Reviewer 1

We are grateful to the reviewer for their time and energy in providing helpful comments and guidance that have improved the manuscript. In this document, we describe how we have addressed the reviewer's comments. Referee comments are shown in black italics and author responses are shown in blue regular text.

The manuscript is unusual in that it considers the indirect effect of wildfires on the boreal carbon balance via emissions of atmospheric pollutants. The results are novel and the simulated effect is surprisingly large, which makes the results interesting for ACP. There is some validation of results against observations, and some evaluation of effect strength directly using site-based observations. This strengthens the paper, which otherwise relies on a very complex modelling system. I consider the subject material to be fully within scope for ACP. However, the title does not correspond to the above assessment but sets different priorities. Possibly it reflects the original idea for the manuscript on ecosystem health but the focus has changed due to the negative results regarding ozone pollution. The manuscript therefore seriously lacks focus.

→ We appreciate the reviewer's support and helpful evaluation of this study. We agree that the original title is not appropriate for the content of the analyses. Based on the comments below, we revise the title to: "Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America" so as to better reflect the main focus of the study.

Major comments:

I can see at least the following scientific questions either being addressed, or requiring attention:

1) Do wildfires affect ecosystem health in boreal environments beyond its direct impact through higher ozone concentrations, i.e. far away from the fire or long after the fire has ended?
2) How can the effect be quantified, i.e. is NPP a valid proxy?
3) How do the direct and indirect effects compare?
4) Will the strength of this effect change in the future?
5) How do wildfires affect the carbon balance of boreal environments indirectly through atmospheric pollution away from the burned area?
6) How does this effect compare to the direct effect on the carbon cycle in the burned area?
7) How will this change in the future?
8) Are the results representative of all boreal regions?

Questions 1-4 correspond to the title, but Questions 5-8 to the actual focus of the paper (but still not all of them are being answered).

In order to become publishable, either the title needs to be changed to reflect the true focus of the paper, or the focus of the paper needs to be changed and much more detail on ecosystem health effects need to be included. The latter is probably beyond scope, so the best way forward must be the former. In that case, however, more depth is required regarding the carbon cycle, as NPP is only one of many components, and all of Questions 5-8 need to be answered. If the impact on the carbon cycle were to be the focus, then the title would have to be adapted and the manuscript would have to include more discussion that puts the results into the perspective of the regional and global carbon cycle. Some of it is there, but not enough to give the reader a sufficiently good feel for how important this really is. So if the focus is to be on the carbon cycle, more results need to be included or a more detailed and in-depth discussion is needed. Or, what is also possible, restrict the paper to impacts on NPP alone. After all, you also include GPP, and that is already a step that involves changes in plant respiration, which also need to be projected. What happens here?

→ Questions 1-4 are related to ecosystem health while the main focus of this study is the responses of ecosystem primary productivity (including both GPP and NPP) to the combined effects of fire pollutants. As a result, the words 'ecosystem health' used in the original title are not appropriate. We have changed the title to "Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America" to reflect the main objective of this study.

For questions 5-8, we answered and/or discussed them substantially in the paper. Questions 5 and 7 are the main focus of the study and their answers have been shown in Figure 12, with model evaluations in Figures 2-5 as the solid basis. For question 6, we discussed it in the last section: "Fire pollution aerosol increases boreal NPP by 72 Tg C yr^{-1} in the present day, comparable to the direct carbon loss of 68 Tg C yr^{-1} from wildfire CO_2 emissions (product of biomass burned and CO_2 emission factors). By midcentury, increasing fire emissions instead cause a NPP reduction of 118 Tg C yr^{-1} due to the amplified drought. Although NPP is not a direct indicator of the land carbon sink, reduction of NPP is always accompanied with the decline of net ecosystem exchange (NEE) and the enhanced carbon loss. In combination with the enhanced carbon emission of 130 Tg C yr^{-1}, future boreal wildfire presents an increasing threat to the regional carbon balance and global warming mitigation." (Lines 673-681)

