

# Response To Reviewers

## Reviews & Syntheses: Arctic Fire Regimes and Emissions in the 21st Century

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Associate Editor Decision: Publish subject to minor revisions (review by editor)

### Associate Editor:

Thank you for your responses to the reviewers' comments, which are comprehensive and seem to address all the issues raised. Given that all the reviewers asked for a reorganisation of some parts of the manuscript, I would like to see the revised manuscript with these changes implemented so that I can see that the corrections address the concerns and make the story clearer.

**Response.** - We thank Associate Editor, Dr. Sandy Harrison, for this careful consideration of the reorganization of the revised manuscript. We too share the same desire to present a clear and improved manuscript.

We have made one additional change to the introduction of the manuscript to better link the policy questions and the sections of the paper. The last few sentences of the last paragraph of the Introduction now reads:

“This review paper spawned from policy questions (Suppl. Table 2) that the Expert Group on Short-Lived Climate Forcers (SLCF EG) of AMAP, a Working Group of the Arctic Council, was asked to answer for its 2021 Assessment Impacts of short-lived climate forcers on Arctic climate, air quality, and human health (AMAP, 2021). Our specific objectives are to:

- (1) identify and review the key drivers of the Arctic fires today and in the future to characterise an emerging Arctic fire regime, with potential changes (paper sections 2-3 and policy question 1 in Suppl. Table 2);
- (2) characterise fire emissions from ground- and satellite-based data sources in the Arctic, boreal, and temperate regions that impact the Arctic (paper section 4 and policy questions 1,3-5 in Suppl. Table 2);
- (3) contextualise emissions from the Arctic fire regime with other sectoral sources for the Pan-Arctic (paper section 5 and policy questions 5-6 in Suppl. Table 2);
- (4) identify key challenges and research questions that could improve understanding, monitoring, and management of Arctic fires in the 21st century (paper sections 6-8 and policy questions 2 and 6 in Suppl. Table 2).”

All other suggested edits for reorganization by the three reviewers have been made.

Please find the submitted revised manuscript, a marked-up manuscript, and supplemental materials.

The original round of reviews follows below.

### First round of reviews

#### **Reviewer 1:**

##### General Comments

On the whole, this is a well-written review. It is centred around six policy-driven questions, which makes it relevant and useful, and it is usefully divided into several sections which makes it easy to reference and to digest. The main conclusions stated in the abstract are mostly clear, are relevant, and expand current knowledge, especially the new analysis showing how emissions have increased in Arctic regions since 2010. I appreciate the numbering which is intended to make things easier to follow, however, taken together, it is a little confusing to have 6 policy questions, 4 key objectives, 9 paper sections, and 6 conclusions, all of which are slightly different. I wonder if these can be made more consistent, or linked together more. There are also some sections that could benefit from some re-ordering, as outlined below.

The approach for the review and the analysis are valid, and the authors compare a number of datasets to draw the conclusions of their analysis of burned area and emissions. The presentation of the manuscript and figures is good, although some suggestions for improvement are shown below. Overall I believe the paper makes a good contribution to scientific progress.

**Response.** - We thank Reviewer 1 for these constructive comments and specific revisions. To address the overall concern that the outline of the review paper may be confusing, we have revised the introduction of the manuscript to better link the objectives and the paper sections, so that now we identify which sections each of the objectives are being discussed. We moved the policy questions that drove this review to the Supplemental Materials, which still keeps them available to the readers.

##### Specific comments

1. Line 36 – the third conclusion is vague: “... transitions... may increase and decrease open biomass burning”. Increase and decrease in different biomes? At different times Please clarify.

**Done.** - This has been clarified and revised to state: “To some extent, shifting agricultural land use, forest-steppe to steppe, tundra-to-taiga, and coniferous-to-deciduous forest transitions in a warmer climate may increase and decrease open biomass burning, depending on land use in addition to climate-driven biome shifts.

2. Lines 50 – 58. Nice start to the introduction, it’s useful to have the aim of the paper stated up front in the introduction in a concise way. Line 52 states what other published reviews have done, but doesn’t go on to say how this review differs or what new information is offered. It would be useful to include a sentence on this here.

**Done.** - The reviewer makes an excellent point and we have revised to state: “In this paper, we review the current understanding of the changing Arctic fire regime, and its impacts on fires emissions, providing a foundation for future systemic Pan-Arctic fire and fire emissions analyses and coordination in the context of the Arctic Council Members, Permanent Participants, Observers, and Working Groups. This review paper is also the first to link emissions with a changing fire regime for the Pan-Arctic.”

3. Line 68 – “both earlier and later”, presumably this means both earlier start and later finish? Please clarify.

**Done.** - This has been revised to “including earlier springtime fires and fires later in fall”.

4. Line 114 – I think the definition of open biomass burning would fit better in section 1 where the other definitions are, e.g. in paragraph 3.

**Done.** - This sentence defining open biomass burning has been moved to start paragraph 3. We thank the reviewer for having such a keen eye for detail.

5. Line 181 – is this a conclusion of this study based on extrapolation from related literature, or is this part of the findings from Tchebakova et al 2009? Please clarify with a relevant reference.

**Done.** - Line 181 was linked to the Tchebakova et al. (2009) findings and so we have connected these two sentences to make this more explicit: “Topography plays a crucial role in determining shifting habitats, where drying will dominate on tilted surfaces and bogging will dominate on flat terrain (Tchebakova et al., 2009), such that as the Siberian Arctic tundra is dominated by relatively flat terrain, bogging is predicted to prevail.”

6. Lines 175-209 – Figure 1 is useful, but the description of it could be clearer. Some of the conclusions in the text are not linked with increased or decreased fire, and it would make this paragraph clearer to explicitly state the direction of change, for example with the change to light-needled Larix in conclusion 5 it is not totally clear what the impact on fire risk would be and why. Can you also add an explanation for why boreal to deciduous would decrease fire risk. Is transition to forest-steppe just a result of increases in fire regimes (line 191) or also a cause of change in fire risk? There is some explanation of this in section 7.1 but it can be briefly referred to here.

