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).

Reviewer 2

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 authors discuss the hypotheses of a strong coupling between increased future biomass burning in boreal regions and feedbacks on the carbon cycle through air pollutant emissions. These feedbacks work mainly through aerosol impacts on diffuse radiation, and according to the authors less so through ozone. The aerosol feedback causes changes in atmospheric transport, leading to changing rainfall patterns and soil moisture.

While the results are overall fairly plausible, but speculative; the assumptions are not always well described and results not always sufficiently discussed.

A number of aspects of this study are particularly worrying:

- The relationship of aerosol optical thickness and NPP is based on correlations observed at two stations in Canada. The correlations at these two stations are pretty weak, perhaps because there are a number of other factors that are potentially constraining NPP. The extrapolation to other boreal ecosystems is adding large additional uncertainties. This makes the study with regard to AOD highly speculative.

→ In the revised paper, we performed 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)

We extrapolate the AOD-GPP relationships at two sites as representative of North American boreal ecosystems because of the limitation in data availability. The weak correlations between AOD and GPP are observational results. Through comprehensive validation with all available observational data for carbon fluxes, air pollution concentrations, and GPP sensitivities to ozone and diffuse radiation (section 3.2), we assert that our results have been constrained to measurements/observations to the maximum extent possible. Let us reflect that global coupled Earth system models exist exactly to probe the types of underlying process interactions and feedbacks in this study, where it is fundamentally impossible to "see" the effect in observations alone that by nature integrate all processes simultaneously.

- The results presented in this paper are much about the feedbacks in the earth system, changes in transport etc. Yet the authors use a fairly simplified climate modeling approach in which SST is fixed, and part of the feedbacks on longer time scales are excluded. I am aware of a similar earlier paper by these authors on China, where one of the reviewers has made a similar point- and the authors asserted that these feedbacks are not dominating. But what is the evidence for that? I propose that the authors add at least one coupled ocean simulation, and resolve this issue.

The referee misunderstands some aspects of the Earth system model experimental design. The "issue" is not going to be resolved by adding "at least one coupled ocean simulation."

→ Firstly, it is a common and valid approach to investigate regional aerosol-climate feedbacks without ocean responses. For example, Cook et al. (2009) found that dust-climate-vegetation feedback promotes drought in U.S., with a climate model driven by prescribed SSTs. Similarly, Liu (2005) found fire aerosols enhance regional drought using a regional climate model, which even ignores the feedback between local climate and large-scale circulation. Regional climate model frameworks such as WRF-Chem are regularly applied to understand effects of aerosol pollution on weather patterns under the assumption of fixed SSTs. Ocean feedbacks are important but slow (century/millennial), while aerosol effects over land are usually fast (annual/decadal). Applying fixed SSTs, which is the fundamental basis of the Effective Radiative Forcing metric defined in IPCC AR5, allows us to explore the complex system step by step.

Secondly, running with a fully coupled dynamic ocean would require a several-thousands-of-years preindustrial spin-up, followed by several ensemble-member transient preindustrial to present-day runs. We do not have access to the computational resources required for such dynamic ocean simulations that are generally in the remit of the international climate modelling centers. For example, GISS performs these simulations with ModelE2 for the CMIP, but no simulations are available with our coupled vegetation model YIBs. Furthermore, inclusion of dynamical ocean feedbacks might introduce additional uncertainties to the system, making it difficult to identify the direct impact of aerosols.

Thirdly, slab ocean simulations are not viable either because we do not have projections of mixed layer depth by 2050s, which might change substantially, but very uncertain for different CGCMs (Yeh et al., 2009). Therefore, it is not possible to obtain the associated future atmosphere-ocean heat fluxes for our time-slice simulations. The future 2050 time-slice projections in our work do apply future SSTs and sea ice boundary conditions.

Finally, the reviewer connected this question to our recent publication focused on China. Actually, the referee of that paper had some concerns on the dynamical large-scale signals between regional and global scales, though he considered the use of fixed SSTs might introduce exaggerated responses over land due to the artificial land-ocean thermal contrast. Our responses to that paper did not deny such deficit: "Diagnosing long range dynamical mechanisms is out of scope of this study, …, this specific study will not gain from an explicit description of the multi-scale dynamical mechanisms that drive the regional meteorological changes". In another recent study, that was focused at the global-scale, however, we have identified the separate and combined roles of fast aerosol feedbacks associated with the land and slow aerosol feedbacks associated with the ocean: "Unger N, Yue X, Harper KL. (2017) Aerosol climate change effects on land ecosystem services, *Faraday Discuss*, 200, 121-142, DOI:10.1039/C7FD00033B."

- As the authors convincingly show: changes in soil moisture are dominating the carbon cycle feedbacks. However, I haven't seen at all in this publication a discussion on the accuracy of the present soil moisture simulation. Clearly a good baseline modeling of soil moisture is prerequisite for estimating these future impacts. Moreover, the authors should give a better description of what is happening with the vegetation under dryer conditions and how that in turn leads to increased fire risk and burning.

→ Global observations of soil moisture are not available. In the revised paper, we compare soil moisture with two different datasets in Figure S1. The comparisons show that the ModelE2-YIBs model generally reproduces the reasonable spatial pattern with low biases. "For >3300 land grids in the summer, the spatial correlation coefficient is R = 0.25 between ModelE2-YIBs and CLM, and R = 0.34 between CLM and ERA-Interim. The global area-weighted soil moisture is 0.22 $\mathrm{mm^3\ mm^{-3}}$ for ModelE2-YIBs, 0.26 $\mathrm{mm^3\ mm^{-3}}$ for CLM, and 0.23 $\mathrm{mm^3\ mm^{-3}}$ for ERA-Interim. Statistics for winter are very similar to the summer results."

- While the authors may be right that ozone impacts is playing a minor role at high-latitudes, the discussion is very much handwaving and unconvincing. This needs to be improved.

In the revised text, we clarified that:
"The impacts of the boreal fire O_3 on forest photosynthesis are predicted using the flux-based damage algorithm proposed by Sitch et al. (2007), which has been fully evaluated

against available O_3 damage sensitivity measurements globally and over North America (Yue and Unger, 2014; Yue et al., 2016; Yue et al., 2017)" (Lines 125-128)

We explained how Sitch's scheme works:
"For this scheme, O_3 damaging level is dependent on excess O_3 stomatal flux within leaves, which is a function of ambient O_3 concentration, boundary layer resistance, and stomatal resistance. Reduction of photosynthesis is calculated on the basis of plant functional types (PFTs), each of which bears a range of low-to-high sensitivities to O_3 uptake." (Lines 290-294).

We summarized the evaluation of Sitch's scheme:
"With the Sitch et al. (2007) scheme, the YIBs model simulates reasonable GPP responses to $[O_3]$ in North America (Yue and Unger, 2014; Yue et al., 2016). Generally, damage to GPP increases with the enhancement of ambient $[O_3]$, but with varied sensitivities for different plant species (see Fig. 6 of Yue and Unger (2014)). In response to the same level of $[O_3]$, predicted O_3 damages are higher for deciduous trees than that for needleleaf trees, consistent with observations from meta-analyses (Wittig et al., 2007)." (Lines 410-415)

In the following responses, we showed the validation of Sitch et al. (2007) scheme globally and regionally (Figures R1 and R2), which we did not present in the paper because those plots have been published in our previous work.

Finally, we show O_3 stomatal flux in a new Figure 8, which shows that O_3 uptake is limited in boreal North America.

All these results support our conclusion that O_3 vegetation damage, no matter including fire emissions or not, is trivial over boreal North America.

- The uncertainties and caveats described above should be much better described in conclusions and abstract. The necessary steps in modeling and observations to corroborate the findings here should be outlined better.

→ We extend the discussion about the uncertainties and caveats of the research: "In this study, we examine the interactions among climate change, fire activity, air pollution, and ecosystem productivity. To reduce the complexity of the interactions, we focus on the most likely dominant feedback and thus main chain of events: "climate → fire → pollution → biosphere' (Fig. 1). However, our choice of feedback analysis does not mean that the interplay of other processes is unimportant. For example, climate-induced changes in vegetation cover/types can influence fire activity by alteration of fuel load, and air pollution by BVOC emissions (climate → biosphere → fire/pollution). In addition, other feedbacks may amplify ecosystem responses but are not considered. For example, the drought caused by fire aerosols in the midcentury (Fig. 11) may help increase fire activity (fire → pollution → climate → fire). Furthermore, we apply fixed SSTs in the climate simulations because reliable ocean heat fluxes for the future world were not available. Many previous studies have investigated regional aerosol-climate feedbacks without ocean responses. For example, Cook et al. (2009) found that dust-climate-vegetation feedback promotes drought in U.S., with a climate model driven by prescribed SSTs. Similarly, Liu (2005) found fire aerosols enhance regional drought using a regional climate model, which even ignores the feedback between local climate and large-scale circulation. While we do concede that our experimental design is not a complete assessment of all known processes and feedbacks, within these limitations, this study for the first time quantifies the indirect impacts of wildfire on long-range ecosystem productivity under climate change." (Lines 581-599).

Additional model validations (Figure 5) have been performed to corroborate the main findings of this research.

Despite these shortcomings, I find the manuscript interesting and potentially important. I would therefore recommend the authors to address my major concerns and resubmit to ACP.

I have a number of more detailed comments below.

Detailed comments:

l. 1 Title is not accurately describing the more limited content of the paper.

→ The title has been changed to "Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America" to reflect the main focus of the study.

l. 29 scattering and absorption.

→ Revised as suggested.

l. 38 The authors refer to Sitch et al (ozone flux based approach) in the text and here refer to a 40 ppb threshold- probably similar to a AOT40 type of metric. It remains unclear what has been done, and for instance which 'Sitch' (high sensitivity-low sensitivity) has been used. It would be good if the authors could clarify what has been done, and show their actual stomatal ozone fluxes.

→ Yes, we used Sitch et al. (2007) scheme for this study. In our previous work, we have validated Sitch's scheme against available observations. Figure R1 is adopted from Yue and Unger (2014), which shows percentage changes in GPP of different PFTs over North America in response to varied levels of [O3]. Square symbols are from measurements. As Figure R1 shows, evergreen needleleaf forest (ENF) and shrubland (SHR), which are dominant PFTs over boreal North America, have low sensitivity to O_3 damages with a damaging threshold of 40 ppbv. In the paper, we explained more details about O_3 thresholds. We also show the stomatal ozone fluxes in a new figure 8 as suggested.

"Surface O3, including both fire and non-fire emissions (Table 2), causes limited (1-2%) damages to summer GPP in boreal North America (Fig. 7)." (Lines 452-453).

"Over boreal North America, dominant PFTs are ENF (accounting for 44% of total vegetation cover) and tundra (treated as shrubland, accounting for 41% of total vegetation cover). Both species have shown relatively high O_3 tolerance with a damaging threshold of 40 ppbv as calculated with Sitch's scheme (Yue and Unger, 2014). For boreal regions, the mean [O_3] of 28 ppbv (Fig. 4a) is much lower than this damaging threshold, explaining why the excess O_3 stomatal flux (the flux causing damages) is low there (Fig. 8)." (Lines 457-462).

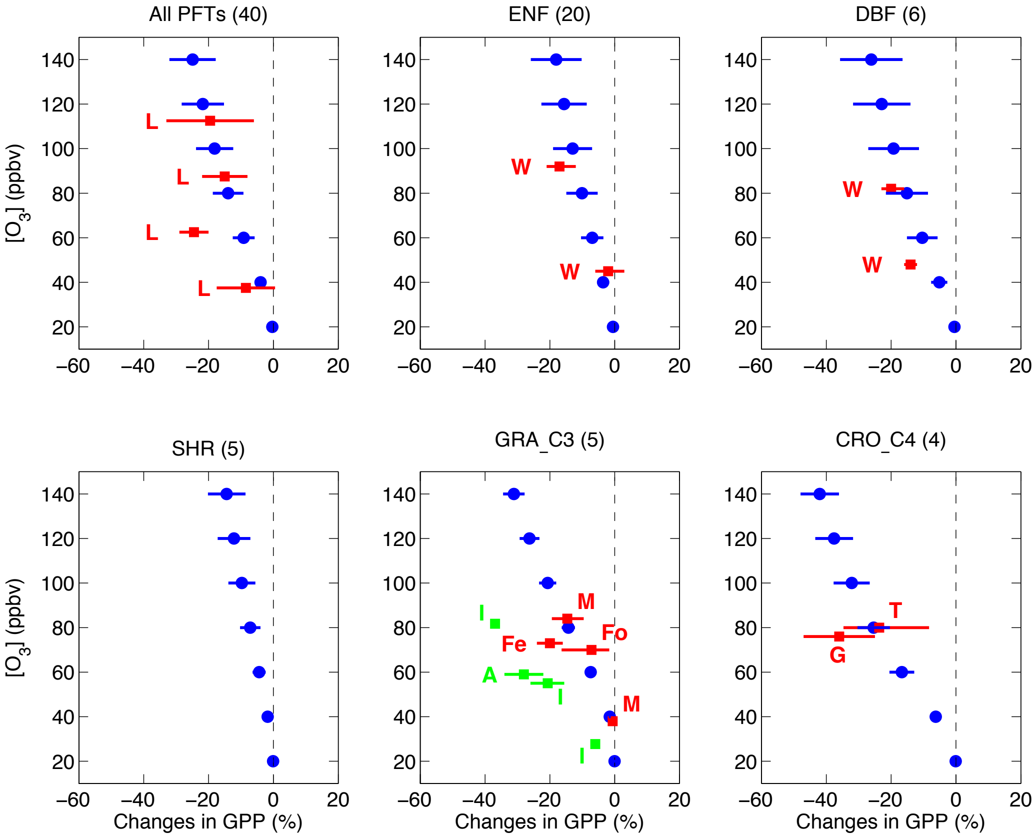

Figure R1. Changes in GPP for all and individual PFTs in the presence of different levels of $[O_3]$ as simulated by the vegetation model. Simulations are performed at 40 North American Carbon Program (NACP) sites with a fixed $[O_3]$ for either low or high O_3 sensitivity. The short blue lines show the damages ranging from low to high O_3 sensitivity, with the blue points indicating the average reductions. The simulation results are averaged for all the sites or for the sites with the same PFT. The number of sites used for average is shown in the title bracket of each subplot. The solid squares with lines show the results (mean plus uncertainty) based on measurements reported by multiple literatures. For more details, please refer to Yue and Unger (2014).

l. 43 the authors will capture only partly the feedbacks since ocean temperatures are fixed SST modelling set-up.