For question 8, we discussed it as follows: "Our analyses of fire pollution effects on boreal North American productivity may not be representative for other boreal ecosystems and/or on the global scale. There is substantial variability in plant species, topography, and climatology across different boreal regions. Such differences indicate distinct GPP sensitivities as well as fire characteristics. At lower latitudes, where anthropogenic pollution emissions are more abundant, ambient ozone concentrations may have exceeded damaging thresholds for most plant species. In those regions, additional ozone from a fire plume may cause more profound impacts on photosynthesis than our estimate for boreal North America. For example, Amazonian fire is predicted to reduce forest NPP by 230 Tg C yr^{-1} through the generation of surface ozone (Pacifico et al., 2015). Meanwhile, solar radiation is more abundant at lower latitudes, indicating more efficient increases in photosynthesis through aerosol DFE because the sunlit leaves receive saturated direct light in those regions. As shown in Beer et al. (2010), partial correlations between GPP and solar radiation are positive in boreal regions but negative over the subtropics/tropics, suggesting that light extinction by fire aerosols has contrasting impacts on plant photosynthesis in the high versus low latitudes. Further simulations and analyses are required to understand the net impacts of ozone and aerosols from biomass burning on the global carbon cycle." (Lines 685-701)

In the revised paper, we show the changes in plant respiration in Figure S2. We found that: "Such changes in NPP are a consequence of changes in GPP and autotrophic respiration (Fig. S2). Variations in plant respiration resemble those of GPP, because higher photosynthesis leads to faster leaf/tissue development, resulting larger maintenance and growth respiration." (Lines 496-499)

Finally, the result must be backed up more by measurements. The main effect is surprising, but it will be crucial that there is a thorough evaluation of how the model simulates the impact of changes in diffuse and direct light on GPP, as opposed to the measurements.

→ In the revised paper, we performed additional validations by conducting two new simulations at sites CA-Gro and CA-Qfo. The simulated GPP responses to diffuse and direct PAR are consistent with observations as shown in Figure 5, suggesting that the model can reasonably capture changes in GPP due to aerosol-induced perturbations in radiation.

"The model also reproduces observed light responses of GPP to diffuse radiation in boreal regions. With the site-level simulations, we evaluate the modeled GPP-PAR_{dif} relationships at the hourly (instead of half-hourly) time step during summer. For 1342 pairs of GPP and PAR_{dif} at the site CA-Gro, the observed correlation coefficient is 0.42 and regression slope is 0.011, while the results for the simulation are 0.60 and 0.014, respectively. At the site CA-Qfo, the observations yield a correlation coefficient of 0.46 and regression slope of 0.007 for 1777 pairs of GPP and PAR_{dif}. The simulated correlation is 0.61 and the regression is 0.011 at the same site. The GPP sensitivity to PAR_{dif} in the model is slightly higher than that of the available observations, likely because the latter are affected by additional non-meteorological abiotic factors. To remove the influences of compound factors other than radiation, we follow the approach of Mercado et al. (2009) to discriminate GPP responses to 'diffuse' and 'direct' components of PAR at the two sites (Fig. 5). The model successfully reproduces the observed GPP-to-PAR sensitivities. Increase in PAR boosts GPP, but the efficiency is much higher for diffuse light than that for direct light, suggesting that increase of diffuse radiation is a benefit for plant growth." (Lines 415-430)

The third possibility would be to simply focus on the effect of atmospheric pollution from wildfires on GPP (not NPP) in boreal North America (and change the title accordingly).

→ Yes, we have changed the title to "Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America" to reflect the main objective of this study.

Another major comment: the different chains of events discussed here are enormously complicated and the effect is very indirect. I suggest the authors show this in a suitable graphic. We have changes in climate affecting fire weather, but also affecting vegetation composition and fuel load. In addition we have changes in land use, in particular forestry and fire management (See Fig. 3 in Doerr and Satin showing for the U.S. increasing burned area, fewer fires, and an enormous rise in fire suppression costs). Both impact burned area and fire emissions. But then we also have atmospheric circulation patterns which are influenced by all sorts of things, among them greenhouse gas concentrations and aerosol load, some of it from boreal forest fires. And all of these together influence boreal forest NPP which in turn impacts the regional and global carbon cycle. Given this enormously complex web of causes and effects, I am not sure what we really learn here. It us up to the authors to clarify and give us a clear picture of what this paper is really about. Do that, I suggest considering the main questions and sub-questions as above, and then re-structuring the paper in order to answer them all in a systematic way. Much of it is there, but the information is too scattered.