**Done.** - Conclusion 5 has been updated to indicate why light-needled Larix would maintain a high fire risk: “Permafrost is not predicted to thaw deep enough to sustain dark-needled taiga (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*), nonetheless light-needled coniferous Larix is predicted to continue to dominate in eastern Siberia, maintaining a higher fire risk according to the Russian fire hazard rankings (Melekhov, 1980). The Russian fire hazard ranking systems shows a decrease in fire risk from light needle conifers (Scots pine, larch) to deciduous broad-leaf tree species (birch, aspen, willow) that exist between the temperate and boreal zones, as well as along river valleys. Fire risk is also lower in dark-leaf conifers (Melekhov, 1980). Fire return intervals (FRI) are consistent with Melekhov, with a mean FRI of 36 years (range 17-133) in light coniferous forest compared with a mean FRI of 196 years (range 75-725) in dark-coniferous forest (Soja et al., 2006; Shvidenko and Nilsson, 2000; Furyaev, 1996). Larix are a fire-tolerant species, and dark-coniferous species are shade-tolerant secondary-succession cohort (Shugart et al., 1992).”

We have also revised conclusion 6 to strengthen conclusion 5. It now reads “Sixth, forest-steppe and steppe is predicted to dominate over half of Siberia, largely forced by climate and increases in fire regimes (Tchebakova et al., 2009). The forest-steppe that exists at the southernmost extent of the Siberian boreal forest is transitioning to steppe due to: increases in extreme fires that burn the soil organic matter to mineral soil, and repeated fires and high temperatures that kill regenerating seedlings.”

New citations have been added:

Melekhov, I.S.: Forest Science. Moscow (in Russian), 1980.

Soja, A.J., Shugart, H.H., Sukhinin, A., Conard, S., and Stackhouse Jr., P.W.: Satellite-Derived Mean Fire Return Intervals As Indicators Of Change In Siberia (1995–2002), *Mitig Adapt Strat Glob Change* 11, 75–96, <https://doi.org/10.1007/s11027-006-1009-3>, 2006.

Shvidenko, A.Z., and Nilsson, S.: Extent, distribution, and ecological role of fire in Russian forests, in: *Fire, climate change, and carbon cycling in the boreal forest*, edited by Kasischke E.S., and Stocks B.J., Springer, New York, NY, 132-150, [https://doi.org/10.1007/978-0-387-21629-4\\_16](https://doi.org/10.1007/978-0-387-21629-4_16), 2000.

Furyaev, V.V.: Pyrological regimes and dynamics of the southern taiga forests in Siberia, in: *Fire in ecosystems of boreal Eurasia*, edited by: Goldammer J.G., and Furyaev V.V., Springer, Dordrecht, Netherlands, 168-185, [https://doi.org/10.1007/978-94-015-8737-2\\_12](https://doi.org/10.1007/978-94-015-8737-2_12), 1996.

Shugart, H.H., Leemans, R. and Bonan, G.B.: *A Systems Analysis of the Global Boreal Forest*, Cambridge University Press, New York, USA, 1-565, <https://doi.org/10.1017/CBO9780511565489.022>, 1992.

We also added an explanation for why transition from boreal forests to deciduous forests would decrease fire risk. Line 181-183 now read: “Second, anticipated transitions of boreal forest to deciduous forest stands would decrease fire risk in eastern Canada and small regions of interior Alaska (Terrier et al., 2013; Foster et al., 2019; Mekonnen et al., 2019), as deciduous species are less flammable than coniferous species (Päätaalo, 1998; Krawchuck et al., 2006).” The two citations added are:

Päätaalo, M.-L.: Factors influencing occurrence and impacts of fires in northern European forests, *Silva Fenn.*, 32: 185, <https://doi.org/10.14214/sf.695>, 1998.

Krawchuk, M. A., Cumming, S.G., Flannigan, M.D., and Wein, R.W.: Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest, *Ecology*, 87, 458, <https://doi.org/10.1890/05-1021>, 2006.

7. Lines 195-209 – I think this would fit better as a separate paragraph. The 8 points in the previous lines clearly relate to Fig 1, but these additional lines are broader. It would also help to break down this very long paragraph.

**Done.** - This paragraph has been made into two paragraphs, starting at this section after the eight points referring to Fig. 1.

8. Section 3 – paragraphs 1 and 3 are both about lengthening fire seasons, whereas paragraph 2 is about vegetation shifts. I would swap paragraphs 2 and 3 around for a more logical order.

**Done.** - These paragraphs have been swapped for a more logical order.

9. Lines 244-246 – This relate to human management rather than climate change, not sure it fits in this section.

**Done.** - This line has been moved to the end of Section 2 and now states “Further, suppression of wildfire in Canadian boreal communities has increased their likelihood of flammability, allowing fuels to build up in and near populated places (Parisien et al., 2020), calling into question what other wildland-urban interfaces in the Arctic region may experience increased fire risk and fires due to long term aggressive fire suppression.”

10. Line 342 – noting the dotted line as stated in the text, it looks like FINN shows a negative trend, not positive.

**Done.** - We thank the reviewer for catching this and we have revised the text to read “This trend is pronounced in GFED and GFAS, with these two models showing a positive trend (note the dotted line in Fig. 2), and FINN showing a slight decrease in later years even as total MODIS active fire detections increased (bottom panels in Fig. 2).”

11. Line 367 – is there a reference for the statement that Greenland is a novel fire regime in the Arctic? Table 2 only shows 1 year of data so we cannot tell if it is unusual from this.

**Done.** - Greenland has experienced two wildland fires, in 2017 and 2019. 2019 is noted in Table 2. We have added a citation and this sentence now reads: “Greenland is a novel fire regime in the Arctic, with two relatively substantial wildfires in 2017 (Evangelou et al., 2019) and 2019 (Table 2), that accounted for more burned area and emissions than Norway or Finland.

12. Fig 2 – GFEDv4s data are now available to 2020. Can Fig 2 be extended to 2020 to match the later results?

**Not done.** - This review article has been performed to be fed in the AMAP short-lived climate forcers assessment, which had to be completed for review by Arctic Council member states by mid-2020. All the modeling, studies, and comparison with observations have been performed for this assessment are inclusive of 2018. Therefore, the time frame of this analysis was aligned accordingly, further extension of the long term emissions to 2020 is therefore out of the scope of this manuscript.

13. Fig 7 – It would be better to have the global results on the left to match figures 4-6, and the description in the text.

**Done.** - This figure has been changed to present the global results in the left column and the latitudinal ranges in the right column. A description in the caption and text has been updated.

