Author response to RC2 by Angelica Feurdean

Dear Angelica Feurdean,

we are happy to receive your review of our manuscript and wish to thank you for your time and effort. We welcome the feedback you provided, expanding especially our interpretation of the pollen record in important ways. Please find below your original comments in black, and our author response in green:

The manuscript by Glückler et al., is timely executed study of past wildfire dynamics and associated drivers in Eastern Siberia. The manuscript is based on high quality data and statistical analysis, is clearly written and well referenced. The study concluded that, at this temporal scale, it is climate and human impact, rather than vegetation driving the past millennial to centennial changes in wildfire activity.

Thank you for this assessment!

One of my main concern is the approach to the vegetation. The study is conducted in Larix (larch) dominated forests of Siberia. Larix is notoriously underestimated in the pollen records, and this should make it difficult to accurately reconstruct its past dynamics. Plant macrofossil analysis, mostly abundant needles (deciduous conifer tree), could help constrain its past dynamics, however, this is appropriately done in small basins or cores close to the lake margin, which is not the case of this site. The pollen record presented in this study neither show that Larix was an abundant taxon nor that its proportion have changed in the past, which likely highlights the problems above. I suggest adding a few lines acknowledging the problem of reconstructed past Larix dynamics based on pollen.

Thank you for raising this important issue. The Lake Khamra sediments did not provide many plant macrofossils and, as you mention, is not a perfect archive for the purpose of such analysis (also considering the suggested likelihood of prolonged permafrost-related terrestrial residence of macrofossils, as discussed for the chronology in the manuscript). We will update the manuscript to clearly acknowledgement the issue of *Larix* pollen dynamics in the discussion part for vegetation by adding the following starting in L455: "Furthermore, reconstructions of *Larix* dynamics based on fossil pollen are affected by a limited pollen dispersal distance of larch trees, as well as poor preservation of their pollen grains (Müller et al., 2010). This can lead to an underestimation of *Larix* in fossil pollen records (Edwards et al., 2000) and thus complicate the evaluation of larch tree dynamics. A comparably low share of fossil *Larix* pollen at Lake Khamra, despite *Larix gmelinii* being a predominant tree taxon within the study area, may well reflect that issue. This indicates how future studies, aiming at specifically comparing past fire regime changes with *Larix* population dynamics, may benefit from including plant macrofossil analysis, if possible (e.g. Birks, 2001; Stähli et al., 2006). Due to a lack of macrofossils in the Lake Khamra sediment core and their suggested prolonged terrestrial residence time, as implied by the chronology, this was not an option in the present study. These factors, together with a remaining ambiguity in morphotype classification, likely explain the rather weak correlations of pollen and charcoal records."

The other concerns on the chronology and charcoal peak analysis have been highlighted by the other reviewer (P. Higuera).

Please refer to our author response to review comment 1 to see our answers and improvements made in these regards.

Specific comments:

l. 63-63 Barhoumi et al.2019 study lies in European Russia not in Siberia, please correct

This will be corrected in the revised manuscript, by adding in L62/63: "[…] allowed the assessment of fire return intervals in boreal European Russia and western Siberian evergreen forests, revealing […]"

l.100 Note here that Larix gmelinii as one of the main tree taxa

This was probably meant to be related to L103 following; the sentence will be expanded as follows: "[…] forest consisting predominantly of *Larix gmelinii*, together with *Pinus sylvestris*, […]"

l.177 What do you mean by this? You broke the charr particles with a needle?

These preparatory needles were mainly used as a size reference. However, it turned out that they could also well be used to provide some "haptic" feedback when touching or pushing particles. This was helpful in some instances to differentiate between type B particles (those that have a brownish-black color instead of being uniformly black, but still solid pieces) or partially charred plant material (type Z), which will slightly bend when being touched by the needle. Breaking charcoal particles would render the re-counting of samples useless and was therefore avoided. To clarify this, we added to the sentence beginning in L175: "These needles also allowed the careful and non-destructive evaluation of the flexibility of particles of unknown origin, since […]".

Palynological analysis l. 191-194, Ok, but it would be useful to also state the resolution of pollen samples

We agree and will therefore move the statement about the resolution of charcoal samples, expanded with the timespan covered by the pollen samples specifically, to the results section in L280, where we think this information fits well: "Mean sampling resolution of the whole record is 7.1 ± 4.1 yrs (max: 27, min: 3), including the pollen samples, which on themselves cover on average 8.9 ± 3.8 yrs (max: 25, min: 4)."

l. 200 Which subsequent analysis? How were the % calculated?