→We agree that multiple factors, including climate change, land use change, and human activities (forest management) will affect both wildfire and ecosystem productivity. As the reviewer commented, these processes interplay with each other, leading to large uncertainties in the estimate. For the current study, we clarify that we limit our focuses to the processes shown in Figure 1. For other indirect processes, we either use fixed values for present day and midcentury (e.g., fuel load and vegetation cover) or ignore the related impacts due to the large uncertainties (e.g., forest management). In the discussion section, we explained why we used fixed fuel load and vegetation cover (Lines 624-640, or see the following response).

In the Introduction section, we present a new Figure 1 to clarify the main processes we examined in this study: "The major chain we investigate includes i) generation of aerosols and surface ozone from wildfire emissions and ii) impact of fire-emitted aerosols and ozone on plant photosynthesis through physical and biogeochemical processes." (Lines 116-118)

Increases in boreal wildfire activity: this manuscript builds heavily on Yue et al. (2015), which in turn builds heavily on Yue et al. (2013). This compartmentalisation of research is necessary given the said complexity of the subject. However, the foundations and basic assumptions on which the story rests here get a bit lost. This is particularly true for the fundamental assumption of increasing wildfire emissions, which here is stated as a matter of fact. While total burned area and even more average burned area per fire in the U.S. have increased in recent decades, it is far less clear whether burn severity has *increased as well (again: Doerr and Santin 2016). And burn severity is linked to the total amount of fuel combusted which is proportional to the emissions of carbon (but not necessarily to O3, NOx etc.). For all these, burned area is a necessary but not a sufficient predictor.*

→ Yes, we built the fire projections on the previous studies of Yue et al. (2013) and Yue et al. (2015). The decision is justified because of the complexity of this interdisciplinary research and because those previous published studies underwent rigorous uncertainty analysis. However, to avoid the confusion mentioned here, and to make this study complete and independent from earlier work, we explained more details about fire prediction and the foundations of our assumptions in the revised paper.

For this study, we apply constant fuel load for both present day and midcentury, but we consider impacts of climate change on fuel consumption by implementing responses of fuel moisture. As we discussed in section 4.2, changes in area burned likely dominate the projected changes in fire emissions:
"We apply constant land cover and fuel load for both present day and midcentury, but we estimate an increase in fuel consumption due to changes in fuel moisture. Future projection of boreal fuel load is highly uncertain because of multiple contrasting influences. For example, using a dynamic global vegetation model (DGVM) and an ensemble of climate change projections, Heyder et al. (2011) predicted a large-scale dieback in boreal-temperate forests due to increased heat and drought stress in the coming decades. On the contrary, projections using multiple DGVMs show a widespread increase in boreal vegetation carbon under the global warming scenario with CO_2 fertilization of photosynthesis (Friend et al., 2014). In addition, compound factors such as greenhouse gas mitigation (Kim et al., 2017), pine beetle outbreak (Kurz et al., 2008), and fire management (Doerr and Santin, 2016) may exert varied impacts on future vegetation and fuel load. Although we apply constant fuel load, we consider changes of fuel moisture because warmer climate states tend to dry fuel and increase fuel consumption (Flannigan et al., 2016). With constant fuel load but climate-driven fuel moisture, we calculate a 9% increase in boreal fuel consumption by the midcentury (Yue et al., 2015). Although such increment is higher than the prediction of 2-5% by Amiro et al. (2009) for a doubled-CO_2 climate, the consumption-induced uncertainty for fire emission is likely limited because changes in area burned are much more profound." (Lines 624-640)

Fire emission is largely dependent on area burned, not only because the amount of biomass burned is in ratio to area burned, but also because the larger area burned usually causes higher severity (Turetsky et al., 2011). From this aspect, larger area burned may have both positive (higher severity) and negative (fewer fuel left) impacts on emissions. For this study, we select area burned as the main metric to reduce the possible uncertainties in the estimate of fire emissions.

