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 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."

- 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).

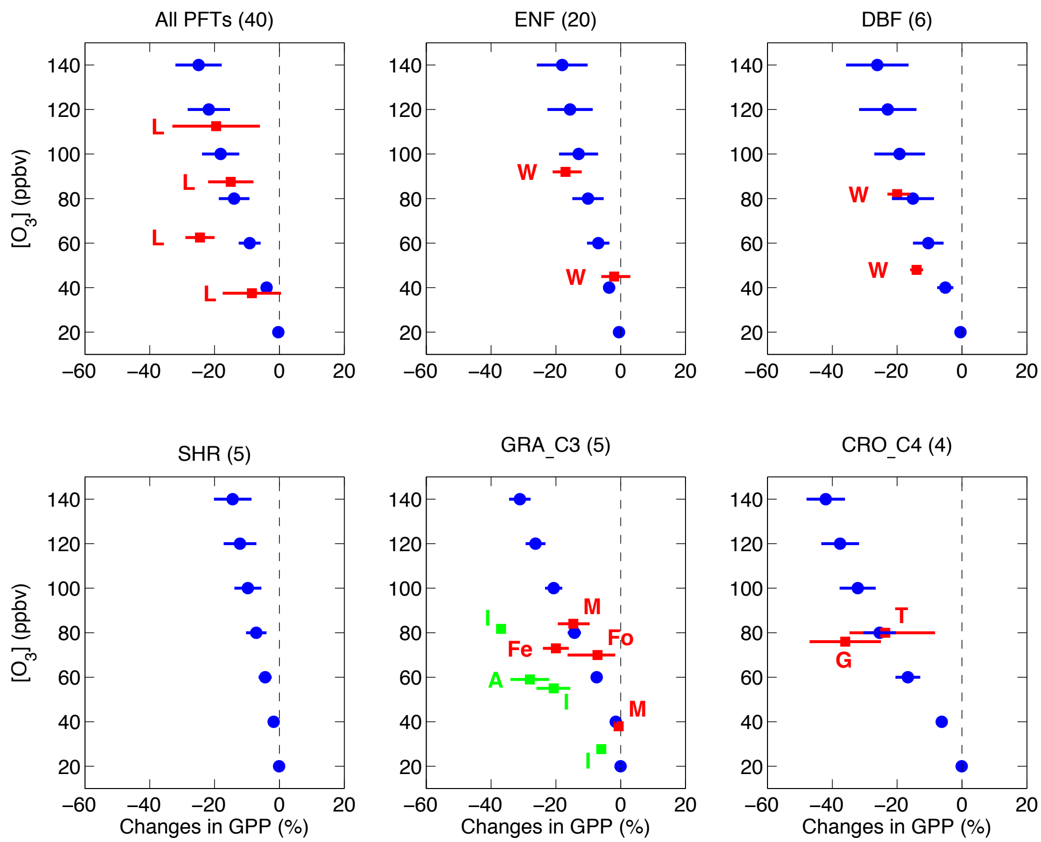

Figure R1. Changes in GPP for all and individual PFTs in the presence of different levels of [O_3] as simulated by the vegetation model. Simulations are performed at 40 North American Carbon Program (NACP) sites with a fixed [O_3] for either low or high O_3 sensitivity. The short blue lines show the 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)