#### Technical Corrections

14. Line 169 – Boike et al showed that

**Done.**

15. Line 402 – because it was produced

**Done.**

16. Line 537 – reword: “it is important to note that”, or “important to note is that”

**Done.**

17. Line 398 – reword: “explicitly considers environmental policies and assesses their impact”

**Done.**

#### Reviewer 2:

The manuscript by McCarty et al. presents a review of our current understanding on fire regimes in the Arctic and boreal regions, as well as how they are changing. The work has been motivated by policy questions, and therefore its content is of both science and policy relevance. The main foci of the review are a) the drivers of Arctic fires, b) the future of Arctic fires,

c) emissions from high-latitude fires, and c) the role of humans. In addition to reviewing existing literature, the authors also present new analysis on Arctic wildfire emissions that builds on the 2015 AMAP assessment of black carbon and ozone. I find the paper well-written and nicely structured, and its content a useful addition to the existing literature on Arctic wildfire and its future. I have no major reservations regarding the manuscript, and believe that it will be ready for publication following the minor refinements that I list below.

**Response.** - We thank Reviewer 2 for these constructive comments and have refined the manuscript as suggested.

#### SPECIFIC COMMENTS:

1. Page 2, Line 41: I suggest rephrasing to “and how severe future Arctic wildfire seasons can potentially be”.

**Done.** - This has been revised.

2. Page 3, Line 68: Suggested rephrasing: “(both starting earlier and ending later)”

**Done.** - This has been revised to “including earlier springtime fires and fires later in fall”.

3. Section 3, paragraph 3: It is worth also highlighting that the Arctic has been identified as a hot-spot region for the interannual variability of key atmospheric constituents, with wildfire being the major driver of this variability (Fisher et al., 2010; Monks et al., 2012; Voulgarakis et al., 2015).

**Done.** - We have started paragraph 3 of section 3 with the following sentence: Previous work has identified the Arctic as a regional “hot spot” for interannual variability of key atmospheric constituents, with wildfire being the major driver of this variability (Fisher et al., 2010; Monks et al., 2012; Voulgarakis et al., 2015).

4. These three citations have also been added to the manuscript’s References section.

Page 3, Line 90: Subscript 2 in CO<sub>2</sub>.

**Done.**

5. Page 4, Lines 114-115: Aren’t forest fires and peat fires different kinds of wildfires (and, therefore, wildland fires, which is the broader term)? Also, doesn’t the term ‘wildland fire’ include prescribed fires?

**Done.** - We have revised this sentence to make it more clear that this review quantifies fires in the Pan-Arctic across wild and human-dominated landscapes and natural and human-caused ignitions: “For this review paper, the definition of open biomass burning in the Arctic will include wildland fires (sometimes referred to as and encompassing of wildfires, forest fires, peat fires, as well as prescribed fires in natural areas) and fires in human-dominated landscapes (i.e., agricultural open burning, prescribed burning in agroforestry, timber, rangelands, etc.), with natural fires (lightning ignitions) and human-caused fires differentiated where possible.”

Based on feedback from other reviewers, we have moved this sentence to the third paragraph of the introduction section.

6. Page 4, Lines 117-118: Fuel condition as well as ignitions depend on climate too. Could rephrase to “Broadly speaking, wildfires are driven by climate and weather conditions influencing flammability, fuels and fuel conditions...”

**Done.** - We have revised this sentence to: “Broadly speaking, wildfires are driven by climate and weather conditions influencing flammability, fuels, and fuel conditions (Silva and Harrison, 2010; de Groot et al., 2013).”

7. Page 4, Line 119: Human-caused fires can also be accidental.

**Done.**- This line has been revised to add accidental.

8. Page 4, Line 120: Need a space before “Pollen-based”.

**Done.**

9. Page 4, Lines 125-127: This sentence is probably not needed, as it is stating something obvious, which is not true just for Arctic fires.

**Done.** - We have removed this sentence while keeping the definition of fire risk in Supplemental Table 1.

10. Page 5, Lines 129: Precipitation is also a determinant of fire weather. Also, what about fuel abundance?

**Done.** - This lines has been revised to: “Ignition from lightning strikes, fire weather (i.e., temperature, humidity, precipitation, and wind), and fuel abundance (build-up) and conditions (moisture) are the typical controlling processes for ‘natural’ fires, i.e. fires not caused directly by human activity.”

11. Page 5, Line 133: scenario 8.5 -> scenario RCP8.5

**Done.**

12. Fig. 1: Instead of “boreal forest” or “boreal”, maybe use “taiga”, to be consistent with other parts of the manuscript?

**Done.** - We thank the reviewer for a keen eye to detail. We have updated Fig.1 to state taiga in Siberia, where it is most commonly used, and maintained the use of boreal for North America and Fennoscandia. We have added a small revision to the figure caption to note this change and complexity of the usage of taiga versus boreal: “Note that taiga is used in northern forest zones completely contained in Russia while boreal is used for the rest of the Pan-Arctic northern forests.” .

13. Page 6, Line 185: Why “in turn”?

**Done.** - We have removed “in turn” as we do not mean to imply that the previous expansion of grassland ecosystems is related to increased lightning ignitions.

14. Page 7, Line 203: “predicted to expand by as much as 20 days globally” – under which scenario?

**Done.** - We have deleted this sentence here as it is repeated, with the designated scenarios, in lines 214-218: “By the end of the century, wildland fire risk is expected to increase, with length of fire seasons - measured in terms of daily severe fire weather occurrence - predicted to expand by as much as 20 days for high northern latitudes using the A1B (roughly corresponding to RCP6.0), A2 (~ RCP8.5), and B1 (~RCP4.5) scenarios (Flannigan et al., 2013).”

15. Page 9, Line 270: I suggest rephrasing to “and a decrease in its regeneration cycle”

**Done.** - This has been rephrased.

16. Page 10, Lines 298-299: I am not sure it will be clear to the reader after reading this paragraph why “Therefore... the springtime burning of northern grasslands, peatlands, and croplands - often human-caused - means these emissions are more likely to be transported to the Arctic than summertime forest fires”. Please clarify.

**Done.** - This has been clarified to “Therefore, while boreal forest fires emit more SLCFs than grasslands and cropland fires, the springtime burning of northern grasslands, peatlands, and croplands - often human-caused - means these emissions are more likely to be transported to the Arctic during favourable transport conditions in March, April, and May than summertime forest fires.” Please note that earlier in this paragraph, we explain this mechanism, and now are reinforcing this documented mechanism.

17. Page 11, Line 335: I would suggest “Note, however” rather than “Note also”.

**Done.** - This has been revised to “Note, however...”.

18. Page 11, Line 340: Certainly there is a sharper trend in >60N, but I would not say that the following statement is supported by the figure: “More fire is now taking place north of 60° N than in the temperate zone of 45° to 50° N”. Also, FINN does not show an increasing trend anywhere.