The fire prediction used here by the authors is based mainly on fire weather indices. The approach is statistical, and scientifically certainly valid. However, there are other *approaches that need to be mentioned and recognised. For example, the method used by the authors neglects the influence of changes in vegetation and fuel load on fire spread (please correct me if I got that wrong). But wildfires don't only need favourable fire weather to spread, they also need sufficient fuel and a continuous fuel bed. If it burns more often, there will be less fuel to burn and fire spread may be reduced. Has this negative feedback been taken into account? Has the impact of changing vegetation cover on burned area been taken into account? All these need to be better discussed.*

→ For this study, we predict area burned on the ecoregion basis. In each ecoregion, similar impacts of topography, human activity, and vegetation (fuel types and load) on the spread of wildfires are expected. This approach facilitates the comparisons of area burned in the present day and the future climate for regions with varied landscape features. Analyses of multiple observations have shown that weather parameters play the dominant role in regulating fire activity in boreal ecoregions (Gillett et al., 2004; Flannigan et al., 2005; Fauria and Johnson, 2006; Girardin and Wotton, 2009; Meyn et al., 2010), supporting the concept of fire prediction using weather factors/indexes.

We agree that other non-climatic factors influence wildfire ignition and spread efficiency. For example, fuel changes will alter the possibility of fire occurrence. These interactive processes are hardly included in a fire-weather model but could be considered in dynamic global vegetation models (DGVM). However, large uncertainties and complex feedbacks will diminish the credibility of fire predictions from DGVMs. For example, using different DGVMs, order of magnitude differences in the area burned changes are predicted over the U.S. (Bachelet et al., 2003; Rogers et al., 2011). In addition, for many DGVMs, the present-day area burned is not validated against observations. Furthermore, coupling an interactive fire scheme to the dynamic carbon cycle as a disturbance is a relatively new emerging research area. Meanwhile, the regressions used by Yue et al. (2015) explain 34-75% of variances of boreal area burned during 1980-2009.

In the revised paper, we explained how to consider the impact of fuel availability on fire spread as follows:
"We derive 1°×1° gridded area burned based on the prediction for each ecoregion following the approach by Yue et al. (2015). Temporally, the annual area burned estimated with regressions is first converted to monthly area burned using the mean seasonality for each boreal ecoregion during 1980-2009. Spatially, large fires tend to burn in ecosystems where historical fires are frequent because of favorable conditions (Keane et al., 2008). In each 1°×1° grid square, we calculate the frequency of fires larger than 1000 ha during 1980-2009; these fires account for about 85% of total area burned in boreal North America. We arbitrarily attribute 85% of area burned within each ecoregion to a number of fires with fixed size of 1000 ha. We then allocate these large fires among the 1°×1° grid cells based on the observed spatial probability of large fires. For example, if one grid box (named grid 'A') bears 1% of large fires (>1000 ha) within an ecoregion at present day, the same grid will bear the same possibility for large fires in the future. On the other hand, fuel availability limits reburning and fire spread during the forest return interval, suggesting that local burning will decrease the possibility of fires in the same location. To consider such impact, we scale the observed probabilities by the fraction

remaining unburned in each grid box, and then use this modified probability distribution to allocate large fires for the remaining months. For example, if present-day fires have consumed 20% of the total area within the grid 'A', then the possibility of large fire will be 0.8% (1%×0.8, instead of 1%) for this grid. Finally, we disaggregate the remaining 15% of area burned into fires 10 ha in size, and randomly distribute these fires across all grid boxes in the ecoregion. With this method, we derive the gridded area burned for boreal North America by eliminating reburning issues. Sensitivity tests show that specifying different area burned to the large fires (100 or 10 000 ha rather than 1000 ha) yields < 1 % changes in predicted biomass burned, suggesting that this approach is not sensitive to the presumed fire size in the allocation procedure." (Lines 204-227)

Specific comments:

L29: This is a factual statement about the future. These should be avoided in the scientific literature.

→ We changed the statement to: "Wildfire area burned is projected to increase significantly in boreal North America by the midcentury" (Lines 32 – 33)

L36: this is not 'boreal' area burned. North America does not even comprise half of the boreal zone.

→ We changed the sentence to: "area burned is predicted to increase by 66% in boreal North America" (Lines 39-40).

