; Ziegler, W. Succession after stand replacing disturbances by fire, wind throw, and insects in the dark Taiga of Central Siberia. *Oecologia* **2005**, *146*, 77–88. [CrossRef] [PubMed]
41. Lapenis, A.; Shvidenko, A.; Shepaschenko, D.; Nilsson, S.; Aiyyer, A.; Schepaschenko, D. Acclimation of Russian forests to recent changes in climate. *Glob. Chang. Biol.* **2005**, *11*, 2090–2102. [CrossRef]
42. Shorohova, E.; Kuuluvainen, T.; Kangur, A.; Jogiste, K. Natural stand structures, disturbance regimes and successional dynamics in the Eurasian boreal forests: A review with special reference to Russian studies. *Ann. For. Sci.* **2009**, *66*, 201. [CrossRef]
43. Tchebakova, N.M.; Parfenova, E.; Soja, A.J. The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. *Environ. Res. Lett.* **2009**, *4*, 045013. [CrossRef]
44. Goldammer, J.G. *Vegetation Fires and Global Change-Challenges for Concerted International Action: A White Paper Directed to the United Nations and International Organizations*; Remagen-Oberwinter: Remagen, Germany, 2015.
45. Grieser, J.; Gommes, R.; Bernardi, M. New LocClim-the local climate estimator of FAO. *Geophys. Res. Abstr.* **2006**, *8*, 2.
46. Bezrukova, E.V.; Letunova, P.P.; Vershinin, K.E.; Krivonogov, S.K.; Abzaeva, A.A.; Krapivina, S.M.; Khomutova, M.Y. Paleoenvironmental changes in Baikal Basin in the late glacial and Holocene. *Berliner Palaeobiologische Abh.* **2003**, *4*, 111–120.
47. Demske, D.; Heumann, G.; Granoszewski, W.; Nita, M.; Mamakowa, K.; Tarasov, P.E.; Oberhänsli, H. Late glacial and Holocene vegetation and regional climate variability evidenced in high-resolution pollen records from Lake Baikal. *Glob. Planet. Chang.* **2005**, *46*, 255–279. [CrossRef]
48. Leys, B.; Carcaillet, C.; Dezileau, L.; Ali, A.A.; Bradshaw, R. A comparison of charcoal measurements for reconstruction of Mediterranean paleo-fire frequency in the mountains of Corsica. *Quat. Res.* **2013**, *79*, 337–349. [CrossRef]
49. Rius, D.; Vannière, B.; Galop, D.; Richard, H. Holocene fire regime changes from multiple-site sedimentary charcoal analyses in the Lourdes basin (Pyrenees, France). *Quat. Sci. Rev.* **2011**, *30*, 1696–1709. [CrossRef]
50. Blaauw, M.; Christen, J.A. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.* **2011**, *6*, 457–474. [CrossRef]
51. Reim Reimer, P.J.; Bard, E.; Bayliss, A.; Beck, J.W.; Blackwell, P.G.; Ramsey, C.B.; Grootes, P.M.; Guilderson, T.P.; Haflidason, H.; Hajdas, I.; et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **2013**, *55*, 1869–1887. [CrossRef]
52. Hua, Q.; Barbetti, M.; Rakowski, A. Atmospheric Radiocarbon for the Period 1950–2010. *Radiocarbon* **2013**, *55*, 2059–2072. [CrossRef]
53. Blaauw, M. Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quat. Geochronol.* **2010**, *5*, 512–518. [CrossRef]
54. Mustaphi, C.J.C.; Davis, E.L.; Perreault, J.T.; Pisaric, M.F.J. Spatial variability of recent macroscopic charcoal deposition in a small montane lake and implications for reconstruction of watershed-scale fire regimes. *J. Paleolimnol.* **2015**, *54*, 71–86. [CrossRef]

55. Higuera, P.E.; Peters, M.E.; Brubaker, L.B.; Gavin, D. Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quat. Sci. Rev.* **2007**, *26*, 1790–1809. [CrossRef]
56. Remy, C.C.; Hély, C.; Blarquez, O.; Magnan, G.; Bergeron, Y.; Lavoie, M.; Ali, A.A. Different regional climatic drivers of Holocene large wildfires in boreal forests of northeastern America. *Environ. Res. Lett.* **2017**, *12*, 035005. [CrossRef]
57. Higuera, P.E.; Brubaker, L.B.; Anderson, P.M.; Brown, T.; Kennedy, A.T.; Hu, F.S. Frequent Fires in Ancient Shrub Tundra: Implications of Paleorecords for Arctic Environmental Change. *PLoS ONE* **2008**, *3*, e0001744. [CrossRef]
58. Ali, A.A.; Higuera, P.; Bergeron, Y.; Carcaillet, C. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. *Quat. Res.* **2009**, *72*, 462–468. [CrossRef]
59. Brossier, B.; Oris, F.; Finsinger, W.; Asselin, H.; Bergeron, Y.; Ali, A. Using tree-ring records to calibrate peak detection in fire reconstructions based on sedimentary charcoal records. *Holocene* **2014**, *24*, 635–645. [CrossRef]
60. Higuera, P.E.; Brubaker, L.B.; Anderson, P.M.; Hu, F.S.; Brown, T. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecol. Monogr.* **2009**, *79*, 201–219. [CrossRef]
61. R Core Team—European Environment Agency. 2020. Available online: https://www.eea.europa.eu/data-and-maps/indicators/oxygen-consuming-substances-in-rivers/r-development-core-team-2006 (accessed on 2 May 2021).
