

Biogeosciences Discuss., author comment AC3  
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## Reply on RC3

Jessica L. McCarty et al.

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Author comment on "Reviews and syntheses: Arctic fire regimes and emissions in the 21st century" by Jessica L. McCarty et al., Biogeosciences Discuss.,  
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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

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."

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.

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)."

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 Kicklighter 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 (Kicklighter 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.

Kicklighter, 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.

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'.

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."

L199-201: Connect with or move to L169.

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

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'.

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.

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.

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, ...".

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

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

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

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). "

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."

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).

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.

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

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

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.

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”.

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)."

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.

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.

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."

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)."

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."

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."

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.

L537: Missing words before "Important".

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

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."

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)..."

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 Tchepakova and Parfenova have repeatedly used the past and present vegetation distributions to validate their ESM. For example, in Tchepakova 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)."

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)."

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)."