L38: ambient [O3] - could this rise above critical thresholds close the active fires? The statement sounds as if it was referring to average conditions and it does not take into account the episodic nature of wildfires. This is later discussed (L350ff), but it would be good for the reader to learn this already here.

→ We clarified as follows: "Fire O_3 causes negligible impacts on NPP because ambient O_3 concentration (with fire contributions) is below the damage threshold of 40 ppbv for 90% summer days." (Lines 40-42)

L53: please provide more recent examples, there are plenty.

→ We added two recent examples (Groot et al., 2013; Wang et al., 2015) as suggested.

Groot, W. J. d., D.Flannigan, M., and S.Cantin, A.: Climate change impacts on future boreal fire regimes, Forest Ecology and Management, 294, doi:10.1016/j.foreco.2012.09.027, 2013.

Wang, X., Thompson, D. K., Marshall, G. A., Tymstra, C., Carr, R., and Flannigan, M. D.: Increasing frequency of extreme fire weather in Canada with climate change, Climatic Change, 130, 573-586, doi:10.1007/s10584-015-1375-5, 2015.

L64: I suggest dropping the topic of plant health altogether in this manuscript. Sitch et al. (2007) is about the carbon cycle and stomatal closure, and does not address the question of plant health.

→ We revised this sentence as follows: "Surface O3 causes damages to photosynthesis through stomatal uptake (Sitch et al., 2007)" The words "plant health" have been removed throughout the paper.

L76: would drop the word "changes" here: aerosols impact the nature of the radiation, which impacts NPP. But changes in NPP do not necessarily mean changes in C uptake. This depends on changes in respiration. Needs discussion.

→ We revised this sentence as follows: "Furthermore, the aerosol radiative effects indirectly influence ecosystem productivity through concomitant meteorological perturbations that are only beginning to be examined" (Lines 81-83)

For this study, we show the responses in respiration in Fig. S2.

L95: usually, ensemble averages fear better when it comes to whether, seasonal or even decadal climate prediction. If this also applies to climate projections, however, is not something we know for sure.

→ We revised the sentence as follows:
"The multi-model ensemble approach has shown superior predictability over single models in historical climate simulations (Flato et al., 2013) and near-term climate predictions (Kirtman et al., 2014), and has been used as a standard technique to assess changes of climate variables in the long-term projections (Collins et al., 2013)." (Lines 99-103)

L127: "The number . . . is much fewer. . ." Awkward. Better: "There are much fewer . . .".

→ Revised as suggested.

L154: -> "A cloud mask applied to..."

→ Revised as suggested.

L182: What is was trying to understand here is whether fuel load is constant through time. It sounds like. This is an important point that needs to be clarified and discussed through the manuscript.

→ Yes, we use constant fuel load for this study because of large uncertainties exist for fuel projection. Instead, we consider changes in burning severity due to perturbations in fuel moisture.

In section “2.2 Wildfire emissions”, we explained as follows:
“As in Amiro et al. (2009) and Yue et al. (2015), we apply constant fuel load for both present day and midcentury because opposite and uncertain factors influence future projections (Kurz et al., 2008; Heyder et al., 2011; Friend et al., 2014; Kim et al., 2017). Instead, we consider changes in burning severity due to perturbations in fuel moisture as indicated by CFWI indexes (Yue et al., 2015). On average, we estimate a 9% increase in fuel consumption over boreal North America by the midcentury, because higher temperature and lower precipitation result in a future with drier fuel load (Flannigan et al., 2016).” (Lines 237-244)

In section “4.2 Limitations and uncertainties” we discussed as follows:
“We apply constant land cover and fuel load for both present day and midcentury, but we estimate an increase in fuel consumption due to changes in fuel moisture. Future projection of boreal fuel load is highly uncertain because of multiple contrasting influences. For example, using a dynamic global vegetation model (DGVM) and an ensemble of climate change projections, Heyder et al. (2011) predicted a large-scale dieback in boreal-temperate forests due to increased heat and drought stress in the coming decades. On the contrary, projections using multiple DGVMs show a widespread increase in boreal vegetation carbon under the global warming scenario with CO_2 fertilization of photosynthesis (Friend et al., 2014). In addition, compound factors such as greenhouse gas mitigation (Kim et al., 2017), pine beetle outbreak (Kurz et al., 2008), and fire management (Doerr and Santin, 2016) may exert varied impacts on future vegetation and fuel load. Although we apply constant fuel load, we consider changes of fuel moisture because warmer climate states tend to dry fuel and increase fuel consumption (Flannigan et al., 2016). With constant fuel load but climate-driven fuel moisture, we calculate a 9% increase in boreal fuel consumption by the midcentury (Yue et al., 2015). Although such increment is higher than the prediction of 2-5% by Amiro et al. (2009) for a doubled-CO_2 climate, the consumption-induced uncertainty for fire emission is likely limited because changes in area burned are much more profound.” (Lines 624-640)