62. Binney, H. *Vegetation of Eurasia from the Last Glacial Maximum to the Present: The Pollen Data*; University of Southampton: Southampton, UK, 2017. [CrossRef]
63. Jackson, S.; Williams, J.W. Modern Analogs in Quaternary Paleoecology: Here Today, Gone yesterday, Gone Tomorrow? *Annu. Rev. Earth Planet. Sci.* **2004**, *32*, 495–537. [CrossRef]
64. Guiot, J. Methodology of the last climatic cycle reconstruction in France from pollen data. *Palaeogeogr. Palaeoclim. Palaeoecol.* **1990**, *80*, 49–69. [CrossRef]
65. Prokopenko, A.A.; Khursevich, G.K.; Bezrukova, E.V.; Kuzmin, M.I.; Boes, X.; Williams, D.F.; Fedenya, S.A.; Kulagina, N.V.; Letunova, P.P.; Abzaeva, A.A. Paleoenvironmental proxy records from Lake Hovsgol, Mongolia, and a synthesis of Holocene climate change in the Lake Baikal watershed. *Quat. Res.* **2007**, *68*, 2–17. [CrossRef]
66. Bush, A.B. CO2/H2O and orbitally driven climate variability over central Asia through the Holocene. *Quat. Int.* **2005**, *136*, 15–23. [CrossRef]
67. Higuera, P.E.; Sprugel, D.G.; Brubaker, L.B. Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. *Holocene* **2005**, *15*, 238–251. [CrossRef]
68. Soja, A.J.; Tchebakova, N.M.; French, N.H.; Flannigan, M.; Shugart, H.; Stocks, B.J.; Sukhinin, A.I.; Parfenova, E.; Chapin, F.S.; Stackhouse, P.W. Climate-induced boreal forest change: Predictions versus current observations. *Glob. Planet. Chang.* **2007**, *56*, 274–296. [CrossRef]
69. Gauthier, S.; Vaillancourt, M.-A. *Aménagement Écosystémique en Forêt Boréale*; Presses de l'Université du Québec: Québec, QC, Canada, 2008.
