

Interactive comment on “How past fire disturbances have contributed to the current carbon balance of boreal ecosystems?” by C. Yue et al.

Anonymous Referee #1

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GENERAL COMMENTS

The Yue et al study aims to quantify the legacy effects of forest fires on the carbon cycle in boreal systems. They utilize an integrated ecosystem-fire model to simulate decadal vegetation structure and fire regimes from CE 1850-2010 in the northern hemisphere boreal zone. Their model also incorporates the influence of atmospheric carbon and climate change via the fertilization effect on successional vegetation following fire. Using an iterative approach, the authors identify the proportion of the modern carbon sink that is related to the legacy effect of fires in previous decades. They identify an increasing temporal trend in the contribution of decadal fires to the modern carbon sink, with fires in the most recent 4 decades accounting for 60% of the total legacy effect on the enhanced carbon storage. However, the overall legacy effect of past fires in contributing to the sink roughly balances the contribution of modern burning to carbon sources. Nonetheless, if the boreal fire regime changes in the future, it is possible that the impact of enhanced burning may exceed the fire-legacy carbon sink. Classifying the fire regimes based on fire return intervals (yrs.fire), the authors find that regions with FRIs between 10-50 years are the largest contributor to the fire-legacy carbon sink, which has important implications if fires become more frequent in the future.

Overall, this study is unique because it not only considers the effect of fires on the boreal carbon cycle, but examines this effect through time by partitioning the model into various decades. This allows for examination of how temporal changes in the fire regime along with anthropogenic changes impact the carbon sink in the boreal zone. In general, the paper is rather heavy on methods, which is understandable given the many datasets and model parameters that need to be explained. However, I think the paper needs a more substantial discussion and introduction in order to appeal to a larger audience and to clarify the implications of the study. The current discussion seems more like a list of how well the model performed and how it compares to other studies, and lacks the key component of really explaining the findings and placing those findings into a broader context. Thus, I strongly suggest that the authors restructure the discussion to give it more focus. I have some general suggestions about that, but the main point is that I want to know what the authors think their findings mean and how those findings fit into what we already know. Furthermore, the results section was rather short and not explained in a quantitative way (which may not be possible). I found it difficult to properly assess how successful the study was because there are very few statistics to help assess the model results. However, this could potentially be addressed with some modifications to the figures and some statements in the results about the impact of these errors.

Despite these issues, I do believe that the paper is suitable for Biogeosciences. It is an interesting study with some compelling implications. I would suggest accepting the paper pending revisions.

[Response] We thank the reviewer for the valuable comments. Please find our detailed responses below each comment in blue. All the modified texts are marked as red in the revised texts, with big blocks of deleted texts being marked using the "edit" mode, to make it easy to follow which parts of texts have been modified in response to review comments.

1. P 14835, L 3-5: The link between CO₂ and temperature increase on vegetation productivity should be made explicitly in this sentence. The previous sentence talks about soil carbon and the following sentence about vegetation. The logical link gets lost without being specific as to how the carbon sink is enhanced

by these forcing mechanisms.

[Response] This link is now made explicitly, see the revised texts in the first paragraph in the introduction.

2. P 14835, Line 22: What does the phrase “in parallel with post-fire ecosystem recovery” mean? Do you mean that the equilibrium conditions of the soil following a fire occur at the same temporal scale as that of vegetation following combustion? I am not sure that is true, if that is what you mean. Please clarify.

[Reponse] Yes, this is what we originally mean. In theory this should be the case given stable environmental conditions and fire regimes. In reality, the extent of soil carbon recovery might depend on various factors including post-fire vegetation type, the stand density of forest that regenerates after fire, etc (Kashian et al., 2006). Harden et al. (2012) pointed out that during intervals of fire disturbance, about 20% of NPP over the fire cycle enters the organic soil layers and become available for stabilisation or loss via decomposition. They also showed that organic soil carbon indeed restores as vegetation recovers from fire. We have modified the text to indicate that soil carbon will restore in correspondence parallel with vegetation carbon recovery, but not necessarily within the exact same temporal span.