L292: In addition to the observed GPP-PARdiff and GPP-PAR relationships, there should also be a sub-section on modelled GPP-PARdiff / GPP-PAR relationships. I say should, but in fact this will be crucial in order to establish the credibility of the present manuscript.

→ In section 3.2, we added additional model validation for GPP-PARdif relationships:
“The model also reproduces observed light responses of GPP to diffuse radiation in boreal regions. With the site-level simulations, we evaluate the modeled GPP-PAR_{dif} relationships at the hourly (instead of half-hourly) time step during summer. For 1342 pairs of GPP and PAR_{dif} at the site CA-Gro, the observed correlation coefficient is 0.42 and regression slope is 0.011, while the results for the simulation are 0.60 and 0.014, respectively. At the site CA-Qfo, the observations yield a correlation coefficient of 0.46 and regression slope of 0.007 for 1777 pairs of GPP and PAR_{dif}. The simulated

correlation is 0.61 and the regression is 0.011 at the same site. The GPP sensitivity to PAR_{dif} in the model is slightly higher than that of the available observations, likely because the latter are affected by additional non-meteorological abiotic factors. To remove the influences of compound factors other than radiation, we follow the approach of Mercado et al. (2009) to discriminate GPP responses to 'diffuse' and 'direct' components of PAR at the two sites (Fig. 5). The model successfully reproduces the observed GPP-to-PAR sensitivities. Increase in PAR boosts GPP, but the efficiency is much higher for diffuse light than that for direct light, suggesting that increase of diffuse radiation is a benefit for plant growth." (Lines 415-430)

L305: This paragraph could mention that the AOD-GPP slope at CA-Gro is not significantly different form zero.

→ We clarified as follows:
"However, the slope of regression between GPP and AOD is lower (and not significant) at CA-Gro compared with that at CA-Qfo" (Lines 384-385)

L319 "within 20%" requires continuation with "of . . .".

→ We revised the sentence as follows:
"Simulated GPP reasonably captures the spatial distribution with a high correlation coefficient of 0.77 ($p << 0.01$) and relatively small biases within 20% of the data product." (Lines 395-397)

L417: Yes, but what about the model?

→ We have validated the modeled GPP-PARdif relationships in the revised paper (see section 3.2).

L443: I disagree. Long-term radiation changes will certainly be reflected in shade/sun adaptation of the leaves. If there is less PAR, then saturated rates of photosynthesis will decline making photosynthesis more efficient at lower rates of radiation. This is already included in the original model by Farquhar et al. (1980), which you cite here.

→ Photosynthesis might be more efficient if PAR is reduced on the long-term period. However, such acclimation of photosynthesis is not unlimited. The validation in Figure 5 shows that the model (using Farquhar-Ball-Berry scheme) can reasonably capture GPP responses if both direct and diffuse radiation is reasonable. At the high latitudes, solar radiation is less abundant compared with that at lower latitudes. As a result, sunlit leaves at boreal regions are more sensitive to the reduction of direct light, offsetting the benefit of increased diffuse light. Observations also support this conclusion. "As shown in Beer et al. (2010), partial correlations between GPP and solar radiation are positive in boreal regions but negative over the subtropics/tropics, suggesting that light extinction by fire aerosols has contrasting impacts on plant photosynthesis in the high versus low latitudes." (Lines 696-699).

L467: I agree, intuitively, but I think there is no way we could quantify those uncertainties.