→ Yes, we are limited to fixed SST for the difficulty in the configuration of ocean heat flux, large uncertainty of ocean-atmosphere interaction, and the step-by-step strategy of research. Please refer to our responses to the major comments.

l. 45 How much are these direct emissions and how does it compare to the feedback effects?

→ We added values of direct emissions as suggested "Our results suggest that future wildfire may accelerate boreal carbon loss, not only through direct emissions increasing from 68 Tg C yr^{-1} at present day to 130 Tg C yr^{-1} by midcentury, but also through the biophysical impacts of fire aerosols." (Lines 47-50)

L 55 see l. 45. What is found in this study and how does it relate to the air pollution change in carbon budget?

→ We have added the number of direct fire emissions in the abstract as suggested (see the above response).

L68: more uncertain- this is a value judgement in reality we also do not know the ozone impact well either. Perhaps what the authors want to say is that the potential impact is even larger, and can swap sign.

→ Yes, ozone effect is uncertain in magnitude (species dependent) but is generally negative. We use the statement 'more uncertain' here to indicate that aerosol impact on photosynthesis may change signs at certain conditions.

L81: on the other hand: to me it looks quite consistent when considering the uncertainties.

→ The statement has been removed.

l. 82-95: part of the differences can be due to just using different climate scenarios, and are more or less comparing apples and pears.

→ We added some results from our previous study to support the conclusion:
"The increasing rate in Balshi et al. (2009) is higher than that in Amiro et al. (2009), indicating substantial uncertainties in fire projections originating from both fire models and simulated future climate. However, even with the same fire models and climate change scenario, large uncertainties (in both magnitude and signs) are found in the projection of area burned among individual climate models (Moritz et al., 2012; Yue et al., 2013)." (Lines 94-99)

l. 95: perhaps some words why A1B- and how it maps to RCPs (I think it is RCP6.0 equivalent). In the discussion you mention that the various scenarios until 2050 it is statistically almost similar, in my experience it is the 2050s where scenarios start diverging.

→ The 2050 CO_2 concentration is projected to 532 ppm in the A1B scenario, similar to the value of 541 ppm in the RCP8.5 but higher than the value of 478 ppm in the RCP6.0. In method section 2.2, we explain the connection between A1B and RCP8.5 scenarios as follows:

"In the A1B scenario, CO_2 concentration is projected to 532 ppm by the year 2050, similar to the value of 541 ppm in IPCC RCP8.5 scenario (van Vuuren et al., 2011) archived for the Coupled Model Intercomparison Project Phase 5 (CMIP5)." (Lines 199-202).

L 113- this is a very short description. What sensitivity was included? How is consistency between the atmospheric model and land model ensured, how are fluxes calculated? Is Sitch still reflecting the newest knowledge? One can write a whole paper on what is here cryptically mentioned in one sentence.

→ The Sitch et al. (2007) scheme has been fully evaluated in our previous researches (Figures R1 and R2). We simplify our description here only to emphasize our main focus of this study, which is to examine impacts of fire pollution on ecosystem productivity. In the revised text, we explained more details:

"The impacts of the boreal fire O_3 on forest photosynthesis are predicted using the flux-based damage algorithm proposed by Sitch et al. (2007), which has been fully evaluated against available O_3 damaging measurements globally and over North America (Yue and Unger, 2014; Yue et al., 2016; Yue et al., 2017)." (Lines 125-128)

"An interactive flux-based O_3 damage scheme proposed by Sitch et al. (2007) is applied to quantify the photosynthetic responses to ambient O_3 (Yue and Unger, 2014). For this scheme, O_3 damaging level is dependent on excess O_3 stomatal flux within leaves, which is a function of ambient O_3 concentration, boundary layer resistance, and stomatal resistance. Reduction of photosynthesis is calculated on the basis of plant functional types (PFTs), each of which bears a range of low-to-high sensitivities to O_3 uptake." (Lines 288-294)

"… simulations F10O3 and F50O3 calculate offline O_3 damage based on the simulated O_3 from all sources including fire emissions. For these simulations, reductions of GPP are calculated twice with either low or high O_3 sensitivity. However, both of these GPP changes are not fed back into the model to influence carbon allocation and tree growth." (Lines 308-311)

"With the Sitch et al. (2007) scheme, the YIBs model simulates reasonable GPP responses to $[O_3]$ in North America (Yue and Unger, 2014; Yue et al., 2016). Generally, damage to GPP increases with the enhancement of ambient $[O_3]$, but with varied sensitivities for different plant species (see Fig. 6 of Yue and Unger (2014)). In responses to the same level of $[O_3]$, predicted O_3 damages are higher for deciduous trees than that for needleleaf trees, consistent with observations from meta-analyses (Wittig et al., 2007).” (Lines 410-415)

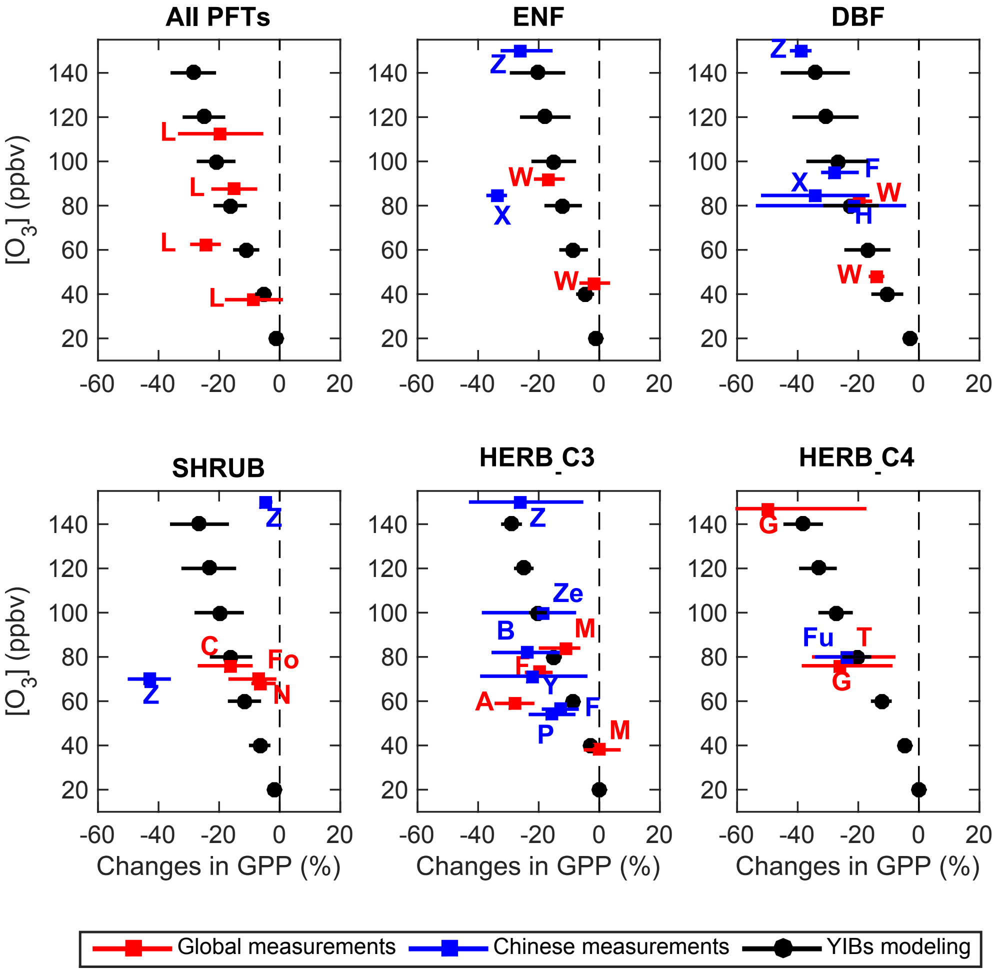

Figure R2. Evaluation of O$_3$ damaging scheme over China. For more details, please refer to Yue et al. (2017).

l. 138-142 most relevant to discuss performance of MODIS retrieval over boreal areas even if it doesn’t coincide with the flux sites. Summarize here what Strada found?

→ We summarized the findings by Strada et al. (2015) as follows:

“Strada et al. (2015) used ground-based AOD observations from the Aerosol Robotic Network (AERONET) near AMF sites to validate the sampling technique of MODIS 3-km AOD product. They found high correlations of 0.89-0.98 and regression slopes from 0.89 to 1.03 for daily AOD between AERONET and MODIS at four AMF sites.” (Lines 153-157).

l. 162 would be good to provide the statistics in the supplementary and give summary *here. It is really hard to understand here what is meant with 'much fewer' and how it can still be used.*

→ The number of sample pairs has been shown in Table 4. We added these numbers to the revised text:

"At the two selected sites, we calculate the Pearson's correlation coefficients between half-hourly GPP and different components of PAR. In total, we select 2432 and 3201 pairs of GPP and PAR measurements at CA-Gro and CA-Qfo, respectively." (Lines 146-148)

"In total, we select 65 pairs of GPP and AOD at CA-Gro site and another 59 pairs at CA-Qfo site. The GPP-AOD sampling pairs are much fewer than GPP-PAR, because …" (Lines 176-178)

l. 160-190 for clarity: future burning is assumed to be depending on fire-weather alone (regression relationship). Is there a relationship of fuel load with CO2 and fire management, if not what could be the possible uncertainties from these assumptions? Not clear here if the climate simulations would include a feedback on fires via the fire weather risk.

→ We do not consider changes in fuel load due to large uncertainties in the projection. However, we include response of fuel moisture to climate change. We clarified 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)

We discuss the uncertainties of our consumptions in the section 4.2:
"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)

l. 194 please give the values. What is meant with much higher?

→ We clarified as follows:
"We use the average value of 1.6 g NO per Kg dry mass burned (DM) from six studies as NO_x emission factor, because the number of 3.0 g NO per Kg DM reported in Andreae and Merlet (2001) is much higher than that of 1.1 g NO per Kg DM from field observations (Alvarado et al., 2010)." (Lines 248-251)

l. 228-232 Give a short summary on what the flux scheme is about. Summarize in a few lines what was the outcome of this benchmarking, and the consequence for this study.

→ We clarified as follows:
"An interactive flux-based O_3 damage scheme proposed by Sitch et al. (2007) is applied to quantify the photosynthetic responses to ambient O_3 (Yue and Unger, 2014). For this scheme, O_3 damaging level is dependent on excess O_3 stomatal flux within leaves, which is a function of ambient O_3 concentration, boundary layer resistance, and stomatal resistance. Reduction of photosynthesis is calculated on the basis of plant functional types (PFTs), each of which bears a range of low-to-high sensitivities to O_3 uptake." (Lines 288-294)

l. 252 how does the RCP8.5 scenario how link to the use of the A1B scenario mentioned earlier (l 95).

→ We explained the link between RCP8.5 and A1B scenario as follows:
"In the A1B scenario, CO_2 concentration is projected to 532 ppm by the year 2050, similar to the value of 541 ppm in IPCC RCP8.5 scenario (van Vuuren et al., 2011) archived for the Coupled Model Intercomparison Project Phase 5 (CMIP5)." (Lines 199-202)

l. 255 can a short description of the practical implications coming from the climate scenarios be given.

→ We added the following descriptions:
"Decadal average monthly-varying SST and sea ice of 2006-2015 are used as boundary

conditions for present-day (2010s) runs while that of 2046-2055 are used for future (2050s) runs. In the RCP8.5 scenario, global average SST increases by 0.62 °C while sea ice area decreases by 13.8% at the midcentury compared to the present-day level." (Lines 322-325)

l. 258 does CO2 impact fires and fire emissions?

→ We explained as follows:
"The enhancement of CO_2 will affect climate (through longwave absorption) and ecosystem productivity (through CO_2 fertilization), but not the fire activity and related emissions directly." (Lines 328-330)

l. 260 Explain better the model set-up: if area is burnt, does that also change the land-cover? Would that contradict the use of prescribed landcover?

→ We do not predict changes in land cover as multiple factors interplay and offset.
"As a result, a land cover dataset derived from satellite retrievals (Hansen et al., 2003) is applied as boundary conditions for both the 2010s and 2050s." (Lines 336-338).

"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." (Lines 624-634)

l. 273-274 2 years spin-up and 10 years seems to be a short time scale for ecosystem responses. Can the authors comment to what extent this represents full response.

→ As we showed below (Figure R3), NPP in four offline simulations reaches equilibrium within a short period, suggesting that a two-year spin-up is enough for the offline simulations.

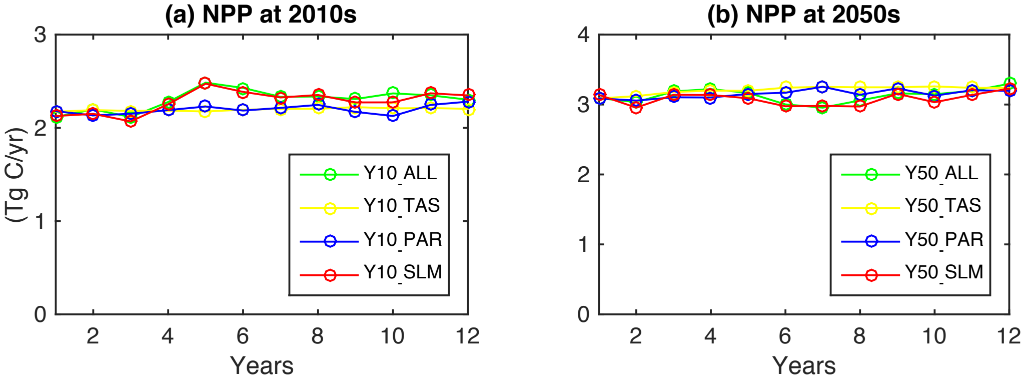

Figure R3. Simulated annual NPP over boreal North America at (a) 2010s and (b) 2050s.

l. 235-275 I would like to see a description of how the Yale model is treating regrowth after fires fires, and how the dynamics work out on time scales longer than 10 years. Can we expect an interaction between changes in age-structure and ozone and aerosol effects?