**Done.** - We have revised this statement to say: “Fire emissions are increasing more north of 60° N compared to the temperate zone of 45° to 50° N, where large amounts of human-caused burning and wildfires throughout North America, Europe, and Eurasia occur (Fig. 2).” As we are comparing emission estimates and not direct fire counts or burned area, focusing on the trend is a more appropriate finding.

Further, how the trend in FINN data is described has been revised. We have revised the text to read “This trend is pronounced in GFED and GFAS, with these two models showing a positive trend (note the dotted line in Fig. 2), and FINN showing a slight decrease in later years even as total MODIS active fire detections increased (bottom panels in Fig. 2).”

19. Page 11, Lines 344-346: 2008 appears both in highest and in lowest!

**Done.** - We thank the reviewer for catching that error. The lowest years should be 2007 and 2013, while 2008 was one of the highest. This sentence now reads: “The lowest annual average BC emission from the five global fire emissions models are 2007 and 2013, both with 0.27 Tg..”

20. Page 11, Line 352: Please subscript 4 in CH<sub>4</sub>.

**Done.** - Thank you for finding that error. It has been subscripted.

21. Page 12, Lines 366-367: “fires in temperate zones of the CONUS tend to emit double the emissions of boreal ecosystems” – would be useful to the readers to comment on why this happens.

**Done.** - It should be noted that while Canada and CONUS reported similar official statistics for burned area, fires in temperate zones of the CONUS tend to emit double the emissions of boreal ecosystems (Table 2) due to higher fuel loadings, emission factors, and combustion completeness (Suppl. Table 2).

22. Page 12, last paragraph of section: Focusing on BC deposition effects in Greenland is nice, but maybe this section requires some mention of findings from other regions regarding this mechanism? Otherwise the focus on Greenland seems a bit disproportional.

**Done.** - In this paragraph, we wanted to explore the new novel fire regime in the Arctic that Greenland represents. We have tried to emphasize that, as well as citing literature on BC deposition from North American fires to situate the Greenlandic sources of BC deposition.

23. Page 12, Lines 372: on deposition -> on BC deposition

**Done.** - This has been revised to state “on BC deposition”.

24. Page 12, Lines 386-387: “while the average instantaneous BOA (Bottom Of the Atmosphere) radiative forcing over Greenland at noon on 31 August 2017 (post-fire) was between 0.03 and 0.04 Wm<sup>-2</sup>, with locally occurring maxima up to 0.77 Wm<sup>-2</sup>” – does this refer to the atmospheric effect of aerosols (not the surface albedo effect)? Please clarify.

**Done.** - We have clarified the sentence by adding the following: “The maximum albedo change due to BC and BrC deposition from the Greenland fires was -0.007 at maximum, while the average instantaneous BOA (Bottom Of the Atmosphere) radiative forcing over Greenland at noon on 31 August 2017 (post-fire) was between 0.03 and 0.04 Wm<sup>-2</sup>, with locally occurring maxima up to 0.77 Wm<sup>-2</sup>. Here, the BOA included both the aerosol effects of BC and BrC in the atmosphere and deposited on the snow. The albedo effect (a decrease) was very low (0.007), practically unmeasurable.”

25. Section 5: There are some bits where GFAS emissions are referred to as “wildfire emissions”. Given that they also include e.g. agricultural fire emissions, I would suggest referring to them as “biomass burning emissions”.

**Partially done.** - The reviewer is correct that GFAS includes all types of fire emissions, not just wildfires. To make this more clear, we have revised Section 5 to describe the GFAS data and why it is referred to as wildfire emissions in this review. In particular, the GFAS data hosting site refers to emissions database as ‘wildfire and biomass burning’ emissions (<https://www.ecmwf.int/en/forecasts/dataset/global-fire-assimilation-system>). Further, CAMS and ECMWF branded science outreach refers to GFAS emissions as ‘wildfire emissions’ (see an example from Twitter here: [https://twitter.com/m\\_parrington/status/1402532919890096128?s=20](https://twitter.com/m_parrington/status/1402532919890096128?s=20)). The pertinent sentences in the first paragraph of Section 5 now reads: “The GFAS wildfire and biomass burning emissions include all open biomass burning activity, with no differentiation between human-caused ignitions and natural sources, like lightning, but attempt to remove spurious fire emissions from industrial, volcanic, and geothermal sources (Rémy et al., 2017). Data was clipped to Pan-Arctic extents at 50°N, 60°N, and 65°N. The GFAS emissions data, referred to as wildfire emissions in this review due to inability to differentiate fire types in the emissions data, has a spatial resolution of 0.1°, so it was aggregated to 0.5° for comparison with GAINS.”

26. Page 13, Line 411: Maybe “replicate” is too strong a word?

**Done.** - This has been revised so “replicate” is now “represent”.

27. Page 14, Line 427: phenomena -> phenomenon

**Done.** - This has been revised.

28. Page 14, Line 450: black -> black carbon

**Done.** - This has been revised.

29. Page 15, Lines 464-466: Suggest rephrasing to "...and fires from grasslands, forests, and agricultural lands in southern Siberia (Kukavskaya et al., 2016) and the Russian Far East (Hayasaka et al., 2020) are most common during the spring months of March, April, and May."

**Done.** - This has been revised.

30. Page 15, Line 491: Maybe instead of "in practical terms" the authors meant to write "in theory"?

**Done.** - This has been revised: "To date, the effectiveness of this campaign is unclear, but in theory it should reduce fire risk."

31. Page 16, Line 515: is important -> they are important

**Done.** - This has been revised to "fires are important".

32. Page 17, Lines 533-535: This sentence may need to be rephrased as it does not read very clearly.

**Done.** - This sentence has been revised to: "Future Arctic fire regimes will be influenced by shifting vegetation types (Tchebakova et al., 2009; Sizov et al., 2021), with both climate change and subsequent fire seasons, i.e., fire disturbance, determining the species and locations of future vegetation on Arctic and boreal landscapes (Foster et al., 2019)."

33. Page 18, Lines 569-571: There has also been an important body of recent laboratory work on how organic soils burn and how peat fires spread, e.g. Christensen et al. (2020), Santoso et al. (2021), Huang et al. (2019), Huang et al. (2017), Huang et al. (2015), Prat-Guitart (2016), Yuan et al. (2021), amongst others.

**Done.** - A sentence has been added to this section noting improved understanding of peat burn processes from laboratory experiments: "Recent laboratory work on fire mechanisms of organic soils and how peat fires spread improves the understanding of these processes (for example, Huang et al., 2017; Huang et al., 2015; Prat-Guitart, 2016; Huang et al., 2019; Christensen et al., 2020; Santoso et al., 2021; Yuan et al., 2021), though a need for Pan-Arctic field observations persists."