→ As in the Introduction section, we include citations to support the statement:
"Such an approach may help reduce model uncertainties in climatic responses to CO_2 changes (Collins et al., 2013; Kirtman et al., 2014), …" (Lines 602-604)

L516: I would really like to understand what you mean by a "missing land carbon source due to future wildfire pollution". Is the source missing now, or will it be missed in the future. And who will miss it anyway? Can you see how cloudy this statement is? But this is a good start for getting more in-depth as far as the carbon cycle is concerned (see major comments). Doesn't your model simulate the full carbon balance, including soil carbon? What happens there? Or if not, what could happen?

→ We agree that the expression "missing land carbon" was somewhat vague in the original manuscript version. We emphasize that fire pollution dampens land carbon assimilation in the 'future', instead of 'present day'. The climate model ModelE2-YIBs includes full carbon cycle for land ecosystem, but the current version does not include dynamic atmospheric CO_2 or dynamic ocean CO_2 cycle. The soil respiration takes thousands of years to reach equilibrium in the model, evolves on much longer timescales than air pollution chemistry (centuries/millennia versus years/decades), and requires transient versus time-slice simulations. Therefore, we made a decision to focus on ecosystem productivity, rather than the longer-term land carbon storage, as our metric of impact. In the discussion, we clarify that NPP is different from NEE but can be used as an indicator for the ecosystem carbon uptake: "Although NPP is not a direct indicator of the land carbon sink, reduction of NPP is always accompanied with the decline of net ecosystem exchange (NEE) and the enhanced carbon loss." (Lines 677-679)

In the revised paper, we extend our discussion to other regions: "Our analyses of fire pollution effects on boreal North American productivity may not be representative for other boreal ecosystems and/or on the global scale. There is substantial variability in plant species, topography, and climatology across different boreal regions. Such differences indicate distinct GPP sensitivities as well as fire characteristics. At lower latitudes, where anthropogenic pollution emissions are more abundant, ambient ozone concentrations may have exceeded damaging thresholds for most plant species. In those regions, additional ozone from a fire plume may cause more profound impacts on photosynthesis than our estimate for boreal North America. For example, Amazonian fire is predicted to reduce forest NPP by 230 Tg C yr^{-1} through the generation of surface ozone (Pacifico et al., 2015). Meanwhile, solar radiation is more abundant at lower latitudes, indicating more efficient increases in photosynthesis through aerosol DFE because the sunlit leaves receive saturated direct light in those regions. As shown in Beer et al. (2010), partial correlations between GPP and solar radiation are positive in boreal regions but negative over the subtropics/tropics, suggesting that light extinction by fire aerosols has contrasting impacts on plant photosynthesis in the high versus low latitudes. Further simulations and analyses are required to understand the net impacts of ozone and aerosols from biomass burning on the global carbon cycle." (Lines 685-701).

References:

Amiro, B. D., Cantin, A., Flannigan, M. D., and de Groot, W. J.: Future emissions from Canadian boreal forest fires, Can. J. For. Res., 39, 383-395, doi:10.1139/X08-154, 2009.

Bachelet, D., Neilson, R. P., Hickler, T., Drapek, R. J., Lenihan, J. M., Sykes, M. T., Smith, B., Sitch, S., and Thonicke, K.: Simulating past and future dynamics of natural ecosystems in the United States, Global Biogeochemical Cycles, 17, doi:10.1029/2001gb001508, 2003.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rodenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I., and Papale, D.: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, Science, 329, 834-838, doi:10.1126/Science.1184984, 2010.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Jr., W. J. G., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 1029-1136, 2013.

Doerr, S. H., and Santin, C.: Global trends in wildfire and its impacts: perceptions versus realities in a changing world, Phil. Trans. R. Soc. B, 371, doi:10.1098/rstb.2015.0345, 2016.

Fauria, M. M., and Johnson, E. A.: Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions, J. Geophys. Res., 111, G04008, doi:10.1029/2006jg000181, 2006.

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., and Stocks, B. J.: Future area burned in Canada, Clim. Change, 72, 1-16, doi:10.1007/S10584-005-5935-Y, 2005.