3. Overall, I think the introduction is very straightforward. However, I think that that the discussion regarding the conceptual framework should be moved to the introduction as well. I found the entire first paragraph of section 2.2 very confusing, and ultimately had to read the Gasser and Ciais 2013 paper to understand what it meant. My general suggestion here is to introduce. . .very clearly. . .the concept of CCN in the introduction. Make it very clear to the reader that there are environmental perturbations that are new to the system since the industrial era that affect the post-fire vegetation recovery. Thus, although the boreal system has long been fire-adapted, it is the new state of CCN perturbations that enhance the legacy effect of past fires. I felt like I had to read between the lines to get that information, and it would be MUCH better if it was explained to me very clearly in the beginning. For example, HOW do these three components impact carbon storage following fires, specifically? THEN, having clearly introduced that in the intro (it would fit nicely after the paragraph about fire), KEEP the section 2.2, but make it very clear HOW you incorporate that conceptual framework into your model. For example, you talk about land use change, but that is not part of the CCN model, is it? Take the time to clearly explain each part of your model, using Fig 1A and B to really help with it. I think this will help the reader immensely and make the entire first half of the paper more easy to understand.

[Reponse] Following the suggestion by the reviewer, we inserted two paragraphs after the original Paragraph 3 in the introduction section, elaborating the carbon dynamics with and without CCN perturbations while referring to the revised Figure 1, we hope now this is more clear.

4. In regards to comment #3, I would also suggest a few changes to Figure 1. Is it possible to add some arrows that give the reader a visual understanding of the fluxes of carbon and how they differ for different portions of the landscape? I.e, thick arrows = high flux, thin = low? And/or, it would help a lot to have aspects of your equation added to the figure as well if that is possible. I.e, I think the illustration is nice, but it doesn't add a lot to helping the reader understand the conceptual design without a bit more visual information. I ended up drawing all over the figure as I read the equation before it was clear what it all meant. Remember, not everyone uses these models, so I suggest using the first figure as a way to outline the conceptual framework very clearly. Also note, the terms in your figure are not explained in the caption of the figure. There should be a legend or a more precise caption for that figure.

[Reponse] We made several modifications in Figure 1 trying to make it more clear. The original panel (b) now becomes panel (a) as this is first referred to in the introduction. Arrows with different colors and widths are added on top of the small squares representing different aged fire cohorts, to indicate quantitatively the nature (sink or source) and size of their carbon fluxes. The same mathematical symbols

as used in Equation (2) are now added in the figure to facilitate understanding. The figure legend is also improved with the aim to make the figure self-explaining.

5. P17839, Lines 10-14: You illustrate the way in which CCN can affect emissions and legacy sinks, which is helpful. However, I think it would be suitable to list multiple ways in which this works, instead of just two examples. There needs to be a logical and clearly defined link between how CCN affects these two aspects of the carbon balance AND it needs to be explicit how these components are handled in the model. If you list the ways CCN impacts the system here, you can refer back to those examples when you explain the model. For example, you mention on P14840 that one of the terms in your equation is the carbon flux from the CCN perturbation. Why not give an example of the conditions in which this term would be high versus low? I.e., high atmospheric CO₂ versus low atmospheric CO₂? Warm summers versus cold summers? Etc. This would make it very clear to readers who do not use these type of models and really help in outlining how the model actually works. It does not have to be a lot of text. . . just some clear examples so that the reader clearly understands how the model works.

[Reponse] We have followed the reviewer's suggestion to include another two paragraphs fully explaining the effects of CCN in the introduction. These explanations are again referred to in the revised first paragraph of section 2.2 to facilitate the understanding of our attribution framework. As effects of different CCN factors on post-fire vegetation carbon dynamics (i.e., decadal fire contributions) and fire emissions are not individually separated in our attribution but rather they're contained in the quantified fire contribution as a whole, we think to describe in detail the various links between CCN and carbon dynamics or fire emissions is not our primary objective and could add further complexities. With all the revisions mentioned above, we think readers are given sufficient background to understand our attribution framework, therefore these two sentences are now removed from the texts. Also, as the CCN is described quite clearly in the revised introduction section, we think no further examples are needed.

6. P 14841, L10-12: Similar to comment # 5, I am not sure I understand this. You state that the CCN perturbations are not separated in the model. I assume that means the atmospheric carbon and climate layers are lumped together. However, it is unclear to me, based on the previous text, what exactly the CCN perturbation actually is...i.e, I just know it has something to do with climate, carbon, and nitrogen. Please be very clear about this and offer examples which will make that easier to understand.