These references have been added to the paper:

Santoso, M.A., Cui, W., Amin, H.M., Christensen, E.G., Nugroho, Y.S. and Rein, G.: Laboratory study on the suppression of smouldering peat wildfires: effects of flow rate and wetting agent, *Int J Wildland Fire*, 30, 378-390, <https://doi.org/10.1071/WF20117>, 2021.

Christensen, E.G., Fernandez-Anez, N. and Rein, G.: Influence of soil conditions on the multidimensional spread of smouldering combustion in shallow layers, *Combust Flame*, 214, 361-370, <https://doi.org/10.1016/j.combustflame.2019.11.001>, 2020.

Huang, X. and Rein, G.: Upward-and-downward spread of smoldering peat fire, *Proc Combust Inst*, 37, 4025-4033, <https://doi.org/10.1016/j.proci.2018.05.125>, 2019.

Huang, X., and Rein, G.: Downward spread of smouldering peat fire: the role of moisture, density and oxygen supply. *Int J Wildland Fire.*, 26, 907-918, <https://doi.org/10.1071/WF16198>, 2017.

Huang, X., and Rein, G.: Computational study of critical moisture and depth of burn in peat fires, *Int J Wildland Fire*, 24, 798-808, <https://doi.org/10.1071/WF14178>, 2015.

Prat-Guitart, N., Rein, G., Hadden, R.M., Belcher, C.M. and Yearsley, J.M.: Propagation probability and spread rates of self-sustained smouldering fires under controlled moisture content and bulk density conditions, *Int J Wildland Fire*, 25, 456-465, <https://doi.org/10.1071/WF15103>, 2016.

Yuan, H., Richter, F., and Rein, G.: A multi-step reaction scheme to simulate self-heating ignition of coal: Effects of oxygen adsorption and smouldering combustion, *Proc Combust Inst*, 38, 4717-4725, <https://doi.org/10.1016/j.proci.2020.07.016>, 2021.

Loisel, J., Gallego-Sala, A.V., Amesbury, M.J., Magnan, G., Anshari, G., Beilman, D.W., Benavides, J.C., Blewett, J., Camill, P., Charman, D.J. and Chawchai, S.: Expert assessment of future vulnerability of the global peatland carbon sink, *Nat. Clim. Chang.*, 11, 70–77, <https://doi.org/10.1038/s41558-020-00944-0>, 2021.

Lasslop, G., Coppola, A.I., Voulgarakis, A., Yue, C. and Veraverbeke, S.: Influence of Fire on the Carbon Cycle and Climate, *Curr Clim Change Rep*, 5, 112–123, <https://doi.org/10.1007/s40641-019-00128-9>, 2019.

34. Page 18, Line 580: Here it is worth mentioning that peat fires and related feedbacks are not typically represented in current Earth system models, which limits predictability of the future. Suitable references could be Loisel et al. (2020) and Lasslop et al. (2019).

**Done.** - We have added a sentence in this paragraph: “Current Earth system models do not typically characterize well or include peat fires and related feedbacks (Lasslop et al., 2019; Loisel et al., 2020), further limiting our ability to predict future emissions from peatland burning.”

35. Page 20, Lines 687-688: What does “agreement was less than 10%” mean?

**Done.** - We have revised this sentence to clarify what 10% means: “Agreement of burned area within Siberian forests between official Russian statistics and four satellite-based burned area products was less than 10% (Kukavskaya et al., 2013).”

36. Page 22, Lines 700-702: it is worth mentioning whether there is any explanation of why GWIS may be giving such contrasting performance when compared to ground-truth information compared in neighbouring locations such as Norway and Sweden.

**Done.** - We have added to this section a possible explanation but also clarification: “The work of the SLCF EG was unable to determine exact reasons for why this mismatch occurs, though previous work has shown that satellite-based fire observations are more likely to align with official records as fire sizes increase (Fusco et al., 2019). Both Norway and Finland reported the lowest fire activity and burned area (Table 2). Future open biomass burning emissions will need improved satellite fire detection methodologies for the Arctic and boreal regions and shorter latency in ground reports and statistics from official agencies. Further, verifying and relating satellite detections of fires to ground-level verification will require a concerted effort and likely lead to a better understanding of how and why these two fire data sources do not presently align.”

37. Conclusions: It would be good to highlight how important it will be to improve our understanding of the future of Arctic wildfires and emissions, for being able to better predict the future of Earth system processes, both at high latitudes and globally.

**Done.** - This has been added to the first paragraph in Conclusions: “Improving our understanding of the future of Arctic fires and fire emissions will also allow us to better predict future Earth system processes - both at high latitudes and globally.”

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### Reviewer 3:

#### Overall comments

In this manuscript, McCarty et al. aim to compile a comprehensive review of what is known about the controls on Arctic and peri-Arctic vegetation fire regimes, how changing climate and anthropogenic factors might influence fire and vegetation in the future, and what additional knowledge would be especially helpful for improving scientific understanding of such. The material the authors have brought together is extensive and varied, and would be more than appropriate for publication in Biogeosciences as it could be a valuable resource for many in the scientific community.

However, much work remains to be done on this manuscript to bring it up to a quality level appropriate for publication. Many assertions need to be more fully explained and/or justified, organization within sections needs to be overhauled, and various sentences need to be reworked for clarity. As such, I recommend that this manuscript be resubmitted with major revisions.

We thank Reviewer 3 for the detailed comments. We have revised the manuscript, with a focus on improving organization and clarity. As suggested, more citations have been added.

#### Specific comments

1. L120-123: Information in this sentence doesn't support the conclusion of "highlighting the dependence of... fire on climate."

**Done.** - Thanks for catching this poor wording. This phrase has been revised to: "..., highlighting the connections between fire, climate and human-dominated landscapes."

2. L130-140: Should be in Sect. 3.

**Done.** - These sentences have been moved to section 3 and combined with the first paragraph of section 3.1.

3. L157: Explain to the reader how timber extraction and site preparation cause wildfires. What are people doing, exactly?

**Done.** - This sentence has been revised to clarify what has happened: "Timber extraction and site preparation, including operation of machinery and vehicles on ground covered with dry wood residues, currently cause large wildfires in the Arctic Council region, including the 2014 Västmanland fire in Sweden ignited by forestry vehicles during subsoiling activities (Lidskog et al., 2019), which actively burned for 18 days creating a burn scar of over 14,000 ha (Pimentel and Arheimer, 2021).