→ The YIBs model does not simulate vegetation dynamics (changes in PFT distribution), but does simulate changes in LAI, growth and tree heights. Please see Response to Reviewer (1) for a full description of our simplified treatment of fuel availability on fire spread in present and future. To our knowledge, there is no available measurement data on age-structure and ozone and aerosol effects, and as such they are not considered here. These types of "second order" interactions will need to be addressed in future research (5-10 year plan) as the coupled chemistry-carbon-climate models advance.

In the revised paper, we emphasize the current limitations of the YIBs model:

"YIBs is a process-based vegetation model that dynamically simulates changes in leaf area index (LAI) through carbon assimilation, respiration, and allocation for prescribed PFTs." (Lines 278-279)

"The YIBs vegetation model cannot simulates changes in PFT fractions. … As a result, a land cover dataset derived from satellite retrievals (Hansen et al., 2003) is applied as boundary conditions for both the 2010s and 2050s." (Lines 331-338)

l. 287 can you show in supplementary the interpolated fields for the relevant time periods?

→ Gridded GPP and AOD from observations have been shown in Figures 3c and 3d with a resolution of 2°×2.5°.

l. 300 would such a light saturation still be valid under changing CO2 conditions? Please *comment, and what could be the impact.*

→ We do not have available field observations under changing CO_2 conditions, and as a result, we cannot derive the GPP-PAR_{dir} relationships under the changing CO_2 conditions. Increased CO_2 enhances GPP but inhibits stomatal conductance. These effects may affect light responses of photosynthesis with unclear extents.

l. 311 Correlation of AOD and GPP is weak to very weak. The value 3.5+/- 1.1 is just the average of the two slopes? What is the meaning of 1.1 is it one standard deviation based on two observation sets?

→ Yes, the correlation between AOD and GPP is weak at the site CA-Gro but significant at the site CA-Qfo. The poor data availability limits our exploration of AOD-GPP relationships in boreal region. Here, we calculate the average of slopes at sites CA-Gro and CA-Qfo. The value 1.1 is not standard deviation but the range of slopes between two sites. We clarified in the paper as follows: "On average, GPP sensitivity (denoted as mean ± range) is estimated as 3.5 ± 1.1 μmol m^{-2} s^{-1} per unit AOD at lower latitudes of boreal regions in the summer." (Lines 388-389)

l. 323 Indeed patterns look everywhere reasonable except the western part. What could be the cause of this. Any indication on MODIS data quality? Or missing sources in the NASA model that can explain this? Volcanoes?

→ We plotted AOD from Multi-angle Imaging SpectroRadiometer (MISR) in Figure R4. Similar to MODIS, the MISR AOD also shows high values in western Canada. "The simulation fails to capture the high values in the west, possibly due to a climate model underestimation of biogenic secondary organic aerosol, which may be an important contribution over the western boreal forest." (Lines 401-403)

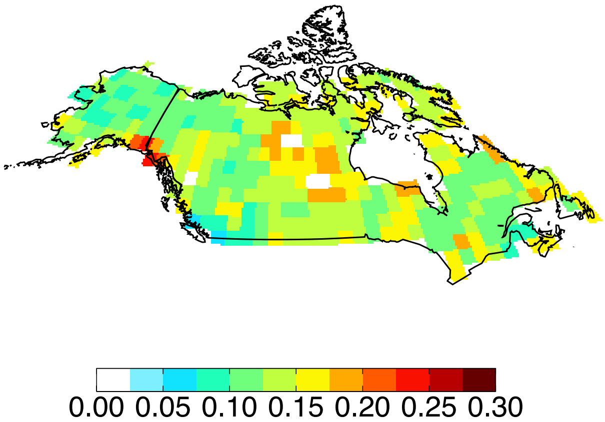

Figure R4. Observed summer AOD from MISR *l. 326 What is compared here? 24 hr mean over June, July, August? Did the authors compare at the measurement altitude? I would recommend to focus on daytime values, as more relevant for ozone damage and usually less local conditions .The Sitch approach requires fluxes, and the methodology in this paper needs to be described as well.*

→ We changed the validation from 24-hour mean [O3] to maximum daily 8-hour average (MDA8) [O3] in Figure 4. The MDA8 [O3] is a common metric to represent daytime [O3]. For Sitch's scheme, we have explained how it works in the method section 2.3: "For this scheme, O_3 damaging level is dependent on excess O_3 stomatal flux within leaves, which is a function of ambient O_3 concentration, boundary layer resistance, and stomatal resistance. Reduction of photosynthesis is calculated on the basis of plant functional types (PFTs), each of which bears a range of low-to-high sensitivities to O_3 uptake." (Lines 290-294). We also showed ozone stomatal flux in Figure 8.

l. 331-341. The increase in emissions needs to be described here. How is the contribution of wildfire emissions present determined (zero-out?). It seems that the % increase in ozone scales near-linear with the NOx (and other) emissions? But the contribution to AOD much less due to the abundance of secondary organics from BVOC emissions?

→ We explained more details about fire emissions as follows:
"During 1980-2009, wildfire is observed to burn 2.76×10^6 ha and 156.3 Tg DM every year over boreal North America. Similarly, the ensemble prediction with fire regression models estimates present-day area burned of 2.88×10^6 ha yr^{-1} and biomass burned of 160.2 Tg DM yr^{-1} (Yue et al., 2015). By the midcentury, area burned is projected to increase by 77% (to 5.10×10^6 ha yr^{-1}) in boreal North America, mainly because of the higher temperature in future fire seasons. Consequently, biomass burned increases by 93% (to 308.6 Tg yr^{-1}) because fuel consumption also increases by 9% on average in a drier climate (Yue et al., 2015)." (Lines 434-441)

The contribution of wildfire emissions is calculated as: fire-induced air pollution / (background plus fire-induced air pollution) × 100%. As a result, the fire-induced air pollution is not zero out in the denominator.

We showed absolute changes of ozone and aerosols as follows:
"On average, wildfire emissions contribute 7.1 ± 3.1% (2.1 ± 0.9 ppbv) to surface O_3 and 25.7 ± 2.4% (0.03 ± 0.003) to AOD in the summer over boreal North America in the present day. By midcentury, these ratios increase significantly to 12.8 ± 2.8% (4.2 ± 0.9 ppbv) for O_3 and 36.7 ± 2.0% (0.05 ± 0.003) for AOD." (Lines 445-448) As it shows, absolute change of AOD is less than O_3, which is not relate to the abundance of BSOA.

Changes of O_3 and AOD are not only dependent on emissions, but also on chemical processes and physical deposition. In a warmer climate, production of O_3 is faster, which may in part explain why O_3 enhancement is higher than AOD. In addition, atmospheric circulation may cause different diffusion for O_3 and aerosols due to their different mass load. As a result, we cannot conclude that [O_3] is linear to emissions while aerosol is non-linear.

l. 344-355 the ozone damage discussion is extremely handwaving and confusing. Where is the 40 ppb threshold coming from, and how does that compare to the use of the Sitch method? Only from Figure 4 I understand that indeed the Sitch high and low sensitivities have been used, but it is not discussed in the text. Anyway it seems that the model has a lot of data point above 40 ppb- but it hard to figure out how good the model performance is where the fire emissions have an impact.

→ We added new statement and analyses in the revised paper (see the responses to the major comments) to support our conclusions about ozone effects. Here, we explained why 40 ppbv is used as a threshold: "Over boreal North America, dominant PFTs are ENF (accounting for 44% of total vegetation cover) and tundra (treated as shrubland, accounting for 41% of total vegetation cover). Both species have shown relatively high O_3 tolerance with a damaging threshold of 40 ppbv as calculated with Sitch's scheme (Yue and Unger, 2014)" (Lines 457-460)

l. 357 at this point it is not clear what optical properties have been assigned to particles.

→ We explained in the method section 2.3 about the optical properties for aerosols: "Size-dependent optical parameters computed from Mie scattering, including extinction coefficient, single scattering albedo, and asymmetry parameters, are applied for each aerosol type (Schmidt et al., 2014)." (Lines 267-270)

l. 369-381 The circulation feedbacks are an important result of the paper, but due to the approach of constraining SST will include only part of the feedbacks. I would argue that the authors should try to address in one additional simulation why they can ignore these longer timescales.

→ Please see our response to the major comments.

l. 402-414 We shouldn't expect a full attribution of feedbacks due to aerosol- so this is pretty convincing. However, as soil moisture is the most important feedback- I am missing here completely a discussion on how realistic soil moisture is represented in the current modeling system, and how the soil moisture feedback is leading to increased burning. At this moment a discussion of the short effects on the carbon cycle by increased burning is missing.

→ We evaluated the baseline simulation of soil moisture in Fig. S1. For this study, we do not consider the feedback of soil moisture on biomass burning. The fire prediction is performed independently by considering impacts of temperature, relative humidity, and fire indexes (Yue et al., 2013; Yue et al., 2015).

Reviewer (1) also commented on the many possible interactions among climate, fire, and carbon cycle. However, Reviewer (1) suggests to clarify the main chain of events to reduce the complexity and uncertainty of the analyses: "*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.*" By considering the opinions of both reviewers, we plotted the new figure 1 to illustrate the main processes examined.

L 433 In Amazonia a large fraction (perhaps more than 50 %) is due to deforestation fires, and may not have a link to soil moisture. Discuss

→ The comparison here is for the aerosol diffuse fertilization. Both studies compare the changes of carbon fluxes by perturbations of diffuse radiation induced by fire aerosols. No effects of soil moisture are included.

l. 434 discrepancy or just a difference.

→ We revised to: "There are at least two reasons for such a difference" (Line 550)

l. 457 Again- we need to know more about how good soil water is represented in the model- as the paper relies so much on the changes of soil moisture.

→ We presented the evaluation of soil moisture in Figure S1. The comparisons show that the ModelE2-YIBs model generally reproduces the reasonable spatial pattern with low biases. "For >3300 land grids in the summer, the spatial correlation coefficient is R = 0.25 between ModelE2-YIBs and CLM, and R = 0.34 between CLM and ERA-Interim. The global area-weighted soil moisture is 0.22 mm^3 mm^{-3} for ModelE2-YIBs, 0.26 mm^3 mm^{-3} for CLM, and 0.23 mm^3 mm^{-3} for ERA-Interim. Statistics for winter are very similar to the summer results."

l. 493 actual->observed

→ Changed as suggested.

l. 524 where is this number coming from.

→ A similar number of 68 Tg C yr^{-1} is estimated for present day. These numbers are calculated as product of biomass burned and emission factors for CO_2 from Andreae and

Merlet (2001). In the paper, we clarified as follows:
"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)." (Lines 673-675)

l. 402-527 Discussion should better reflect the uncertainties of this work, and contrast them to other climatic effects on the boreal carbon cycle.

→ We extend the discussion about the uncertainties and caveats of the research: "In this study, we examine the interactions among climate change, fire activity, air pollution, and ecosystem productivity. To reduce the complexity of the interactions, we focus on the most likely dominant feedback and thus main chain of events: "climate → fire → pollution → biosphere' (Fig. 1). However, our choice of feedback analysis does not mean that the interplay of other processes is unimportant. For example, climate-induced changes in vegetation cover/types can influence fire activity by alteration of fuel load, and air pollution by BVOC emissions (climate → biosphere → fire/pollution). In addition, other feedbacks may amplify ecosystem responses but are not considered. For example, the drought caused by fire aerosols in the midcentury (Fig. 11) may help increase fire activity (fire → pollution → climate → fire). Furthermore, we apply fixed SSTs in the climate simulations because reliable ocean heat fluxes for the future world were not available. Many previous studies have investigated regional aerosol-climate feedbacks without ocean responses. For example, Cook et al. (2009) found that dust-climate-vegetation feedback promotes drought in U.S., with a climate model driven by prescribed SSTs. Similarly, Liu (2005) found fire aerosols enhance regional drought using a regional climate model, which even ignores the feedback between local climate and large-scale circulation. While we do concede that our experimental design is not a complete assessment of all known processes and feedbacks, within these limitations, this study for the first time quantifies the indirect impacts of wildfire on long-range ecosystem productivity under climate change." (Lines 581-599)

ModelE2-YIBs represents the full carbon cycle for land ecosystems and terrestrial vegetation, 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)

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Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America

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Keywords: wildfire emissions, ozone, aerosols, net primary productivity, climate change, diffuse fertilization effect, carbon loss, earth system modeling

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Abstract

Biomass burning is an important source of tropospheric ozone (O_3) and aerosols. These air pollutants can affect vegetation photosynthesis through stomatal uptake (for O_3) and light scattering and absorption (for aerosols). Wildfire area burned is projected to increase significantly in boreal North America by the midcentury, while little is known about the impacts of enhanced emissions on the terrestrial carbon budget. Here, combining site-level and satellite observations and a carbon-chemistry-climate model, we estimate the impacts of fire emitted O_3 and aerosols on net primary productivity (NPP) over boreal North America. Fire emissions are calculated based on an ensemble projection from 13 climate models. In the present day, wildfire enhances surface O_3 by 2 ppbv (7%) and aerosol optical depth (AOD) at 550 nm by 0.03 (26%) in the summer. By midcentury, area burned is predicted to increase by 66% in boreal North America, contributing more O_3 (13%) and aerosols (37%). 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. Fire aerosols reduce surface solar radiation but enhance atmospheric absorption, resulting in enhanced air stability and intensified regional drought. The domain of this drying is confined to the North in the present day, but extends southward by 2050 due to increased fire emissions. Consequently, wildfire aerosols enhance NPP by 72 Tg C yr^{-1} in the present day but decrease NPP by 118 Tg C yr^{-1} in the future, mainly because of the soil moisture perturbations. Our results suggest that future wildfire may accelerate boreal carbon loss, not only through direct emissions increasing from 68 Tg C yr^{-1} at present day to 130 Tg C yr^{-1} by midcentury, but also through the biophysical impacts of fire aerosols.

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1 Introduction

Wildfire area burned is increasing in recent decades over North America boreal regions (Stocks et al., 2002; Kasischke and Turetsky, 2006). Fire activity is closely related to weather conditions and large-scale atmospheric oscillations (Gillett et al., 2004; Duffy et al., 2005), and is projected to increase significantly in the future due to climatic changes (Flannigan et al., 2005; Balshi et al., 2009; Groot et al., 2013; Wang et al., 2015). More area burned and the consequent fire emissions are accelerating carbon loss in boreal North America (Bond-Lamberty et al., 2007; Turetsky et al., 2011). Meanwhile, fire-induced air pollution, including ozone (O_3) and aerosols, is predicted to increase in boreal and downwind regions by midcentury (Yue et al., 2013; Yue et al., 2015). Wildfire emissions have large impacts on air quality (Wotawa and Trainer, 2000; Morris et al., 2006), weather/climate conditions (Randerson et al., 2006; Zhao et al., 2014), and public health (Zu et al., 2016; Liu et al., 2017). However, little is known about how these pollutants affect ecosystem carbon assimilation, and how this impact will change with the increased wildfire activity in the future.