The sentence starting in L199 will be expanded for clarification: "For subsequent statistical analyses, relative frequencies of individual pollen taxa were calculated from the sum of terrestrial pollen. Spore, algae and non-pollen palynomorph percentages are based on the sum of pollen plus either spores, algae or non-pollen palynomorphs, respectively (Andreev et al., 2020)."

l. 240 Please state what exactly was desired with the correlation between charcoal and pollen (not vegetation), and which pollen types were chosen and why. I got the feeling that the results from pollen record are minimized.

We will clarify the reason for the correlation test by changing the sentence beginning in L241 as follows: "Assuming that the various charcoal morphotypes were formed by different types of vegetation burning, we would expect an increase of a specific morphotype to coincide with changes in the distribution of some plant types in the vegetation composition, also represented by the pollen spectra. To explore this hypothesis, we applied a correlation test using Kendall's τ (package "psych"; Revelle, 2020) to clr-transformed relative distributions of pollen groups that were expected to be impacted by wildfires (pollen sums of arboreal, non-arboreal, deciduous and evergreen taxa, respectively) and charcoal classes following Dietze et al. (2020)." By stating the reason behind the correlations more clearly, the following discussion of the results is emphasized.

L.320 What was the propose on running CHAR on separate grain size and morphotypes? This is not stated in the methods.

We totally agree and will update the methods section to feature the following sentence in L238: "This was done in order to assess in detail their individual contribution to the sum of all particles, the way they capture a fire signal to see if different charcoal groups represent different types of fires, potential relationships between charcoal particle size and source area, and whether certain charcoal types represent varying fuel types over time."

l.325 Is there a difference between angular S and B morphotypes?

They possess the same overall features (angular shape, showing a charred surface structure), but in contrast to the jet-black type S particles, those of type B show brownish-black colors as well. This is based on the classification scheme by Enache and Cumming (2007). To clarify this difference, the sentence starting in L324 will be expanded as follows: "The most prevalent morphotypes present in the sediment are […], S (angular/black, 20.6%), and B (angular/brownish-black, 7.2%), with all others […]".

l.334 Do you mean similar pattern for all charcoal morphotypes?

If this relates to the sentence in L330, then yes! We will clarify this part as follows: "The three charcoal morphotype groups show a similar temporal pattern for their background and peak component distributions […]. However, when assessed individually, large particles have a generally lower variability than the other size classes, whereas the variability of irregular morphotypes is higher than that of elongated or angular particles (see Supplement)."

3.3 Vegetation history. I suggest adding the pollen diagram into the main paper. Would it make sense / increase visibility, to use continuous lines i.e, curves instead of bars to show trends in the pollen record? The past trends in vegetation are described in just two lines 353-355, an expansion of this is needed. In the pollen diagram (A1) there are two zones and at minimum the composition /differences between the 2 should be highlighted.

Thank you for your recommendation! We agree that added lines improve visibility of changes through time, while also keeping the bars gives clear indication of the position of samples involved. Please find the updated pollen diagram (Fig. 1) below, which we also expanded with an age axis and will now include in the results section directly.

To expand the description of past vegetation and the pollen zones, we will re-phrase the paragraph starting in L347 as follows: "The pollen and NPP record, covering the whole sediment core and reaching back c. 2350 yrs, generally indicates a relatively stable vegetation composition (Fig. 5). The dominant arboreal pollen (AP) types comprise most of the pollen spectra (average ratio of AP:NAP = 8.3:1) and include the trees and shrubs recorded around the lake. In descending order, regarding their share of the pollen sum, these are *Pinus*, *Betula*, *Picea*, *Abies*, *Alnus*, and *Larix*, with smaller amounts of *Salix*, *Juniperus*, and *Populus*. Non-arboreal pollen (NAP) types are predominantly represented by Cyperaceae, followed by less abundant Poaceae, Ericales, and *Artemisia*. Despite similar general palynomorph distributions, pollen assemblages are separated into two subzones, with the upper subzone (Ib) seeing intervals of increased variability in the shares of some tree pollen and Cyperaceaea (around 10 and 120 cm depth, corresponding to c. 1950 and 700 CE, respectively). The lower subzone (Ia) demonstrates generally lower shares of *Abies* and Cyperaceae pollen."

l. 347-355 I am confused by this statement, why is now Larix listed last? Additionally, the tree pollen composition may reflect that of the surrounding forest, but not the proportion. For ex Larix is one of the dominant taxa in the forest presently (according to the introduction and study area), however it was only found with scarred pollen grains.

We agree that the sentence beginning in L348 can be confusing as to whether is relates to modern vegetation or the pollen record. To clarify this order, we will add: "In descending order, regarding their share of the pollen sum, these are […]". By clearly stating that this is the list of shares in the pollen spectrum in descending order, the issue of underestimated *Larix* pollen is also emphasized, as it will be discussed shortly thereafter based on your previous comments.

l. 393 Barhoumi et al.2019 not in west Siberia

This will be corrected in the updated manuscript by adding in L392: "[…] lies within the range of the few comparable studies in boreal European Russia or western Siberia."

l. 405 Agree but this needs to be stated earlier in the methods and results.