4. L159-160: "Likely"? How much agreement is there about expansion? And how much fire is associated with cropland there?

**Done.** - To clarify what we mean by likely, we have provided context for how much cropland burning is currently detected by satellite data and reported by farmers themselves in west Siberia. Further, the Parfenova manuscript is based on the capacity of the landscape to sustain humans (attractiveness, habitability) as climate changes and the ability of the landscape and climate to sustain agriculture. This land is currently not habitable. Besides the two citations provided that agree on expansion under climate change scenarios (King et al., 2018; Tchebakova et al., 2016), we have cited additional work from

Kickligher et al. (2014) that found food crops will expand by 15% into the North under “business as usual” climate change scenarios. We have also provided additional context that from an economic point of view, expansion of agriculture northward is more likely in Siberia than reclamation of abandoned lands in the highly degraded steppe (Prishchepov et al., 2020).

The revised passage now reads: “Northward agricultural expansion will likely increase human-caused open burning as wheat and maize production is expected to grow in previously permafrost areas of West Siberia (Parfenova et al., 2019). West Siberia is currently a minor source region of agricultural burning (Hall and Loboda, 2017), with many farmers insisting that fire is necessary to clear fields under present-day management and resource constraints despite bans on open agricultural burning (Theesfeld and Jelenik, 2017). This northward agricultural land could expand into the cold regions of the boreal zone (Kickligher et al., 2014; King et al., 2018), nearing the Arctic Circle for Central Siberia (Tchebakova et al., 2016). Of course, the northward agricultural expansion will also be dependent on local and/or in-situ conditions limiting its expansion, such as inferior soils, existing land uses not compatible with agricultural conversion, and topographic limitations (Ioffe and Nefedova, 2004; Dronin and Kirilenko, 2011; Tchebakova et al., 2011). However, given the degraded conditions of most abandoned agricultural land in the steppes of Siberia and high interest in northern agricultural development by neighbouring Asian countries, northward development of grains and other commodity crops is expected (Prishchepov et al., 2020).”

These references have been added to the paper:

Prishchepov, A.V., Schierhorn, F., Dronin, N., Ponkina, E.V., and Müller, D.: 800 Years of Agricultural Land-use Change in Asian (Eastern) Russia, in: KULUNDA: Climate Smart Agriculture, Innovations in Landscape Research, edited by: Frühauf, M., Guggenberger, G., Meinel, T., Theesfeld, I., Lentz, S., Springer, Cham, Switzerland, 67-87, [https://doi.org/10.1007/978-3-030-15927-6\\_6](https://doi.org/10.1007/978-3-030-15927-6_6), 2020.

Kickligher, D.W., Cai, Y., Zhuang, Q., Parfenova, E.I., Paltsev, S., Sokolov, A.P., Melillo, J.M., Reilly, J.M., Tchebakova, N.M., and Lu, X.: Potential influence of climate-induced vegetation shifts on future land use and associated land carbon fluxes in Northern Eurasia, *Environ. Res. Lett.*, 9, 035004, <https://doi.org/10.1088/1748-9326/9/3/035004>, 2014.

5. Organization of Sect. 3 needs to be rethought. “Natural fires” and “non-forest fires” are not mutually exclusive, and there are far too many topics within each of these. Consider sub-sections based instead on, e.g.: climate/weather, biogeography, insects, etc.

**Done.** - We have reorganized Sect. 3 with two headings of ‘3.1 Climate change and future fires’ and ‘3.2 Biogeography of future fires’.

6. L177-209: Most of these 8 topics (esp. 2, 3, 5, and 6) need to be expanded and more fully addressed. Each should have its own paragraph’s worth of information.

**Done.** - We have expanded this section somewhat to address the reviewers' concerns. We have added new citations where appropriate. Further, these eight topics are addressed throughout the paper. The reviewer specifically mentions 2,3,5, and 6 and here is how these have been addressed:

Topic 2 has been expanded and now reads: “Second, anticipated transitions of boreal forest to deciduous forest stands would decrease fire risk in eastern Canada and small regions of interior Alaska (Terrier et al., 2013; Foster et al., 2019; Mekonnen et al., 2019), as deciduous species are less flammable than coniferous species (Päätaalo, 1998; Krawchuk et al., 2006).”

Topic 3 is addressed more fully in section 3.2

Topic 5 has been expanded and now reads: “Fifth, the interaction between climate-driven changes in fire regimes and permafrost will compel a decrease in and a northern migration of Siberian taiga, which will result in the transition of tundra

to taiga in northern Siberia (Tchebakova et al., 2009, 2011; Sizov et al., 2021). Permafrost is not predicted to thaw deep enough to sustain dark-needled taiga (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*), nonetheless light-needled *Larix* is predicted to continue to dominate in eastern Siberia, maintaining a higher fire risk according to the Russian fire hazard rankings (Melekhov, 1980). The Russian fire hazard ranking systems shows a decrease in fire risk from light needle conifers (Scots pine, larch) to deciduous broad-leaf tree species (birch, aspen, willow) that exist between the temperate and boreal zones, as well as along river valleys. Fire risk is also lower in dark-leaf conifers (Melekhov, 1980). Fire return intervals (FRI) are consistent with Melekhov (1980), with a mean FRI of 36 years (range 17-133) in light coniferous forest compared with a mean FRI of 196 years (range 75-725) in dark-coniferous forest (Furyaev, 1996; Shvidenko and Nilsson, 2000; Soja et al., 2006). Larch are fire-tolerant species, and dark-coniferous species are shade-tolerant secondary-succession cohorts (Shugart et al., 1992).”

Topic 6 has been expanded and now reads: “Sixth, forest-steppe and steppe are predicted to dominate over half of Siberia, largely forced by climate and increases in fire regimes (Tchebakova et al., 2009). The forest-steppe that exists at the southernmost extent of the Siberian boreal forest is transitioning to steppe due to: increases in extreme fires that burn the soil organic matter to mineral soil, and repeated fires and high temperatures that kill regenerating seedlings.”

7. L199-201: Connect with or move to L169.

**Done.** - This line has been moved to follow L169.

8. Sect 3.1 title: Is number of fires really the thing we should care about? Isn't burned area more important?

**Done.** - We agree with the reviewer that the number of fires is not the most important aspect, as burned area is important, too. Based on Reviewer 3's previous comment that this section should be reorganized, we have reorganized Sect. 3 with two headings of '3.1 Climate change and future fires' and '3.2 Biogeography of future fires'.