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Surface O_3 causes damages to photosynthesis through stomatal uptake (Sitch et al., 2007). In the present climate state, fire-induced O_3 enhancements are predicted to reduce net primary productivity (NPP) in the Amazon forest by 230 Tg C yr^{-1} (1 Tg = 10^{12} g), a magnitude comparable to the direct release of CO_2 from fires in South America (Pacifico et al., 2015). The aerosol effects are more uncertain because both positive and negative feedbacks occur. Appearance of aerosols increases diffuse light, which is beneficial for shaded leaves in the lower canopy. Consequently, photosynthesis of the whole ecosystem will increase as long as the total light availability is not compromised (Kanniah et al., 2012). Rap et al. (2015) estimated that biomass burning aerosols increase Amazon NPP by 78–156 Tg C yr^{-1}, which offsets about half of the damage caused by fire O_3 (Pacifico et al., 2015). In contrast, strong light attenuation associated with high aerosol loading may decrease canopy photosynthesis (Cohan et al., 2002; Oliveira et al., 2007; Cirino et al., 2014). Furthermore, the aerosol radiative effects indirectly influence ecosystem productivity through concomitant meteorological perturbations that are only beginning to be examined (Yue et al., 2017).

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Future wildfire activity is projected to increase over boreal North America but with large uncertainties (Flannigan et al., 2005; Tymstra et al., 2007; Girardin and Mudelsee, 2008; Nitschke and Innes, 2008; Amiro et al., 2009; Balshi et al., 2009; Bergeron et al., 2010; Wotton et al., 2010; de Groot et al., 2013; Wang et al., 2016). For example, Amiro et al. (2009) predicted an increase of 34% in Canadian area burned for a 2×CO_2 scenario (2040-2060) relative to a 1×CO_2 condition (1975-1995), using the Canadian Fire Weather Index (CFWI) and output from Canadian global climate model (CGCM) version 1. Balshi et al. (2009) projected that area burned in boreal North America would double by the year 2045-2050 relative to 1991-2000, using the Multivariate Adaptive Regression Splines (MARS) approach and meteorological output from CGCM version 2. The increasing rate in Balshi et al. (2009) is higher than that in Amiro et al. (2009), indicating substantial uncertainties in fire projections originating from both fire models and simulated future climate. However, even with the same fire models and climate change scenario, large uncertainties (in both magnitude and signs) are found in the projection of area burned among individual climate models (Moritz et al., 2012; Yue et al., 2013). 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). Following this strategy, Yue et al. (2015) used output from 13 climate models to drive fire regression models and predicted an average increase of 66% in boreal area burned at 2046-2065 relative to 1981-2000 under the IPCC A1B scenario (Solomon et al., 2007). Yue et al. (2015) further calculated that the wildfire emission increase by the 2050s would increase mean summertime surface O_3 by 5 ppbv in Alaska and 3 ppbv in Canada. The study found regional maximum O_3 enhancements as high as 15 ppbv, suggesting the potential for possible vegetation damage and land carbon loss due to the enhanced boreal fire-related air pollution. Wildfire aerosols are also expected to increase significantly but not predicted in Yue et al. (2015).

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In this study, we quantify the impacts of O_3 and aerosols emitted from boreal wildfires on the land carbon uptake in North America in the present climate state and in the future world at 2050, taking advantage of the ensemble projection of future wildfire emissions by Yue et al. (2015). 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 (Fig. 1). We first analyze relationships between gross primary production (GPP) and aerosol optical depth (AOD) at 550 nm over the boreal regions based on observations. We then perform a suite of Earth system model simulations using NASA GISS ModelE2 that embeds the Yale Interactive Terrestrial Biosphere model (YIBs), a framework known as ModelE2-YIBs (Yue and Unger, 2015). Future projections of wildfire emissions from Yue et al. (2015) are applied as input to ModelE2-YIBs model to project fire-induced O_3 and aerosol concentrations in the 2010s and 2050s. The impacts of the boreal fire O_3 on forest photosynthesis are predicted using the flux-based damage algorithm proposed by Sitch et al. (2007), which has been fully evaluated against available O_3 damage sensitivity measurements globally and over North America (Yue and Unger, 2014; Yue et al., 2016; Yue et al., 2017). Fire aerosols induce perturbations to radiation, meteorology, and hydrology, leading to multiple influences on the land carbon uptake. Sensitivity experiments are performed using the YIBs model in offline mode to isolate the contributions of changes in the individual meteorological drivers.

2 Materials and methods

2.1 Observed GPP-AOD relationships

Following the approach by Strada et al. (2015), we investigate the GPP sensitivity to diffuse radiation and AOD variability in boreal regions. First, we identify study sites in Canada and Alaska from the AmeriFlux (AMF) network (http://ameriflux.lbl.gov/). There are much fewer boreal sites than those in temperate regions. We select AMF sites providing hourly (or half-hourly) simultaneous measurements of GPP (non gap-filled) and photosynthetically active radiation (PAR, total and diffuse) for at least 3 consecutive years. Only two Canadian sites meet the criteria: Groundhog River (CA-Gro, 82.2°W, 48.2°N), a mixed forest (MF), and Quebec Mature Boreal Forest Site (CA-Qfo, 73.4°W, 49.7°N), an evergreen needleleaf forest (ENF). At the two selected sites, we calculate the Pearson's correlation coefficients between half-hourly GPP and different components of PAR. In total, we select 2432 and 3201 pairs of GPP and PAR measurements at CA-Gro and CA-Qfo, respectively. We then apply instantaneous Level 2 Collection 6 of AOD pixels at 3-km resolution retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS, https://ladsweb.nascom.nasa.gov/)

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onboard the Aqua and Terra satellites (Levy et al., 2013). The MODIS 3-km AOD product has been fully validated against ground-based sun photometers at both global (Remer et al., 2013) and urban/suburban (Munchak et al., 2013) scales. Strada et al. (2015) used ground-based AOD observations from the Aerosol Robotic Network (AERONET) near AMF sites to validate the sampling technique of MODIS 3-km AOD product. They found high correlations of 0.89-0.98 and regression slopes from 0.89 to 1.03 for daily AOD between AERONET and MODIS at four AMF sites. For this study, the validation against ground-based AOD observations was not possible because no AERONET stations exist near to the selected AMF sites.

Every day, MODIS satellite sensors pass a specific region between 10:00 and 14:00 Local Time (LT), leaving patchy signals around the AmeriFlux sites. Most of MODIS AOD data at high latitudes are available only in boreal summer; as a result, we narrow our explorations of the GPP-AOD relationships to the noontime (10:00-14:00 LT) from June to August. The chosen noontime window limits the contributions that confounding factors such as low solar angles and high diffuse fraction may have on the amount of diffuse PAR and plant productivity (Niyogi et al., 2004). For each summer day, we select instantaneous MODIS 3-km AOD pixels that are (a) located within a distance of 0.03° (about 3 km) from the targeted AMF site and (b) "quasi-coincident" with AMF data, which are available each half-hour. Because of the unavoidable temporal differences between MODIS overpass and AMF data availability, we name this selection "quasi-coincident". A cloud mask applied to the MODIS retrieval procedure conveniently filters out cloudy instants and should reduce the effect of clouds in the scattering process. We calculate both the correlation and regression coefficients between "quasi-coincident" GPP and AOD at the selected sites. Negative GPP is considered as a missing value. To further reduce the influence of cloud cover, we discard instants (both AMF and MODIS data) when precipitation is non-zero. In total, we select 65 pairs of GPP and AOD at CA-Gro site and another 59 pairs at CA-Qfo site. The GPP-AOD sampling pairs are much fewer than GPP-PAR, because we select instants when both instantaneous AOD and GPP data are available. In addition, AOD is screened for clear instants to exclude the impacts of clouds.

2.2 Wildfire emissions

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Wildfire emissions used in climate modeling are calculated as the product of area burned, fuel consumption, and emission factors. To predict area burned, we build stepwise regressions for area burned in 12 boreal ecoregions (Yue et al., 2015). Observed area burned aggregated from inter-agency fire reports is used as the predictand. Predictors are selected from 44 (5×6+7×2) variables including five meteorological parameters (mean and maximum temperature, relative humidity, precipitation, and geopotential height at 500 hPa) of six different time intervals (winter, spring, summer, autumn, fire season (May-October), and the whole year), as well as the mean and maximum values of 7 fire indexes from the CFWI system during fire season. We consider the impacts of antecedent factors on current fire activity by including all above variables at the same year and those in the previous two years, making a total of 132 (44×3) factors. The final formats of regression are different among ecoregions, depending on the selection of the factors that contribute the maximum observed variance in predictand but remain the minimum collinearity among predictors. These regression functions are then driven with output from 13 Coupled Model Intercomparison Project Phase 3 (CMIP3) climate models under A1B scenario (Meehl et al., 2007) to predict area burned at present day (1981-2000) and midcentury (2046-2065). In the A1B scenario, CO_2 concentration is projected to 532 ppm by the year 2050, similar to the value of 541 ppm in IPCC RCP8.5 scenario (van Vuuren et al., 2011) archived for the Coupled Model Intercomparison Project Phase 5 (CMIP5).

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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 large fires (>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 current burning will decrease the possibility of future 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.

Fuel consumption, the dry mass burned per fire area, is the product of fuel load and burning severity. For fuel load in Alaska, we use 1-km inventory from the US Forest Service (USFS) Fuel Characteristic Classification System (FCCS, McKenzie et al., 2007). For fuel load in Canada, we use a 1-km fuel type map from the Canadian Fire Behavior Prediction (FBP) system (Nadeau et al., 2005), combined with fuel-bed definition from the FCCS. Burning severity, the fraction of fuel load burned by fires, is calculated with the USFS CONSUME model 3.0 following the approach described in Val Martin et al. (2012). With both fuel load and burning severity, we derive fuel consumption and further calculate biomass burned in boreal North America with the predicted area burned. 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).

Fire emissions for a specific species are then estimated as the product between biomass burned and the corresponding emission factor, which is adopted from measurements by Andreae and Merlet (2001) except for NO$_x$. We use the average value of 1.6 g NO per Kg dry mass burned (DM) from six studies as NOx emission factor, because the number of 3.0 g NO

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per Kg DM reported in Andreae and Merlet (2001) is much higher than that of 1.1 g NO per Kg DM from field observations (Alvarado et al., 2010). Based on projected area burned and observation-based fuel consumption and emission factors, we derive fire emissions of NO_x, carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs, Alkenes and Alkanes), NH_3, SO_2, black (BC) and organic carbon (OC) in the present day and midcentury.

2.3 NASA ModelE2-YIBs model

The NASA ModelE2-YIBs is an interactive climate-carbon-chemistry model, which couples the chemistry-climate model NASA ModelE2 (Schmidt et al., 2014) and the YIBs vegetation model (Yue and Unger, 2015). NASA ModelE2 is a general circulation model with horizontal resolution of 2°×2.5° latitude by longitude and 40 vertical layers up to 0.1 hPa. It dynamically simulates both the physical (emissions, transport, and deposition) and chemical (production, conversion, and loss) processes of gas-phase chemistry (NO_x, HO_x, O_x, CO, CH_4, and NMVOCs), aerosols (sulfate, nitrate, ammonium, BC, OC, dust, and sea salt), and their interactions. In the model, oxidants influence the photochemical formation of secondary aerosol species (e.g., sulfate, nitrate, and biogenic secondary organic aerosol), in turn, aerosols alter photolysis rates and influence the online gas-phase chemistry. Size-dependent optical parameters computed from Mie scattering, including extinction coefficient, single scattering albedo, and asymmetry parameters, are applied for each aerosol type (Schmidt et al., 2014). The model also considers interactions between climate and atmospheric components. Simulated climate affects formation, transport, and deposition of atmospheric components, in turn, both O_3 and aerosols influence climate by altering radiation, temperature, precipitation, and other climatic variables. Both observation-based evaluations and multi-model inter-comparisons indicate that ModelE2 demonstrates skill in simulating climatology (Schmidt et al., 2014), soil moisture (Fig. S1), radiation (Wild et al., 2013), atmospheric composition (Shindell et al., 2013b), and radiative effects (Shindell et al., 2013a).

YIBs is a process-based vegetation model that dynamically simulates changes in leaf area index (LAI) through carbon assimilation, respiration, and allocation for prescribed PFTs. Coupled photosynthesis-stomatal conductance is simulated with the Farquhar-Ball-Berry scheme (Farquhar et al., 1980; Ball et al., 1987). Leaf-level photosynthesis is upscaled to canopy level by separating diffuse and direct light for sunlit and shaded leaves (Spitters,

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1986). Plant respiration considers thermal dependence as well as acclimation to temperature (Atkin and Tjoelker, 2003). Soil respiration is calculated based on the carbon flows among 12 biogeochemical pools (Schaefer et al., 2008). Net carbon uptake is allocated among leaves, stems, and roots to support leaf development and plant growth (Cox, 2001). The YIBs model has been benchmarked against *in situ* GPP from 145 eddy covariance flux tower sites and satellite retrievals of LAI and phenology (Yue and Unger, 2015). An interactive flux-based O_3 damage scheme proposed by Sitch et al. (2007) is applied to quantify the photosynthetic responses to ambient O_3 (Yue and Unger, 2014). For this scheme, O_3 damaging level is dependent on excess O_3 stomatal flux within leaves, which is a function of ambient O_3 concentration, boundary layer resistance, and stomatal resistance. Reduction of photosynthesis is calculated on the basis of plant functional types (PFTs), each of which bears a range of low-to-high sensitivities to O_3 uptake.