To state the relationship of particle size and source area earlier, we will move this information to L322 in the results section: "When assessed individually, more fire episodes are identified for smaller particles than for larger particles (Table 2). This is expected, as smaller particles tend to have a larger source area, potentially incorporating more fire events into the signal (Conedera et al., 2009)." This will also be mentioned in the methods section (2.4), where we now improved the wording on our reasons for applying the statistics to individual charcoal classes as noted above.

l. 414 A few hundred meters is really little.

We agree that a charcoal source area of few hundred meters seems very small, however, there is some empirical evidence to include such a small area as a lower limit. For example, Ohlson and Treyterud (2000) used a grid of charcoal traps to capture particles from a fire of known location, and report a very high spatial resolution in the meter range for locally deposited large (> 500 µm) particles. Since we know from satellite imagery that fires burned directly at the lake's shore in 2006/7 (see Fig. 1b in the manuscript), we would therefore use this as a lower boundary of our source area. To clarify that this is considered to be a lower limit, we will re-phrase this part in the revised version of the discussion: "We therefore assume a charcoal source area between few hundred metres directly around the lake for low-intensity fires (Conedera et al., 2009) and increasing distance of up to several kilometres for more intense fires producing stronger convection, resulting in a total source area estimate of up to c. 100 km².”

l. 419 How then?

If this is related to the way we expect charcoal particles reaching the lake, we suggest that it is mainly via primary input through the air. We will include this important piece of information as follows: "This might indicate that morphotype distribution within the record is not controlled by potential filtering effects of secondary charcoal transport, but rather by the type of biomass burning. This is also implied by the predominantly primary charcoal input through the air due to the densely vegetated surrounding slopes, and mirrors the stable vegetation composition seen in the pollen record."

l. 425. I am a bit confused here. To which letter /type do the elongated type belong? I believe that burning graminoids would produce elongated charr particles also in Siberia, judging from other studies on the L:W ratio. However, there are others fuel types that have elongated morphologies.

We agree that the possibility of elongated charcoal from graminoids exits also in boreal Siberia, depending on the local vegetation. To clarify, we will update this part starting in L423: "Pereboom et al. (2020) found elongated charcoal particles after experimentally burning tundra graminoids, potentially hinting at the origin of the many elongated type F particles at Lake Khamra. However,

these type F particles quite closely match the appearance of charred *Picea* needles reported by Mustaphi and Pisaric (2014)."

4.2.1 Vegetation l. 435. Apart of the problem of large site and footprint on pollen record, please think whether biases with Larix pollen could have also 'falsely' contributed to this monotony. Are there other pollen diagrams in the region to document how vegetation composition varied regionally?

We agree that this is an important factor here. We will include the issue of underestimated *Larix* pollen in the revised discussion of the vegetation history, as laid out above. To the best of our knowledge the closest pollen record is located c. 600 km north-east of Lake Khamra, according to entries of the Neotoma database (www.neotomadb.org, accessed Jan 11th 2021), and therefore already within the predominantly deciduous forest as opposed to the more mixed evergreen/deciduous forest at our site. While this lack of well-comparable data is unfortunate, we hope that this study is able to contribute some first insight for future research to build upon.

l. 448 increased proportion of...

The sentence starting in L447 will be updated: "An increased proportion of evergreen trees might enable more intense crown fires."

l. 450 do you imply that pollen is more problematic than charcoal?

No, we rather wanted to put emphasis on the differences between the two proxies which might hamper their direct comparison as a way to test our hypotheses. We will clarify this by changing the sentence as follows: "In addition to differences in proxy source area and taphonomy between macroscopic charcoal and pollen grains, a variety of factors likely obscures traces of potential fire impacts: […]"

l.478 which? Please state the age range?

We will clarify the age we are referring to in the sentence starting in L476 by adding: "The following onset of increased fire frequency in phase 4 (c. 1750 CE onwards) is concurrent with a gradual increase in Arctic temperatures during the last two centuries […]"

l. 480 you may want to look at the moisture record https://doi.org/10.1016/j.quascirev.2019.105948