9. L214-221: Duplicated information from earlier.

**Done.** - We removed as much duplication as possible, adding details on prediction of future fire seasons to when these references are first introduced.

10. L226-227: Explain how transitioning from boreal to deciduous forest would decrease fire risk.

**Done.** - These are the results found in the publication cited. However, deciduous forests have a higher fire return interval in North America (N Am) in comparison to N Am coniferous species. Also, the climate in eastern Canada is predicted to be wetter, have less fire risk, and is expected to be a climate that will sustain deciduous species. Every species cohort has a particular associated fire return interval. *P. sylvestris* in southern Siberia is surface fire dominated every 10-20 years and further north surface fire dominated every 20-50 years. There is no N Am equivalent. Coniferous forest in NAm is crown-fire dominated and burns more often than wetter deciduous forest. We have also added more of this information in the previous section to further explain why these results are presented in this review.

11. L231-232: Shrubs might be “coniferous species,” but lichens and mosses definitely are not.

**Done.** - We concur with Reviewer 3 and did not mean to cause this confusion. The commas were meant to separate this list. This has been revised to: “Further work in mature deciduous forests of Interior Alaska show that current canopy “gaps” are related to ecological shifts to evergreen shrubs and lichens, grasses, and mosses, ...”.

12. L234-235: “Likelihood of flammability” doesn't make sense. Likelihood of burning, maybe?

**Done.** - We have changed this to “likelihood of burning”.

13. L252: This sentence is so vague as to not convey any useful information. Either expand on what Reyer et al. (2017) said or remove this sentence.

**Done.** - We have removed this sentence. Reyer et al. (2017) has been removed from the references. The reorganized section does not need this

14. L258-260: Unclear how the two effects in this example are “opposite.”

**Done.** - We thank the reviewer for pointing this out. It should say “negative”, and not “opposite”. This revised sentence now reads: “However, abiotic and biotic damages in particular may have negative effects on forest growth and dynamics (Seidl et al., 2014). “

15. L261-262: Explain how shortening soil frost period would lead to more wind damage.

**Done.** - This sentence has been revised to: “Wind damage risk is expected to increase due to the shortening of soil frost period (Venäläinen et al., 2020), as frozen soils anchor trees in the ground, thus making them less vulnerable to uprooting.”

16. L285-299: Historical information should be in Sect. 2. Perhaps a “seasonality” subsection would make sense to include there.

**Done.** - We have this historical information here to contextualize recent and current changes in early season burning and how that might translate into future BC emissions and deposition on sea ice. We have revised this section to make it clear that the recent and current earlier fire seasons are relevant for understanding future BC emissions and deposition. This builds on and links to your subsequent comment (which is fully addressed).

17. L294-295: Explain why widespread snow and sea ice make early-season fires “particularly relevant.”

**Done.** - This sentence has been revised to: “Given this, current and future early season fires are particularly relevant because Arctic snow and sea-ice coverage are much more widespread in the early burning season than late season – meaning earlier BC deposition could accelerate springtime melt to April, before the usual start of the melt season in May (Stroeve et al., 2014).”

New reference added:

Stroeve, J.C., Markus, T., Boisvert, L., Miller, J. and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, *Geophys. Res. Lett.*, 41, 1216-1225, <https://doi.org/10.1002/2013GL058951>, 2014.

18. L310-312: Duplicated information here re: use of active fire product in GFED4s.

**Done.** - Duplicate information has been removed.

19. L378: Consider using a smaller unit (e.g., Mg) so values are easier to read.

**Done.** - We have kept the Tg in order to be consistent with the rest of the emissions reported throughout the review paper but have added Mg so that it is easier to read and compare.

20. L394: Sect. 5 title needs to be reworked.

**Done.** - Section 5 title has been reworded as “Relevance of fire sources in global and Arctic emissions”.

21. L409-412: This analysis does not seem to have actually been included anywhere.

**Done.** - We have revised these sentences, as we did not mean to imply that we completed a 2050 modeling of emissions using GAINS and GFAS. Rather, we used the 2020 GFAS fire emissions as a proxy for 2050, given how extreme the Arctic fire season was in 2020 (particularly in Siberia).

This now reads: “Since the 2020 wildland fire season in the Arctic was unprecedented (Witze, 2020), with approximately 27% of fires in Siberia burning above 65°N (Conard and Ponomarev, 2020), the 2020 GFAS emissions can be used to represent what potential future fire regimes by mid-century, i.e., 2050, may be like, with climate change-driven expansion of fire seasons and likelihood for extreme fire weather and risk (see Sect. 3).”

22. L451: 60°N should be 65°N.

**Done.** - The sentence reads “At these northern latitudes, wildfires and flaring are the main sources of black carbon, especially north of 65°N with these two sectors accounting for 93% of black carbon emissions, compared to 88% for 60°N.” So north of 60°N, the wildfire and flaring emissions make up 88% of the BC emissions, and north of 65°N they comprise 93% of emissions. So the sentence, and 60°N, is correct.

23. L476: Is “allowing wildfires to burn under non-severe fire weather conditions” really “active” fuels management?

**Done.** - We have removed “Active” at the beginning of this sentence. Allowing wildfires to burn under non-severe conditions, classified as ‘Wildland Fire Use’ in earlier years, is a method that is often used (see [https://www.fs.fed.us/rm/pubs/rmrs\\_gtr198.pdf](https://www.fs.fed.us/rm/pubs/rmrs_gtr198.pdf) and <https://link.springer.com/content/pdf/10.1007/s40725-015-0013-9.pdf>). However, calling it active could be confusing. So we have revised this based on the Reviewer’s comment/question.

24. L484-485: This bit about re-greening seems unconnected to the topic at hand. Or is it? Explain.

**Done.** - We wanted to add this context on re-greening to give the readers an idea of how quickly the landscape and fuelbeds recover in the tundra. We have revised this sentence to reflect that: “Privately-owned grassy tussock tundra and dwarf shrub tundra vegetation types are more likely to burn than low shrub tundra in Alaska (Hu et al., 2015), with relatively rapid vegetation re-greening within a decade after burning for shrub and tussock tundra (Rocha et al., 2012) - potentially a re-establishing the shrub and tussock tundra fuelbed for repeat burns.”

25. L500-501: Incomplete sentence?

**Done.** - This sentence has been rephrased to: Human ignition sources, including predicting future demographic, migration, and/or development patterns in these changing northern landscapes, will impact fire activity and related emissions (Robinne et al. 2016; Reilly et al. 2019).”