2.4 Simulations

Using the NASA ModelE2-YIBs model, we perform 6 time-slice simulations, three for present-day (2010s) and three for midcentury (2050s), with atmosphere-only configuration to explore the impacts of fire emissions on NPP in boreal North America (Table 1). Simulations F10CTRL and F50CTRL turn off all fire emissions as well as O_3 vegetation damage for the 2010s and 2050s, respectively. However, climatic feedbacks of aerosols from other sources (both natural and anthropogenic) and related photosynthetic responses are included. Simulations F10AERO and F50AERO consider the responses of plant productivity to perturbations in radiation and meteorology caused by aerosols, including emissions from wildfires and other sources, but do not include any O_3 vegetation damage. In contrast, simulations F10O3 and F50O3 calculate offline O_3 damage based on the simulated O_3 from all sources including fire emissions. For these simulations, reductions of GPP are calculated twice with either low or high O_3 sensitivity. However, both of these GPP changes are not fed back into the model to influence carbon allocation and tree growth. Plant respiration is changing in response to meteorological perturbations, either due to climate change or aerosol radiative effects. We assume no impact of O_3 damage to plant respiration and examine vegetation NPP, the net carbon uptake by biosphere, for the current study. The difference between AERO and CTRL runs isolates the impacts of fire aerosols on NPP, and the

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difference between O3 and CTRL runs isolates O_3 vegetation damage caused by fire and non-fire emission sources.

All simulations are conducted for 20 years and outputs for the last 15 years are used for analyses. The simulations apply sea surface temperatures (SSTs) and sea ice distributions from previous NASA GISS experiments under the IPCC RCP8.5 scenario (van Vuuren et al., 2011). Decadal average monthly-varying SST and sea ice of 2006-2015 are used as boundary conditions for present-day (2010s) runs while that of 2046-2055 are used for future (2050s) runs. In the RCP8.5 scenario, global average SST increases by 0.62 °C while sea ice area decreases by 13.8% at the midcentury compared to the present-day level. Decadal average well-mixed greenhouse gas concentrations and anthropogenic emissions of short-lived species, both at present day and midcentury, are adopted from the RCP8.5 scenario (Table 2). The enhancement of CO_2 will affect climate (through longwave absorption) and ecosystem productivity (through CO_2 fertilization), but not the fire activity and related emissions directly. Natural emissions of soil and lightning NO_x, biogenic volatile organic compounds (BVOC), dust, and sea salt are climate-sensitive and simulated interactively. The YIBs vegetation model cannot simulates changes in PFT fractions. The RCP8.5 land cover change dataset shows limited changes in land cover fractions between 2010s and 2050s (Oleson et al., 2010). For example, relative to the 2010s, a maximum gain of 5% is predicted for grassland in the 2050s, resulting from a 1% loss in deciduous forest and another 1% loss in needleleaf forest over boreal North America. As a result, a land cover dataset derived from satellite retrievals (Hansen et al., 2003) is applied as boundary conditions for both the 2010s and 2050s.

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To evaluate the simulated GPP responses to changes in diffuse radiation, we perform site-level simulations using standalone YIBs model, which is driven with observed hourly meteorology (including temperature, relative humidity, surface pressure, wind speed, and soil moisture) and both diffuse and direct PAR at sites CA-Gro and CA-Qfo. To isolate the impact of individual aerosol-induced climatic perturbations on NPP, we perform 10 sensitivity experiments using the offline YIBs model driven with offline meteorology simulated by ModelE2-YIBs model (Table 3). For example, the offline run Y10_CTRL is driven with variables from the online simulation of F10CTRL (Table 1). The run Y10_TAS adopts the same forcing as Y10_CTRL except for temperature, which is simulated by the climate simulation of F10AERO. In this case, we quantify the NPP responses to individual

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and/or combined climate feedback (mainly in temperature, radiation, and soil moisture) by fire aerosols. Each offline run is conducted for 12 years and the last 10 years are used for analyses.

2.5 Observation datasets

We use observations to evaluated GPP, AOD, and O_3 in boreal North America simulated by ModelE2-YIBs. For GPP, we use a benchmark data product upscaled from FLUXNET eddy covariance data using an ensemble of regression trees (Jung et al., 2009). For AOD observations, we use satellite retrieval at 550 nm from Terra MODIS Level 3 data product. For O_3, gridded datasets are not available. We use site-level observations from 81 U.S. sites at the Clean Air Status and Trends Network (CASTNET, https://www.epa.gov/castnet) and 202 Canadian sites at the National Air Pollution Surveillance (NAPS, http://www.ec.gc.ca/rnspa-naps/) program. All datasets are averaged over the 2008-2012 period to represent present-day climatological conditions. Gridded datasets are interpolated to the same 2°×2.5° resolution as ModelE2-YIBs model.

3 Results

3.1 Observed GPP-AOD relationships

Positive correlations between GPP and diffuse PAR are found at the two boreal sites (Figs 2b-2c). The magnitude of diffuse PAR is similar for these sites, possibly because they are located at similar latitudes (Fig. 2a). GPP values at CA-Gro are generally higher than that at CA-Qfo, likely because deciduous broadleaf forest (DBF) has higher photosynthetic rates. Consequently, the slope of regression between GPP and PAR_{dif} is higher at CA-Gro than that at CA-Qfo, suggesting that GPP of DBF (or MF) is more sensitive to changes in diffuse PAR than that of ENF. We find almost zero correlation between GPP and PAR_{dir} at the two sites (Table 4), indicating that photosynthesis is in general light-saturated for sunlit leaves at these sites during boreal summer noontime. As a result, modest reductions in direct light by aerosols will not decrease GPP of the whole canopy.

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With satellite-based AOD, we find positive correlations between GPP and AOD at both sites (Figs 2d-2e). However, the slope of regression between GPP and AOD is lower (and not significant) at CA-Gro compared with that at CA-Qfo, opposite to the GPP-PAR$_{dif}$ regressions. The cause of such discrepancy might be related to the limitation of data availability. For the same reason, the GPP-AOD correlation is insignificant at CA-Gro site. On average, GPP sensitivity (denoted as mean ± range) is estimated as 3.5 ± 1.1 μmol m^{-2} s^{-1} per unit AOD at lower latitudes of boreal regions in the summer.

3.2 Model evaluations

Simulated summer GPP shows high values in mid-western Canada (Alberta and Saskatchewan) and the Southeast (Ontario) (Fig. 3a). Forest GPP at high latitudes is low because of the cool weather and light limitation there. Simulated GPP reasonably captures the spatial distribution with a high correlation coefficient of 0.77 ($p \ll 0.01$) and relatively small biases within 20% of the data product. Simulated AOD reproduces the observed spatial pattern including the high values in boreal forests (Fig. 3b). In contrast to the MODIS observations, predicted AOD is relatively uniform over the West with a background value of ~0.1. This discrepancy explains the low correlation coefficient ($R = 0.25$, $p<0.01$) between the model and MODIS data. The simulation fails to capture the high values in the west, possibly due to a climate model underestimation of biogenic secondary organic aerosol, which may be an important contribution over the western boreal forest. Simulated maximum daily 8-hour average (MDA8) [O$_3$] shows low values in boreal North America and high values in the western and eastern U.S. (Fig. 4a). This pattern is consistent with surface observations (Fig. 4b), but the model overestimates the measured surface O$_3$ by 22%. The Canadian measurement sites are located near the southern boundary, and as a result do not represent the average state over the vast boreal region at higher latitudes.

With the Sitch et al. (2007) scheme, the YIBs model simulates reasonable GPP responses to [O$_3$] in North America (Yue and Unger, 2014; Yue et al., 2016). Generally, damage to GPP increases with the enhancement of ambient [O$_3$], but with varied sensitivities for different plant species (see Fig. 6 of Yue and Unger (2014)). In responses to the same level of [O$_3$], predicted O$_3$ damages are higher for deciduous trees than that for needleleaf trees, consistent with observations from meta-analyses (Wittig et al., 2007). The model also reproduces

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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.

3.3 Simulation of wildfire O_3 and aerosols

During 1980-2009, wildfire is observed to burn 2.76×10^6 ha and 156.3 Tg DM every year over boreal North America. Similarly, the ensemble prediction with fire regression models estimates present-day area burned of 2.88 ×10^6 ha yr^{-1} and biomass burned of 160.2 Tg DM yr^{-1} (Yue et al., 2015). By the midcentury, area burned is projected to increase by 77% (to 5.10 ×10^6 ha yr^{-1}) in boreal North America, mainly because of the higher temperature in future fire seasons. Consequently, biomass burned increases by 93% (to 308.6 Tg DM yr^{-1}) because fuel consumption also increases by 9% on average in a drier climate (Yue et al., 2015). Enhanced fire emissions increase concentrations of surface O_3 and column AOD, especially over Alaska and central Canada (Fig. 6). The maximum centers of air pollutants are collocated for O_3 and AOD but with unproportional magnitudes, suggesting non-linear conversion among fire emission species as well as the interactions with natural emission sources (e.g., lightning/soil NO_x and BVOC). On average, wildfire emissions contribute 7.1 ± 3.1% (2.1 ± 0.9 ppbv) to surface O_3 and 25.7 ± 2.4% (0.03 ± 0.003) to AOD in the summer over boreal North America in the present day. By midcentury, these ratios increase significantly to 12.8 ± 2.8% (4.2 ± 0.9 ppbv) for O_3 and 36.7 ± 2.0% (0.05 ± 0.003) for AOD.

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3.4 Simulation of fire pollution impacts on NPP

Surface O$_3$, including both fire and non-fire emissions (Table 2), causes limited (1-2%) damages to summer GPP in boreal North America (Fig. 7). The most significant damage is predicted over eastern U.S., where observed [O$_3$] is high over vast forest ecosystems (Fig. 4). In the western U.S., [O$_3$] is also high but the O$_3$-induced GPP reduction is trivial because low stomatal conductance in the semi-arid ecosystems limits O$_3$ uptake there (Yue and Unger, 2014). Over boreal North America, dominant PFTs are ENF (accounting for 44% of total vegetation cover) and tundra (treated as shrubland, accounting for 41% of total vegetation cover). Both species have shown relatively high O$_3$ tolerance with a damaging threshold of 40 ppbv as calculated with Sitch's scheme (Yue and Unger, 2014). For boreal regions, the mean [O$_3$] of 28 ppbv (Fig. 4a) is much lower than this damaging threshold, explaining why the excess O$_3$ stomatal flux (the flux causing damages) is low there (Fig. 8). Statistics in Yue et al. (2015) show that maximum daily 8-hour average (MDA8) [O$_3$] with fire contributions can be higher than 40 ppbv in Alaska and Canada. However, such episodes appear at 95 percentile for present day and 90 percentile for midcentury, suggesting that O$_3$ vegetation damage is rare in boreal North America and fire-induced O$_3$ enhancement does not exacerbate such damages. Therefore, we do not consider O$_3$ damage effects further.

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Fire aerosols cause significant perturbations in shortwave radiation at surface (Fig. 9). The direct light is largely attenuated especially over Alaska and central Canada, where fire aerosols are most abundant (Fig. 6). In contrast, diffuse light widely increases due to particle scattering. In the present day, the average reduction of 5.6 W m^{-2} in the direct light component is in part offset by the enhancement of 2.6 W m^{-2} in the diffuse light component, leading to a net reduction of 3.0 W m^{-2} in solar radiation over boreal North America. By the midcentury, a stronger reduction of 9.5 W m^{-2} in direct light is accompanied by an increase of 4.0 W m^{-2} in diffuse light, resulting in a net reduction of 5.5 W m^{-2} in solar radiation. Fire-induced BC aerosols strongly absorb solar radiation in the atmospheric column (Figs 10a-10b). On average, fire aerosols absorb 1.5 W m^{-2} in the present day and 2.6 W m^{-2} by the midcentury.

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Atmospheric circulation patterns respond to the aerosol-induced radiative perturbations (Figs 10c-10d). Surface radiative cooling and atmospheric heating together increase air stability and induce anomalous subsidence. In the present day, such descending motion is confined to 55-68°N, accompanied by a rising motion at 52-55°N (Fig. 10c). As a result, fire aerosols induce surface warming at higher latitudes but cooling at lower latitudes in boreal regions (Fig. 11a). Meanwhile, precipitation is inhibited by the subsidence in northwestern Canada but is promoted by the rising motion in the Southwest (Fig. 11c). By the midcentury, the range of subsidence expands southward to 42°N (Fig. 10d) due to strengthened atmospheric heating (Fig. 10b). The downward convection of warm air offsets surface radiative cooling (Fig. 9b), leading to a significant warming in the Southwest (Fig. 11b). The expanded subsidence further inhibits precipitation in vast domain of Canada (Fig. 11d). Soil moisture is closely related to rainfall and as a result exhibits dipole changes (drier north and wetter south) in the present day (Fig. 11e) but widespread reductions (Fig. 11f) by the midcentury.

In response to the climatic effects of fire aerosols, boreal NPP shows distinct changes between the present day and midcentury (Fig. 12). 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. In the 2010s, forest NPP increases by 5-15% in Alaska and southern Canada, but decreases by 5-10% in northern and eastern Canada. This pattern of NPP changes (ΔNPP) is connected to the climatic effects of aerosols, especially changes in soil moisture (Fig. 11). The correlation between ΔNPP (Fig. 12a) and changes in soil moisture (Fig. 11e) reaches $R = 0.56$ (n = 356), much higher than the values of $R = -0.11$ for temperature change (Fig. 11a) and $R = 0.22$ for precipitation change (Fig. 11c). At the continental scale, the patchy responses of NPP offset each other. Since the dominant fraction of carbon uptake occurs in southern Canada (Fig. 3a), where positive NPP change is predicted (Fig. 12a), wildfire aerosols enhance the total NPP by 72 Tg C yr^{-1} in the present day (Table 5). In contrast, increased wildfire emissions in the 2050s inhibit precipitation (Fig. 11d) and decrease soil moisture in boreal North America (Fig. 11f), leading to widespread NPP reductions and a total NPP loss of 118 Tg C yr^{-1} (Fig. 12b, Table 5).

4 Discussion

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4.1 Roles of aerosol climatic feedback

The contrasting sign of NPP responses in the present day and midcentury are closely related to the aerosol-induced surface climatic feedback. Sensitivity experiments using offline YIBs model (Table 3) allowed assessment of the impacts of individual changes in the major meteorological drivers, including temperature, radiation (diffuse and direct), and soil moisture (Table 5). The offline simulations driven with changes in all three variables yield ΔNPP of 126 Tg C yr^{-1} for the 2010s and -97 Tg C yr^{-1} for the 2050s. These values are different from the online simulations, which predict ΔNPP of 72 Tg C yr^{-1} for the 2010s and -118 Tg C yr^{-1} for the 2050s. Missing of other aerosol climatic feedbacks in the offline model, for example, changes in relative humidity, surface pressure, soil temperature, and turbulence momentum, may cause such discrepancy between the online and offline simulations. Seasonal analyses show that summertime ΔNPP is 99 Tg C at present day and -95 Tg C at midcentury, dominating the NPP changes all through the year, because both wildfire emissions and ecosystem photosynthesis maximize in boreal summer.