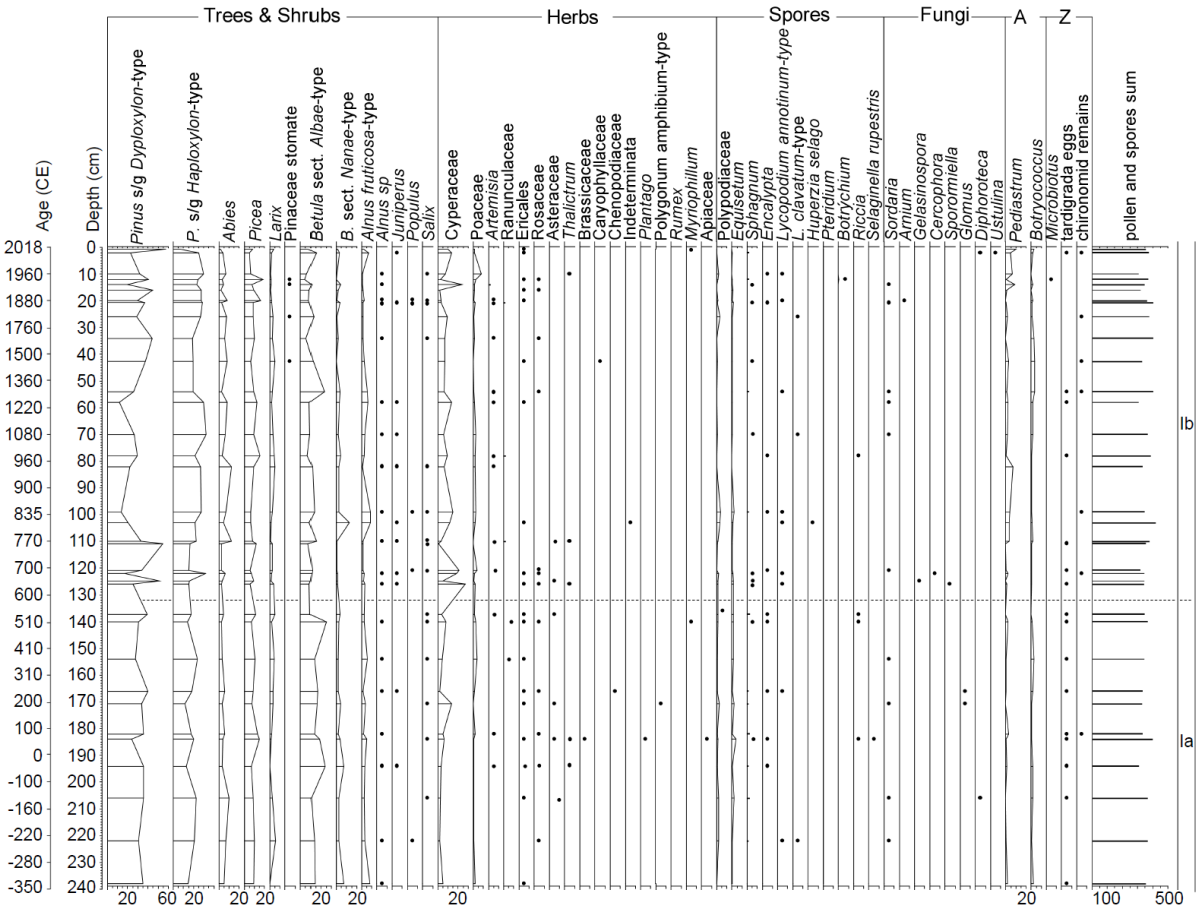
Thank you for drawing our attention to this study! Seeing that climatic periods such as the MCA and LIA could be identified provides further evidence for their manifestation in Siberia, and the reconstruction of wet and dry periods is a valuable addition. We will include this study in the discussion of the climatic impact (4.2.2) in the revised manuscript.

l. 550 given the large lake size, could charcoal input over time have been affected by different locations of fire in the catchment and the subsequent charcoal delivery into the lake?

Yes, unlike fire scar records from tree rings, we capture fires from a larger region. Fires closer to the lake likely lead to larger amounts of charcoal being deposited in its sediment, thus suspected to be responsible for outstanding peaks within the charcoal record. By retrieving the sediment core from the deepest point of the lake, which is suspected to be the terminal destination of sediment surface transportation pathways, we suspect to capture the highest possible amount of deposited charcoal. As discussed before, we expect the amount of secondary input via surface runoff to be limited by dense vegetation and gentle slopes within the catchment area. However, together with a revised discussion of lake size effects we will also acknowledge that in combination with a surface fire regime, some fires may be missed in our record: "Even though some extreme fires may well surpass this estimate and, occasionally, small fires within might fail to contribute sufficient amounts of

charcoal, identified fire episodes in the charcoal record should still be biased towards fires closer to the lake, especially when they consist of predominantly large charcoal particles (Conedera et al., 2009; Whitlock and Larsen, 2001)."

Figure 1: Revised pollen percentage diagram. Pollen and non-pollen palynomorphs from sediment core EN18232-3 at Lake Khamra (dots represent pollen taxa <1%; A = algae; Z = invertebrate remains; horizontal dashed line = separation in subzones Ia and Ib).



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