26. L508-510: This sentence is trying to do too much. There are two separate ideas: when the cropland burning occurs, and when transport is likely. These should be separately explained, then brought back together to show that they coincide.

**Partially done.** - We have revised this sentence to better explain how these two mechanisms are related: “Thus, burning of croplands, grasslands, and deciduous forests often occur at times when transport of fire emissions to the Arctic is likely, i.e., late winter/early spring for Russia (Hall and Loboda, 2018; Qi and Wang, 2019) as well as Canada and north central U.S. (Viatte et al., 2015), respectively.”

27. L521: “particularly in the context of emissions reductions” feels disconnected from everything else. Please elaborate or remove.

**Done.** - This has been revised to: “Collaboration, cooperation, and innovation are needed for future Arctic wildland firefighting techniques, practices, and implementation, particularly in the context of potential emissions mitigation.”

28. L533-552: This paragraph feels like it would make more sense in Sect. 3. Either move it there, or explain what exactly here is especially uncertain.

**Partially Done.** - We have revised this section to note that this is uncertain because current spatial and temporal modelling needs to be improved to predict and understand future fire regimes, particularly when coupling fire-climate-land use-ecological modelling across space and time. We would argue that the spatial distribution and frequency of fires, fuel loadings, etc., will change in the future and there is some understanding of drivers (as discussed earlier) but such drivers have not been used to create predictions of future fire landscapes for the Arctic. While there is need for such projections, they are burdened with uncertainties that could be reduced by systematic assessment.

29. L537: Missing words before “Important”.

**Done.** - This has been revised to: “It is important to note...”.

30. L547: What does “Zonal” mean here?

**Done.** - These tree species or cohorts survive in a specific climatic zone, similar to looking at maps of tropical, desert, grassland, temperate, boreal, and Arctic zones but on a regional ecotype zonal basis. This sentence has been revised to: “Dark conifers, which survive in specific climatic zones, would shift northwards and eastwards following permafrost retreat, and light-needed tree species (e.g., *Pinus sylvestris* and *Larix sibirica*) would follow them, expanding from the south. In the transition zone between dark-needed and light-needed tree species, birch and mixed light conifer-hardwoods subtaiga and forest-steppe would dominate, likely reducing fire risk.”

31. L554: What does it mean for a forest to “decrease”? Decrease in what way?

**Done.** - The area of the forest is decreasing - the climatic zone that defines its existence is decreasing and moving. Evidence has been found at the southern and northern extent of the zones. We have revised this sentence to note that area is decreasing and now reads: “Total area of Siberian forests are predicted to decrease and shift northwards, with forest-steppe and steppe ecosystems predicted to dominate 50% of Siberia by 2080 under RCP 8.5 (Parfenova et al., 2019)...”

32. L587-589: How can ESMs have a mis-estimate for a future period? By definition we do not have observations for the future against which to compare future ESM simulations.

**Done.** - Earth System Models should compare their ability to estimate the current and past climates. Every good model should have verification and validation criteria. For example, the regional SiBCliM model publications by Tchebakova and Parfenova have repeatedly used the past and present vegetation distributions to validate their ESM. For example, in Tchebakova et al. (2009), the HadCM3 A1FI and B1 climate change scenarios (Figure 3 on page 6:

<https://iopscience.iop.org/article/10.1088/1748-9326/4/4/045013/pdf>) and is compared to known vegetation zones. SiBCliM is also used by others to constrain their ESM simulations for Siberia (see <https://bg.copernicus.org/articles/18/207/2021/>). This model in question from Helbig et al. 2020 (<https://www.nature.com/articles/s41558-020-0763-7#Sec6>) compared current vapour pressure deficit, available energy (the sum of sensible and latent heat flux), and the aerodynamic and surface conductance for water vapour transfer to modelled variables (RCP 4.5 and 8.5) to assess the likely future uncertainty of water availability in boreal peatlands. We have revised this sentence to say: “Current Earth system models underestimate evaporative water loss and overestimate current and future water availability for boreal peatland systems under RCP 4.5 and 8.5 warming scenarios when compared to current climatic conditions, perhaps underestimating fire risk, activity, and emissions in peat systems (Helbig et al., 2020).”

33. L634-635: 3.5 million cubic meters of permafrost what, exactly?

***Done.*** - We thank the reviewer for finding this error, when we meant to say that 3.5 million cubic meters of permafrost had thawed. The revised sentence is: “For instance, recent work in Sakha Republic found that a 36 km<sup>2</sup> wildfire in an open larch with shrub and moss lichen landscape northwest of the Batagaika megaslump resulted in approximately 3.5 million cubic meters of thawed permafrost five years later (Yanagiya & Furuya, 2020).”

34. 7.5: This section feels weird to me. It seems like the Russia records are being cast as “bad” when they disagree with remote sensing data, but Finland and Norway records are “good” when they do. (See L700-701: GWIS “overestimates” burned area in Norway and Finland—couldn’t you also say that the official records underestimate burned area?) These judgments are not necessarily wrong, but they should be better justified.

***Done.*** - The authors have re-read this section, with an eye towards fairness. We appreciate the reviewer’s assessment as this was not the intention of this section to qualitatively demarcate any particular country’s fire record keeping as good or bad. We have deleted one sentence that was not making the point intended and could have been cast as “bad”. On the other hand, Russian long-term data just doesn’t exist. They did not try to quantify the burned area in the far north of Siberia, not bad, just is and is understandable. The landscape is huge. Alaska easily fits into Sakha Republic (also known as Yakutia). Also, published works do show that in comparison to many datasets, the Russia burned area does differ (underestimated historically and overestimated currently).

The revised portion of this section now reads: “Agreement of burned area within Siberian forests between official Russian statistics and four satellite-based burned area products was less than 10% (Kukavskaya et al., 2013). Average official satellite-derived Russian burned area estimates differ by a mean of 48% from 2002 to 2015 in comparison to the Loboda et al. (2017) regionally-tuned product, which only differs by a mean of 18% in comparison official burned area statistics for Alaska and Canada. One reason for these differences could be regional-to-global scale algorithms may not have the sensitivity necessary to define surface fire, which is the dominant fire type in Siberia in normal fire years. Also, North American and Nordic countries have long-term ground-based boreal burned area records that span 50 years or greater, which aids in calibrating current satellite data records and analysing relationships between fire regimes, vegetation, weather, and climate. Long-term accurate fire records do not exist for much of Russia, primarily because fire was not historically recorded in the remote ‘unprotected territories’ (Sofronov et al., 1998; Soja et al., 2004).”