Observations show that aerosols can promote plant photosynthesis through increasing diffuse radiation (Niyogi et al., 2004; Cirino et al., 2014; Strada et al., 2015). Our analyses with ground data also show positive correlations between GPP and PAR_{dif} (Fig. 2 and Table 4), and the model reproduces observed GPP responses to perturbations in direct and diffuse PAR (Fig. 5). Wildfire aerosols enhance diffuse radiation by 2.6 W m^{-2} (1.7%) at present day and 4.0 W m^{-2} (2.3%) at midcentury in boreal North America (Fig. 9). With these changes, simulated NPP increases by 8 Tg C yr^{-1} at the 2010s and 14 Tg C yr^{-1} at the 2050s (Table 5). Near the two AmeriFlux sites (Fig. 2a), wildfires increase local AOD by 0.03 (Fig. 6c). Meanwhile, we estimate that summer average (00:00-24:00) GPP increases by 0.04 μmol m^{-2} s^{-1} in the same region due to aerosol diffuse fertilization effects (DFE) based on the results of (Y10_PAR – Y10_CTRL). This change suggests a simulated GPP sensitivity of 1.2 μmol m^{-2} s^{-1} (22%) per unit AOD. Observed GPP sensitivity to AOD at the two sites are 2.3 (19%) and 4.5 μmol m^{-2} s^{-1} (58%) per unit AOD, respectively (Figs 2d-2e). The absolute value of GPP sensitivity from simulations is much smaller than that of observations, because the former is for 24-h average while the latter is only for noontime (10:00-14:00). The relative change of 22% in YIBs model falls within the observed range of 19-58%.

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The estimated NPP changes of 8 Tg C yr^{-1} by the radiative effects of boreal fire aerosols are much weaker than the enhancement of 78-156 Tg C yr^{-1} by fires in Amazon basin (Rap et al., 2015). There are at least two reasons for such a difference in the DFE between boreal and Amazon fire aerosols. First, wildfire emissions and associated impacts on radiation are much smaller in boreal regions. Wildfires in Alaska and Canada directly emit 68 Tg C yr^{-1} at the 2010s, resulting in enhancement of summer AOD by 35% and diffuse radiation by 1.7%. These boreal emissions are much smaller than the ~240 Tg C yr^{-1} in Amazon basin (van der Werf et al., 2010), where fires enhances regional PM2.5 concentrations by 85% and diffuse radiation by 6.2% in dry seasons (Rap et al., 2015). Second, larger solar insolation in lower latitudes allows stronger DFE for the same unit change of diffuse radiation. In our prediction, most of NPP changes occur at high latitudes of boreal regions (Fig. 12), where total insolation is not so abundant as that at the tropical areas. Consequently, decline of direct radiation in boreal regions more likely converts the light availability of sunlit leaves from light-saturation to light-limitation, offsetting the benefit from enhanced diffuse radiation for shaded leaves. For this study, we do not find GPP reduction by the decline of direct light at the two Ameriflux sites (Table 4), possibly because these sites are located at middle latitudes (<50°N). In the future, more observations at higher latitudes (> 55°N) are required to explore the sensitivity of GPP to AOD at the light-limited conditions.

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Simulations have shown that absorbing aerosols can cause regional drought by increasing air stability (Liu, 2005; Cook et al., 2009; Tosca et al., 2010). Our results confirm such tendency but with varied range of hydrological responses depending on the magnitude of wildfire emissions (Figs 11c-11f). Observations suggest that precipitation (and the associated soil moisture) is the dominant driver of the changes in GPP over North America, especially for the domain of cropland (Beer et al., 2010). Sensitivity experiments with offline YIBs model show that changes in soil moisture account for 82.5% of ΔNPP at present day and 70.5% of ΔNPP at midcentury (Table 5). These results suggest that aerosol-induced changes in soil water availability, instead of temperature and radiation, dominantly contribute to the changes of boreal NPP, consistent with observational and experimental results (Ma et al., 2012; Girardin et al., 2016; Chen et al., 2017).

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4.2 Limitations and uncertainties

In this study, we examine the interactions among climate change, fire activity, air pollution, and ecosystem productivity. To reduce the complexity of the interactions, we focus on the most likely dominant feedback and thus main chain of events: “climate → fire → pollution → biosphere’ (Fig. 1). However, our choice of feedback analysis does not mean that the interplay of other processes is unimportant. For example, climate-induced changes in vegetation cover/types can influence fire activity by alteration of fuel load, and air pollution by BVOC emissions (climate → biosphere → fire/pollution). In addition, other feedbacks may amplify ecosystem responses but are not considered. For example, the drought caused by fire aerosols in the midcentury (Fig. 11) may help increase fire activity (fire → pollution → climate → fire). Furthermore, we apply fixed SSTs in the climate simulations because reliable ocean heat fluxes for the future world were not available. Many previous studies have investigated regional aerosol-climate feedbacks without ocean responses. For example, Cook et al. (2009) found that dust-climate-vegetation feedback promotes drought in U.S., with a climate model driven by prescribed SSTs. Similarly, Liu (2005) found fire aerosols enhance regional drought using a regional climate model, which even ignores the feedback between local climate and large-scale circulation. While we do concede that our experimental design is not a complete assessment of all known processes and feedbacks, within these limitations, this study for the first time quantifies the indirect impacts of wildfire on long-range ecosystem productivity under climate change.

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We use the ensemble projected fire emissions from Yue et al. (2015). Area burned is predicted based on the simulated meteorology from multiple climate models. Such an approach may help reduce model uncertainties in climatic responses to CO_2 changes (Collins et al., 2013; Kirtman et al., 2014), but cannot remove the possible biases in the selection of climate scenarios and fire models. All predictions in Yue et al. (2015) are performed under the IPCC A1B scenario. With two different scenarios, A2 of high emissions and B2 of low emissions, Balshi et al. (2009) showed that future area burned in boreal North America increases at a similar rate until the 2050s, after which area burned in A2 scenario increases much faster than that in B2 scenario. On average, boreal area burned in Balshi et al. (2009) increases by ~160% at 2051-2060 compared with 2001-2010, much higher than the change of 66% in Yue et al. (2015). In contrast, Amiro et al. (2009) predicted that boreal area burned at the $2\times CO_2$ scenario increases only by 34% relative to the $1\times CO_2$ scenario. This ratio is only half of the estimate in Yue et al. (2015), which compared results between periods with 1.44×CO_2 and 1×CO_2. The discrepancies among these studies are more likely attributed to the differences in fire models. Although both Amiro et al. (2009) and Yue et al. (2015) developed fire-weather regressions in boreal ecoregions, the former study did not include geopotential height at 500 hPa and surface relative humidity as predictors, which make dominant contributions to area burned changes in the latter study. On the other hand, Balshi et al. (2009) developed nonlinear regressions between area burned and climate at grid scale, which helps retain extreme values at both the temporal and spatial domain. Compared to previous estimates, Yue et al. (2015) predicted median increases in future fire emissions over boreal North America.

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.

Predicted surface [O_3] is much higher than observations over boreal North America (Fig. 4). This bias does not affect main conclusions of this study, because predicted O_3 causes limited damages to boreal GPP even with the overestimated [O_3] (Fig. 7). The result confirms that fire-induced O_3 vegetation damage is negligible in boreal North America. For aerosols, the

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model captures reasonable spatial pattern of AOD but with a background value of ~0.1 outside fire-prone regions, where the observed AOD is usually 0.1-0.2 (Fig. 3). This discrepancy may be related to the insufficient representations of physical and chemical processes in the model, but may also result from the retrieval biases in MODIS data due to the poor surface conditions (Liu et al., 2005) and small AOD variations (Vachon et al., 2004) at high latitudes.

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Simulated aerosol climatic effects depend on radiative and physical processes implemented in the climate model. We find that present-day boreal fire aerosols on average absorb 1.5 W m^{-2} in the atmosphere (Fig. 10), which is much smaller than the value of 20.5 ± 9.3 W m^{-2} for fires in equatorial Asia (Tosca et al., 2010). This is because boreal fires enhance AOD only by 0.03 while tropical fires increase AOD by ~0.4. Previous modeling studies showed that fire plumes induce regional and downwind drought through enhanced atmospheric stability (Feingold et al., 2005; Tosca et al., 2010; Liu et al., 2014). Most of these results were based on the direct and/or semi-direct radiative effects of fire aerosols. Inclusion of the indirect aerosol effect may further inhibit precipitation and amplify drought, but may also introduce additional uncertainties for the simulations. The fire-drought interaction may promote fire activity, especially in a warmer climate. Ignoring this interaction may underestimate future area burned and the consequent emissions.

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4.3 Implications

Inverse modeling studies have shown that the land ecosystems of boreal North America are carbon neutral in the present day, with the estimated land-to-air carbon flux from -270 ± 130 Tg C yr^{-1} to 300 ± 500 Tg C yr^{-1} (Gurney et al., 2002; Rodenbeck et al., 2003; Baker et al., 2006; Jacobson et al., 2007; Deng et al., 2014). Here, we reveal a missing land carbon source due to future wildfire pollution, taking into account full coupling among fire activity, climate change, air pollution, and the carbon cycle. 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)

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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. Furthermore, the NPP reductions are mostly located in southern Canada, where cropland is the dominant ecosystem, newly exposing the future wildfire-related air pollution risk to food production.

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.

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Table 1. Online simulations with ModelE2-YIBs climate model [a]

Simulations	SST	[CO_2]	Emissions	Fires	O_3 effect	Aerosol effect
F10O3	2010s	2010s	2010s	2010s	Yes	No
F10AERO	2010s	2010s	2010s	2010s	No	Yes
F10CTRL	2010s	2010s	2010s	No	No	Yes
F50O3	2050s	2050s	2050s	2050s	Yes	No
F50AERO	2050s	2050s	2050s	2050s	No	Yes
F50CTRL	2050s	2050s	2050s	No	No	Yes

[a] Values of SST, [CO_2], and emissions are adopted from RCP8.5 scenario, with the average of 2006-2015 for the 2010s and that of 2046-2055 for the 2050s. For fire emissions, values at the 2010s are predicted based on meteorology for 1981-2000 and those at the 2050s are for 2046-2065.

Table 2. Emissions from wildfires and non-fire sources over boreal North America

Species	Fire emissions (Tg yr^{-1})		Non-fire emissions (Tg yr^{-1})	
	2010s	2050s	2010s	2050s
NO_x [a]	0.39	0.74	2.43	2.08
CO	15.7	28.8	5.9	4.0
SO_2 [a]	0.12	0.22	1.95	1.28
NH_3	0.22	0.40	0.80	1.15
BC	0.08	0.16	0.03	0.01
OC	1.10	2.04	0.04	0.02
NMVOC	0.39	1.34	0.49	0.30
BVOC [b]	N/A	N/A	15.3	15.1

[a] Natural emissions are included for NO_x (lightning and soil) and SO_2 (volcano).

[b] ModelE2-YIBs calculates BVOC emissions using photosynthesis-dependent scheme implemented by Unger et al. (2013).

Table 3. Simulations with YIBs vegetation model driven by offline meteorology from ModelE2-YIBs climate model

Simulations	Base forcing	Temperature	PAR	Soil moisture
Y10_CTRL	F10CTRL			
Y10_ALL	F10CTRL	F10AERO	F10AERO	F10AERO
Y10_TAS	F10CTRL	F10AERO		
Y10_PAR	F10CTRL		F10AERO	
Y10_SLM	F10CTRL			F10AERO
Y50_CTRL	F50CTRL			
Y50_ALL	F50CTRL	F50AERO	F50AERO	F50AERO
Y50_TAS	F50CTRL	F50AERO		
Y50_PAR	F50CTRL		F50AERO	
Y50_SLM	F50CTRL			F50AERO

Table 4. Pearson's correlation coefficients for GPP-PAR and GPP-AOD relationships at Ameriflux (AMF) sites [a]

Site	Period [b]	Pearson's *R*					
		GPP-PAR	GPP-PAR$_{dir}$	GPP-PAR$_{dif}$	GPP-AOD	AOD-PAR$_{dif}$	AOD-PAR$_{dir}$
CA-Gro	2004-2013	**0.19** (2432)	-0.01 (2432)	**0.42** (2432)	0.15 (65)	**0.60** (65)	**-0.52** (65)
CA-Qfo	2003-2014	**0.16** (3201)	**-0.04** (3201)	**0.45** (3201)	**0.36** (59)	**0.91** (34)	**-0.80** (34)

[a] Both GPP and PAR (direct PAR$_{dir}$ and diffuse PAR$_{dif}$) data are adopted from site-level AMF measurements. AOD data are adopted from instantaneous MODIS Aqua and Terra 3-km retrievals. Correlations are calculated for quasi-coincident AMF and MODIS data over summer noontime (June-August, 10:00-14:00 Local Time). The sampling number for each correlation is denoted in brackets. Significant (p<0.05) correlation coefficients are bolded.

[b] For CA-Gro site, diffuse PAR observations of 2005-2009 have been discarded because of poor calibration, as documented on the AMF website.

Table 5. Changes in NPP (Tg C yr^{-1}) caused by composite and individual climatic effects of fire aerosols

	2010s	2050s
Online [a]	72	-118
Offline total [b]	126	-97
Temperature	11	-22
Radiation	8	14
Soil moisture	104	-86

[a] Online results are calculated using the ModelE2-YIBs model with (F10AERO – F10CTRL) for the 2010s and (F50AERO – F50CTRL) for the 2050s.

[b] Offline results are calculated with the YIBs model driven with individual or combined changes in temperature, radiation, and soil moisture.