70. Zoltai, S.C.; Morrissey, L.; Livingston, G.P.; Groot, W.J. Effects of fires on carbon cycling in North American boreal peatlands. *Environ. Rev.* **1998**, *6*, 13–24. [CrossRef]
71. Ivanov, A.Y. Unique phenomena in Lake Baikal, Russia, imaged and studied with SAR and multi-sensor images. *Int. J. Remote Sens.* **2012**, *33*, 7579–7598. [CrossRef]
72. Clark, D.; Kneeshaw, D.; Burton, P.; Antos, J. Coarse woody debris in sub-boreal spruce forests of west-central British Columbia. *Can. J. For. Res.* **1998**, *28*, 284–290. [CrossRef]
73. Harper, K.A.; Bergeron, Y.; Drapeau, P.; Gauthier, S.; De Grandpré, L. Structural development following fire in black spruce boreal forest. *For. Ecol. Manag.* **2005**, *206*, 293–306. [CrossRef]
74. Greene, D.F.; Noël, J.; Bergeron, Y.; Rousseau, M.; Gauthier, S. Recruitment of Picea mariana, Pinus banksiana, and Populus tremuloides across a burn severity gradient following wildfire in the southern boreal forest of Quebec. *Can. J. For. Res.* **2004**, *34*, 1845–1857. [CrossRef]
75. Greene, D.; Splawinski, T.; Gauthier, S.; Bergeron, Y. Seed abscission schedules and the timing of post-fire salvage of Picea mariana and Pinus banksiana. *For. Ecol. Manag.* **2013**, *303*, 20–24. [CrossRef]
76. Keeley, J.E.; Pausas, J.; Rundel, P.W.; Bond, W.; Bradstock, R.A. Fire as an evolutionary pressure shaping plant traits. *Trends Plant Sci.* **2011**, *16*, 406–411. [CrossRef] [PubMed]
77. Andreĭ Alekseevich, V.; Wright, H.E.; Barnosky, C.W. *Late Quaternary Environments of the Soviet Union*; University of Minnesota Press: Minneapolis, MN, USA, 1984.
78. Blyakharchuk, T. Western Siberia, a review of Holocene climatic changes. *J. Sib. Fed. Univ. Biol.* **2009**, *2*, 4–12.
79. Korovin, G.N. Analysis of the Distribution of Forest Fires in Russia. In *Biosafety of Forest Transgenic Trees*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 1996; pp. 112–128.
80. Kobe, F.; Bezrukova, E.V.; Leipe, C.; Shchetnikov, A.A.; Goslar, T.; Wagner, M.; Kostrova, S.S.; Tarasov, P.E. Holocene vegetation and climate history in Baikal Siberia reconstructed from pollen records and its implications for archaeology. *Archaeol. Res. Asia* **2020**, *23*, 100209. [CrossRef]
81. Weber, M.; Scholz, D.; Schröder-Ritzrau, A.; Deininger, M.; Spötl, C.; Lugli, F.; Mertz-Kraus, R.; Jochum, K.P.; Fohlmeister, J.; Stumpf, C.F.; et al. Evidence of warm and humid interstadials in central Europe during early MIS 3 revealed by a multi-proxy speleothem record. *Quat. Sci. Rev.* **2018**, *200*, 276–286. [CrossRef]

82. Tarasov, P.; Bezrukova, E.; Karabanov, E.; Nakagawa, T.; Wagner, M.; Kulagina, N.; Letunova, P.; Abzaeva, A.; Granoszewski, W.; Riedel, F. Vegetation and climate dynamics during the Holocene and Eemian interglacials derived from Lake Baikal pollen records. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2007**, *252*, 440–457. [CrossRef]
83. Power, M.J.; Marlon, J.; Ortiz, N.; Bartlein, P.J.; Harrison, S.P.; Mayle, F.E.; Ballouche, A.; Bradshaw, R.H.W.; Carcaillet, C.; Cordova, C.; et al. Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. *Clim. Dyn.* **2008**, *30*, 887–907. [CrossRef]
84. Marlon, J.R.; Bartlein, P.; Daniau, A.-L.; Harrison, S.; Maezumi, S.; Power, M.J.; Tinner, W.; Vanniére, B. Global biomass burning: A synthesis and review of Holocene paleofire records and their controls. *Quat. Sci. Rev.* **2013**, *65*, 5–25. [CrossRef]
85. Dietze, E.; Mangelsdorf, K.; Andreev, A.; Karger, C.; Hopmans, E.; Schreuder, L.; Sachse, D.; Rach, O.; Nowaczyk, N.; Herzschuh, U. Anhydrosugars in Sediments pf Lake El'gygytgyn—Fire Regime Reconstructions of Ne Siberia During the Last Two Interglacials. In Proceedings of the 29th International Meeting on Organic Geochemistry, Gothenburg, Sweden, 1–6 September 2019.
86. Walker, X.J.; Baltzer, J.L.; Cumming, S.G.; Day, N.; Ebert, C.; Goetz, S.; Johnstone, J.; Potter, S.; Rogers, B.M.; Schuur, E.A.G.; et al. Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nat. Cell Biol.* **2019**, *572*, 520–523. [CrossRef] [PubMed]