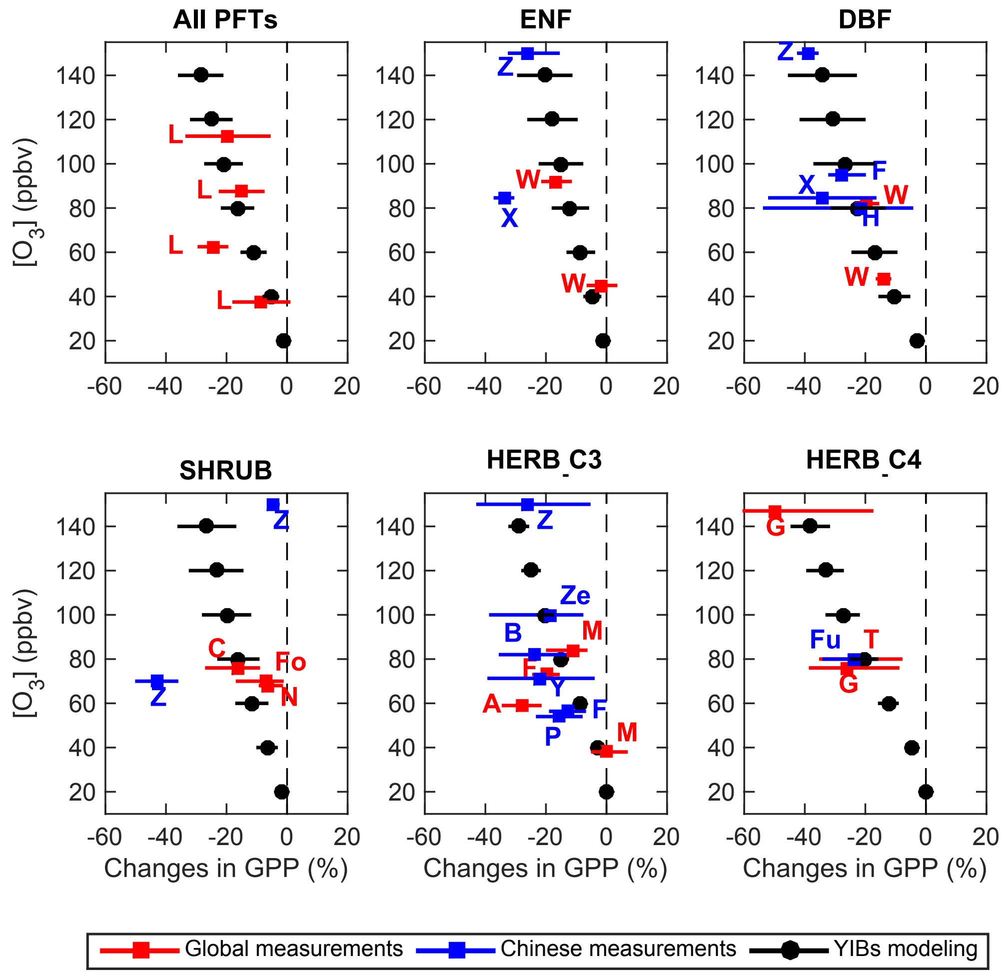

Figure R2. Evaluation of O_3 damaging scheme over China. For more details, please refer to Yue et al. (2017).

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.

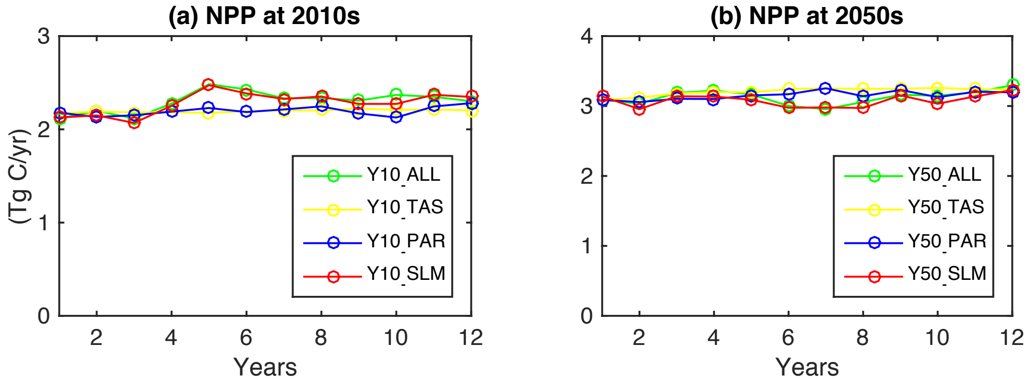

Figure R3. Simulated annual NPP over boreal North America at (a) 2010s and (b) 2050s.