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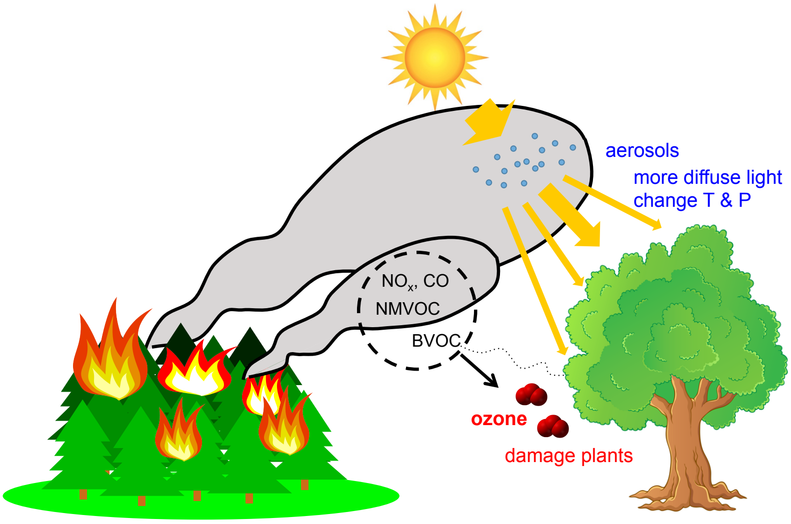

Figure 1. Illustration of atmospheric chemistry and physics, and biospheric processes investigated in the study. Carbonaceous aerosols from fire plumes increase diffuse light and change temperature and precipitation, influencing vegetation photosynthesis. Ozone generated photochemically from fire-emitted precursors (NOx, CO, and non-methane volatile organic compound (NMVOC)) and associated BVOC changes causes direct damage to plant photosynthesis.

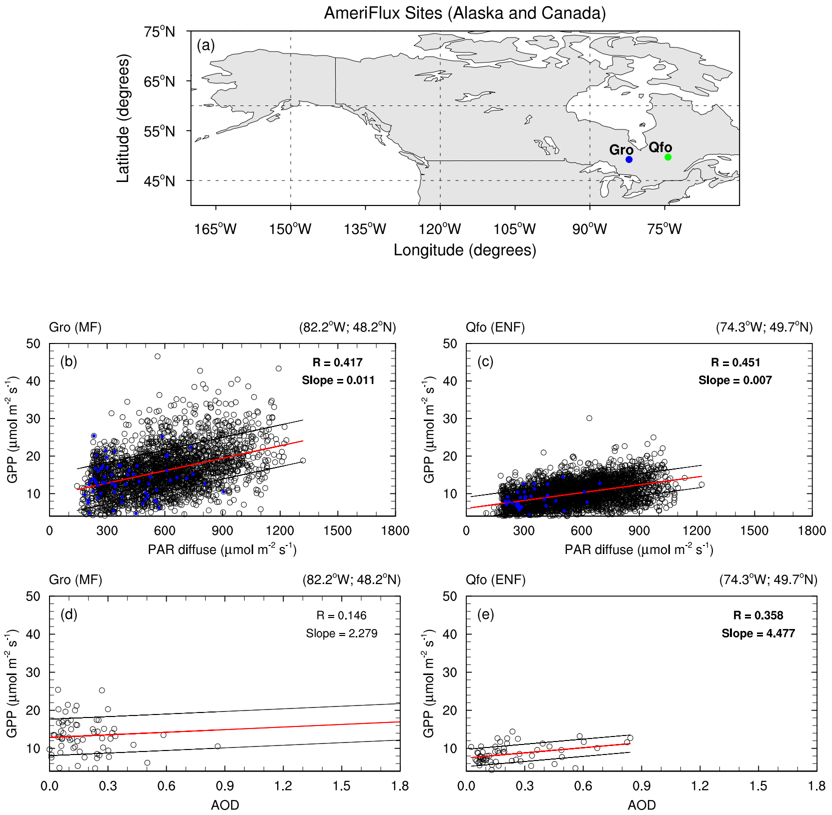

Figure 2. Relationships between (b, c) GPP and diffuse PAR and (d, e) GPP and MODIS AOD at (a) two boreal sites: Groundhog River (Gro) and Quebec Mature Boreal Forest Site (Qfo). The two sites are from the AmeriFlux network in Canada and are dominated by mixed forest (MF at Gro) and evergreen needleleaf forest (ENF at Qfo) (Table 1). Data cover summer days (June-August). AmeriFlux diffuse PAR and GPP (in μmol m^{-2} s^{-1}) are half-hourly observations (10:00-14:00 LT). Instantaneous MODIS Aqua and Terra 3-km AOD are selected in a time span centered on AmeriFlux record time. For each plot: the red line indicates the regression line, black lines depict the 1- σ interval; the regression slope and correlation coefficient are both included for each site (in bold if statistically significant at 95% confidence level). Blue dots in (b, c) show instants when MODIS Aqua and Terra 3-km AODs overlap AmeriFlux data.

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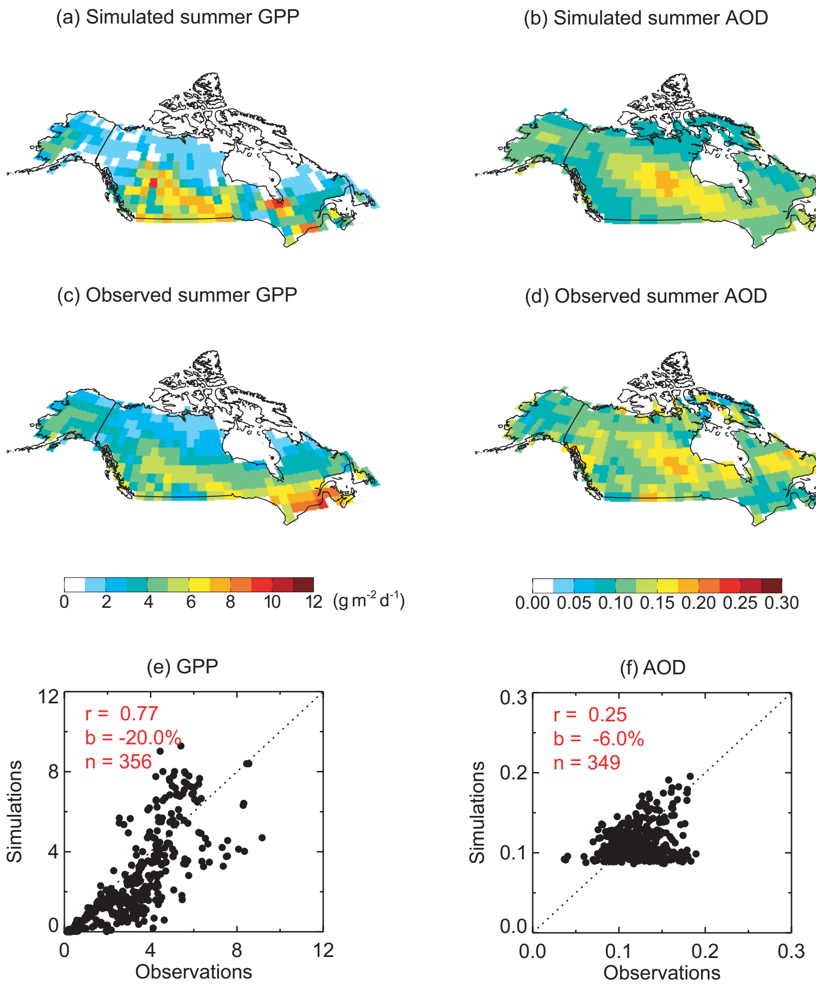

Figure 3. Evaluation of simulated summer (a) GPP and (b) AOD at 550 nm with (c, d) observations. Simulation results are from F10AERO (Table 1). Each point on the (e, f) scatter plot represents one grid square in boreal North America. The number of points (n), correlation coefficient (r), and relative bias (b) for the evaluation are presented on the plot.

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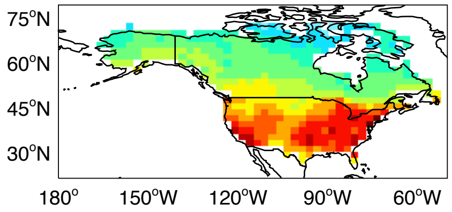
(a) Simulated summer MDA8 O_3



(b) Observed summer MDA8 O_3

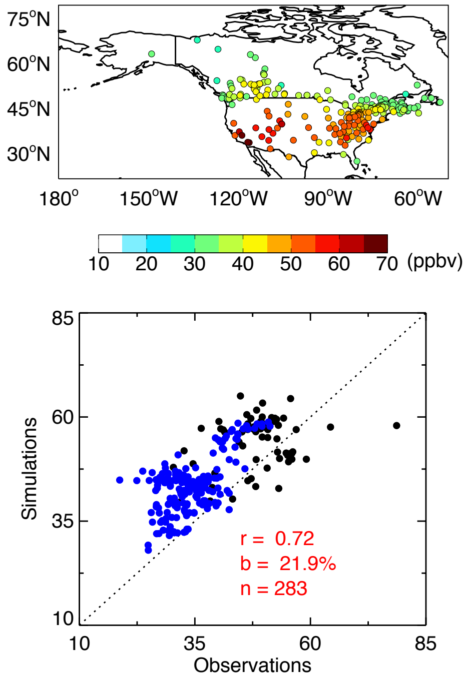


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Figure 4. Evaluation of simulated summer surface maximum daily 8-hour average [O_3] with observations for 2008-2012. Observations are collected from 81 U.S. sites at the Clean Air Status and Trends Network (CASTNET) and 202 Canadian sites at the National Air Pollution Surveillance (NAPS) program. The number of points (n), correlation coefficient (r), and mean bias (b) for the evaluation are presented on the plot. Values over Canada and Alaska are denoted with blue points.

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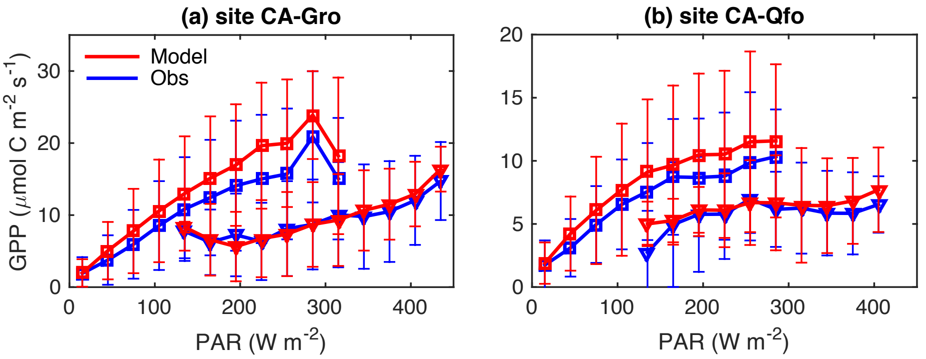

Figure 5. Observed (blue) and simulated (red) response of GPP to diffuse (square) and direct (triangle) PAR at boreal sites (a) CA-Gro (2004-2013) and (b) CA-Qfo (2004-2010). Observations and simulations are split into ‘diffuse’ and ‘direct’ conditions if the diffuse fraction is >0.8 and < 0.2, respectively. Data points are then averaged over PAR bins of 30 W m^{-2} with error bars indicating one standard deviation of GPP for each bin.

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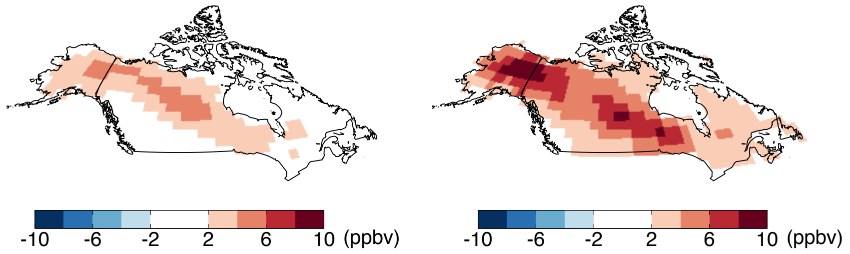
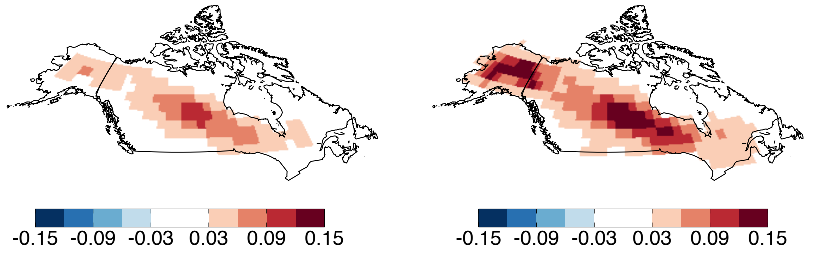

(a) ΔO_3 by wildfire in 2010

(b) ΔO_3 by wildfire in 2050


(c) ΔAOD by wildfire in 2010

(d) ΔAOD by wildfire in 2050

Figure 6. Changes in summer (a, b) [O_3] and (c, d) AOD at 550 nm induced by wildfire emissions in (a, c) the 2010s and (b, d) the 2050s over boreal North America. Only significant changes (p<0.05) are shown.

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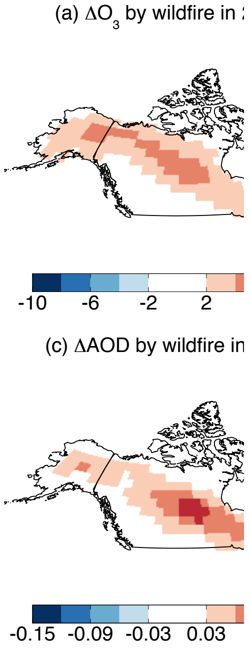

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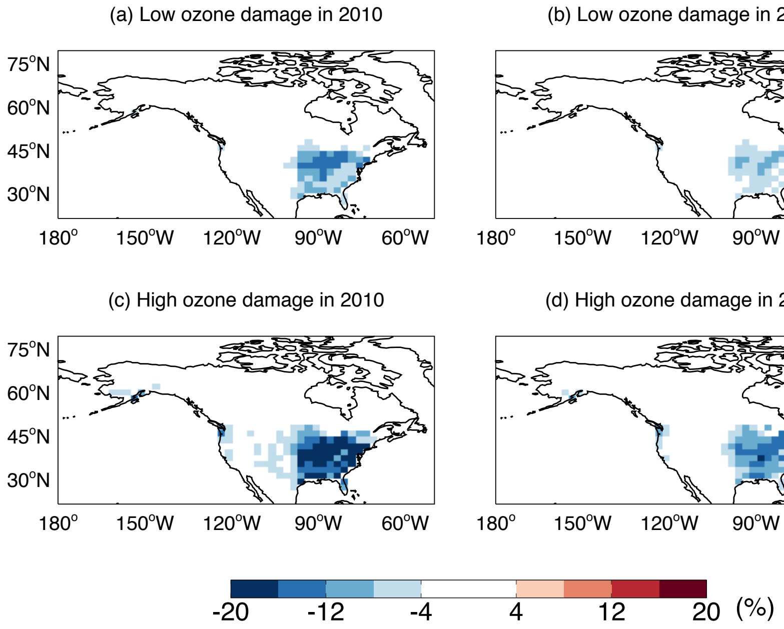

Figure 7. Simulated O_3 damages to summer GPP in North America. Results shown are from simulations with (a, b) low and (c, d) high O_3 sensitivities for (a, c) 2010 and (b, d) 2050. Simulated [O_3] includes contributions from both wildfire and non-fire emissions. Results for 2010 are derived as (F10O3/F10CTRL-1)×100%. Results for 2050 are derived as (F50O3/F50CTRL-1)×100%.