[Reponse] The reviewer's understanding is correct: atmospheric carbon and climate effects are lumped together and contained inside the quantified fire contributions and their individual effects are not separated. This is now further made clear in the last paragraph of the introduction section. The separation of different CCN effects could be considered in follow-up studies. As stated above, the CCN effects are now clearly elaborated in the revised introduction, we hope this could reduce confusion.

7. P1782, 2nd paragraph – There are a few things that need to be clarified here:

a. What does CRUNCEP stand for?

[Reponse] The name of CRUNCEP simply comes from binding the name of CRU and NCEP. This is now explained in the revised texts regarding introduction of CRUNCEP data with proper reference to the web site where the forcing is available.

b. What is the NCEP temporal resolution?

[Reponse] The CRUNCEP is six-hourly climate data, now indicated in the revised texts.

c. What type of climate data is the CRU data? Is it summer temperature? Annual moisture? Be explicit.

[Reponse] The climate fields contained in CRUNCEP and their data sources are now explained in more detail in the revised texts (the 3rd paragraph of section 2.3).

d. Was there an atmospheric CO₂ dataset used in this model? On P 14841, L 25, you state that you account for climate change (CRUNCEP dataset), atmospheric CO₂ (?), and simulated fires (lightning and human population datasets).

[Reponse] We applied a single atmospheric CO₂ concentration everywhere rather than using space-time CO₂ variations. Given the fact that the growth rate of CO₂ is similar between summer and winter, and that the mean CO₂ difference between summer and winter in the Northern Hemisphere is 10 ppm and changes little with time we think that not accounting for space-time CO₂ variations to drive the ORCHIDEE model will have negligible effects on changes in the simulated carbon fluxes. This is now explained in the revised texts (the 3rd paragraph of section 2.3).

8. Results section: Overall, there needs to be a bit more information about how well these datasets perform. Is there any quantitative way to assess overall model performance? For example, there seem to be some large areas where the tree cover is overestimated by quite a lot (30-50%). Is this an acceptable amount in these types of models? It seems like the model ultimately matches up well with what we know, which is surprising given the large overestimates. Along these same lines, I also find figures 2-4 difficult to digest. What do the scales mean? There are no units on the figures. A possible solution - Why not create a map that shows the difference between the two datasets? This way, it is very clear to the reader which areas are problematic and gives a more quantitative overview of the model performance. I.e., deep red = areas where the vegetation cover or fire is overestimated, deep blue where the veg/fire is underestimated. I don't know if that is possible, but if it is, it could provide better visual information to the reader.

[Reponse] We think it does not help a lot in our case to use a single quantitative metrics (such as root mean square error or RMSE between simulated and observation data) because ultimately, one has to look down in detail for which region model errors occur. In order to evaluate model error in a more comprehensive way as a response to the reviewer's comments, we have expanded the evaluation data sets to include further three land cover data sets: the ESA CCI land cover v1.1 for year 2010, GLC2000 (JRC, 2003), and ISLSCP II vegetation continuous field for 1992–1993 (DeFries and Hansen, 2009). We further calculated the model error in a quantitative manner. All these results are now included in the section 1 of the newly added Supplement. We keep the Figure 2 and Figure 3 unchanged in the main text because the simulation of tree cover is not the central point of our paper and we would like to keep this section brief, however readers are directed to the Supplement for more detailed and quantitative comparison. We acknowledged the simulation systematic errors in terms of tree cover and simulated burned area, however as our conclusions are based on the simulated total burned area, fire emissions and carbon fluxes on the regional scale, we argue that despite large local systematic errors, our conclusions remain solid. The units for Figure 2-4 are clarified.

9. Discussion section – overall, I think this section could be restructured a bit to make it more appealing to a broader audience and to more fully explain what the findings tell us. It is a bit technical as written and focuses too much on the model performance and not enough on big-picture implications of the findings. I felt like I had to figure out what the implications of this study were on my own. . .and I did not really have enough information to do that. The discussion should clearly explain how the findings of this study add another piece of information to what we know about the fire-vegetation- carbon cycle. To do this, you need to give the readers a nice overview of what is already known and then place your findings into that context. I have a few suggestions below that may help.