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)

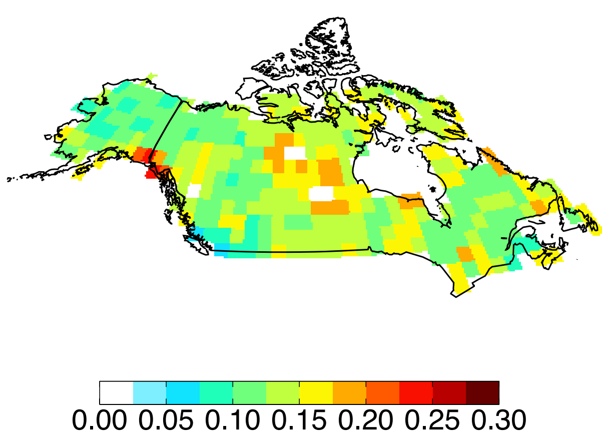

Figure R4. Observed summer AOD from MISR *l. 326 What is compared here? 24 hr mean over June, July, August? Did the authors compare at the measurement altitude? I would recommend to focus on daytime values, as more relevant for ozone damage and usually less local conditions .The Sitch approach requires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

References

Alvarado, M. J., Logan, J. A., Mao, J., Apel, E., Riemer, D., Blake, D., Cohen, R. C., Min, K. E., Perring, A. E., Browne, E. C., Wooldridge, P. J., Diskin, G. S., Sachse, G. W., Fuelberg, H., Sessions, W. R., Harrigan, D. L., Huey, G., Liao, J., Case-Hanks, A., Jimenez, J. L., Cubison, M. J., Vay, S. A., Weinheimer, A. J., Knapp, D. J., Montzka, D. D., Flocke, F. M., Pollack, I. B., Wennberg, P. O., Kurten, A., Crounse, J., St Clair, J. M., Wisthaler, A., Mikoviny, T., Yantosca, R. M., Carouge, C. C., and Le Sager, P.: Nitrogen oxides and PAN in plumes from boreal fires during ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite observations, Atmos. Chem. Phys., 10, 9739-9760, doi:10.5194/Acp-10-9739-2010, 2010.

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

Andreae, M. O., and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochemical Cycles, 15, 955-966, 2001.

Balshi, M. S., McGuirez, A. D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J.: Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach, Global Change Biology, 15, 578-600, doi:10.1111/J.1365-2486.2008.01679.X, 2009.

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

Cook, B. I., Miller, R. L., and Seager, R.: Amplification of the North American ''Dust Bowl'' drought through human-induced land degradation, Proceedings of the National Academy of Sciences of the United States of America, 106, 4997-5001, doi:10.1073/pnas.0810200106, 2009.

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

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

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

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C., and Sohlberg, R. A.: Global Percent Tree Cover at a Spatial Resolution of 500 Meters:

First Results of the MODIS Vegetation Continuous Fields Algorithm, Earth Interactions, 7, 1-15, doi:10.1175/1087-3562(2003)007<0001:GPTCAA>2.0.CO;2, 2003.
Heyder, U., Schaphoff, S., Gerten, D., and Lucht, W.: Risk of severe climate change impact on the terrestrial biosphere, Environmental Research Letters, 6, 034036, doi:10.1088/1748-9326/6/3/034036, 2011.
Kim, J. B., Monier, E., Sohngen, B., Pitts, G. S., Drapek, R., McFarland, J., Ohrel, S., and Cole, J.: Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios, Environmental Research Letters, 12, 045001, doi:10.1088/1748-9326/aa63fc, 2017.
Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., and Safranyik, L.: Mountain pine beetle and forest carbon feedback to climate change, Nature, 452, 987-990, doi:10.1038/nature06777, 2008.
Liu, Y.: Enhancement of the 1988 northern U.S. drought due to wildfires, Geophysical Research Letters, 32, L10806, doi:10.1029/2005GL022411, 2005.
Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P. M.: Impact of changes in diffuse radiation on the global land carbon sink, Nature, 458, 1014-1017, doi:10.1038/Nature07949, 2009.
Moritz, M. A., Parisien, M.-A., Batllori, E., Krawchuk, M. A., Dorn, J. V., Ganz, D. J., and Hayhoe, K.: Climate change and disruptions to global fire activity, Ecosphere, 3, doi:10.1890/ES11-00345.1, 2012.
Pacifico, F., Folberth, G. A., Sitch, S., Haywood, J. M., Rizzo, L. V., Malavelle, F. F., and Artaxo, P.: Biomass burning related ozone damage on vegetation over the Amazon forest: a model sensitivity study, Atmospheric Chemistry and Physics, 15, 2791-2804, doi:10.5194/acp-15-2791-2015, 2015.
Schmidt, G. A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G. L., Aleinov, I., Bauer, M., Bauer, S. E., Bhat, M. K., Bleck, R., Canuto, V., Chen, Y. H., Cheng, Y., Clune, T. L., Del Genio, A., de Fainchtein, R., Faluvegi, G., Hansen, J. E., Healy, R. J., Kiang, N. Y., Koch, D., Lacis, A. A., LeGrande, A. N., Lerner, J., Lo, K. K., Matthews, E. E., Menon, S., Miller, R. L., Oinas, V., Oloso, A. O., Perlwitz, J. P., Puma, M. J., Putman, W. M., Rind, D., Romanou, A., Sato, M., Shindell, D. T., Sun, S., Syed, R. A., Tausnev, N., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M. S., and Zhang, J. L.: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive, Journal of Advances in Modeling Earth Systems, 6, 141-184, doi:10.1002/2013ms000265, 2014.
Sitch, S., Cox, P. M., Collins, W. J., and Huntingford, C.: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, Nature, 448, 791-794, doi:10.1038/Nature06059, 2007.
Strada, S., Unger, N., and Yue, X.: Observed aerosol-induced radiative effect on plant productivity in the eastern United States, Atmospheric Environment, 122, 463–476, doi:10.1016/j.atmosenv.2015.09.051, 2015.
van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration

pathways: an overview, Climatic Change, 109, 5-31, doi:10.1007/s10584-011-0148-z, 2011.
Wittig, V. E., Ainsworth, E. A., and Long, S. P.: To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments, Plant Cell and Environment, 30, 1150-1162, doi:10.1111/J.1365-3040.2007.01717.X, 2007.
Yeh, S.-W., Yim, B. Y., Noh, Y., and Dewitte, B.: Changes in mixed layer depth under climate change projections in two CGCMs, Climate Dynamics, 33, 199-213, doi:10.1007/s00382-009-0530-y, 2009.
Yue, X., Mickley, L. J., Logan, J. A., and Kaplan, J. O.: Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century, Atmos. Environ., 77, 767-780, doi:10.1016/J.Atmosenv.2013.06.003, 2013.
Yue, X., and Unger, N.: Ozone vegetation damage effects on gross primary productivity in the United States, Atmospheric Chemistry and Physics, 14, 9137-9153, doi:10.5194/acp-14-9137-2014, 2014.
Yue, X., Mickley, L. J., Logan, J. A., Hudman, R. C., Martin, M. V., and Yantosca, R. M.: Impact of 2050 climate change on North American wildfire: consequences for ozone air quality, Atmospheric Chemistry and Physics, 15, 10033-10055, doi:10.5194/acp-15-10033-2015, 2015.
Yue, X., Keenan, T. F., Munger, W., and Unger, N.: Limited effect of ozone reductions on the 20-year photosynthesis trend at Harvard forest, Global Change Biology, 22, 3750-3759, doi:10.1111/gcb.13300, 2016.
Yue, X., Unger, N., Harper, K., Xia, X., Liao, H., Zhu, T., Xiao, J., Feng, Z., and Li, J.: Ozone and haze pollution weakens net primary productivity in China, Atmospheric Chemistry and Physics, 17, 6073-6089, doi:10.5194/acp-17-6073-2017, 2017.