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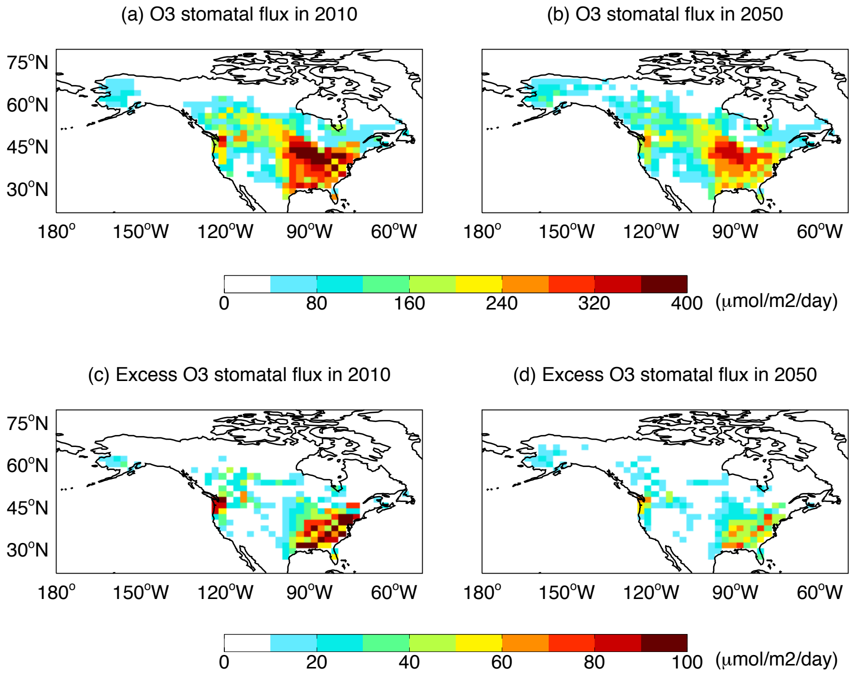
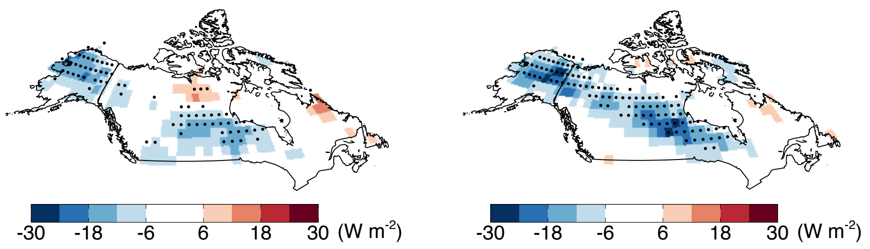
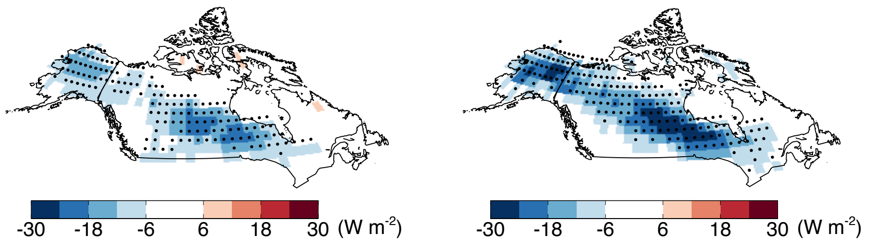


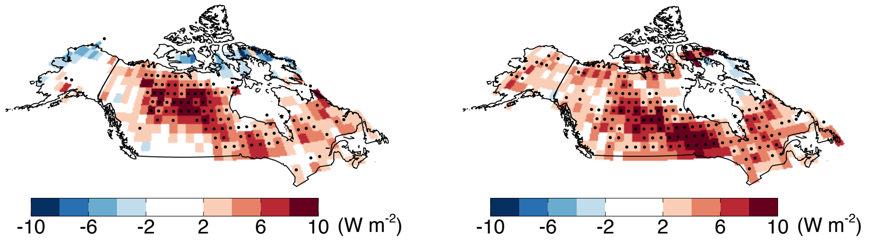
Figure 8. Simulated summertime O_3 stomatal fluxes in boreal North America. Results shown are the (a, b) mean and (c, d) excess flux at (a, c) 2010 and (b, d) 2050. Simulated $[O_3]$ includes contributions from both wildfire and non-fire emissions. Excess O_3 stomatal flux is calculated as the difference between the stomatal flux and a PFT-specific threshold as defined in Sitch et al. (2007).


(a) ΔSW_tot by fire aerosol in 2010

(b) ΔSW_tot by fire aerosol in 2050


(c) ΔSW_dir by fire aerosol in 2010

(d) ΔSW_dir by fire aerosol in 2050


(e) ΔSW_dif by fire aerosol in 2010

(f) ΔSW_dif by fire aerosol in 2050

Figure 9. Changes in surface radiative fluxes induced by wildfire aerosols in boreal North America. Results shown are for the changes in summertime (June-August) (a, b) total, (c, d) direct, and (e, f) diffuse solar radiation at surface caused by aerosols from wildfire emissions at (a, c, e) present day and (b, d, f) midcentury. Significant changes (p<0.05) are marked with black dots. Results for 2010 are calculated as (F10AERO - F10CTRL). Results for 2050 are calculated as (F50AERO - F50CTRL).

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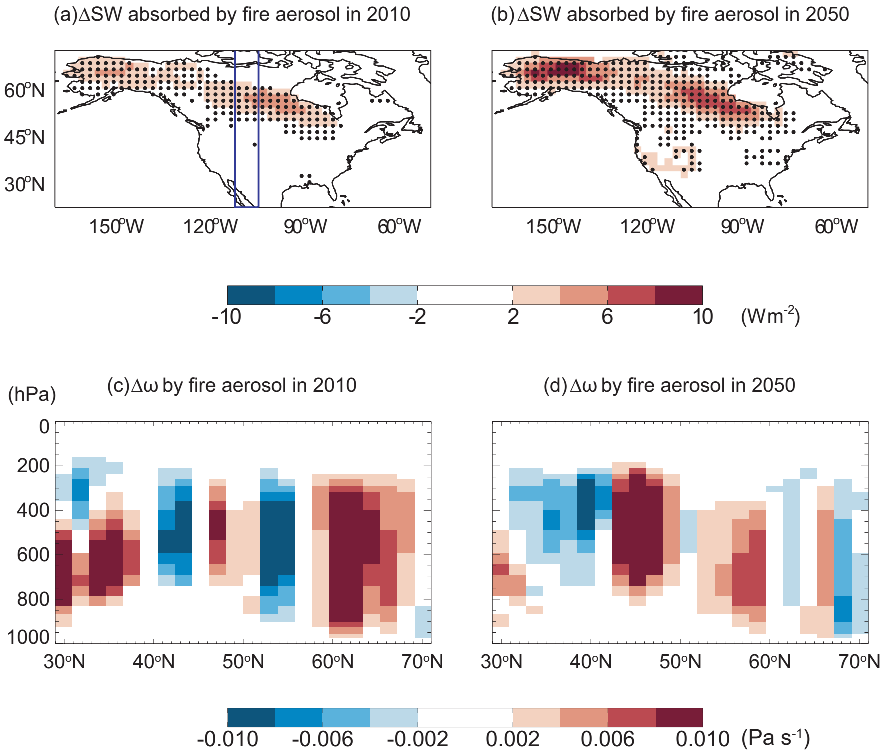

Figure 10. Predicted (a, b) absorption of shortwave radiation and (c, d) perturbations in vertical velocity by wildfire aerosols at (a, c) present day and (b, d) midcentury. The absorption of shortwave radiation is calculated as the differences of radiative perturbations between top of atmosphere and surface. Vertical velocity is calculated as the longitudinal average between 105°W and 112.5°W (two blue lines in a). Positive (negative) values indicate descending (rising) motion. Results for the 2010s are calculated as (F10AERO - F10CTRL). Results for the 2050s are calculated as (F50AERO - F50CTRL). Significant changes ($p < 0.05$) in (a, b) are indicated as black points.

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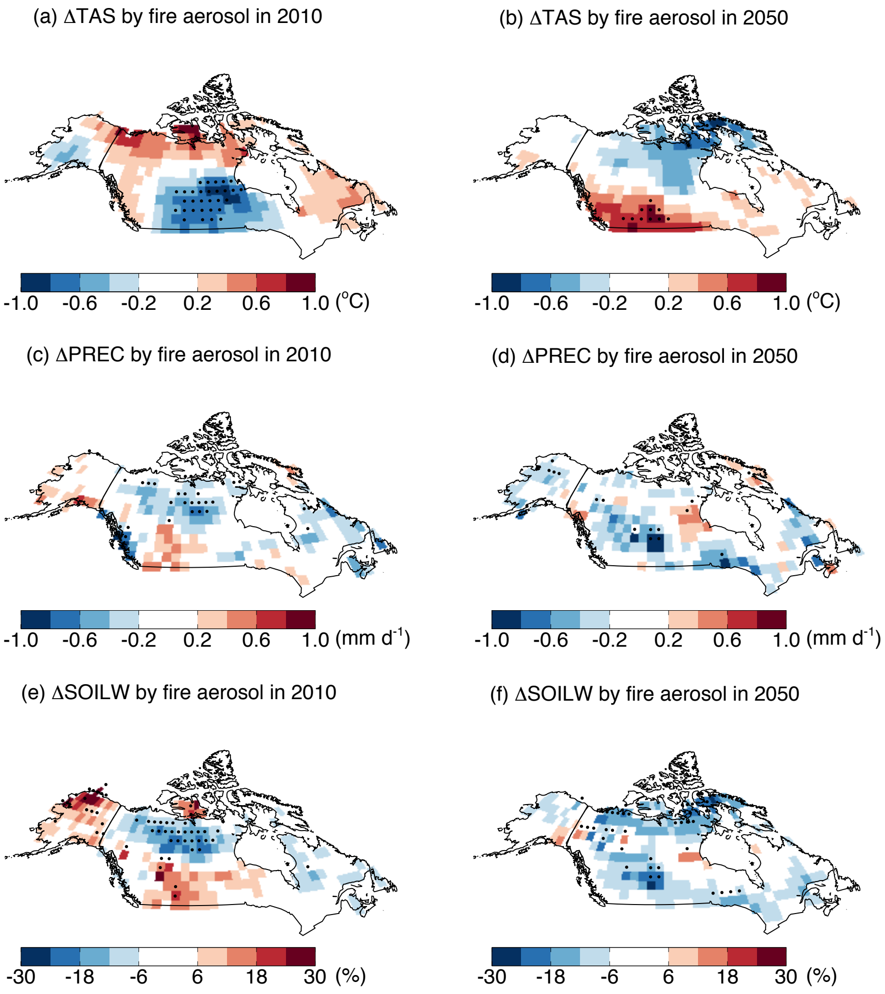

Figure 11. Predicted changes in summertime (a, b) surface air temperature, (c, d) precipitation, and (e, f) soil water content at surface caused by aerosols from wildfire emissions at (a, c, e) present day and (b, d, f) midcentury. Results for temperature and precipitation are shown as absolute changes. Results for soil water are shown as relative changes. Results for the 2010s are calculated as (F10AERO - F10CTRL). Results for the 2050s are calculated as (F50AERO - F50CTRL). Significant changes (p<0.05) are marked with black dots.

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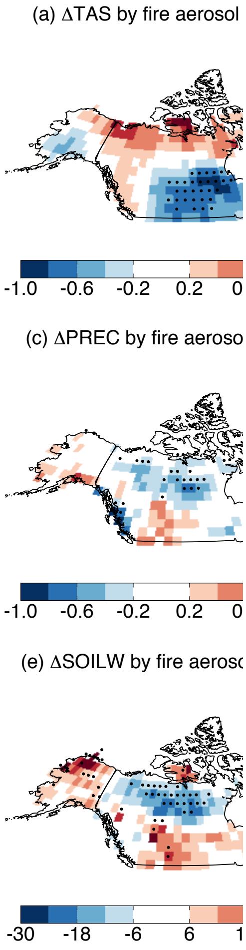

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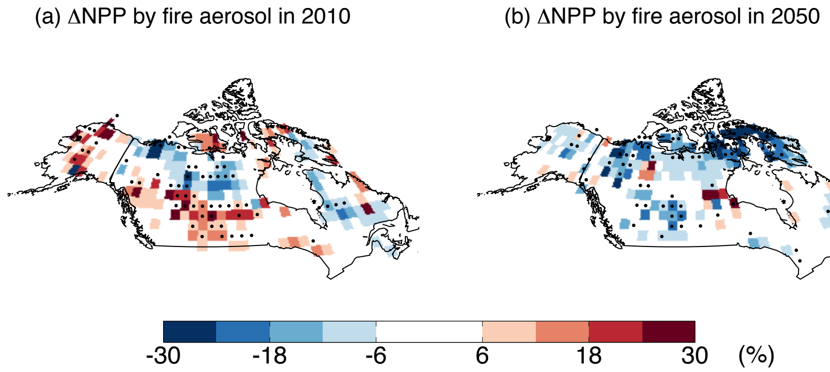

Figure 12. Predicted percentage changes in summer NPP caused by wildfire aerosols at (a) present day and (b) midcentury. Results for the 2010s are calculated as (F10AERO/F10CTRL - 1) × 100%. Results for the 2050s are calculated as (F50AERO/F50CTRL - 1)×100%. Significant changes ($p<0.05$) are marked with black dots.

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