[Reponse] Following the reviewer's suggestion, we restructured the discussion to highlight the scientific significance of our finding and provided better contexts for readers to understand our study. A new

discussion section 4.1 has been added focusing on general aspects of fire-climate-vegetation feedbacks in boreal regions, the role of fire in regional carbon cycle, major findings from our study and its implication. An additional paragraph was also added just after the title of section 4 to explain the discussion structure. Original discussion sections 4.1, 4.2 and 4.3 now become sections 4.2, 4.3, and 4.4, with relevant material being moved to new section 4.1, redundant material removed for the purpose of being concise. We argue that section 4.2, 4.3 and 4.4 are still necessary as it follows the general logic to understand a study: model error -> comparison with other studies -> perspectives.

a. Discussion – Section 4.1 – It is a bit underwhelming to start your discussion off with model performance, but I suppose it has to be done somewhere. It would be more interesting to start off with your major findings and then narrow down to things like model issues, but that is ultimately personal preference.

[Reponse] Following the reviewer's suggestion, we added a new section 4.1 focusing on the general background of the current study and discussed the scientific implication of our finding.

b. I feel like you are missing a key discussion section or paragraph – you need to introduce the concept of the fire-vegetation feedback, with some nice examples of how the fire regime helps structure boreal vegetation and how post-fire succession is affected by fire frequency. I feel like this link is not made in an explicit way and it should be because it is half of your major point. I.e, post-fire succession is part 1, and the impact of CCN on this process is part 2. Additionally, if you made section 4.1 the Fire-Vegetation feedback section, then you could talk about the aspects of your model that a) capture this effect and b) do not capture it well because of model issues. Since this is a key component of your study, I think it is worth really explaining in it a broader context.

[Reponse] The fire-climate-vegetation feedbacks are described in the newly added section 4.1. However, we don't expand further too much on the CCN perturbations because 1) their effects are not separated in our study and their collective effects are sufficiently discussed and our model does not have nitrogen-carbon interactions, 2) they're sufficiently introduced in the revised introduction section, 3) to avoid discussing each CCN factor in too much detail helps keep the discussions concise.

c. Discussion section 4.2 – If you devote the first section to the vegetation-fire feedback as suggested, this section could be focused more on the impact of fires in the carbon balance under CCN perturbations. Instead of focusing on how your model differs from others, you could restructure this section and really focus on the role of fire in the carbon balance, how other studies have examined that role, and how your study takes this a step further by examining the legacy fire effect under CCN. Again, the information is all there, just as in the previous section, but it is a bit underwhelming as written.

[Reponse] This section now becomes section 4.3. The role of fire in carbon balance and the uniqueness of our study is discussed in the newly added section 4.1. We keep the detailed comparisons with other similar studies here because we think it's necessary for readers to understand in detail our difference with previous studies. Another point is that quantifying the size of carbon flux (total carbon sink, fire-carbon emissions, and contributions of fires of different past decades) is also the central point of our study which must involve numbers and values. Such detailed comparison could potentially allow the readers to know the state of the art on this issue.

d. I feel like the most important point in the discussion section is the paragraph starting with P14850, Lines 22-25. Personally, I would start the discussion with this and then explain the vegetation feedback, move into the impact of CCN, then reiterate your findings. But again, that is differences in style. I.e, if section 4.1 is restructured to focus on the fire-vegetation feedback and section 4.2 focuses on the impact of CCN on this relationship, then this point becomes very powerful and the reader will have a clear

understanding of how your results show this. I.e., you will have given them the information they need to clearly understand why your findings are so interesting.

[Reponse] This is now moved to newly added section 4.1 after a decent description of fire-climate-vegetation feedbacks and the role of fires in the regional carbon cycle. We hope now it's more clear.

e. I found it rather compelling that 1) more recent fires contribute most to the legacy carbon sink (ie, P14846, L 20-25) and 2) fire groups with short FRIs (10-50 years) are the biggest contributor to the carbon sink (P 14847, L4-6). This seems like a very interesting finding, but it is not really brought up again in the discussion. A discussion of this could improve your implications sections. It suggests to me that areas of early successional vegetation are really strong sinks of carbon. Why? Do areas with short FRIs and recent burning have more deciduous vegetation? Higher biomass? What is the implication for the boreal biome if fires become more frequent in the future? Will the impact of CCN on these areas result in a stronger boreal sink in the long run, simply due to this vegetation feedback? Is there a threshold of burning that enhances the legacy effect, but once burning become very frequent (ie, 2-5 yr FRIS), will the legacy effect diminish and those areas act as a carbon source? I feel like you have enough information to speculate a bit about what your findings mean in a broader context. Without some sort of discussion about it, I am unsure why you added the FRI analysis at all. What does it mean?