Flannigan, M. D., Wotton, B. M., Marshall, G. A., Groot, W. J. d., Johnston, J., Jurko, N., and Cantin, A. S.: Fuel moisture sensitivity to temperature and precipitation: climate change implications, Climatic Change, 134, 59, doi:10.1007/s10584-015-1521-0, 2016.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., and Rummukainen, M.: Evaluation of Climate Models, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465-570, 2013.

Friend, A. D., Lucht, W., Rademacher, T. T., Keribin, R., Betts, R., Cadule, P., Ciais, P., Clark, D. B., Dankers, R., Falloon, P. D., Ito, A., Kahana, R., Kleidon, A., Lomas, M. R., Nishina, K., Ostberg, S., Pavlick, R., Peylin, P., Schaphoff, S., Vuichard, N., Warszawski, L., Wiltshire, A., and Woodward, F. I.: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2, Proc. Natl. Acad. Sci. u. s. a., 111, 3280-3285, doi:10.1073/pnas.1222477110, 2014.

Gillett, N. P., Weaver, A. J., Zwiers, F. W., and Flannigan, M. D.: Detecting the effect of climate change on Canadian forest fires, Geophys. Res. Lett., 31, L18211, doi:10.1029/2004gl020876, 2004.

Girardin, M. P., and Wotton, B. M.: Summer Moisture and Wildfire Risks across Canada, Journal of Applied Meteorology and Climatology, 48, 517-533, doi:Doi 10.1175/2008jamc1996.1, 2009.

Heyder, U., Schaphoff, S., Gerten, D., and Lucht, W.: Risk of severe climate change impact on the terrestrial biosphere, Environmental Research Letters, 6, 034036, doi:10.1088/1748-9326/6/3/034036, 2011.

Kim, J. B., Monier, E., Sohngen, B., Pitts, G. S., Drapek, R., McFarland, J., Ohrel, S., and Cole, J.: Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios, Environmental Research Letters, 12, 045001, doi:10.1088/1748-9326/aa63fc, 2017.

Kirtman, B. P., Min, D., Infanti, J. M., Kinter, J. L., III, Paolino, D. A., Zhang, Q., van den Dool, H., Saha, S., Mendez, M. P., Becker, E., Peng, P., Tripp, P., Huang, J., DeWitt, D. G., Tippett, M. K., Barnston, A. G., Li, S., Rosati, A., Schubert, S. D., Rienecker, M., Suarez, M., Li, Z. E., Marshak, J., Lim, Y.-K., Tribbia, J., Pegion, K., Merryfield, W. J., Denis, B., and Wood, E. F.: The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction, Bulletin of the American Meteorological Society, 95, 585-601, 2014.

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., and Safranyik, L.: Mountain pine beetle and forest carbon feedback to climate change, Nature, 452, 987-990, doi:10.1038/nature06777, 2008.

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P. M.: Impact of changes in diffuse radiation on the global land carbon sink, Nature, 458, 1014-1017, doi:10.1038/Nature07949, 2009.

Meyn, A., Taylor, S. W., Flannigan, M. D., Thonicke, K., and Cramer, W.: Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920-2000, Global Change Biology, 16, 977-989, doi:Doi 10.1111/J.1365-2486.2009.02061.X, 2010.

Pacifico, F., Folberth, G. A., Sitch, S., Haywood, J. M., Rizzo, L. V., Malavelle, F. F., and Artaxo, P.: Biomass burning related ozone damage on vegetation over the Amazon forest: a model sensitivity study, Atmospheric Chemistry and Physics, 15, 2791-2804, doi:10.5194/acp-15-2791-2015, 2015.

Rogers, B. M., Neilson, R. P., Drapek, R., Lenihan, J. M., Wells, J. R., Bachelet, D., and Law, B. E.: Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest, J. Geophys. Res., 116, G03037, doi:10.1029/2011jg001695, 2011.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E., and Kasischke, E. S.: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands, Nature Geoscience, 4, 27-31, doi:10.1038/Ngeo1027, 2011.

Yue, X., Mickley, L. J., Logan, J. A., Hudman, R. C., Martin, M. V., and Yantosca, R. M.: Impact of 2050 climate change on North American wildfire: consequences for ozone air quality, Atmospheric Chemistry and Physics, 15, 10033-10055, doi:10.5194/acp-15-10033-2015, 2015.