[Reponse] Following the reviewer's suggestion, these two points are now discussed in section 4.3 in two newly added paragraphs. Correspondingly, Figure S5 and Table S1 are added in the Supplement Material and cited in the discussion. In brief, we think the higher sink contribution by recent decades of fires are due to a combination of three factors: higher young- to medium-aged forest carbon uptake in forest succession, higher burned area, and the CCN perturbations. Higher fire frequency might lead to higher sink if vegetation remains unchanged (i.e., forest regenerates after forest fire rather than being replaced by grassland), however lower sink may also happen if forests are replaced by grasslands in case of strong fire disturbance.

TECHNICAL CORRECTIONS

1. P 14835, L 6: More vulnerable to what? Be explicit.

We think this expression is OK, as is put at the beginning of this sentence, "as climate change continues, boreal forest may become more vulnerable ...", it implies boreal forest is more vulnerable to the consequences of climate change, but to be more clear, we changed "boreal forest" to "carbon stocks in boreal forest".

2. P 14835, L 7: What is vegetation activity? Do you mean productivity?

We changed "activity" to "productivity".

3. P 14835, L 19: Replace "Besides" with "Additionally", or another word.

We changed "Besides" to "Additionally".

4. P 14835, L 21: after "charcoal, I would add a comma and say "which restores soil carbon. . ."

This is now changed to a new sentence in order to be more clear: " Furthermore, organic soil carbon also restores in correspondence with post-fire vegetation carbon recovery (Harden et al., 2012), though the extent of restoration might depend on factors like post-fire vegetation type and regenerating forest stand density (Kashian et al., 2006)."

5. P 14836, L 12 – What does the “contemporary period” mean? Last 150 years? Anthropocene? Be specific and clarify.

We changed "comtemporany period" to "the current time".

6. P14387, L19: What are “lightening-ignited fires by human”? Do you mean “sup- pressed by humans”?

We mean fires ignited by lightning but suppressed by human, it's now changed to "the human suppression of lightning-ignited fires" to be more clear.

7. P14838, L3: Replace “On top of” with something like “in addition to”

We changed "On top of" to "in addition to".

8. P14838, L8: What does DGVM stand for?

We changed DGVM to "dynamic vegetation module" to be more precise.

9. P14838, L25: “Evidences” is the wrong word here. Perhaps “Previous studies”?

This paragraph is now removed following the reviewer's suggestion to restructure the introduction on the CCN perturbations.

10. P14838, L26-27: “Environmental perturbations” can mean anything, including fire. Do you specifically mean “anthropogenic impacts”? If so, state that explicitly. I know you offer a list in the next sentence, but those terms are also vague. Atmospheric CO₂ is not a perturbation. Rapidly increasing atmospheric CO₂ in response to an- thropogenic activities is a perturbation. I suggest restructuring these two sentences to make to make it very clear which variables you are referring to.

We changed "environmetal perturbations" to "anthropogenic perturbations", to explicitly mean those perturbations on the environment (of the living vegetations) that are caused directly (such as atmospheric CO₂ change) or indirectly (such as climate change throught the CO₂ effect) by human activities.

11. P11839, L 4: “natural land ecosystem” is a very odd phrase. What is mean by “natural”? Be specific. . .do you mean prior to human modification?

This paragraph is now removed following the reviewer's suggestion to restructure the introduction on the CCN perturbations.

12. P14839, L7 – “regrowth” is misspelled.

Not sure what the reviewer means, if you mean "regrowth" – this exact word is misspelled, but I find its usage is quite common in literature when searching "vegetation regrowth" with google scholar.

13. P14841, L4: “Different with explicit cohort simulation” – Do you mean “In contrast with the explicit. . .” Consider rewording.

We changed to "in constrast with".

14. P 14842, L25-26: I think there is a typo in this sentence. “Both lightning data sets” – do you mean “Both the lightening and population datasets”? Or were there two lightening datasets?

We changed to " Both lightning and population density data sets " to be more precise.

15. P14843, L21 – please add a comma before “deciduous needlleef” to show it is a separate group.

The comma is added.

16. Figure 6 – put citations in the figure legend to make it clear that these points are from other sources and that you are comparing your findings to them. I had no idea what these points were until I found them in the main text. If not in the legend, they need to be in the figure caption.

The citations are put in the figure legend.